School of Civil, Environmental and Mining Engineering

Thesis submitted for the Degree of
Doctor of Philosophy (PhD)

The Impact of Rolling Dynamic Compaction

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February 2020

This thesis is dedicated to my wife

Brooke

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Abstract

Rolling dynamic compaction (RDC) consists of a non-circular module of 3, 4 or 5 sides, that rotates as it is towed, causing it to fall to the ground and compact it dynamically. There is currently little guidance available for geotechnical practitioners regarding the depths of improvement that are possible in varying soil conditions. Current practice dictates that practitioners rely on personal experiences or available published project case studies that are limited in scope and applicability as they are typically aimed at achieving a project specification. There is a reluctance to adopt RDC as a ground improvement technique as there is uncertainty regarding its limitations and capabilities.

The underlying objective of this research is to quantify the ground response of the 8-tonne 4-sided impact roller. This research has used full-scale field trials and bespoke instrumentation to capture the ground response due to dynamic loading in homogeneous soil conditions. It was found that towing speed quantifiably influenced the energy imparted into the ground, with towing speeds of 10-12 km/h found to be optimal.

Targeted full-scale field trials were undertaken to quantify the depth of improvement that can be achieved using RDC. Field results were compared to a number of published case studies that have used the 8-tonne 4-sided roller. Significantly, separate equations have been developed to allow practitioners to predict the depths that can be improved for the two major applications of RDC: improving ground in situ and compacting soil in thick layers.

Finally, the in-ground response of RDC was measured using buried earth pressure cells (EPCs) and accelerometers. Force was determined from the measured change in stress recorded by EPCs whereas displacement was inferred from the double integration of acceleration-time data to give real-time load-displacement behaviour resulting from a single impact. The energy delivered to the soil by RDC is quantified in terms of the work done, defined as the area under the force versus displacement curve.

Quantifying the energy imparted into the ground in terms of the work done is a key difference from past studies. Previous estimates of the energy delivered by impact roller at the ground surface has traditionally been predicted based on either gravitational potential energy (12 kJ) or kinetic energy (30 kJ to 54 kJ for typical towing speeds of 9 to 12 km/h). The two different values have caused confusion amongst practitioners.

This research has determined that the maximum energy per impact that the 8-tonne 4-sided impact roller is capable of imparting to the ground is between 22 kJ to 30 kJ for typical towing speeds of 9 to 12 km/h.

Quantifying the effectiveness of the 8-tonne 4-sided impact roller in terms of towing speed, depth of influence, and soil response measured via real-time measurements will lead to a greater understanding of the practical applications and limitations of RDC. Significantly, more accurate assessments of RDC will reduce design conservatism and construction costs, reduce instances where the predicted ground improvement does not occur and enable RDC to be used and applied with greater confidence.

Statement of Originality

I certify that this work contains no material which has been accepted for the award of any other degree or diploma in my name, in any university or other tertiary institution and, to the best of my knowledge and belief, contains no material previously published or written by another person, except where due reference has been made in the text. In addition, I certify that no part of this work will, in the future, be used in a submission in my name, for any other degree or diploma in any university or other tertiary institution without the prior approval of the University of Adelaide and where applicable, any partner institution responsible for the joint-award of this degree.

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19/02/2020

Brendan T. Scott

Date

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I wish to thank the School of Civil, Environmental and Mining Engineering for their support and patience during my candidature. I wish to acknowledge the support given to me by the School's laboratory and instrumentation staff (past and present), in particular: Mr. Gary Bowman, Mr. Ian Cates; Mr. Terry Cox; Mr. Simon Golding; Mr. Tom Stanef; and Mr. Stan Woithe, who each contributed to this research through their dedication, persistence and hard work in developing equipment aimed at capturing the ground response of the impact roller. It took many trials, failures and refinements to develop the bespoke software program and data acquisition system, earth pressure cell configuration and accelerometers that were used in this research.

The generous support from Broons, in particular company Director, Mr. Stuart Bowes is greatly appreciated. The time, patience and support (financial and in-kind), that Broons provided me, has given me many opportunities to conduct research in different soil conditions and at various sites across Australia. The costs and logistics of providing access to the impact roller, personnel to operate it, hire of earthmoving equipment, flights, meals and accommodation in many parts of Australia are significant; the work undertaken in this thesis would not have been possible but for their contribution. The support of Broons staff who have assisted with and helped organise dedicated research-intensive field trials is greatly appreciated, in particular, Mr. Bruce Constable, Mr. Guy Bowden, Mr. Angus Bowes, Mr. John Drogemuller and Mr. Ron Hanson.

I wish to acknowledge the assistance of the following organisations for who have allowed me to work on impact rolling field trials and compaction projects at sites that were under their control: Ascon, BAM Clough, Bardavcol, Bechtel, Collins Transport, Ertech, Evansbuilt, Flinders Ports, Hansen Yuncken, HWE Mining, Leighton Contractors, Monarto Quarries, Puma Roseneath, Terra Forma Civil, Territory Iron and Windsor Earthmoving. Having access to the 4-sided impact roller in a range of site conditions across Australia has significantly helped my understanding and provided invaluable practical experience for which I am very grateful.

I wish to thank my colleague Dr. Yien Lik Kuo for his friendship, suggestions and encouragement. In addition, I would like to thank Ms. Cathy Cates for her assistance with typing and formatting this document.

Since 2010, a number of final year undergraduate students have assisted with field work related to this research. I would like to thank the following students for their enthusiasm and hard work in the field: Tom Bierbaum, Gianfranco Canala, Stefan Chenoweth, Jordan Colbert, Chris Gauro, Rob Lane, Dapeng Liu, Jackson March, Nicole Mentha, Jessica Piotto, Simon Pointon, Julianne Saw, Chris Smith, Richard Strapps, Aidan Symons, Tom Treloar, Ross Vince and Penelope Wrightson.

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Chapter 1: Introduction and General Overview

1.1 Introduction

Rolling Dynamic Compaction (RDC) imparts energy to the ground via the use of a heavy non-circular module of 3, 4 or 5 sides that rotates as it is towed, causing it to fall to the ground and compact it dynamically. It is commonly used for improving ground in situ, but can also be adopted for compacting soil that is placed in thick loose layers.

RDC is a ground improvement technique that is used to improve a soil's shear strength and stiffness, or reduce its permeability. RDC has been used in earthworks applications involving the improvement of poor quality ground, the compaction of thick layers for in-filling deep excavations, the proof rolling of road and subgrade materials and the compaction of reclaimed land. RDC has also been used to construct haul roads in the mining industry, as well as in agriculture, where it is used to compact soil in irrigated areas to reduce soil permeability and conserve water.

Even though RDC evolved during the 1970s, there is significant scope for the technical understanding of RDC to be further improved. Whilst there have been many case studies published over the years, limited research is a contributing reason why this technology has not been applied more universally.

1.2 Background

The following book chapter and conference papers were written as part of this candidature, and provide background context and a review of literature that supports the papers in the main body of this thesis.

Scott, B.T. & Jaksa, M.B. (2015). The effectiveness of rolling dynamic compaction – a field based study. In B. Indraratna, J. Chu, & C. Rujikiatkamjorn (Eds.), Ground Improvement Case Histories: Compaction, Grouting and Geosynthetics, pp. 429-452, Kidlington, Oxford: Elsevier. doi: 10.1016/B978-0-08-100698-6.00014-3.

A copy of this book chapter is included in Appendix A.

Scott, B.T., Jaksa, M.B. & Kuo, Y.L. (2012). Use of proctor compaction testing for deep fill construction using impact rollers. International Conference on Ground Improvement and Ground Control, Wollongong, Australia, pp. 1107-1112.

A copy of this conference paper is included in Appendix B.

Scott, B.T. & Jaksa, M.B. (2008). Quantifying the influence of rolling dynamic compaction. Proceedings 8th Young Geotechnical Professionals Conference, Wellington, New Zealand, pp. 199-204.

A copy of this conference paper is included in Appendix C.

An extended literature review covering the history and development, compaction theory, applications and verification of RDC is included in the book chapter written by the author that is included in Appendix A. A key knowledge gap identified from this literature review is the variable and often unpredictable depth to which ground can be improved is one of the biggest limitations on the use of RDC, particularly when improving in situ material, as a back-up plan may need to be implemented if ground improvement is not achieved to the required (or expected) depths.

Whilst there are a number of published case studies [Clifford (1978), Avalle (2004), Avalle and Young (2004), Avalle (2007), Avalle and Grounds (2004), Avalle and Mackenzie (2005), Avalle and Carter (2005), Avalle (2007), Scott and Suto (2007), Whiteley and Caffi (2014) and Scott and Jaksa (2014)] that each describe the performance of the 4-sided 8-tonne ‘impact roller’ in specific site conditions, there is little published information that predicts depths of treatment for varying soil conditions. It is often up to the project engineer to predict if the use of RDC will improve the ground sufficiently for a desired project outcome. Unless site conditions match well with a previously published case study, the extent of published information that is currently available is of limited help to project engineers. As a result, the lack of guidance that is available restricts the use of RDC due to unknown and variable depths of improvement that can be achieved. Whilst RDC is capable of compacting large soil volumes quickly and efficiently, there is a need to understand and quantify its limitations, this is particularly important at marginal or difficult sites.

Clifford & Bowes (1995) predicted the impact energy of the square impact roller based on kinetic energy and concluded that the speed of the module striking the ground was the most significant parameter contributing to the energy imparted by the module. This is in stark contrast to the findings of Heyns (1998) who found that the dominant component of the energy delivered by a 3-sided impact roller was due to potential energy. There is clearly a need to determine if potential, kinetic, or some combination thereof, is appropriate for quantifying the energy imparted to the ground by RDC.

The paper in Appendix B discusses a review of literature regarding compaction theory and the suitability of RDC for compacting fill in thick layers. The key knowledge gaps from this paper include that whilst RDC is able to compact large volumes of soil effectively and efficiently, there is a lack of understanding regarding how the field performance relates to basic laboratory tests such as the standard and modified proctor compaction tests. There is a need to quantify the energy that RDC applies to the ground and the resultant ground response.

The paper in Appendix C was written prior to commencing the majority of field work associated with this research, and focusses on summarising knowledge gaps regarding the depths that can be improved by RDC. Whilst acknowledging that RDC has been used successfully on many projects in Australia and overseas, this paper discusses that there are cases where the expected ground improvement has not occurred, and highlights the lack of information indicating what the zone of influence of the roller is, and also regarding how much compactive effort is required for different soil conditions.

1.3 Research Gaps

Although RDC has been used on many projects in Australia and overseas, the current poor understanding of RDC theory is a key limitation that restricts its use. Unless geotechnical practitioners have personal experience with RDC or are dealing with ground conditions that are comparable to a published case study, there is a reluctance to try something different when there are ‘tried and tested’ approaches that could be adopted, even if they are less cost effective than RDC. Widespread adoption of RDC by project engineers will not occur until such time that the benefits and limitations of RDC are better understood. There is significant scope for the practical application of RDC to be improved, as current knowledge in this field has had little progression since its inception in the 1970s.

Firstly, there is a need to quantify what, if any, effect that towing speed has on the effectiveness of RDC. RDC imparts energy to the ground via the use of a heavy non-circular module that impacts the ground. At project sites involving mixed soils, isolating and quantifying the effects of a single constraint such as towing speed is difficult due to soil heterogeneity. To ensure that the effects of towing speed are not concealed by other variables, there is a need to vary towing speed in homogeneous soil conditions in dedicated research field trials.

Secondly, there is a limited depth to which ground improvement using RDC is effective. There is little published information quantifying depths to which ground can be improved, and how that may vary depending upon the soil type. Additionally, there is confusion between two common applications of RDC: (1) compacting soil in thick lifts and (2) improving soil in situ; these are two distinctly different applications of RDC that must be treated separately. This research will distinguish between the two and will provide recommended improvement depths for both applications using the results of research field trials and published case studies over the past four decades.

Thirdly, this thesis introduces a new approach to quantify the ground response to RDC via measuring stress (which can be converted to load) using buried earth pressure cells, and measuring the acceleration response due to RDC via accelerometers placed in three orthogonal directions. Double integration of the acceleration-time response allows displacement to be inferred. This research will quantify the in-ground load-displacement response of RDC in real-time that traditional pre- and post-compaction testing is unable to do.

1.4 Research Objectives

The underlying objective of this research is to quantify the impact of RDC. This will enable greater understating of RDC theory so that its application and validation in the compaction and improvement of poor quality ground can be achieved more appropriately and with greater confidence.

The objectives of this research are to:

1. Determine the effects of towing speed for the 4-sided impact roller. Trials will be undertaken using buried earth pressure cells to quantify the differences in

pressure imparted into the ground at various towing speeds in homogeneous soil conditions.

2. Quantify the energy imparted into the ground from a single module impact. Using the results from [1] and the findings from past literature, estimates for the energy that is imparted to the ground from a single impact will be refined.

3. Quantify the depth of improvement of RDC. Trials will be undertaken in homogeneous soil conditions, where commonly used testing methods will be combined with instrumentation that is embedded at various depths in the ground to quantify the depth of improvement of the 4-sided impact roller.

4. Determine if existing mathematical models for deep dynamic compaction that predict the depth of improvement based on the energy imparted into the ground are appropriate, or, can be modified to suit RDC.

5. Measure the in-ground load-displacement response of RDC for a single module impact, and for consecutive module impacts. This will involve building on the work undertaken in [1] to [4] and conducting further field trials using buried earth pressure cells and accelerometers.

1.5 Structure of Thesis

This thesis consists of three journal papers that form the main body of this thesis. Other publication material, one book chapter and six conference papers that the author has written during candidature have been included as Appendices, as they form part of the body of work and are relevant to the research objectives.

1.5.1 Journal Papers

The following journal publications are included in this thesis and have been prepared as a result of this research:

Influence of towing speed on the effectiveness of Rolling Dynamic Compaction

Scott, B.T., Jaksa, M.B. & Mitchell, P.W. (2020).

Journal of Rock Mechanics and Geotechnical Engineering, 12 (1), 126-134.

https://doi.org/10.1016/j.jrmge.2019.10.003

The first journal paper "Influence of towing speed on the effectiveness of Rolling Dynamic Compaction" summarises two full-scale field trials that used buried instrumentation to capture the effects of RDC in real-time to quantify the changes in stress imparted to the ground with increasing towing speed. This paper proposes that the energy imparted to the ground due to RDC should be considered in terms of work done, rather than the use of either gravitational potential energy, or kinetic energy (as is current practice).

Depth of influence of rolling dynamic compaction

Scott, B.T., Jaksa, M.B. & Mitchell, P.W. (2019).

Institution of Civil Engineers, Ground Improvement.

https://doi.org/10.1680/jgrim.18.00117

The second journal paper "Depth of influence of rolling dynamic compaction" addresses arguably the most common question associated with RDC "to what depths can RDC improve soil?" This paper uses the results of a full-scale field trial that was undertaken to determine the depths of homogeneous soil that could be significantly improved by RDC. This paper augments deep dynamic compaction theory and provides relationships for estimating the depths capable of being improved in situ, and layer thicknesses capable of being compacted by RDC. Improving ground in situ and compacting soil in thick layers are two distinctly different applications of RDC that must be treated separately, but are often confused. The relationships that are proposed are in broad agreement with the results of published case studies involving the 8-tonne 4-sided impact roller over the past four decades.

Ground response to rolling dynamic compaction

Scott, B.T., Jaksa, M.B. & Mitchell, P.W. (2019).

Institution of Civil Engineers, Geotechnique Letters, 9 (2), 99-105.

https://doi.org/10.1680/jgele.18.00208

The third journal paper "Ground response to rolling dynamic compaction" captures the in-ground response using bespoke instrumentation in homogeneous soil. The change in vertical stress due to RDC was measured using an earth pressure cell and the acceleration response determined in three orthogonal directions. Rather than rely on testing methods that are undertaken pre- and/or post-compaction, this paper quantified the dynamic behaviour of the soil beneath the ground surface in real-time, enabling the loading and unloading of the soil to be quantified for single and multiple module impacts.

1.5.2 Book Chapter

The following book chapter is included in this thesis and was prepared as a result of this research:

<u>The effectiveness of rolling dynamic compaction – a field based study</u>.

Scott, B.T. & Jaksa, M.B. (2015).

In B. Indraratna, J. Chu, & C. Rujikiatkamjorn (Eds.), Ground Improvement Case Histories: Compaction, Grouting and Geosynthetics, pp. 429-452, Kidlington, Oxford: Elsevier. doi: 10.1016/B978-0-08-100698-6.00014-3.

A copy of this book chapter is included in Appendix A.

1.5.3 Conference Papers

The following conference papers are included in this thesis and were prepared as a result of this research and are of relevance to the research objectives of this thesis:

<u>Use of proctor compaction testing for deep fill construction using impact rollers</u>.

Scott, B.T., Jaksa, M.B. & Kuo, Y.L. (2012).

International Conference on Ground Improvement and Ground Control, Wollongong, Australia, pp. 1107-1112.

A copy of this conference paper is included in Appendix B.

<u>Quantifying the influence of rolling dynamic compaction</u>.

Scott, B.T. & Jaksa, M.B. (2008).

Proceedings 8th Young Geotechnical Professionals Conference, Wellington, New Zealand, pp. 199-204.

A copy of this conference paper is included in Appendix C.

Evaluating rolling dynamic compaction of fill using CPT.

Scott, B.T. & Jaksa, M.B. (2014).

Proceedings 3rd International Symposium on Cone Penetration Testing, Las Vegas, USA, pp. 941-948.

A copy of this conference paper is included in Appendix D.

Mining applications and case studies of rolling dynamic compaction.

Scott, B.T. & Jaksa, M.B. (2012).

Proceedings 11th Australia New Zealand Conference on Geomechanics, Melbourne, Australia, pp. 961-966.

A copy of this conference paper is included in Appendix E.

Verification of an impact rolling compaction trial using various in situ testing methods.

Scott, B.T., Jaksa, M.B. & Syamsuddin, E. (2016).

Proceedings 5th International Conference Geotechnical and Geophysical Site Characterisation, Gold Coast, Australia, pp. 735-740.

A copy of this conference paper is included in Appendix F.

Ground energy and impact of rolling dynamic compaction - results from research test site.

Avalle, D.L., Scott, B.T., & Jaksa, M.B. (2009).

Proceedings 17th International Conference on Soil Mechanics and Geotechnical Engineering, Cairo, Egypt, Vol. 3, pp. 2228-2231.

A copy of this conference paper is included in Appendix G.

1.5.4 Publications not included in thesis

The following publications are not included in this thesis as they are not directly relevant to the research objectives of this thesis, or, the author was not the primary author of the paper. However, they form part of the wider research contribution to understanding RDC by the author of this thesis:

Case study of ground improvement at an industrial estate containing uncontrolled fill.

Scott, B. T & Suto, K. (2007).

Proceedings 10th Australia New Zealand Conference on Geomechanics, Brisbane, Australia, Vol. 2, pp. 150-155.

3D treatment of MASW data for monitoring ground improvement at an uncontrolled fill site.

Suto, K., & Scott, B. T. (2009).

Proceedings 20th International Geophysical Conference and Exhibition. Adelaide, South Australia, 5 pp.

Quantifying the zone of influence of the impact roller.

Jaksa, M. B., Scott, B. T., Mentha, N. L., Symons, A. T., Pointon, S. M., Wrightson, P. T. & Syamsuddin, E. (2012).

Proceedings International Symposium on Recent Research, Advances and Execution Aspects of Ground Improvement Works, Brussels, Belgium, Vol. 2, pp. 41–52.

Assessing the effectiveness of rolling dynamic compaction.

Kuo, Y., Jaksa, M., Scott, B., Bradley, A., Power, C., Crisp, A., & Jiang, J. (2013).

Proceedings of the 18th International Conference on Soil Mechanics and Geotechnical Engineering, Paris, France, pp. 1309-1312.

Physical modeling of rolling dynamic compaction.

Chung, O. Y., Scott, B. T., Kuo, Y. L., Jaksa, M. B. & Airey, D. W. (2017).

Proceedings of the 19th International Conference on Soil Mechanics and Geotechnical Engineering, Seoul, Korea, pp. 905-908.

Comparing the relative merits of dynamic compaction, rapid impact compaction and impact rolling.

Avalle, D., Scott, B., & Bouazza, A. (2019).

Proceedings 13th Australia New Zealand Conference on Geomechanics, Perth, Australia, pp. 815-819.

Quantifying the effect of rolling dynamic compaction.

Jaksa, M., Airey, D., Scott, B., Kuo, Y. L., Ranasinghe, T., Bradley, A., Chung, O. Y., Li, Y., Chen, Y. (2019).

Proceedings of the 4th World Congress on Civil, Structural and Environmental Engineering (CSEE'19) Rome, Italy, ICGRE Keynote 1-1 to 1-20, doi: 10.11159/icgre19.1.

Chapter 2: The effect of towing speed

Introduction

An understanding of how towing speed contributes towards the effectiveness of RDC is an important step to improving the understanding of this ground improvement technique. This paper quantifies the influence of towing speed in homogeneous soil conditions.

In the journal paper in Chapter 2, two full-scale field trials that used buried instrumentation to capture the effects of RDC in real-time, are reported. Homogeneous soils were used in both trials to control other variables and isolate the effect of towing speed. The findings from this paper indicate that towing speed does influence the stress that is imparted to the ground, and highlights the need for a towing speed range to be specified for RDC applications.

This paper proposes that the energy imparted to the ground due to RDC should be considered in terms of work done, rather than the use of either gravitational potential energy, or kinetic energy (as is current practice). The use of gravitational potential energy theory suggests a maximum impact energy of 12 kJ, whereas if kinetic energy theory is used for a towing speed of 12 km/h, then the maximum estimated energy per impact would be 54 kJ. However, this paper has refined the maximum estimated energy that the 8-tonne 4-sided impact roller imparts to the ground is between 22 kJ and 30 kJ for typical towing speeds of 9 and 12 km/h, respectively.

List of Manuscripts

Scott, B.T., Jaksa, M.B. & Mitchell, P.W. (2020). Influence of towing speed on the effectiveness of Rolling Dynamic Compaction. *Journal of Rock Mechanics and Geotechnical Engineering*, 12(1): 126-134. https://doi.org/10.1016/j.jrmge.2019.10.003

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Name of Principal Author (Candidate)	Brendan Scott		
Contribution to the Paper	Performed site work, analysis and interpretation of site data, wrote manuscript.		
Overall percentage (%)	90		
Certification:	This paper reports on original research I conducted during the period of my Higher Degree by Research candidature and is not subject to any obligations or contractual agreements with a third party that would constrain its inclusion in this thesis. I am the primary author of this paper.		
Signature		Date	18/4/2019

Co-Author Contributions

By signing the Statement of Authorship, each author certifies that:

i. the candidate's stated contribution to the publication is accurate (as detailed above);

ii. permission is granted for the candidate in include the publication in the thesis; and

iii. the sum of all co-author contributions is equal to 100% less the candidate's stated contribution.

Name of Co-Author	Mark Jaksa		
Contribution to the Paper	Provided primary supervision and helped evaluate and edit the manuscript.		
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Name of Co-Author	Peter Mitchell		
Contribution to the Paper	Provided secondary supervision and helped evaluate and edit the manuscript.		
Signature		Date	16 Apr 2019

Influence of towing speed on the effectiveness of Rolling Dynamic Compaction (Paper 1)

Abstract

The influence of towing speed on the effectiveness of the 4-sided impact roller using earth pressure cells (EPCs) is investigated. Two field trials were undertaken; the first trial used three EPCs placed at varying depths between 0.5 m and 1.5 m with towing speeds of 9-12 km/h. The second used three EPCs placed at a uniform depth of 0.8 m, with towing speeds of 5-15 km/h. The findings from the two trials confirmed that towing speed influences the pressure imparted to the ground and hence compactive effort. This paper proposes that the energy imparted to the ground is best described in terms of work done, which is the sum of the change in both potential and kinetic energies. Current practice of using either kinetic energy or gravitational potential energy should be avoided as neither can accurately quantify rolling dynamic compaction (RDC) when towing speed is varied.

2.1 Introduction

Improving the ground is a fundamental and essential part of civil construction. Compaction is a prevalent ground improvement technique that involves increasing the density of soil by means of mechanically applied energy to increase shear strength and stiffness or reduce permeability. This paper is concerned with rolling dynamic compaction (RDC) which involves traversing the ground with a non-circular roller. Typical module designs have 3, 4 or 5 sides. As the module rotates, it imparts energy to the soil as it falls and impacts the ground. More introductory information pertaining to RDC is included in Scott and Jaksa (2015) and Ranasinghe et al. (2017).

At filled sites containing significant soil variability, it can be difficult to quantify the effect of a single variable. Similarly, the inherent soil heterogeneity of natural ground can also influence results, often making it hard to quantify the effect of towing speed alone. To overcome this limitation, two compaction trials that used homogeneous soil conditions are described in this paper. Both trials used buried earth pressure cells (EPCs) and were undertaken at a dedicated research site. Whilst replacing natural soil with fill material and conducting full-scale trials are expensive exercises, particularly where the trial is not part of a client funded project, having full control over a site enabled variables other than towing speed to be held constant. The aim of this paper is to determine the influence, if any, of towing speed on the energy imparted to the ground.

The impact roller was originally developed in South Africa with the intention of improving the properties of granular soils, in particular to identify and improve collapsing sands within 3 m below the ground surface in southern Africa (Clifford, 1978). Wolmarans and Clifford (1975) described a case study of compacting Kalahari (collapsing) sand in Rhodesia where at least 25 passes were required; layers were able to be compacted in thicknesses of up to 1.5 m and still achieve the target density. Clifford (1975) stated that the impact roller is not a finishing roller, as it over-compacts the near-surface soils, often requiring the upper 0.1-0.2m to be compacted by rollers used for surfacing works. Ellis (1979) described that one of the main advantages of RDC was to compact cohesionless soils in thick layers; however, he cited a disadvantage that in loose soils, the near-surface soil is disturbed by RDC and must be compacted by other machines, agreeing with the results of Clifford (1975).

The typical operating speed range of the 4-sided impact roller, as shown in Fig. 2.1, is 9-12 km/h. Clifford (1980) stated that one of the difficulties encountered with RDC is the need for rollers to be operated at their optimum speed to ensure that sufficient energy is generated for each impact blow. In cases where the towing speed is slower than the typical range, or the module slides across the surface, Clifford (1980) found that adding a capping layer of material containing a granular/cohesive mixture could reduce lateral shearing effects and aided traction of the module for typical towing speeds. Clifford (1978) described a case study where an insufficiently thick capping layer was adopted which resulted in individual impact blows punching through to the underlying dredged fill; the site was also divided into a series of small working areas in which the roller was unable to maintain a towing speed within the typical range. According to Clifford (1978), both factors cause a reduction in speed and are the key reasons that better results could not be obtained.

Figure 2.1: 4-sided RDC module (Broons)

Clifford (1980) discussed that there is an upper speed limit beyond which an impact blow is not delivered by the face of the module. At towing speeds greater than the typical range, Clifford (1980) stated that the roller can spin as a circular mass and only contact the ground with its corners, a condition that should be avoided. Avsar et al. (2006) described the compaction of a 22-km^2 reclamation area for the new Doha International Airport Project. They identified towing speed as one of the most important indicators that directly influenced the in situ dry density that could be achieved; an optimum towing speed of the 4-sided roller for that project was found to be 11 km/h. Chen et al. (2014) conducted a laboratory investigation on a scale model impact roller device in loose dry sand, by examining the effect of module weight, size and towing speed. They used a Chinese cone penetration test to confirm that towing speed was one of the most important factors contributing to the effectiveness of the impact roller. The aforementioned cases generally support the concept that towing speed influenced the effectiveness, as did the findings of Scott and Suto (2007), who stated that ground near the perimeter of a fenced site could not be improved as successfully as the rest of site due to access-related issues that reduced the towing speed of the module. This paper presents the findings of two full-scale field trials that were undertaken to quantify the effect of towing speed for the 4-sided impact roller.

2.2 Testing Methodology

Each time the module of an impact roller strikes the ground, a pressure wave is created that travels through the soil from the surface. A key aim of the trial is to measure the loading-induced stresses below the ground due to RDC. EPCs allow real-time measurements of stresses imparted to the ground. Rinehart and Mooney (2009) successfully used Geokon Model 3500 semiconductor type EPCs in a field trial to measure dynamic loading induced from vibratory circular drum rollers. They used 100 mm diameter cells that were 10 mm thick with normal stress measurement ranges of 250 kPa, 400 kPa and 1,000 kPa. The same type of cells were selected to measure the pressure imparted into the soil due to RDC, albeit 230 mm diameter cells of 6 mm thickness with a normal stress measurement range of 6,000 kPa to capture the expected higher loads from the impact roller.

It has been well documented by researchers (e.g. Weiler and Kulhawy, 1982; Rinehart and Mooney, 2009) that a buried cell can influence localised stress fields and therefore any measurements may not be representative of the true loading-induced stresses. They discussed that errors can be minimised via the choice of pressure cell design, by undertaking calibration and by the use of correct field placement techniques. Given the challenges associated with measuring in situ stress accurately, it was important to characterise the uncertainty in the measurement techniques adopted. A whole system calibration was performed both pre- and post-testing, whereby the worst-case scenario was a difference of 8.5%. This magnitude of error is generally consistent with that reported by Dave and Dasaka (2011) who compared different calibration techniques for EPCs and stated that pressure cell output could be considered reliable within an error of approximately 10%. The dynamic frequency response (peak capture) was affected by the data acquisition rate and any internal filtering used in the signal path. The data acquisition rate selected was 2,000 samples per second, and the filter used was set at 800 Hz. Fast Fourier transform analysis of the data indicated that the fundamental frequency of impulses due to RDC was less than 800 Hz, confirming that the peak values were not attenuated by the adopted filter.

2.2.1 Trial A

A field trial was undertaken at Monarto Quarries, located approximately 60 km southeast of Adelaide, South Australia. The test site was primarily chosen because there was access to earthmoving equipment, and importantly, homogeneous quarry material was used for the field trial. An area within the quarry where the ground was flat, close to material stockpiles, yet away from quarry operations was chosen for the trial. Natural soil was removed to a depth of 1.75 m, over a plan area that was 10 m long and 5.5 m wide. Three Geokon Model 3500 EPCs were buried at nominal depths of 0.5 m, 1 m and 1.5 m within the quarry fill material that was placed in seven lifts of 250 mm thickness. Bedding sand was placed immediately below and above each pressure cell to ensure horizontal placement and to prevent gravel sized particles of the fill material from damaging the cells. Each lift was wheel-rolled using a Volvo L150E loader; a vibrating plate compactor was used to compact soil within 250 mm from each EPC to prevent possible damage.

2.2.1.1 Material classification

The fill material placed for the trial was a crushed rock with a maximum particle size of 20 mm that was readily available and locally produced. A summary of the particle size distribution and Proctor compaction test results for Trial A is given in Table 2.1. For Trial A, particle size distribution (ASTM D6913-04(2009), 2009) results are the average of nine tests, and the standard (ASTMD698-12, 2012) and modified (ASTMD1557-12, 2012) Proctor compaction results are the average of three curves. The field moisture content (ASTM D2216-10, 2010) reported is the average of nine tests undertaken. Atterberg limit testing (ASTM D4318-10, 2010) confirmed that the fines consisted of clay of low plasticity. According to the Unified Soil Classification System (USCS), the fill material used for this compaction trial could be described as well-graded gravel (GW).

Table 2.1: Particle size distribution, compaction and field moisture test results of 20 mm crushed rock fill material for Trials A and B

Trial	d_{50} (mm)	Gravel size (%)	Sand size (%)	Fines (%)	Std OMC (%)	Std MDD (kN/m^3)	FMC (%)	Mod OMC (%)	Mod MDD (kN/m^3)
A	4.0	57	40	3	7.9	17.9	8.6	7.2	18.9
B	3.5	58	38	4	12.6	19.2	9.6	10.0	19.8

Note: d_{50} = particle size at percent finer of 50%; OMC = optimum moisture content; MDD = maximum dry density; FMC = field moisture content.

The aim of Trial A undertaken in August 2012 was to measure the loading-induced stress at three different depths for 40 passes in total; 10 passes of the roller were conducted at each of the towing speeds of 9, 10, 11 and 12 km/h. Towing speed was controlled via the control panel in the towing unit (i.e. tractor) but was subsequently validated by dividing the distance between EPCs by the time interval between the peak pressures that were measured. Three EPCs were used to measure the pressure imparted to the ground, each offset by one-half of one revolution of the module (2.9 m) in the forward direction of travel. Avalle et al. (2009) used buried instrumentation to capture the ground response of the 4-sided impact roller and their work found that the time during which the impulse load occurred was less than 0.1 s. They found that a sampling frequency of 2 kHz was sufficient to capture the rapid increase in pressure caused by impact from RDC and this same sampling frequency is adopted for the field trial presented in this paper. The selection of thin EPCs used in the present trial provides a much more reliable measurement of in situ soil stress than the bulky load cell used by Avalle et al. (2009), which is significantly stiffer than the surrounding soil.

2.2.1.2 Assessment of EPC Results

Fig. 2.2 presents example results of the measured pressures versus time for a single pass of the impact roller travelling across the test site. The order in which the three traces were recorded is a function of the physical placement of the EPCs in the ground; 1.5 m depth located farthest left, 1 m depth in the middle and 0.5 m farthest right. The largest peak pressure was observed for the EPC buried at 0.5 m depth, whereas the deeper pressure cells at 1 m and 1.5 m depths recorded smaller impulses, indicating that the pressure imparted into the soil reduces in magnitude and increases in area with greater depth, as expected. Fig. 2.3 highlights a single impact blow measured by an EPC, where a loading-induced peak pressure of 648 kPa was recorded at 0.5 m depth. Fig. 2.3 demonstrates the dynamic nature of RDC and the importance of adopting a 2 kHz sampling frequency is evident from the individual data points shown, given that the loading and unloading phases occur over a time period of approximately 0.045 s.

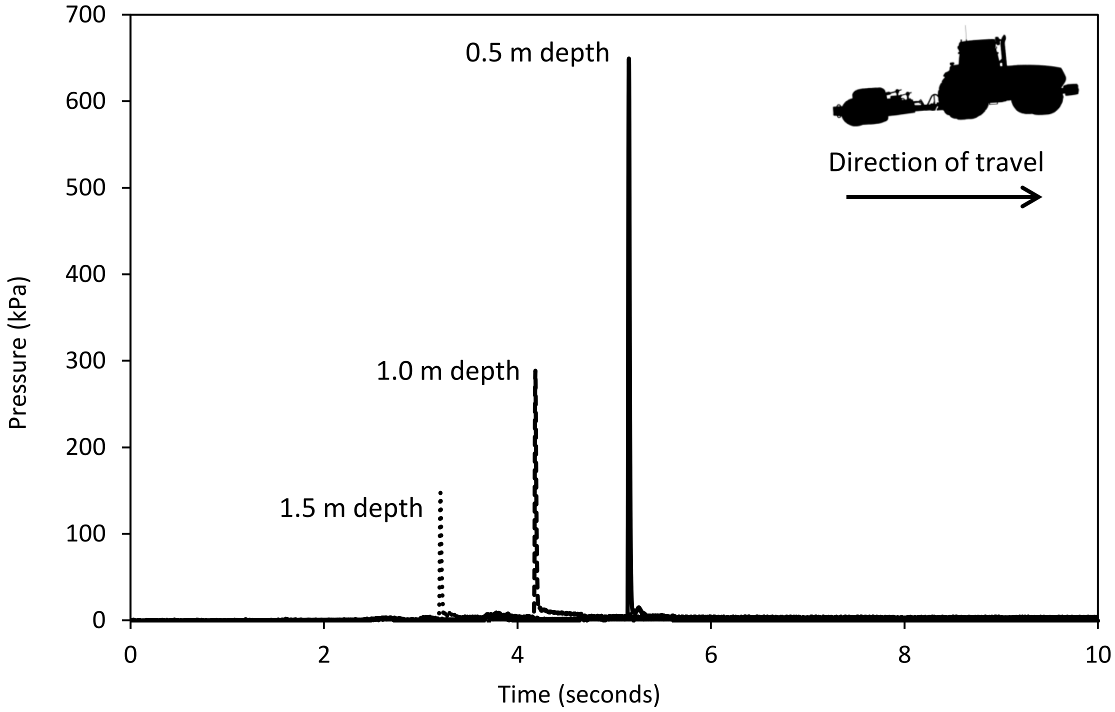

Figure 2.2: Example results for a single pass of the impact roller over buried EPCs.

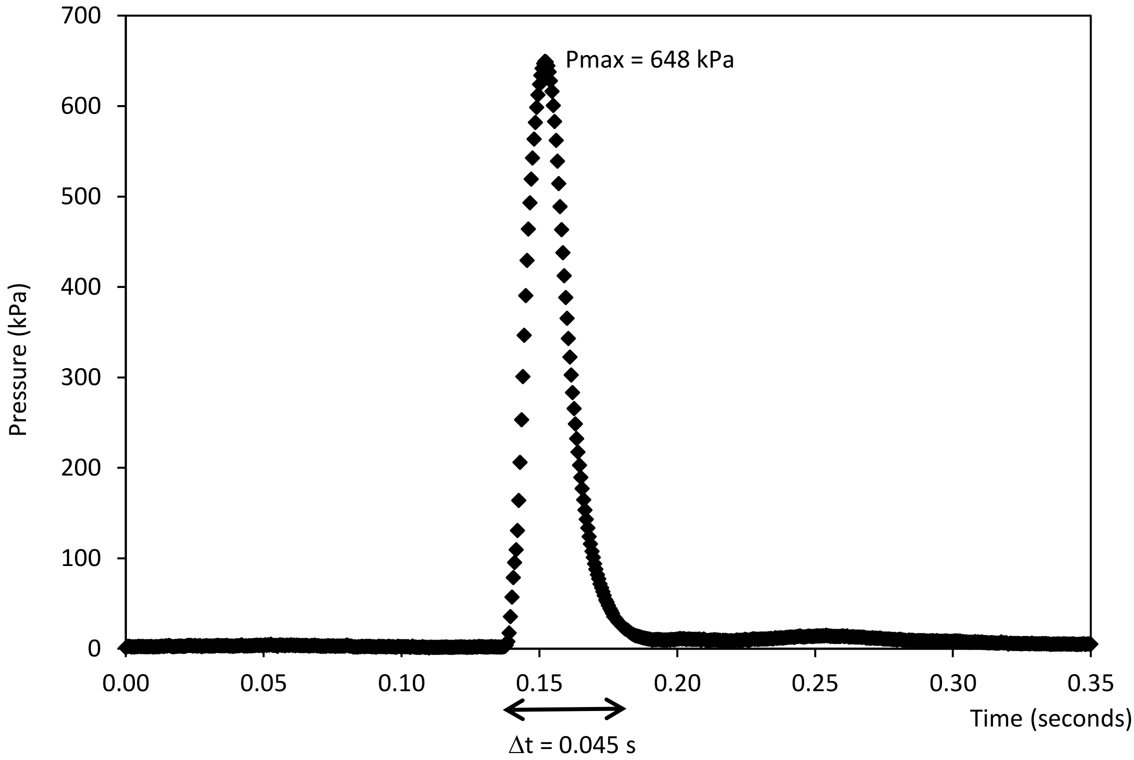

Figure 2.3: Measured impulse pressure at 0.5 m depth.

Fig. 2.4 presents the relationship between the measured peak pressures versus depth for each of the towing speeds examined, with an increasing trend between the peak pressure and towing speed evident for all depths measured, and a decrease in pressure with depth, as one would expect. As can be observed from these results, a clear relationship exists between measured pressure and towing speed, with the slowest speed of 9 km/h yielding the lowest pressures, and progressively increasing with greater speed. Fig. 2.5 presents the results of the measured peak pressure plotted against offset distance for all depths, whereby the offset distance is defined as the distance between the centre of the module and the centre of the buried EPC. From this figure, it can be observed that, at shallow depths, offset distance has a large influence on the peak pressure recorded. However, with increasing depth, the effects of offset distance are less pronounced, suggesting a greater radial effect away from the centre of impact as depth increases. For an EPC depth of 0.5 m, offset distances between -100 mm and 400 mm generated the greatest pressures, apart from an anomalous result at an offset of -275 mm, and two other offsets that coincide with the corners of the module (-650 mm and 650 mm). This finding is generally consistent with Avalle et al. (2009), who found that the zone of maximum impact was located from 0 mm to 400 mm from the centre of the module. In order to further examine the effects of towing speed, an additional field trial was undertaken.

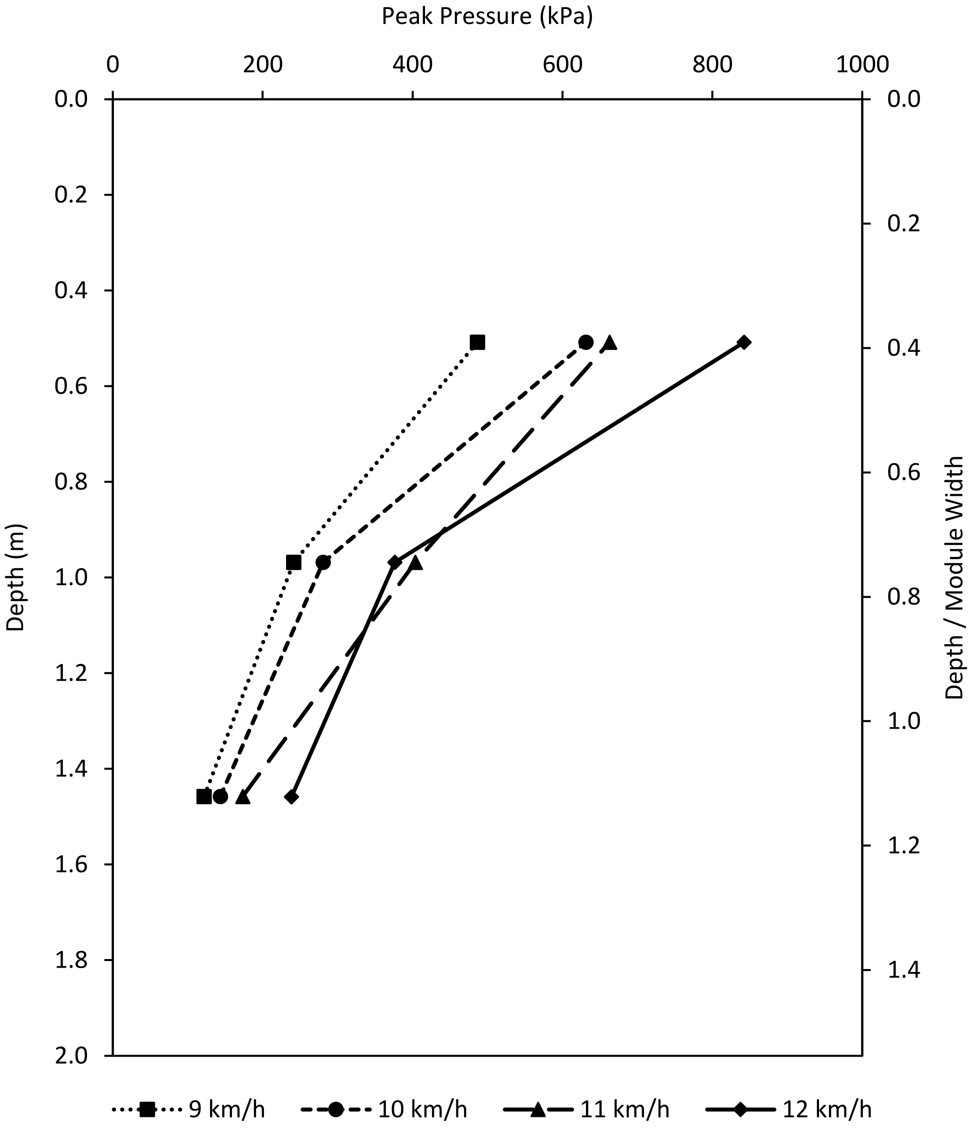

Figure 2.4: Measured peak pressure increasing with towing speed.

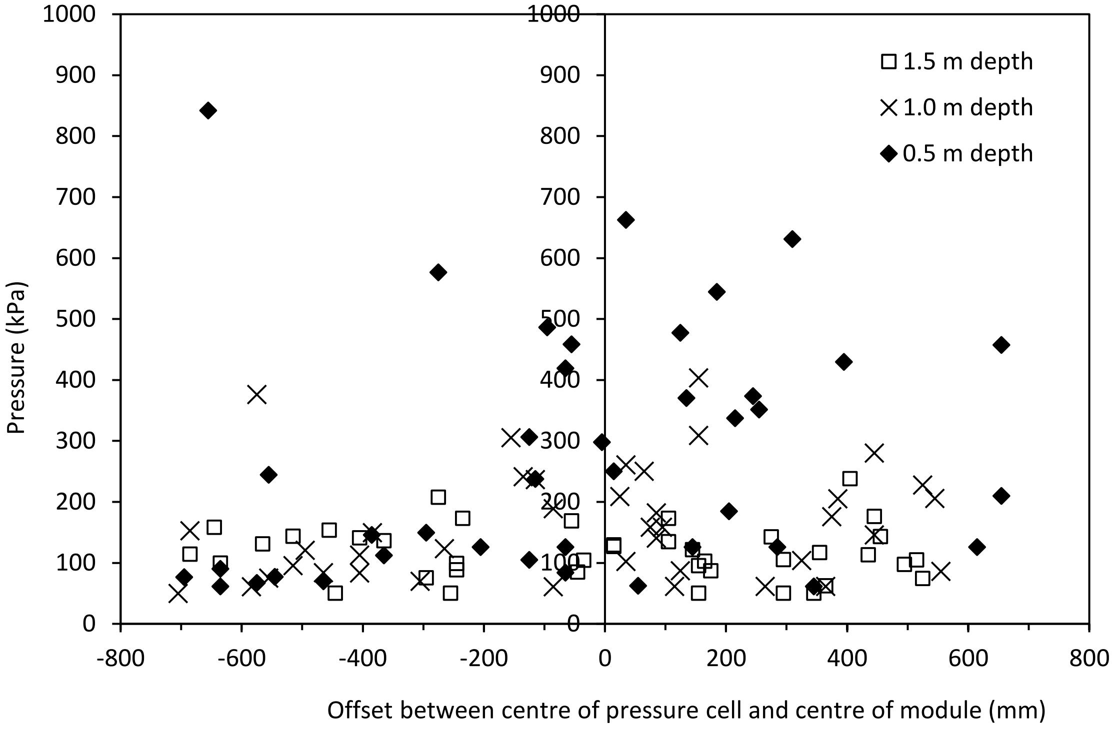

Figure 2.5: Non-uniform pressure distribution measured at 0.5 m, 1.0 m and 1.5 m depths.

2.2.2 Trial B

Field Trial B was undertaken at Monarto Quarries during August 2014, albeit at a different location from Trial A. Natural soil was removed to a depth of 1.2 m, over a plan area 12 m long and 3 m wide. Three Geokon Model 3500 EPCs were placed at a constant depth of 0.8 m. Quarry fill material was placed in six equal lifts of 200 mm thickness, with each lift again being wheel-rolled using a Volvo L150E loader and a vibrating plate compactor used to compact soil within 200 mm from each EPC. The aim of the field trial was to measure the loading-induced stress at a single depth for 100 passes in total; 35 passes of the roller were conducted at a towing speed of 12 km/h prior to comparative EPC measurements being undertaken to achieve effective refusal. Five passes were conducted at each of the following towing speeds and in the following order: 12, 10, 8, 6, 9, 7, 5, 11, 14, 13 and 15 km/h, respectively. Due to time constraints, no EPC measurements were recorded between passes 90 and 100.

2.2.2.1 Material classification

The fill material placed for the trial was a crushed rock with a maximum particle size of 20 mm that was readily available on site. A summary of the particle size distribution (ASTM D6913-04(2009), 2009) and standard (ASTM D698-12, 2012) and modified (ASTM D1557-12, 2012) Proctor compaction test results for Trial B is given in Table 2.1. The test results indicate that the material is similar to that used in Trial A; however, there are differences which can be attributed to the two-year interval between trials, different weather conditions at the time of testing, and the material being sourced from different parts of the quarry. For Trial B, the particle size distribution results are the average of seven tests, and the standard and modified Proctor compaction curves were generated using a minimum of five data points each; both laboratory compaction curves were generated five times. The field moisture content reported is the average of 30 tests undertaken. According to the USCS, the fill material is again classified as well-graded gravel (GW). Atterberg limit testing confirmed that the fines consisted of clay of low plasticity.

Density measurements and other in situ tests were not undertaken during either field trial presented in this paper. However, the authors carried out in situ tests from pre- and post-compaction in very similar soil conditions as this study during a separate field trial that was also conducted at Monarto Quarries. The results have been published in Scott et al. (2016). It is acknowledged that only undertaking pre- and post-compaction testing provides limited information regarding changes in soil state with increasing compactive effort; however, such testing regimes are common as they are effective at determining whether a project specification has been met, or otherwise. A recently published paper by Scott et al. (2019) captured the ground response of a single module impact in real-time using buried EPCs and accelerometers.

2.2.2.2 Assessment of EPC Results

Fig. 2.6 presents the minimum, maximum and average peak pressures that were recorded at varying towing speeds. As mentioned above, five passes were conducted at each target towing speed, with each pass traversing over three EPCs at a uniform depth of 0.8 m, resulting in 15 data points per towing speed. It can be observed that at towing speeds lower than 9 km/h, significantly lower pressure is imparted to the soil. The maximum pressure (1,220 kPa) was recorded at a towing speed of 14 km/h and the highest average peak pressure (646 kPa) at a towing speed of 11 km/h. Large pressure variations were measured for the same towing speed due to limitations of using EPCs that are buried at fixed locations. The location of the centre of the module landing on the ground surface relative to the centre of a buried EPC is variable. As discussed by Avalle et al. (2009), this variability is something unable to be controlled (despite some attempts at trying to do so). As discussed by Scott et al. (2016), whilst the module is nominally a “square”, the sides have curved features, and this results in a non-uniform pressure distribution and is a key contributing factor why some passes yielded much larger peak pressures for the same towing speed than others.

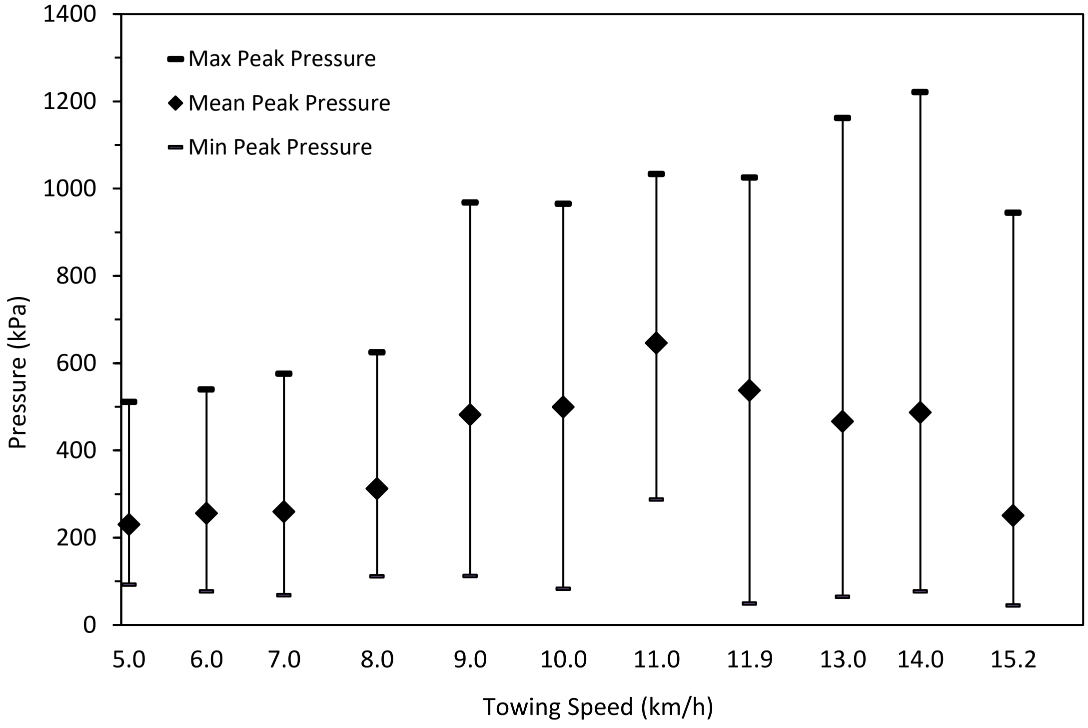

Figure 2.6: Minimum, maximum and average peak pressures for varying towing speeds.

Fig. 2.7 presents the same data set, plotted instead with peak pressure versus offset distance. Adjacent speeds have been combined to yield 30 data points for each line. It can be observed that, for increasing towing speed, greater pressure is imparted to the ground up to 11-12 km/h. For speeds of 13-14 km/h, the shape of the pressure versus offset relationship is in contrast to the other towing speeds, indicating that the corners of the module impart the greatest pressure. This suggests that the behaviour of the module changes with increasing towing speed, which is consistent with the findings of Clifford

(1980) as discussed earlier. In contrast, at slower speeds, the module face produces the greatest impact. Fig. 2.8 shows a plot of the peak pressure versus normalised time for the odd-numbered towing speeds. The largest peak pressure (1,160 kPa) was recorded at a towing speed of 13 km/h.

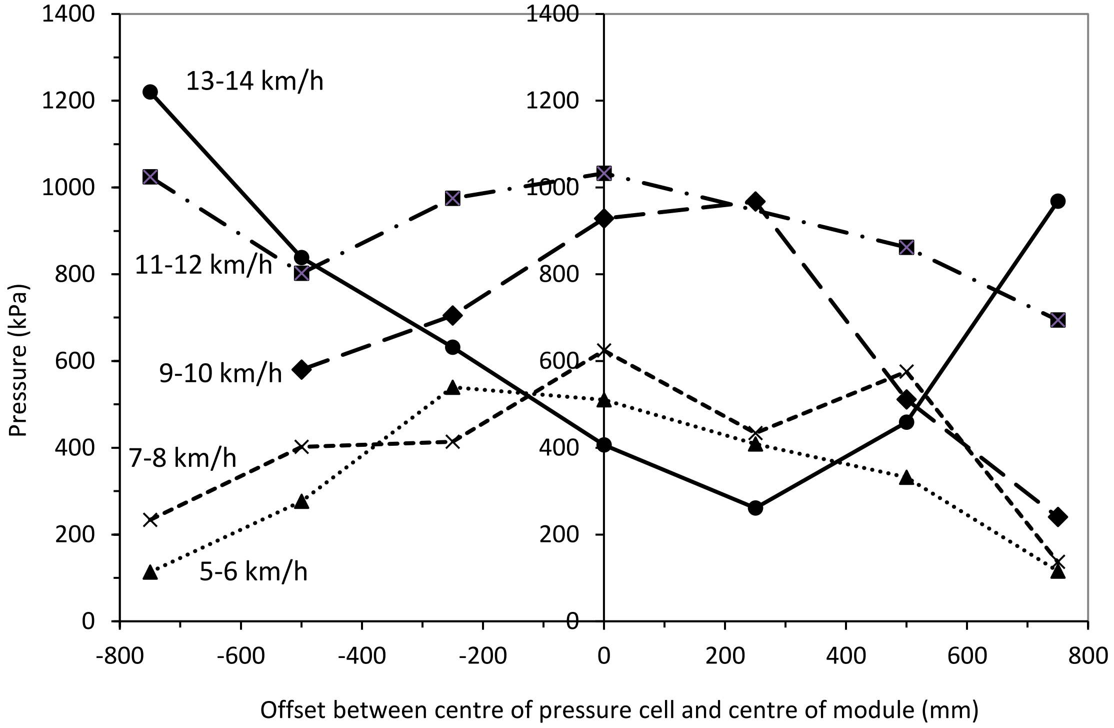

Figure 2.7: Large variation in peak pressure for varying offset distances and towing speeds.

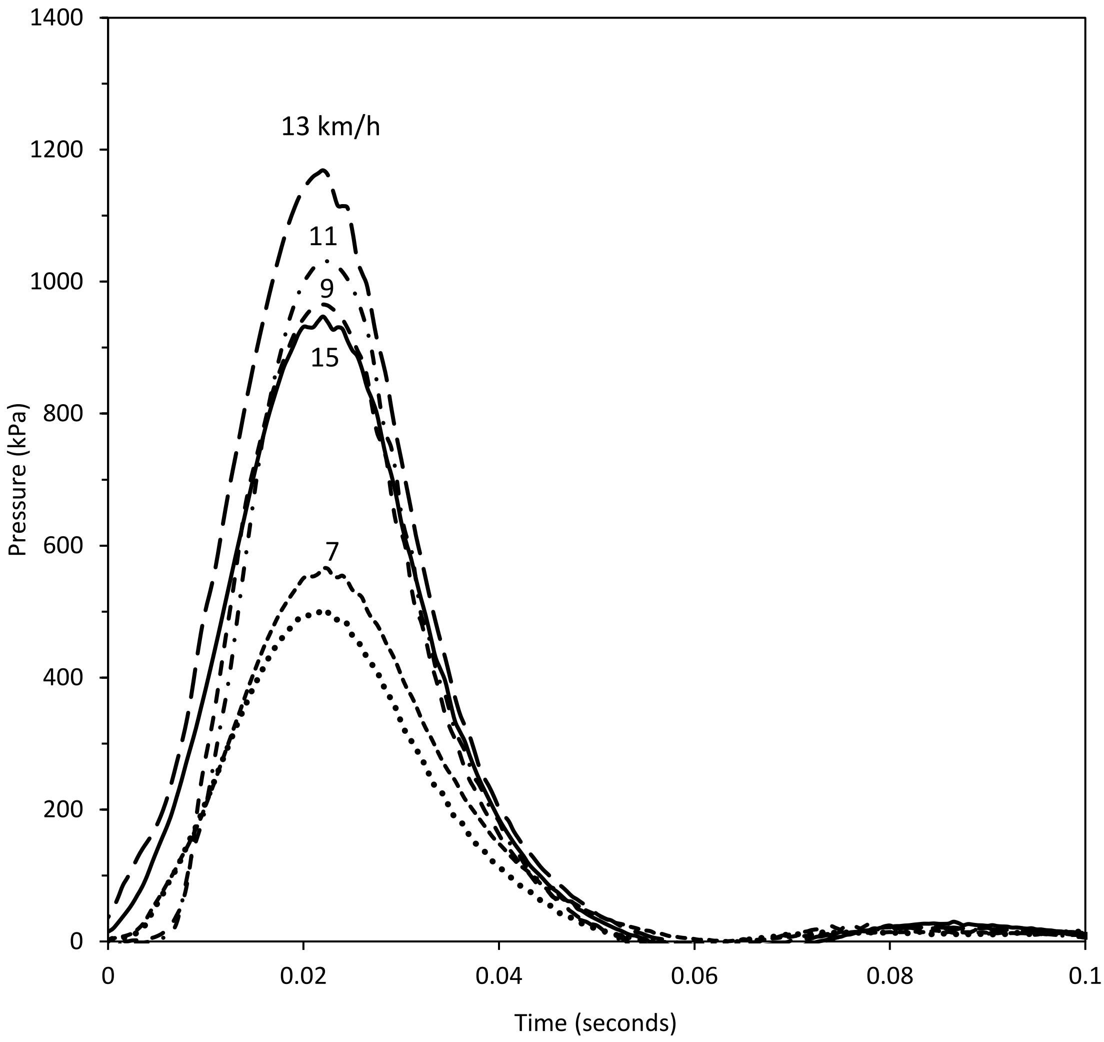

Figure 2.8: Duration of pressure impulse not greatly influenced by towing speed.

To confirm the observations from the pressure cell data, a number of qualitative behaviours were observed; at lower towing speeds, the blows were delivered by the face of the module, which maintained a regular contact pattern with the ground. At faster speeds, the blows were delivered towards the corners, and the module was observed to skip along the surface from corner to corner, which is again consistent with the findings from Fig. 2.7 and Clifford (1980). The spacing between successive blows of the roller module was also monitored and physically measured on site. The module imprint length was measured to be significantly larger than the physical face length (1,450 mm) of the module for towing speeds greater than 13 km/h as indicated in Fig. 2.9, implying non-uniform rotation and skipping behaviour. Bradley et al. (2019) used high-speed photography that captured the kinematics of the 4-sided module at 1000 frames per second. The field work undertaken by Bradley et al. (2019) is highly relevant to the field work of this study even though the two field trials had different aims and motivations and were undertaken on separate (adjacent) test areas within the Monarto Quarries site. There are strong similarities between the two; both field trials were held concurrently, allowing the same 4-sided impact roller to be used and fill material from the same stockpile to be used. The study by Bradley et al. (2019) captured the motion and estimated the kinematic profile of the module during impact to estimate the energy imparted to the ground (23 kJ ± 4 kJ) for a constant towing speed of 10 km/h that was adopted during the trial.

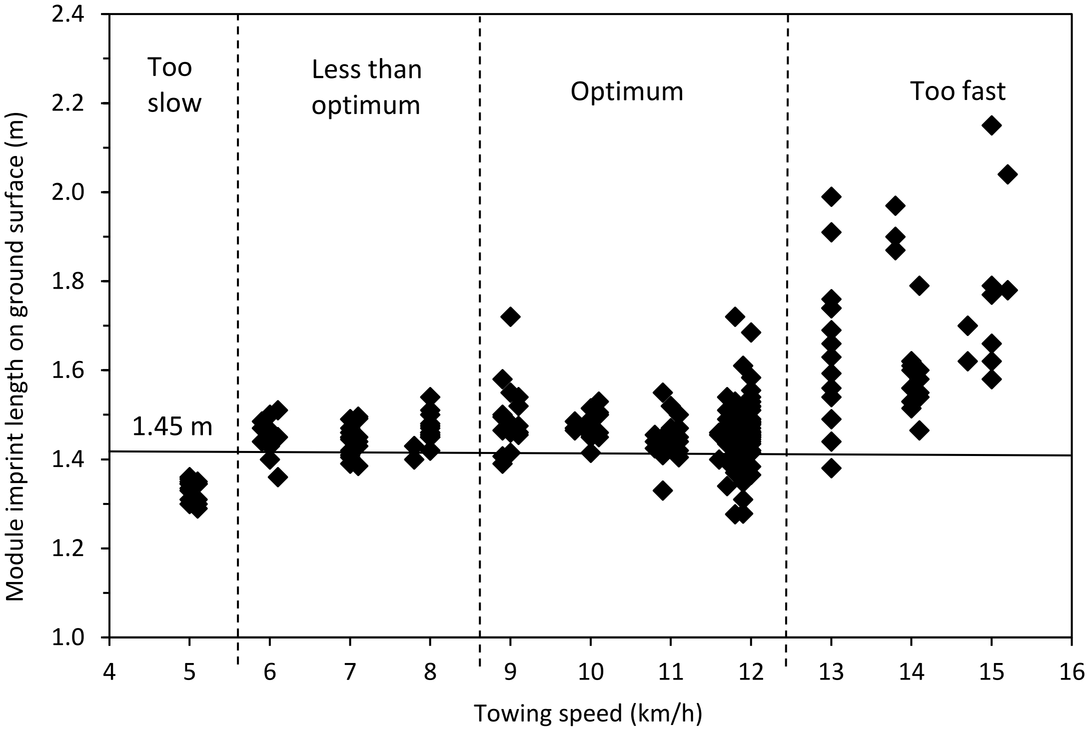

Figure 2.9: Inconsistent module imprint length on ground surface with increasing towing speed.

2.3 Discussion

In this paper, towing speed refers to the horizontal motion of the towing unit, whereas rotational velocity refers to the angular velocity of the module. To quantify the difference between the two, Clifford and Bowes (1995) presented theoretical analyses from independent mathematicians who predicted the change in rotational velocity of the module as it falls to impact the ground. They claimed that towing speed was more significant than other factors such as module mass or lift height. Whilst the use of load cells is referenced in their paper, no experimental results were included to confirm their findings. Clifford and Bowes (1995) used high-speed photography to support their calculations regarding the change in angular velocity of the module during the lifting and falling phases of each impact for a constant towing speed. They explained that a key reason why the angular velocity of the module is not constant (unlike the towing speed) is due to the double-spring-linkage system on the 4-sided impact roller. Clifford and Bowes (1995) explained that the module velocity is slowed during the lifting phase as the springs of the double-linkage system are compressed. This causes the module to lag a little behind the towing frame that is travelling at a constant speed. During the impact phase, the springs are then discharged which cause the module to move faster than the towing frame as the spring energy is released. Whilst no results of the high-speed photography were presented in their paper, they claimed that the spring energy resulted in a decrease in rotational velocity during lifting, and an increase in module velocity during the falling phase. They found that the magnitude of change in module rotational velocity was inconsistent and was dependent upon soil surface irregularities. Their calculations proposed that the energy delivered by the 4-sided roller during a single impact can be described by kinetic energy, estimated to be up to 50 kJ, depending upon their assumptions made regarding the velocity of the module upon impact with the ground, v_f.

McCann (2015) used 3- and 5-sided modules and presented an alternative viewpoint, stating that the magnitude of the gravitational potential energy provides a reasonable estimate of the energy delivered by the 3-sided roller. McCann (2015) cited the work of Heyns (1998) who undertook both theoretical and empirical analyses. Heyns (1998) placed an accelerometer on the axle of a 3-sided impact roller to measure the magnitude of the peak deceleration of the module as it impacted the ground. Heyns (1998) used dynamic compaction theory from Mayne and Jones (1983) to infer the energy imparted to the ground based on the measured peak deceleration. Whilst good agreement between estimated and measured accelerations was noted by Heyns (1998), both are fundamentally based on dynamic compaction theory. The use of this theory without modification for RDC applications is questionable and requires further research. Heyns (1998), cited by Berry (2001), observed that an increase in towing speed resulted in an increase in energy imparted to the ground, but it was not the major component of the energy for towing speeds tested between 9 km/h and 14 km/h. After losses were taken into account, Heyns (1998) concluded that the magnitude of the gravitational potential energy, PE_g (Eq. (2.1)), was a reasonable estimate for the energy delivered by the 3-sided roller to the ground. If this theory is applied to a 4-sided impact roller with a module mass, *m*, of 8-tonne and a maximum module drop height, *h*, of 0.15 m, the estimated energy imparted to the ground would be approximately 12 kJ.

$$PE_g = mgh \qquad [2.1]$$

where *g* is the gravitational acceleration.

Clearly, there is a need for further research as this finding is in stark contrast with that of Clifford and Bowes (1995) who estimated the energy for a single impact using total kinetic energy, KE (Eq. (2.2)), based on an 8-tonne module mass, *m*, and a module landing velocity, v_f, that was assumed to be greater than the towing speed.

$$KE = \frac{1}{2}mv_f^2 \qquad [2.2]$$

The fact that Clifford and Bowes (1995) analysed a 4-sided roller and Heyns (1998) analysed a 3-sided roller may, to some extent, explains the disparity in results. The standard 4-sided impact roller, as shown in Fig. 2.1, consists of a single 8-tonne module that is 1,300 mm wide, 1,450 mm high and rotates with the aid of a double-spring-linkage system. The standard 3-sided impact roller, as shown in Fig. 2.10, consists of twin 6-tonne modules that are each 900 mm wide and 2,170 mm high that rotate about a fixed axle with the aid of a hydraulic accumulator. The concept of energy storage upon lifting and release on impact theoretically increases the potential energy imparted to the ground; however, there is little, if any, published information that quantifies the magnitude of the energy that can be stored and released by either the double-spring-linkage system or the hydraulic accumulator.

Figure 2.10: 3-sided RDC module (Source: Landpac.com)

In an attempt to quantify the effects of the spring-linkage system, Clifford and Bowes (1995) analysed the change in angular velocity of the module before and after impact. They did not, however, quantify the contribution of spring energy in terms of the potential energy imparted to the ground. Whilst differences in impact roller configuration may account for some of the disparity in the estimates provided by Heyns (1998) and Clifford and Bowes (1995), there is clear disagreement as to whether the use of potential energy or kinetic energy provides more accurate estimates. It is also apparent that research is required to determine the effects of the double-spring-linkage system and the hydraulic accumulator to be able to accurately quantify the total potential energy delivered by the 4- and 3-sided impact rollers, respectively.

From both field trials undertaken, it is evident that the towing speed of the module influences the pressure imparted to the ground, suggesting that gravitational potential energy alone does not accurately capture the ground response of RDC. Whilst Heyns (1998) found that towing speed influenced the energy imparted to the ground at towing speeds higher than the typical range, these findings present compelling evidence that the magnitude of the energy imparted to the ground is a function of towing speed, even within the typical operating range of 9-12 km/h. Clifford and Bowes (1995) argued that module speed was a critical parameter, and that the continuous rolling action must be more beneficial than the equivalent falling weight that relied solely on gravitational potential energy. However, the magnitude of peak pressures measured in the ground with changes in towing speeds strongly suggests that the use of total kinetic energy does not accurately describe it either. If it did, greater changes in pressure would have been evident with varying speed. The observations indicate that total kinetic energy over-estimates the contribution of towing speed, and therefore does not provide a reliable estimate of the energy imparted to the ground. Combining the findings of past research and the trials presented in this paper, the energy imparted to the ground appears to be a function of both potential and kinetic energies. To determine the magnitude of energy imparted to the ground by a single blow, it is necessary to analyse the potential and kinetic energy before and after impact in more detail, which is addressed below.

2.3.1 Energy Imparted by RDC

In order to estimate the energy imparted to the ground as a consequence of RDC, the conclusions from the high-speed photography undertaken by Clifford and Bowes (1995) are adopted. They indicated that, when compared to the average, the module velocity decreased by 10-20% during the lifting phase of the module, and increased by 10-20% during the falling phase. The module frame is towed at a relatively constant speed, therefore the speed of the module after impact with the ground is slower than that prior to impact, but is not zero as implied by Clifford and Bowes (1995) for their use of total kinetic energy to be correct. For calculation purposes, a module mass, *m*, has a velocity increase of +10% prior to impact, v_i, and a velocity decrease of -10% after impact, v_f, when compared to the average. These correspond to lower bound values stated by Clifford and Bowes (1995), to determine the work done due to the change in kinetic energy, W_{ke}, which is equal to ΔKE, as defined using Eq. (2.3). The results are presented in Table 2.2.

$$W_{ke} = \Delta\mathrm{KE} = \frac{1}{2}\mathrm{m}v_i^2 - \frac{1}{2}\mathrm{m}v_f^2 \qquad [2.3]$$

Table 2.2: Predicted change in kinetic energy based on high-speed photography by Clifford and Bowes (1995)

v (km/h)	v (m/s)	v_i (m/s)	v_f (m/s)	ΔKE (kJ)
8	2.22	2.44	2.00	7.8
9	2.50	2.75	2.25	10.0
10	2.78	3.06	2.50	12.5
11	3.06	3.36	2.75	14.9
12	3.33	3.67	3.00	17.8
13	3.61	3.97	3.25	20.8

Note: v = speed of towing unit; v_i = module velocity prior to impacting the ground; v_f = module velocity after impacting the ground.

The change in potential energy, ΔPE_g, is equal to the work done due to gravity, W_g, therefore, the module falling to the ground surface can be described by Eq. (2.4), in which the module drop height after impact, h_2, is equal to zero; hence for an 8-tonne mass, m, and a lift height (h_1) of 0.15 m, $\Delta PE_g \approx 12$ kJ.

$$W_g = \Delta PE_g = mgh_1 - mgh_2 \qquad [2.4]$$

It should be emphasised that Eq. (2.4) gives the maximum potential energy that can be delivered to the ground. This energy will not be delivered with every impact as the full gravitational potential energy will only be reached when the module is compacting soil that is hard enough to allow the full lift height to be achieved. It is noted that using high-speed photography will also capture changes in module velocity due to the spring-linkage system, or due to energy losses in the system (such as frictional forces that act between the module and the ground surface). The net work done, W, as described by Eq. (2.5), is a combination of both the change in potential and kinetic energies, as work is being done against gravity, as well as inertia and frictional resistive forces, and is considered a more appropriate means to describe the energy delivered by RDC, rather than relying solely on gravitational potential or total kinetic energy.

$$W = \Delta PE + \Delta KE \quad [2.5]$$

The high-speed photography approach used by Clifford and Bowes (1995) quantified the spring energy in terms of a change in module rotational velocity as the springs are compressed and subsequently released. However, spring energy, as defined by Halliday et al. (1993), is a form of potential energy, therefore the contribution of the dual springs in the linkage system should, more appropriately, be quantified in terms of potential energy.

2.3.1.1 Contribution of the spring-linkage system

The double-spring-linkage system consists of two springs: a large outer spring and a smaller inner spring that fits within the internal diameter of the larger spring. To determine the contribution of each of the springs to the energy imparted by the module, the stiffness of both springs was determined. Each spring was placed separately in a large compression machine whereby the load versus displacement response was quantified. The maximum compression of the dual springs was governed by the limiting compression distance of the outer spring, as both springs compress together in the towing frame. The force in the spring is determined using Hooke's law in Eq. (2.6), where the spring force, F_s, is a function of the spring stiffness, k, and the compression distance of the spring, x:

$$F_s = -kx \quad [2.6]$$

Based on Halliday et al. (1993), the work done by a spring, W_s can be determined using Eq. (2.7):

$$W_s = \int_{-x_{max}}^{0} (F_s)dx = \frac{1}{2}kx_{max}^2 \quad [2.7]$$

Where x_{max} is the maximum spring compression. Using Eq. (2.7), it is possible to determine the work done, W_s, by both the inner and outer springs with varying spring compression distances up to the maximum (limiting) compression, x_{max}. Whilst having different spring stiffnesses, k, both the inner and outer springs compress by the same magnitude in the double-linkage mechanism, the work done by the springs is equal to the change in spring potential energy, ΔPE_s, as described by Eq. (2.8).

$$W_s = \Delta PE_s = \left(\frac{1}{2}kx_{max}^2\right)_{inner} + \left(\frac{1}{2}kx_{max}^2\right)_{outer} \qquad [2.8]$$

The outer spring was found to contribute 84% of the work done by the dual springs combined, due to the larger spring stiffness (k = 370 N/mm), compared to the inner spring (k = 70 N/mm). As observed in Fig. 2.11, the work done by the springs is approximately 5 kJ at the maximum spring compression. This is the maximum energy that the springs are able to deliver, but the full potential energy of the springs will not be delivered with every blow, as both the geotechnical properties of the ground and the undulating surface profile significantly affect the behaviour of the module.

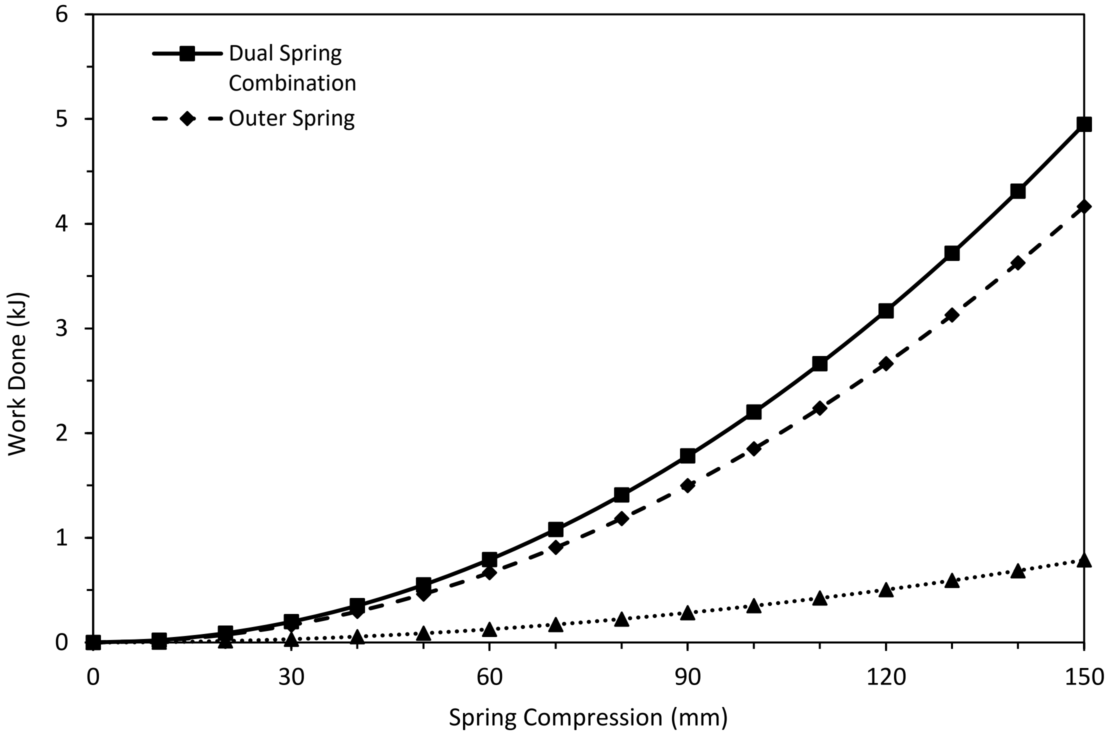

Figure 2.11: Energy contribution of the dual springs in the linkage system of the 4-sided impact roller.

A summary of the work done with varying speed is presented in Fig. 2.12. It is observed that the change in gravitational and spring potential energies is constant for all speeds. The maximum spring energy is more likely to be realised at faster towing speeds; however, further research involving more direct measurement techniques is needed to confirm this. As stated previously, the change in kinetic energy, as quantified by Clifford and Bowes (1995), accounts for spring effects and this is supported by Fig. 2.12, where $\Delta PE_S < \Delta KE$. Without taking into account the spring energy contribution twice, the total work done is equal to the sum of the change in gravitational potential, and kinetic energies (Eq. (2.5)). This yields values of total work done between 22 kJ and 30 kJ for typical towing speeds of 9 km/h and 12 km/h, respectively. For the same speeds, Clifford and Bowes (1995) predicted 30 kJ - 54 kJ, respectively, using Eq. (2.2) and assuming that the spring-linkage system increases the landing velocity of the module by 10%. The predicted energy that is imparted to the ground by Bradley et al. (2019) does support the assumptions made by Clifford and Bowes (1995) regarding the relationship between towing speed and module velocity that were used in this study to estimate the change in kinetic energy. Bradley et al. (2019) quantified the change in energy due to a single module impact from high-speed photography, and estimated that the energy imparted to the ground due to a single module impact was 23 kJ (±4 kJ) for a towing speed of 10 km/h, consistent with the findings of this study.

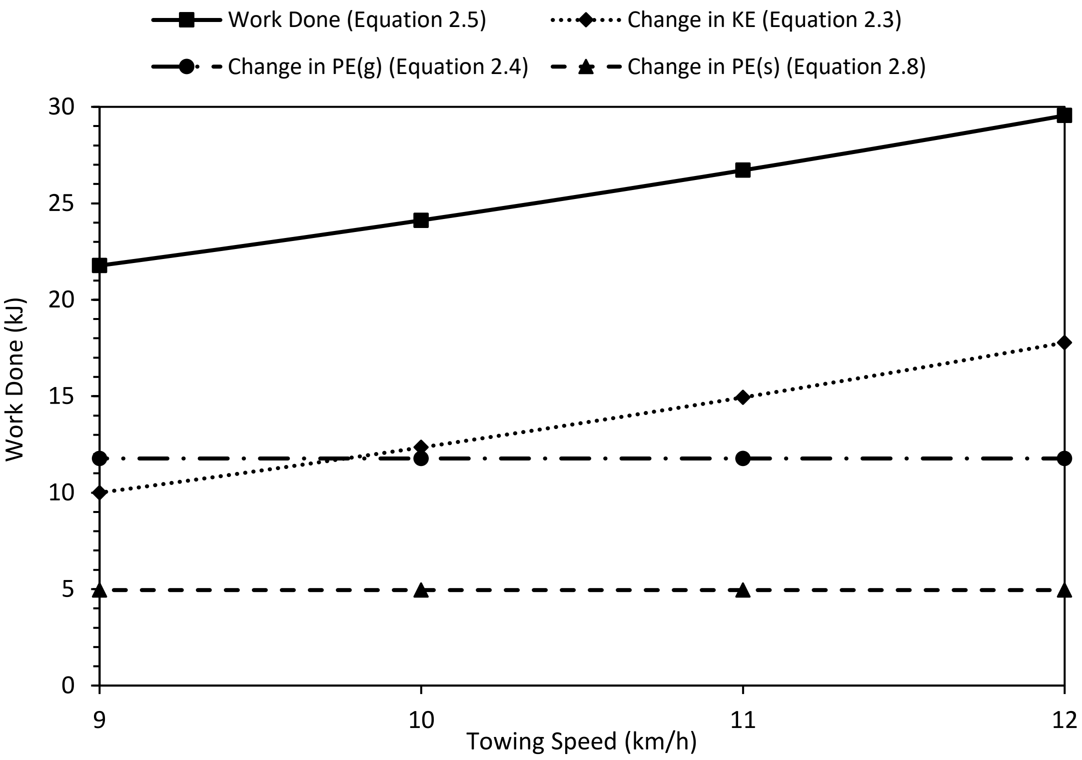

Figure 2.12: Increasing energy for typical towing speeds of the 4-sided impact roller.

2.4 Conclusions

This paper examined the effect of towing speed on the energy imparted to the ground from the 4-sided impact roller. This involved combining theory from Halliday et al. (1993), observations from two full-scale field trials, high-speed photography by Clifford and Bowes (1995), and estimates of energy imparted to the ground for the 3-sided roller by Heyns (1998). The maximum imparted energy delivered to the ground by the 4-sided impact roller was found to lie in the range between 22 kJ and 30 kJ, for typical towing speeds of 9-12 km/h.

It is proposed that the energy imparted by RDC to the ground needs to be considered in terms of work done, which is due to the change in both potential and kinetic energies. Current practice of describing the energy imparted to the ground using total kinetic energy should be avoided as it overestimates the energy imparted to the ground.

Describing the energy via the use of gravitational potential energy should also be avoided, but for a different reason; it is counter-productive for the impact rolling industry to develop specifications stipulating target towing speeds when the rollers are described solely in terms of their gravitational potential energy.

The change in potential energy is derived from a combination of both gravitational and spring energies for the 4-sided impact roller. The values presented in this paper for the potential energy delivered by the springs (5 kJ) and gravitational potential energy (12 kJ) are the maximum values that are theoretically possible. However, they are not values that will be achieved with every impact, as favourable ground conditions are needed for the full potential energy to be delivered. The change in kinetic energy is a function of the friction between the module and the ground surface. Quantifying the friction at the module-soil interface is extremely difficult to evaluate theoretically, as it depends on several variables associated with the module, such as the roughness of the module face in contact with the ground, the presence of wear plates or anti-skid bars, the contact area between the module and soil, and the towing speed. Properties relating to the ground are also significant, with soil type, grading, moisture content, density, elastic modulus and surface geometry all providing different frictional resistance, which makes it complex and extremely difficult to estimate the energy needed to overcome friction as it is material-dependent.

If the energy imparted to the ground was only due to potential energy, then it would be theoretically independent of towing speed and would be limited to a maximum value of 17 kJ. The findings of this research confirm that towing speed does influence the energy imparted to the ground. There is, therefore, a need for specifications to detail a target towing speed range for RDC. Based on the authors' experiences, the optimum speed will vary depending on site conditions. To optimise the use of the 4-sided impact roller, a towing speed range of 10-12 km/h is recommended, which is consistent with the findings of the field trials reported in this paper.

2.5 Declaration of Competing Interest

The authors wish to confirm that there are no known conflicts of interest associated with this publication and there has been no significant financial support for this work that could have influenced its outcome.

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2.7 References

ASTM D6913-04. Standard test methods for particle-size distribution (gradation) of soils using sieve analysis. West Conshohocken, PA, USA: ASTM International; 2009.

ASTM D2216-10. Standard test methods for laboratory determination of water (moisture) content of soil and rock by mass. West Conshohocken, PA, USA: ASTM International; 2010.

ASTM D4318-10. Standard test methods for liquid limit, plastic limit, and plasticity index of soils. West Conshohocken, PA, USA: ASTM International; 2010.

ASTM D698-12. Standard test methods for laboratory compaction characteristics of soil using standard effort. West Conshohocken, PA, USA: ASTM International; 2012.

ASTM D1557-12. Standard test methods for laboratory compaction characteristics of soil using modified effort. West Conshohocken, PA, USA: ASTM International; 2012.

Avalle DL, Scott BT, Jaksa MB. Ground energy and impact of rolling dynamic compaction – results from research test site. In: Proceedings of the 17th International Conference on Soil Mechanics and Geotechnical Engineering, Vol. 3, Alexandria, Egypt, 2009: 2228–2231.

Avsar S, Bakker M, Bartholomeeusen G, Vanmechelen J. Six sigma quality improvement of compaction at the New Doha International Airport Project. Terra et aqua, 2006, 103: 14-22.

Berry AD. Development of a volumetric strain influence ground improvement prediction model with special reference to impact compaction. Dissertation submitted in partial fulfilment of the requirements of the degree of Master of Engineering, University of Pretoria, Pretoria, South Africa, 2001. [Dissertation]

Bradley AC, Jaksa MB, Kuo YL. Examining the kinematics and energy of the four-sided impact roller. Proceedings of the Institution of Civil Engineers – Ground Improvement, 2019, 172 (4): 297-304.

Chen Z, Xu C, Ye G, Shen C. Impact Roller Compaction of Dry Sand in Laboratory Tests. In: Proceedings Geo-Shanghai, Ground Improvement and Geosynthetics, Shanghai, China, 2014: 258-269.

Clifford JM. An introduction to impact rollers. National Institute for Road Research, Internal report RP/2/75, South Africa, 1975.

Clifford JM. Evaluation of Compaction Plant and Methods for the Construction of Earthworks in Southern Africa. Dissertation in partial fulfilment of the requirements for the degree of Master of Science in Engineering, University of Natal, Durban, South Africa, 1978 [Dissertation]

Clifford JM. The development and use of impact rollers in the construction of earthworks in southern Africa. CSIR Report 373, National Institute for Transport and Road Research Bulletin 16, Pretoria, South Africa, 1980.

Clifford JM, Bowes G. Calculating the Energy delivered by an Impact Roller. A trilogy of Papers for the Sept. 1995 Lecture Tour and International Seminars to commemorate the 10th Anniversary of the BH 1300 Standard Impact Roller, Paper Two, 1995.

Dave TN, Dasaka SM. A review on pressure measurement using earth pressure cell. International Journal of Earth Sciences and Engineering, 2011, 4 (6): 1031-1034.

Ellis CI. Pavement engineering in developing countries. Transport and Road Research Laboratory, TRRL Supplementary Report 537, Crowthorne, Berkshire, 1979.

Halliday D, Resnick R, Walker J. Fundamentals of Physics, 4th Edition. John Wiley & Sons, Incorporated, Canada, 1993: 182-250.

Heyns S. Response analysis of an impact compactor. Report LGI98/013, Project No 020-DP, Laboratory for Advanced Engineering Pty Ltd., University of Pretoria, South Africa, 1998.

Mayne PW, Jones JS. Impact stresses during dynamic compaction. Journal of Geotechnical Engineering, 1983, 109 (10): 1342-1346.

McCann K. The use of impact compaction for the near surface compaction on dredged sand land reclamation projects. In: Proceedings 12th Australia New Zealand Conference on Geomechanics, New Zealand Geotechnical Society, Wellington, New Zealand, 2015, 1193-1200.

Ranasinghe RATM, Jaksa MB, Kuo YL, Pooya Nejad F. Application of artificial neural networks for predicting the impact of rolling dynamic compaction using cone penetrometer test results. Journal of Rock Mechanics and Geotechnical Engineering, 2017, 9 (2): 340-349.

Rinehart RV, Mooney MA. Measurement of Roller Compactor Induced Triaxial Soil Stresses and Strains. Geotechnical Testing Journal, 2009, 32 (4): 347-357.

Scott BT, Jaksa MB. The effectiveness of rolling dynamic compaction – a field based study. In: Indraratna B, Chu J, Rujikiatkamjorn C, eds. Ground Improvement Case Histories: Compaction, Grouting and Geosynthetics. Kidlington, Oxford: Elsevier, 2015: 429-452.

Scott B, Jaksa M, Mitchell P. Ground response to rolling dynamic compaction. Geotechnique Letters, 2019, 9 (2): 99-105.

Scott BT, Jaksa MB, Syamsuddin E. Verification of an impact rolling compaction trial using various in situ testing methods. In: Proceedings 5th International Conference on Geotechnical and Geophysical Site Characterisation, Australian Geomechanics Society, Sydney, Australia, 2016, 735-740.

Scott BT, Suto K. Case study of ground improvement at an industrial estate containing uncontrolled fill. In: Proceedings 10th Australia New Zealand Conference on Geomechanics, Australian Geomechanics Society, Brisbane, Australia, 2007, 2: 150-155.

Weiler WA, Kulhawy FH. Factors affecting stress cell measurements in soil. Journal of Geotechnical Engineering, 1982, 108 (12): 1529-1548.

Wolmarans CH, Clifford JM. An evaluation of the CSIR impact roller. 6th Regional Conference for Africa on Soil Mechanics and Foundation Engineering, Durban, South Africa, 1975, 33-39.

Chapter 3: Quantifying the depth of improvement

Introduction

The journal paper in Chapter 3 addresses the need for the applications of: (1) improving ground in situ; and (2) compaction of soil in thick layers; to be treated independently as they are two distinctly different applications of RDC but are often confused. Relationships are proposed to predict depths to which RDC can improve ground in situ, and predict layer thicknesses that can be compacted. This paper augments deep dynamic compaction theory and provides relationships for estimating the depths capable of being significantly improved in situ, and layer thicknesses capable of being compacted by RDC, that are in broad agreement with the results of published case studies involving the 8-tonne 4-sided impact roller over the past four decades.

The conference paper included in Appendix D describes how cone penetration testing was used during a compaction trial at a site involving quartzose and carbonate sand fill to determine the zone of influence of RDC. The results presented quantify the increase in cone tip resistance with depth and illustrates how a number cone penetration tests were used to evaluate changes in soil strength due to increased roller passes, changes in moisture content or placed loose layer thickness.

The conference paper in Appendix E summarises two case studies of thick layer compaction using RDC for the applications of constructing tailings dams and mining haul roads. Increased layer thicknesses enable larger particle sizes to be used, therefore greater reuse of mine spoil material can be undertaken with a reduced need to screen out large quantities of oversized materials. As well as demonstrating how RDC has been used effectively for the compaction of bulk earthworks at two different mine sites, this paper also discusses various aspects and factors associated with conducting a compaction trial on mine spoil materials.

List of Manuscripts

Scott, B.T., Jaksa, M.B. & Mitchell, P.W. (2019). Depth of influence of rolling dynamic compaction. *Ground Improvement, Institution of Civil Engineers.* https://doi.org/10.1680/jgrim.18.00117

Scott, B.T. & Jaksa, M.B. (2014). Evaluating rolling dynamic compaction of fill using CPT. Proceedings *3rd International Symposium on Cone Penetration Testing, Las Vegas, USA*, pp. 941-948. A copy of this paper is included in Appendix D.

Scott, B.T. & Jaksa, M.B. (2012). Mining applications and case studies of rolling dynamic compaction. *Proceedings 11th Australia New Zealand Conference on Geomechanics, Melbourne, Australia*, pp. 961-966. A copy of this paper is included in Appendix E.

Statement of Authorship

Title of Paper	Depth of influence of rolling dynamic compaction.
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Principal Author

Name of Principal Author (Candidate)	Brendan Scott		
Contribution to the Paper	Performed site work, analysis and interpretation of site data, wrote manuscript.		
Overall percentage (%)	90		
Certification:	This paper reports on original research I conducted during the period of my Higher Degree by Research candidature and is not subject to any obligations or contractual agreements with a third party that would constrain its inclusion in this thesis. I am the primary author of this paper.		
Signature		Date	18/4/2019

Co-Author Contributions

By signing the Statement of Authorship, each author certifies that:

i. the candidate's stated contribution to the publication is accurate (as detailed above);

ii. permission is granted for the candidate in include the publication in the thesis; and

iii. the sum of all co-author contributions is equal to 100% less the candidate's stated contribution.

Name of Co-Author	Mark Jaksa		
Contribution to the Paper	Provided primary supervision and helped evaluate and edit the manuscript.		
Signature		Date	18/4/19

Name of Co-Author	Peter Mitchell		
Contribution to the Paper	Provided secondary supervision and helped evaluate and edit the manuscript.		
Signature		Date	16 Apr 2019

Depth of influence of rolling dynamic compaction (Paper 2)

Abstract

The depth of influence of rolling dynamic compaction (RDC) was investigated in a field trial using the 4-sided impact roller. Earth pressure cells (EPCs) were placed at varying depths at a site consisting of homogeneous soil conditions. EPCs measured pressures imparted by RDC at 3.85 m depth; however, the largest magnitudes of pressure were confined to the top 2 m beneath the ground surface. These results were complemented by field density data, penetrometer and geophysical testing. A number of published case studies using the 8-tonne, 4-sided impact roller, for either improving ground in situ or compacting soil in thick layers, are summarised. Finally, equations are presented that predict first, the effective depth of improvement, appropriate for determining the depth to which ground can be significantly improved in situ, and, second, the depth of major improvement for RDC, appropriate for thick layer compaction.

List of notation

D	depth of soil compacted due to gravitational potential energy (m)
d_{50}	particle size at per cent finer of 50%
g	free-fall acceleration (9.81 m/s^2)
h	maximum module drop height (m)
k	ratio of energy imparted to the ground divided by the gravitational potential energy
m	module mass (t)
n	empirical factor in depth of improvement equation
r	reduction factor for determining the depth of major improvement
v	towing speed (m/s)
v_f	module velocity after impacting the ground (m/s)
v_i	module velocity prior to impacting the ground (m/s)
ΔKE	change in kinetic energy (kJ)

3.1 Introduction

There is an increasing need for civil engineers to provide cost-effective solutions for construction on marginal or difficult sites, in particular an understanding of the advantages and limitations of ground improvement options is essential to ensure that technically feasible and constructible solutions are adopted. Compaction is a prevalent ground improvement technique that aims to increase the density of soil by applying mechanical energy to increase soil strength and decrease differential and total settlements within a desired depth range beneath the ground surface. This paper is concerned with a specific type of dynamic compaction known as rolling dynamic compaction (RDC) which involves traversing the ground with a non-circular roller. Typical module designs have three, four or five sides. As the module rotates, it imparts energy to the soil as it falls to impact the ground. High energy impact compaction (HEIC) and high impact energy dynamic compaction (HIEDYC) are alternative names found in different parts of the world, or used by different contractors, for RDC.

When compared to circular drum rollers, RDC can compact thicker layers due to a greater depth of influence beneath the ground's surface. This is derived from a combination of a heavy module mass, the shape of the module and the speed at which it is towed; typically in the range of 9-12 km/h. Depths of improvement for RDC have been found to vary significantly and the factors that affect it are not fully understood. The depth of influence of RDC is often quantified by comparing in situ test results, before and after compaction. At sites containing significant soil variability, the use of pre- and post-compaction testing can be problematic. To overcome this limitation, this paper describes a compaction trial where earth pressure cells (EPCs) were placed at different locations beneath the ground surface in homogeneous soil conditions to quantify the depths to which RDC improves the ground.

3.2 Background

Published case studies involving the standard 4-sided impact roller that have improved the ground in situ, and have compacted soil in thick layers, are summarised in Tables 3.1 and 3.2, respectively. In addition to the referenced published articles, the authors have reviewed dozens of unpublished reports that have utilised the 4-sided, 8-tonne roller in a variety of soil conditions. Their findings are in general agreement with the improvement depths and layer thicknesses summarised in Tables 3.1 and 3.2, respectively. It is clear from Tables 3.1 and 3.2 that the depth of improvement of RDC varies significantly depending upon the soil material type. It is reasonable to conclude that RDC has a greater depth of influence in granular soils compared to clays. It is also evident that the thickness of compacted layers is less than the depth of improvement in the same soil type, as the compacted layer thickness is typically tailored to meet a target specification.

Table 3.1: Improvement depths for compacting in situ

No.	Reference	Soil type	Improvement Depth (m)
1	Clifford (1978)	Sand	>2.5
2	Clifford (1978)	Sand	>2.0
3	Avalle and Young (2004)	Fill (clay)	1.0
4	Avalle (2004)	Fill (sand)	>2.0
5	Avalle and Grounds (2004)	Fill (mixed)	1.5
6	Avalle and Mackenzie (2005)	Fill (clay)	2.0
7	Avalle and Carter (2005)	Fill (sand) over natural sand	3.0
8	Avalle (2007)	Fill (sand)	2.5
9	Scott and Suto (2007)	Fill (gravelly clay)	1.5
10	Whiteley and Caffi (2014)	Fill (mixed)	1.5
11	Scott and Jaksa (2014)	Fill (clayey sand) over natural clay	1.75

Table 3.2: Thickness of compacted layers

ID	Reference	Soil type	Layer Thickness (m)
A	Wolmarans and Clifford (1975)	Sand	1.5
B	Wolmarans and Clifford (1975)	Clay	0.6
C	Clifford (1980)	Clay	0.5
D	Clifford and Coetzee (1987)	Fill (coal discard material)	0.5
E	Avalle and Grounds (2004)	Fill (gravel)	1.0
F	Avalle (2007)	Sandy clay / clayey sand	0.7
G	Scott and Jaksa (2012)	Fill (mixed)	1.0
H	Scott and Jaksa (2014)	Fill (clayey sand)	1.0

Whilst not summarised in these tables, other variables such as moisture content, ground water conditions and the number of passes applied also affect the depth to which ground can be improved using RDC. When reviewing Tables 3.1 and 3.2 it is important to note that the target specification, testing methods used to quantify improvement, and the interpretation of how the depth of improvement is both defined and quantified, varies between the listed references, making it difficult to draw definitive conclusions as to the maximum improvement depth or layer thickness possible. In current practice, it is often the responsibility of the project engineer to predict whether the use of RDC will improve the ground sufficiently for the desired project application. The variable and unknown depth of influence of RDC is a key reason why this ground improvement technique is not used more commonly, and highlights why further research is needed.

Kim (2010) performed finite element simulations on impact rollers of different shapes with the aim of determining the stress distribution and influence depth, which was defined as the depth at which the vertical stress decreased to one-tenth of the applied stress at the surface. This study held module mass, diameter and width of each roller consistent; only the shape and number of sides varied. This study identified that influence depth is a function of both contact area and applied stress, with greater contact area and surface contact pressures resulting in increased depths of influence. A key limitation of this study, given the definition of influence depth adopted, was that the surface contact stresses modelled for impact rolling were not verified using field test results. Significantly, Kim's analysis illustrated stress wave propagation to depths much greater than those typically influenced by static loading. Nazhat (2013) analysed the behaviour of sand subjected to dynamic loading, and identified compaction shock bands via the use of high-speed photography and image correlation techniques from laboratory-based testing. As explained by Nazhat (2013), it is evident that improvements in the ability to measure and quantify dynamic effects are helping to increase knowledge of unseen processes beneath the ground surface; however, it is clear that more research is needed to fully understand the kinematic behaviour of soils subjected to dynamic loading.

3.3 Dynamic Compaction

Dynamic compaction is a ground improvement technique that usually employs a large crane to lift a heavy tamper, which is then dropped onto the ground in a regular grid pattern. Menard and Broise (1975) improved the mechanical characteristics of fine saturated sands using this method, and were the first to propose a relationship between the thickness to be compacted, D, the pounder mass, m, and the drop height, h, as given by Eq. (3.1).

$$D = \sqrt{mh} \qquad [3.1]$$

Menard and Broise (1975) observed that greater depths of improvement could be achieved for partially immersed soils than for soils completely out of water. The initial density and grading were factors that influenced the time taken to reach a liquefied state, after which the low frequency, high amplitude vibrations from dynamic compaction caused the sand particles to be reorganised into a more dense state. In subsequent years, this theory was applied to a wider range of soils conditions, including unsaturated soils, where it was found that in many cases the maximum depth of influence was found to be less than that predicted by Eq. (3.1). A number of different authors, including Leonards et al. (1980), Lukas (1980), Charles et al. (1981) and Lukas (1995) investigated the variation of an empirical factor (n) with different soil conditions and for varying drop heights, h, and pounder masses, m. The general consensus is that n varies with different soil conditions, with lower values for fine-grained soils and larger values for coarse-grained soils, resulting in varying estimations for the depth of improvement, as per Eq. (3.2).

$$D = n\sqrt{mh} \qquad [3.2]$$

Alternatively, Eq. (3.2) can be re-written as shown in Eq. (3.3). In this form, the right-hand side of the equation is a function of gravitational potential energy, *mgh,* and the material characteristics, described by the parameter *n*.

$$D = \sqrt{\frac{n^2}{g}(mgh)} \qquad [3.3]$$

The value of *n* was investigated in detail by Mayne et al. (1984) who collated data from over 120 sites and found that *n* typically varied between 0.3-0.8, but could be as high as 1.0 in some instances. As explained by Mayne et al. (1984) and Lukas (1995) the variation in predicted depth of improvement is not simply a function of the tamper weight and drop height, but is also influenced by other variables such as tamper surface area, total energy applied, contact pressure of the tamper, efficiency of the dropping mechanism, initial soil conditions and ground water levels.

Applying Eq. (3.2) to the range of plotted values for *n* (0.3-0.8) in Mayne et al. (1984) to an 8-tonne, 4-sided impact roller, using the maximum physical drop height of the module that is available on a flat surface (h=0.15 m), the depth of improvement predicted would be in the range of 0.33-0.88 m. Hamidi et al. (2009) applied Eq. (3.2) to RDC and indicated that the use of this equation was subject to controversy as larger depths of improvement have been reported. Table 3.1 confirms the use of dynamic compaction formulae as under-estimating the improvement depths that are achievable using RDC. Whilst the application of deep dynamic compaction theory to RDC without modification is not suitable, the use of a more appropriate *n* value does warrant further investigation, as both dynamic compaction theory and Table 3.1 indicate that soil type is a key variable that influences the depth of improvement.

For dynamic compaction applications, Slocombe (2004) defines the ‘effective depth of influence’ as being the maximum depth at which significant improvement is measurable. The ‘zone of major improvement’ is typically half to two-thirds of the effective depth of influence. As explained by Slocombe (2004), the aforementioned terms have been adopted in the United Kingdom but may have alternative meanings in different parts of the world.

Impact rolling is routinely undertaken in unsaturated soils, whereby the application of mechanical energy expels air from the voids to reduce the void ratio. Within the influence depth of RDC, repeated loading induced stresses imparted into a granular soil are sufficient to cause a permanent rearrangement of soil particles, resulting in increased density and soil settlement. Below the influence depth, the soil remains elastic and does not undergo volume change. Berry (2001) developed an elastoplastic model to determine the depth to which there was permanent deformation using surface settlement as the main input parameter. Whilst Berry's model did not quantify the energy to achieve a particular surface settlement, it was observed that a depth of 3 times the module width was considered appropriate for a 3-sided impact roller. At sites with a shallow water table, it is possible for the high amplitude and low frequency vibrations associated with RDC to induce pore pressures to rise to the surface. In order to prevent liquefaction from occurring the number of passes is typically limited to allow pore water pressures to dissipate. Rather than competing with, impact rollers are often used to complement deeper ground improvement techniques that leave soils within the top 2 m of the surface in a disturbed and weakened condition. Avsar et al. (2006) describe an example of a large land reclamation project whereby impact rolling successfully complemented deeper ground improvement techniques.

In this paper, the depth to which RDC improves the ground is measured in full-scale field trials in homogeneous soil conditions. The measured data are compared to predictions based on dynamic compaction theory to determine the relevance of this approach to RDC applications.

3.4 Field trial to determine depth of improvement

A field trial was conducted using a Broons BH-1300 (8-tonne) 4-sided impact roller as shown in Fig. 3.1 at the Iron Duke Mine located on the Eyre Peninsula in South Australia during June 2011. The test pad was constructed in three separate lifts as illustrated in Fig. 3.2, which also shows the locations of embedded EPCs in plan and elevation. The test pad was constructed using haul trucks, end tipping loose tailings material in stockpiles where a loader and excavator subsequently spread the material over the test pad. The placement process caused the soil to be partially compacted by the self-weight of the plant, however, this method was deemed representative of the proposed construction method for the mine site, therefore was consistent with the generic aim of a field compaction trial, to be as representative as possible given the site constraints. As well as undertaking the trial for research purposes, to determine the depth of influence, there was a need to ascertain the layer thickness that could be placed to achieve a target density of 95% of maximum modified dry density for future projects at the mine.

Figure 3.1: 8-tonne 4-sided impact roller

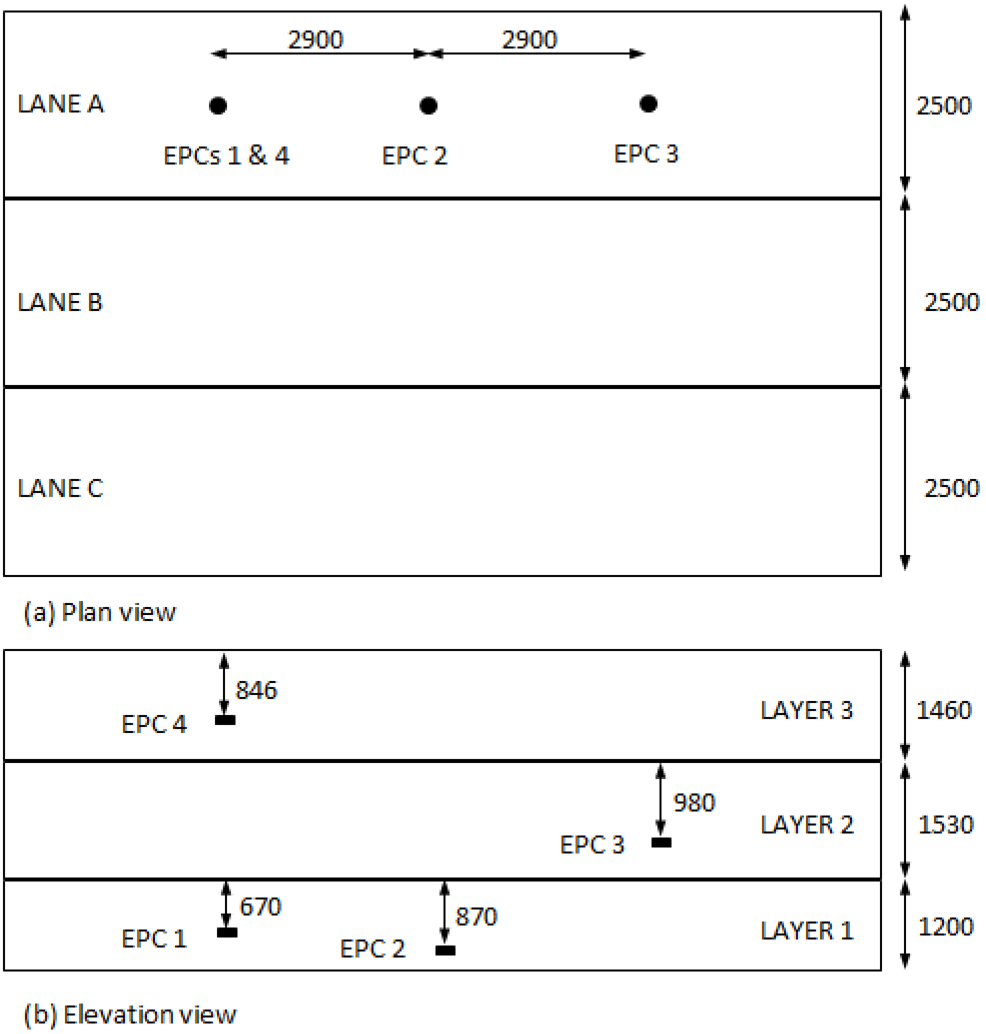

Figure 3.2: Plan and elevation views of test pad including EPC locations (all dimensions in mm)

3.4.1 Material classification

The test pad was constructed using iron magnetite tailings that are a by-product of a consistent rock crushing process. In order to classify and determine the compaction characteristics of the tailings, particle size distribution tests were performed, as well as standard and modified compaction tests, the results of which are summarised in Table 3.3. Particle size distribution (ASTM 2009a) results are the average of 9 tests and the Standard (ASTM 2007) and Modified (ASTM 2009b) Proctor compaction results are the average of 3 curves. The large dry unit weights are a consequence of the sand-sized particles consisting of crushed magnetite. The field moisture content (FMC) (ASTM 2010a) reported is the average of 15 tests undertaken. Atterberg limit testing (ASTM 2010b) confirmed the fines consisted of clay of low plasticity (plastic limit 11%

and liquid limit 22%). According to the Unified Soil Classification System (USCS), the fill material used for this compaction trial could be described as a well-graded sand (SW).

Table 3.3: Particle size distribution, compaction and field moisture test results

Material	d_{50} (mm)	Gravel (%)	Sand (%)	Fines (%)	Standard optimum moisture content (OMC) (%)	Standard maximum dry unit weight (kN/m^3)	FMC (%)	Modified OMC (%)	Modified maximum dry unit weight (kN/m^3)
Magnetite tailings	0.7	14	80	6	6.6	23.9	5.1	5.7	25.8

d_{50}, particle size at per cent finer of 50%.

3.4.2 Earth pressure cells

Four Geokon Model 3500 (230 mm diameter, 6 mm thick) earth pressure cells (EPCs) were used to measure the dynamic pressures imparted by RDC. As shown in Fig. 3.2, the initial lift (1,200 mm thick containing buried EPC1 and EPC2) was first compacted, this was repeated for the second lift of 1,530 mm (containing EPC3) and the third and final lift (1,460 mm containing EPC4). In plan, the EPCs were placed one-half of one rotation of the roller apart (2.9 m) from each other in the forward direction of travel. The EPCs were connected to a bespoke data acquisition system and Labview software program (National Instruments, 2019). A sampling frequency of 2 kHz (i.e. one sample every 0.0005 seconds) was adopted to capture sudden increases in pressure caused by the module impacting the ground. Prior to compaction the EPCs were used to measure the self-weight of the impact rolling module for the roller in an ‘at rest’ condition, centered above each EPC. The measured pressures were compared to predictions using Fadum’s chart (Fadum, 1948) using elastic theory, the results of which are shown in Fig. 3.3. The measured pressures follow the same general trend, but are less than the predicted pressures; the difference between the predicted and measured values is an average of 38% over the depths measured. The most likely explanation for this is that the non-uniform shape of the module face impacting the ground does not produce a uniform pressure distribution, this is exacerbated for shallow EPC depths. A towing speed of 10.5 km/h was selected for all 16 passes that were conducted on each layer.

The staged construction process resulted in the dynamic pressure imparted by RDC to be measured at 9 different depths.

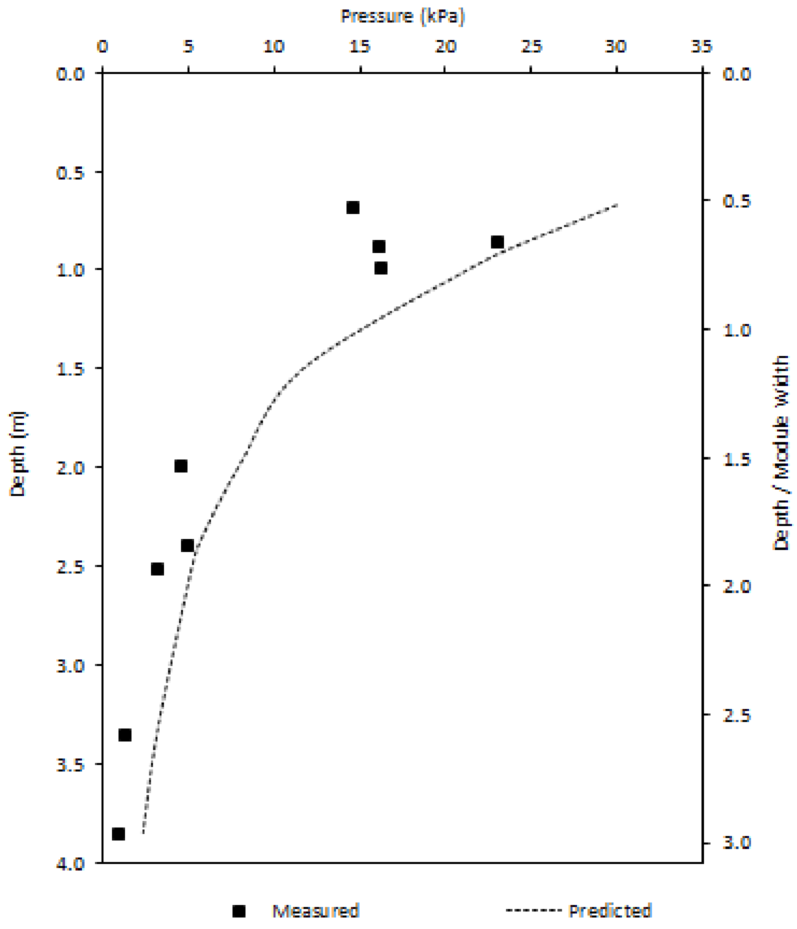

Figure 3.3: Measured and predicted pressures versus depth for impact roller at rest

3.4.3 In situ testing

Various in situ testing methods were performed after 0, 8 and 16 passes to quantify soil improvement with increasing compactive effort. The in situ tests were undertaken in the centre of Lane A in layer 3 as shown in Fig. 3.2. The tests conducted included field density measurements (ASTM 2008), the spectral analysis of surface waves (SASW) geophysical technique and dynamic cone penetration tests (DCPs) to measure and infer changes in density as a function of the number of module passes. SASW testing was conducted using a GDS Surface Wave System using six 4.5 Hz geophones spaced at 1 m intervals with a sledge hammer source impacting a metal strike plate 1 m from the first geophone. DCP testing was undertaken in accordance with the procedure described in AS 1289.6.3.3 (Australian Standards, (SA, 1997)). Verification of RDC was also undertaken using settlement monitoring to quantify the change in ground surface level with the number of passes. This was achieved using a level and staff to measure settlement at 9 points across the test pad in adjacent low points in the undulating surface, as is the normal practice. Due to space constraints, a discussion of testing methods generally employed to verify RDC is not presented here. This is, however, discussed in detail by Avalle and Grounds (2004) and Scott and Jaksa (2008).

3.5 Results of field trial

This section provides details of the results obtained from the field trial; specifically those obtained from the EPCs, in situ and geophysical testing, and settlement monitoring.

3.5.1 Earth pressure cell data

Fig. 3.4 illustrates the results obtained for a typical pass of the impact roller traversing over the first lift of the test pad, where EPCs 1 and 2 were buried at depths of 0.67 m and 0.87 m, respectively. As expected, the shallower EPC recorded the greatest pressure. Fig. 3.5 presents the variation of measured peak pressure with depth, where it is observed that peak pressures greater than 100 kPa were recorded at depths above 2.0 m. The EPC results generally supported other test data that indicated that most of the quantifiable ground improvement occurred within 2 m of the surface. Even the deepest EPC (buried at a depth of 3.85 m below the ground surface) registered positive pressure readings due to the impact roller, suggesting that the depth to which RDC had an influence extended beyond this depth. Whilst the fitted trend line illustrates a good fit to the measured data, extrapolating for shallower than the measured depths is not recommended. A limitation of using EPCs, is that they should not be placed at, or close to the ground surface due to the high probability of damaging the sensors, with the manufacturer’s guidelines recommending that no heavy equipment be used over the cells unless at least 500 mm of material is placed above them (Geokon, 2007). Fig. 3.6 illustrates the measured peak pressures, plotted on a log scale, that were recorded by each EPC as the impact roller traversed directly above (lane A) and in the lanes adjacent to the buried EPCs, representing lateral offset distances of 2.5 m and 5.0 m. For a lateral offset of 2.5 m, a maximum peak pressure was measured at a depth of 2.0 m. For a lateral offset of 5.0 m, all measured peak pressures were considered negligible. Further information on the lateral influence of RDC is discussed by Scott and Jaksa (2014).

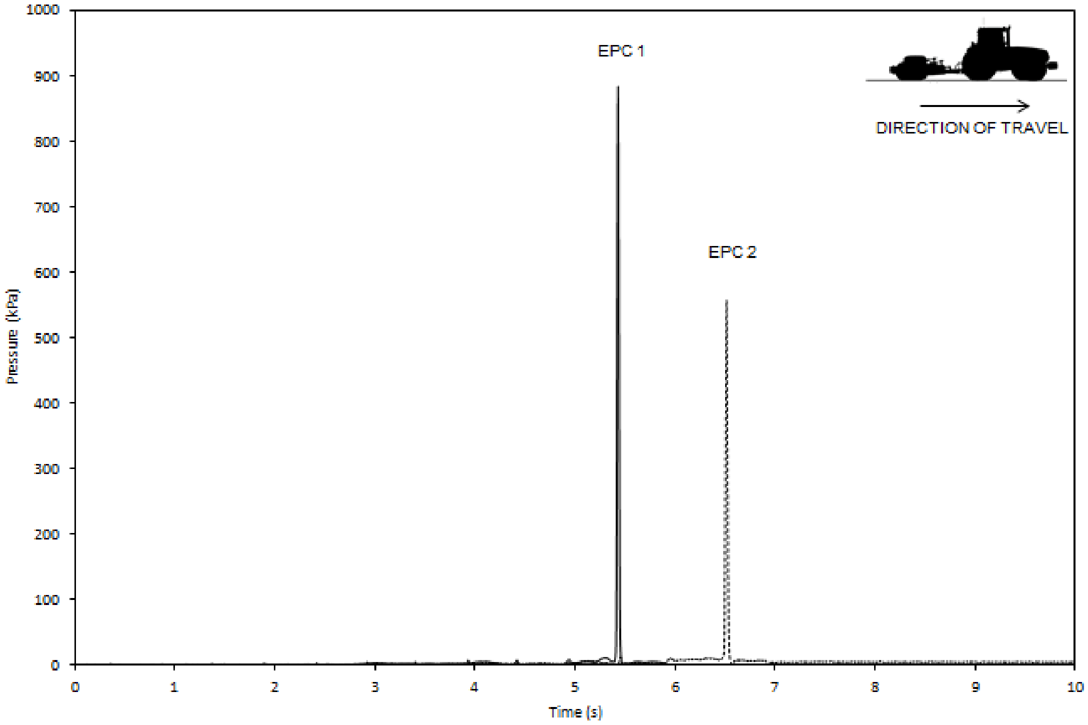

Figure 3.4: Example results of pressure versus time for a single pass of the impact roller: Lift 1 containing EPCs 1 and 2

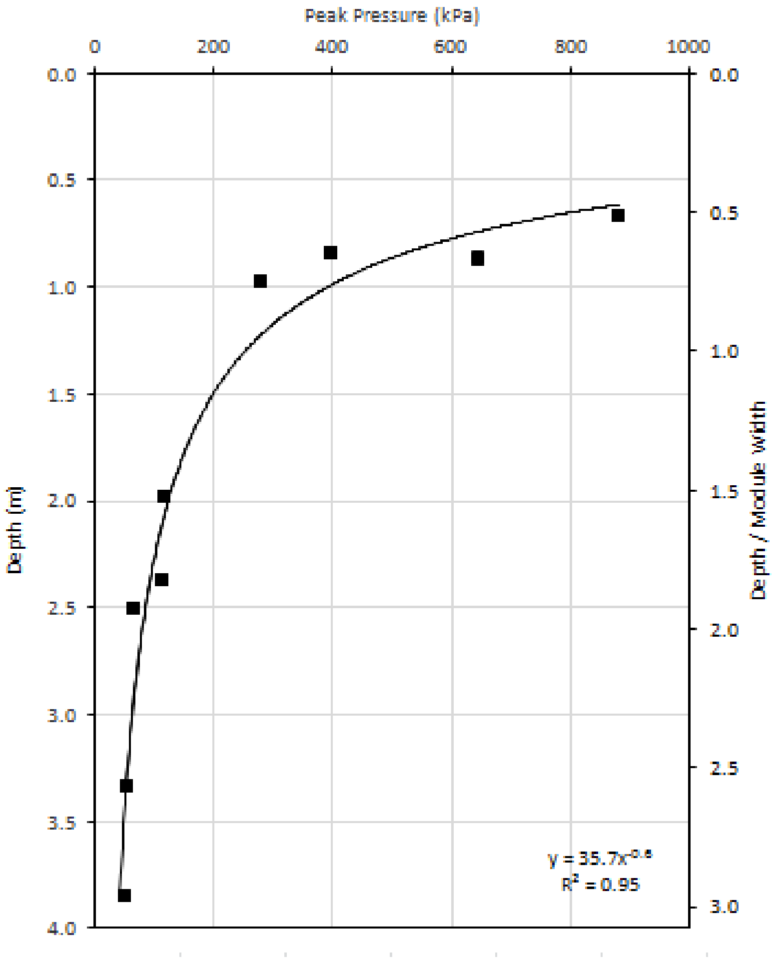

Figure 3.5: Measured peak pressure versus depth with trend line fitted to data

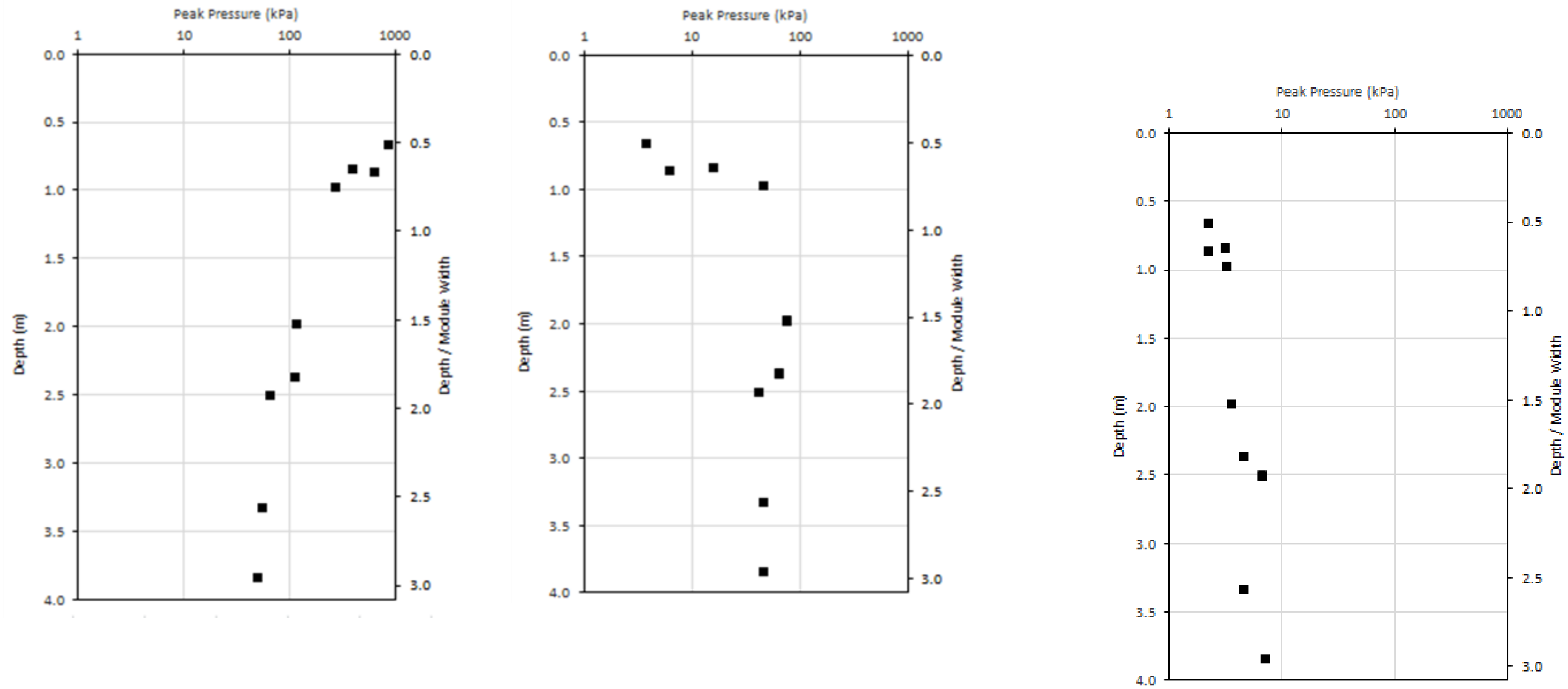

Figure 3.6: Measured peak pressure versus depth for varying lateral distances from the centre of Lane A (a) 0 m (b) 2.5 m (c) 5.0 m

3.5.2 In situ test results

Fig. 3.7 compares the average modified dry density ratio in accordance with ASTM (2009b) versus depth after 8 passes. From the trend line fitted to the data, it is estimated that 8 passes will achieve a dry density ratio of 95%, provided that the layer thickness does not exceed 1.2 m. Due to time constraints on site, density testing was not undertaken after 16 passes.

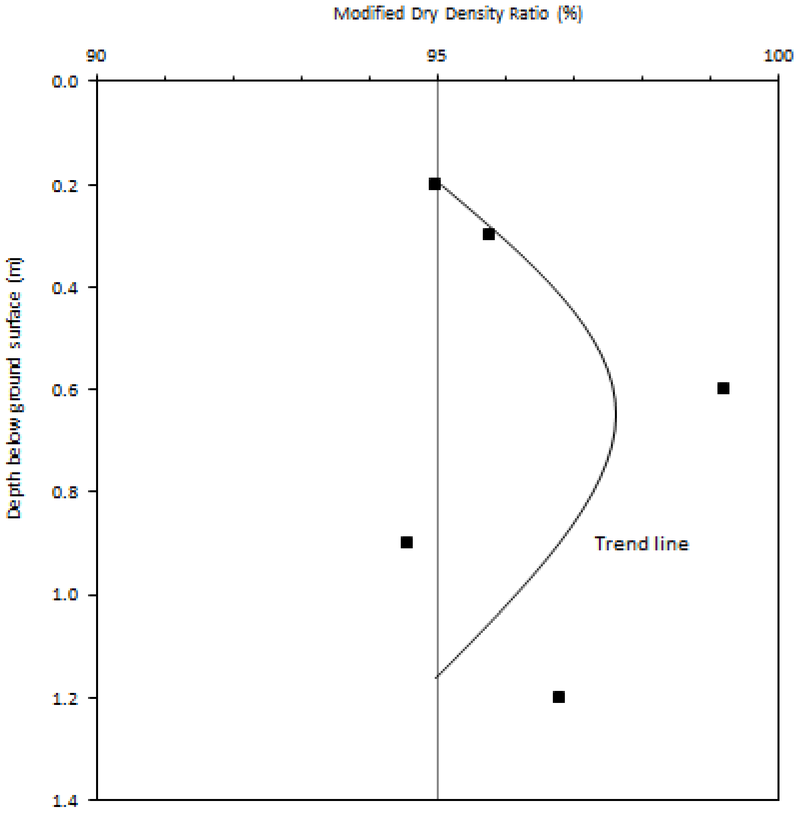

Figure 3.7: Modified maximum dry density ratio against depth after 8 passes

The SASW technique was used in conjunction with DCP tests to assess the improvement with depth at intervals of eight passes. Results for layer 2 are shown in Fig. 3.8, where it can be observed that an increased number of passes results in an increase in shear modulus between depths of 0.5–2.1 m; this is an indication of increased soil density. Below a depth of 2.1 m results were inconclusive due to insufficient data.

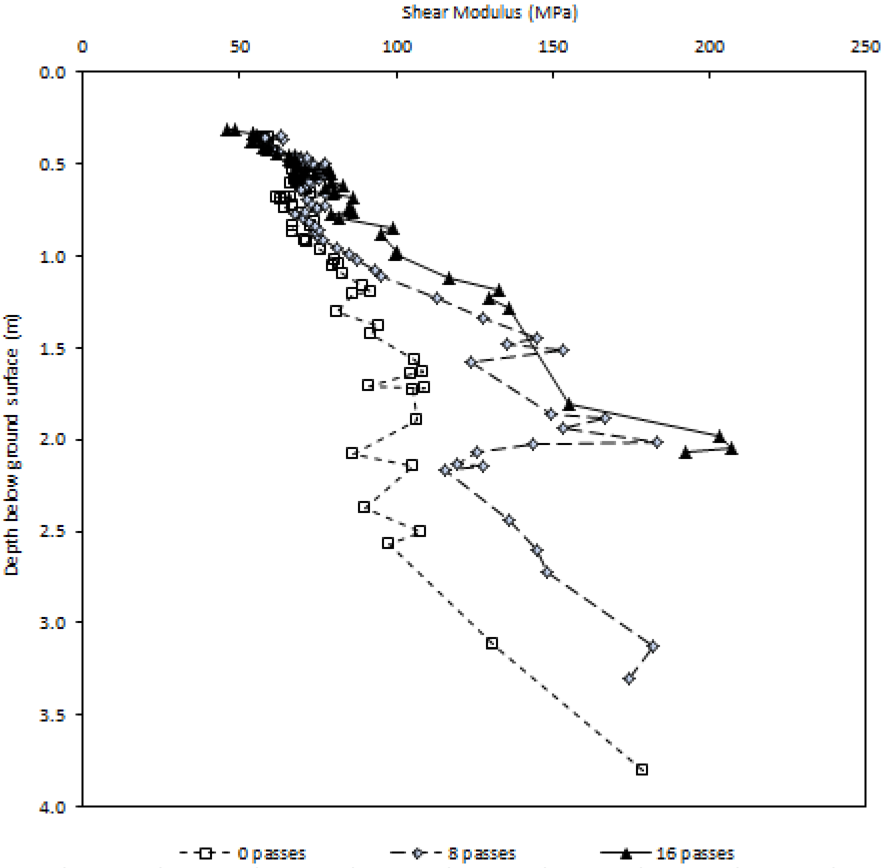

Figure 3.8: Geophysical (SASW) test results for 0, 8 and 16 passes

Fig. 3.9 summarises the number of DCP blows per 50 mm penetration with respect to depth below the ground surface. The tests were terminated at penetration depths of 850 mm due to the limited length of the penetrometer. Salgado and Yoon (2003) found that increasing blow counts are indirectly related to an increase in soil dry density. An increase in blow count is evident with a greater number of passes to depths of between 0.3 m and beyond the 0.85 m limit of the penetrometer. Loosening of near-surface soils (< 0.3 m) as a consequence of RDC is consistent with the findings of Clifford (1975) and Ellis (1979) who both suggested that RDC is unsuitable as a finishing roller.

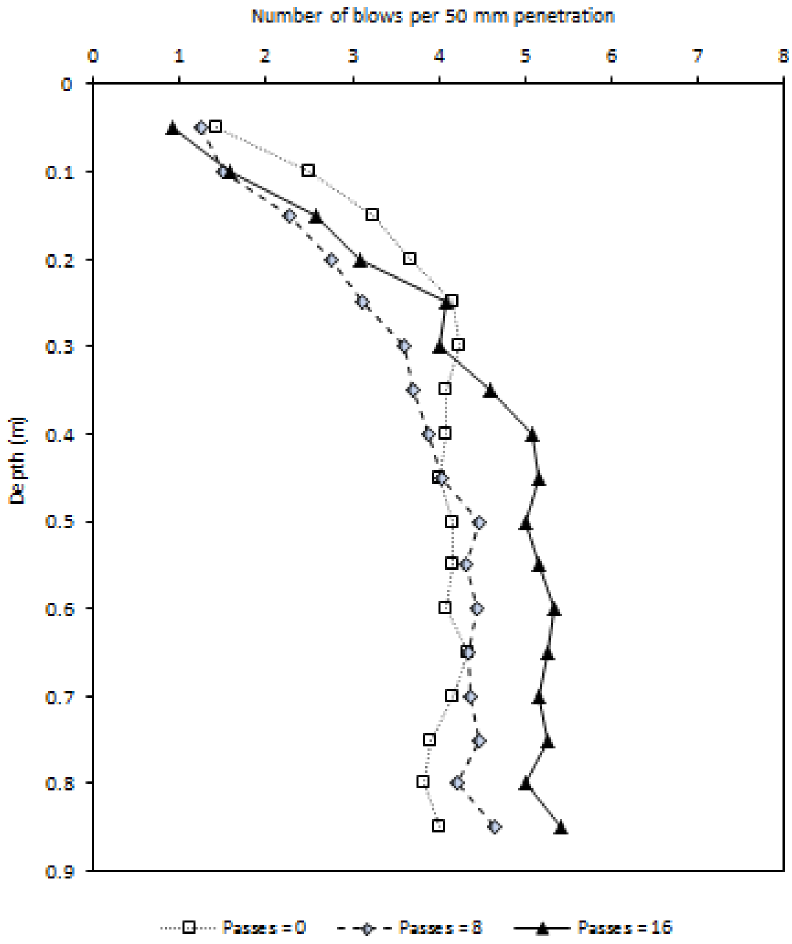

Figure 3.9: Dynamic cone penetrometer test results for 0, 8 and 16 passes

3.5.3 Surface settlement monitoring

The average surface settlement across the test pad versus number of passes was also measured. It was found that the majority of settlement occurred within the first 8 passes, the average surface settlement measured was 106 mm and 128 mm, after 8 and 16 passes, respectively.

3.6 Discussion

In current practice, the influence depth of RDC can be interpreted differently, as there are many in situ techniques that can be, and are, used to measure it. In essence, these estimates are only as good as the quality of the pre- and post-compaction testing undertaken. It is suggested that three basic definitions are relevant in this context. Firstly, the depth of influence, in simple terms, is the depth to which some improvement in density, or reduction in void ratio, is evident, regardless of magnitude. To determine this, predictive models such as that proposed by Berry (2001) could be adopted; applying this theory to the 4-sided roller yields an influence depth of 3.9 m. Alternatively, sensitive measuring equipment, such as EPCs, or intrusive site investigation techniques, such as the cone penetration test and dilatometer test could be used.

Here, no attempt is made to quantify the depth to which RDC has a small positive influence. Instead, an energy-based approach is proposed to provide estimations for depths capable of being significantly improved in situ, and layer thicknesses capable of being compacted by RDC. Gravitational potential energy forms part of the total energy imparted to the ground. Other factors include the potential energy due to the double-spring-linkage system, and the kinetic energy due to friction between the soil and module interface. The effects of the double-spring-linkage system can be quantified via a change in module velocity, hence considered part of the kinetic energy component delivered by the impact roller. For the towing speed adopted in the field trial reported in this paper, the change in potential and kinetic energies are listed in Table 3.4.

Table 3.4: Predicted change in potential and kinetic energies for a towing speed of 10.5 km/h

v (km/h)	v (m/s)	v_i (m/s)	v_f (m/s)	mgh (kJ)	ΔKE (kJ)
10.5	2.92	3.21	2.63	11.8	13.6

Note: v = speed of towing unit; v_f *= module velocity after impacting the ground;* v_i *= module velocity prior to impacting the ground.*

The second definition is applicable when improving ground in situ; in such cases, depths shallower than the maximum capable by RDC are typically targeted for improvement. Working within the limitations of RDC ensures that quantifiable improvement occurs and the properties of the ground are improved such that a specified target criterion is met. The concept of an effective depth of improvement (EDI) is most relevant for applications involving improving ground in situ (as per the case studies referenced in Table 3.1). The EDI can be considered as the equivalent of the term described by Slocombe (2004) for dynamic compaction, being the maximum depth to which significant improvement occurs. As shown in Eq. (3.4), new parameter EDI is calculated as the product of Eq. (3.2) (based on module mass, *m*, lift height, *h*, and empirical factor n from dynamic compaction theory), and a new term k, defined as the ratio of the energy imparted to the ground divided by the gravitational potential energy, as calculated in Table 3.5.

Table 3.5: Values of *k* for different towing speeds based on change in potential and kinetic energies

v (km/h)	mgh (kJ)	ΔKE (kJ)	mgh + ΔKE (kJ)	k
9	11.8	10.0	21.8	1.8
10.5	11.8	13.6	25.4	2.2
12	11.8	17.8	29.6	2.5

Note: v = speed of towing unit; k = ratio of the energy imparted to the ground divided by gravitational potential energy.

$$EDI = k(n\sqrt{mh}) \qquad [3.4]$$

Alternatively, Eq. (3.4) can be re-written as shown in Eq. (3.5). In this form, EDI is written in terms of the material characteristics, *n*, gravitational potential energy, *mgh* and a variable *k*, which depends upon the towing speed, as per Table 3.5.

$$EDI = \sqrt{\frac{k^2n^2}{g}(mgh)} \qquad [3.5]$$

Third, for determining the maximum layer thickness that can be compacted in thick lifts, the concept of a depth of major improvement (DMI) is appropriate. This applies to situations where a target criterion that is comparable to what can be achieved by conventional compaction equipment in thin lifts is required. Consistent with the description adopted by Slocombe (2004) to determine the zone of major improvement from the effective depth of improvement, a reduction factor, r, is used. DMI is equal to r (a constant that varies between 0.5-0.67) multiplied by EDI as defined in Eq. (3.6).

$$DMI = r(EDI) \tag{3.6}$$

Values for EDI and DMI are summarised in Table 3.6, for different values of k, as calculated in Table 3.5, and n, consistent with the range of values proposed by Mayne et al. (1984). Lower values of n are applicable for clay soils; higher values of n are valid for granular soils; mixed soils require intermediate values of n to be adopted. The calculated values in Table 3.6 are in broad agreement with the case studies summarised in Tables 3.1 and 3.2.

Table 3.6: Predicted effective and maximum depths of improvement for RDC

v (km/h)	n	m (t)	h (m)	D (m)	k	EDI (m)	r	DMI (m)
9	0.3	8	0.15	0.33	1.8	0.59	0.5-0.67	0.30-0.40
9	0.5	8	0.15	0.55	1.8	0.99	0.5-0.67	0.49-0.66
9	0.8	8	0.15	0.88	1.8	1.58	0.5-0.67	0.79-1.06
10.5	0.3	8	0.15	0.33	2.2	0.73	0.5-0.67	0.37-0.49
10.5	0.5	8	0.15	0.55	2.2	1.21	0.5-0.67	0.61-0.81
10.5	0.8	8	0.15	0.88	2.2	1.94	0.5-0.67	0.97-1.30
12	0.3	8	0.15	0.33	2.5	0.83	0.5-0.67	0.42-0.56
12	0.5	8	0.15	0.55	2.5	1.38	0.5-0.67	0.69-0.92
12	0.8	8	0.15	0.88	2.5	2.20	0.5-0.67	1.10-1.47

Note: v = speed of towing unit; n = empirical factor in depth of improvement equation (lower values of n for clay, higher values of n for granular soils, intermediate values of n for mixed soils); m = module mass; h = maximum module drop height; D = depth of soil compacted due to gravitational potential energy; k = ratio of the energy imparted to the ground divided by gravitational potential energy; EDI = effective depth of improvement; r = reduction factor for determining the depth of major improvement; DMI = depth of major improvement.

For the field trial described in this paper, RDC was measured to have an influence at a depth of 3.85 m; however, the majority of improvement occurred within the top 2.0 m from the surface, consistent with the definition of EDI. Whilst RDC improves soil beneath this so-called effective depth, for a uniform soil profile, the magnitude of improvement beyond this depth is less significant. A maximum dry density ratio of 95% with respect to modified compaction was obtained for a layer thickness of 1.2 m (DMI). The values for EDI and DMI obtained are consistent with Table 3.6 for an n value of 0.8, reasonable for granular soils, and a k value of 2.2, consistent for the 10.5 km/h towing speed adopted in the trial. Table 3.6 suggests that the depths to which RDC can improve and compact granular soils is influenced more by towing speed than for clay soils. However, not all ground conditions can sustain a towing speed of 12 km/h for the 8-tonne 4-sided impact roller; therefore in the absence of site specific information, a median towing speed of 10.5 km/h is recommended for use in Table 3.6.

3.7 Conclusions

This paper has examined improving ground in situ and compaction of soil in thick layers as they are two distinctly different applications for RDC that, in the authors' opinion, need to be treated independently. For a towing speed of 10.5 km/h for the 8-tonne 4-sided impact roller, the effective depth of improvement, EDI, is estimated to be 0.73 m for clay soils ($n = 0.3$), and 1.94 m for granular soils ($n = 0.8$). This highlights that soil type is the single most important variable in quantifying the depth to which RDC can improve soil. A relationship to evaluate EDI is presented as a function of the energy imparted to the ground by RDC, and is appropriate for determining the depths to which ground can be improved in situ. For the field trial presented in this paper, an EDI of 2.0 m was measured using buried EPCs and complementary in situ testing.

A second relationship to determine the depth of major improvement, DMI, is also introduced, and is appropriate for determining the thickness of layers that can be compacted using RDC, typically half to two thirds of EDI. For the field trial presented in this paper, a DMI of 1.2 m was measured using in situ testing. The equations presented in this paper augment the relationship for dynamic compaction first proposed by Menard and Broise (1975). In addition to soil type, module mass and drop height, the equations presented also incorporate the effect of towing speed. Whilst the equations presented in this paper are relatively simple in nature, the proposed energy-based approach yields estimations for depths capable of being significantly improved in situ, and layer thicknesses capable of being compacted by RDC, that are in broad agreement with the findings of the field trial presented, and the results of published case studies involving the 8-tonne 4-sided impact roller over the past four decades.

3.8 Acknowledgements

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3.9 References

ASTM (2007) D 698: Standard test methods for laboratory compaction characteristics of soil using standard effort. ASTM International, West Conshohocken, PA, USA.

ASTM (2008) D 5195: Standard test methods for density of soil and rock in-place at depths below surface by nuclear methods. ASTM International, West Conshohocken, PA, USA.

ASTM (2009a) D 6913: Standard test methods for particle-size distribution (gradation) of soils using sieve analysis. ASTM International, West Conshohocken, PA, USA.

ASTM (2009b) D 1557: Standard test methods for laboratory compaction characteristics of soil using modified effort. ASTM International, West Conshohocken, PA, USA.

ASTM (2010a) D 2216: Standard test methods for laboratory determination of water (moisture) content of soil and rock by mass. ASTM International, West Conshohocken, PA, USA.

ASTM (2010b) D 4318: Standard test methods for liquid limit, plastic limit, and plasticity index of soils. ASTM International, West Conshohocken, PA, USA.

Avalle DL (2004) Ground improvement using the “square” impact roller – case studies. In Proceedings of the 5th International Conference on Ground Improvement Techniques, Kuala Lumpur, Malaysia, pp. 101-108.

Avalle DL (2007) Trials and validation of deep compaction using the “square” impact roller. Symposium Advances in Earthworks, Australian Geomechanics Society, Sydney, Australia, pp. 63-69.

Avalle DL and Carter JP (2005) Evaluating the improvement from impact rolling on sand. In Proceedings of the 6th International Conference on Ground Improvement Techniques, Coimbra, Portugal, pp. 153-160.

Avalle D and Grounds R (2004) Improving pavement subgrade with the "square" impact roller. 23rd Annual Southern African Transport Conference, Pretoria, South Africa, pp. 44-54.

Avalle DL and Mackenzie RW (2005) Ground improvement of landfill site using the “square” impact roller. Australian Geomechanics, **40(4)**: 15-21.

Avalle D and Young G (2004) Trial programme and recent use of the impact roller in Sydney. Earthworks Seminar, Australian Geomechanics Society, Adelaide, Australia, 5pp.

Avsar S, Bakker M, Bartholomeeusen G and Vanmechelen, J. (2006) Six sigma quality improvement of compaction at the New Doha International Airport Project. *Terra et aqua*, **103**: 14-22.

Berry AD (2001) Development of a volumetric strain influence ground improvement prediction model with special reference to impact compaction. Dissertation submitted in partial fulfilment of the requirements of the degree of Master of Engineering, University of Pretoria, Pretoria, South Africa.

Charles JA, Burford D and Watts KS (1981) Field studies of the effectiveness of dynamic consolidation. In Proceedings of the 10th International Conference on Soil Mechanics and Foundation Engineering, Stockholm, Sweden, 3: 617-622.

Clifford JM (1975) An introduction to impact rollers. National Institute for Road Research, Internal report RP/2/75, South Africa, pp. 1-30.

Clifford JM (1978) Evaluation of Compaction Plant and Methods for the Construction of Earthworks in Southern Africa. Dissertation in partial fulfilment of the requirements for the degree of Master of Science in Engineering, University of Natal, Durban, South Africa.

Clifford JM (1980) The development and use of impact rollers in the construction of earthworks in southern Africa. CSIR Report 373, National Institute for Transport and Road Research Bulletin 16, Pretoria, South Africa, pp. 1-53.

Clifford JM and Coetzee SD (1987) Coal and discard stockpiling with an impact roller. In Proceedings of the International Conference on Mining and Industrial Waste Management, Johannesburg, South Africa, pp. 75-79.

Ellis CI (1979) Pavement engineering in developing countries. Transport and Road Research Laboratory, TRRL Supplementary Report 537, Crowthorne, Berkshire, 35pp.

Fadum RE (1948) Influence values for estimating stresses in elastic foundations. In Proceedings of the 2nd International Conference ISSMFE, Rotterdam, Netherlands, 3: 77-84.

Geokon (2007) Instruction Manual Model 3500, 3510, 3515, 3600 Earth Pressure Cells. Geokon Incorporated, Lebanon, USA, 24pp.

Hamidi B, Nikraz H and Varaksin S (2009) A review of impact oriented ground improvement techniques. Australian Geomechanics **44(2)**: 17-24.

Kim K (2010) Numerical simulation of impact rollers for estimating the influence depth of soil compaction. Dissertation in partial fulfilment of the requirements for the degree of Master of Science, Texas A&M University, Texas, USA.

Leonards GA, Holtz RD and Cutter WA (1980) Dynamic compaction of granular soils. Journal of Geotechnical Engineering Division ASCE **106(1)**: 35-44.

Lukas RG (1980) Densification of loose deposits by pounding. Journal of Geotechnical Engineering Division ASCE **106(4)**: 435-446.

Lukas RG (1995) Dynamic compaction. Geotechnical Engineering Circular No. 1, U.S. DOT, Publication No. FHWA-SA-95-037, Federal Highway Administration, Washington, D.C.

Mayne PW, Jones JS and Dumas JC (1984) Ground response to dynamic compaction. Journal of Geotechnical Engineering ASCE **110(6)**: 757-774.

Menard L and Broise Y (1975) Theoretical and practical aspects of dynamic consolidation. Geotechnique, **25(1)**: 3-18, https://doi.org/10.1680/geot.1975.25.1.3.

National Instruments (2019) http://www.ni.com/en-us/shop/labview.html (accessed 03/05/2019).

Nazhat Y (2013) Behaviour of sandy soil subjected to dynamic loading. Thesis submitted in fulfilment of the requirement for the degree of Doctor of Philosophy, University of Sydney.

SA (Standards Australia) (1997) AS 1289.6.3.3: Methods of testing soils for engineering purposes – Soil strength and consolidation tests – Determination of the penetration resistance of a soil – Perth sand penetrometer test. Standards Australia, Sydney, Australia.

Salgado R and Yoon S (2003) Dynamic cone penetration test (DCPT) for subgrade assessment. Joint Transportation Research Program, West Lafayette, IN, USA, Report FHWA/IN/JTRP-2002/30.

Scott BT and Jaksa MB (2008) Quantifying the influence of rolling dynamic compaction. In Proceedings of the 8th Australia New Zealand Young Geotechnical Professionals Conference, New Zealand Geotechnical Society, Wellington, New Zealand, pp. 199-204.

Scott BT and Jaksa MB (2012) Mining applications and case studies of Rolling Dynamic Compaction. In Proceedings of the 11th Australia New Zealand Conference on Geomechanics, Australian Geomechanics Society, Melbourne, Australia, pp. 961-966.

Scott BT and Jaksa MB (2014) Evaluating rolling dynamic compaction of fill using CPT. 3rd International Symposium on Cone Penetration Testing, Las Vegas, USA, pp. 941-948.

Scott BT and Suto K (2007) Case study of ground improvement at an industrial estate containing uncontrolled fill. In Proceedings of the 10th Australia New Zealand Conference on Geomechanics, Australian Geomechanics Society, Vol. 2, Brisbane, Australia, pp. 150-155.

Slocombe BC (2004) Dynamic Compaction. *Ground Improvement* 2nd Ed. Moseley, M.P and Kirsch, K, eds. Spon Press, New York, pp. 93-118.

Whiteley RJ and Caffi P (2014) Evaluating the effectiveness of rolling impact compaction at a brownfield site with high and low frequency seismic surface waves and geotechnical testing. Near Surface Geophysics **12**: 405-414.

Wolmarans CH and Clifford JM (1975) An evaluation of the CSIR impact roller. 6th Regional Conference for Africa on Soil Mechanics and Foundation Engineering, Durban, South Africa, pp. 33-39.

Chapter 4: Quantifying the ground response to RDC

Introduction

In typical project applications, the effects of RDC are quantified by conducting testing pre- and/or post-compaction to determine if a project specification has been met (or otherwise). However, such testing methods fail to accurately quantify the dynamic effects during the time of impact.

The journal paper in Chapter 4 has used buried earth pressure cells (EPCs) and accelerometers to better understand the ground response to RDC beneath the surface by capturing the ground response in real-time. This paper has captured the pressure distribution at the time of module impact; significantly, the maximum change in vertical stress was approximately 1,100 kPa, with the soil loading and unloading occurring over a duration of approximately 0.05 seconds. The acceleration response was captured in three orthogonal directions, with the vertical accelerations dominant. The accelerations measured in the direction of travel, indicated that the roller direction of travel influences the ground response. Quantifying the dynamic loading and unloading behaviour of the soil beneath the ground surface in real-time for a single impact, and then consecutive impacts, highlights the dynamic behaviour of RDC, and how the uneven module geometry results in some passes imparting significantly higher pressure to the ground than others.

The conference paper in Appendix F compares before and after compaction test results using three in situ testing methods; field nuclear density, dynamic cone penetrometer (DCP) and spectral analysis of surface waves (SASW), as well as the ground response due to RDC using earth pressure cells, accelerometers and surface settlement measurements used during the compaction trial. This paper was based on the same field trial as the aforementioned journal paper in this chapter, but had a broader focus of comparing in situ testing methods and relating them to the ground response using buried instrumentation. The paper in Appendix F analyses the earth pressure cell and accelerometer data at an introductory level, appropriate for the conference at which this paper was presented. This is in contrast to the journal paper contained within the main body of the thesis that focusses on an in-depth analysis of the buried instrumentation that was placed at a depth of 0.7 m below the ground surface.

The conference paper in Appendix G summarises early data and attempts by the author to capture the ground response due to RDC. Following this field trial, significant changes and modifications to instrumentation software and hardware were undertaken; nevertheless the early findings summarised in this paper were important as they dictated what improvements and refinements were required to better capture the ground response in future field trials.

List of Manuscripts

Scott, B.T., Jaksa, M.B. & Mitchell, P.W. (2019). Ground response to rolling dynamic compaction. *Geotechnique Letters, Institution of Civil Engineers*, 9(2): 99-105. https://doi.org/10.1680/jgele.18.00208

Scott, B.T., Jaksa, M.B. & Syamsuddin, E. (2016). Verification of an impact rolling compaction trial using various in situ testing methods. *Proceedings 5th International Conference on Geotechnical and Geophysical Site Characterisation, Gold Coast, Australia*, pp. 735-740. A copy of this paper is included in Appendix F.

Avalle, D.L., Scott, B.T., & Jaksa, M.B. (2009). Ground energy and impact of rolling dynamic compaction - results from research test site. *Proceedings of the 17th International Conference on Soil Mechanics and Geotechnical Engineering, Cairo, Egypt*, Vol. 3, pp. 2228-2231. A copy of this paper is included in Appendix G.

Statement of Authorship

Title of Paper	Ground response to rolling dynamic compaction	
Publication Status	☑ Published ☐ Submitted for Publication	☐ Accepted for Publication ☐ Unpublished and Unsubmitted work written in manuscript style
Publication Details	Scott, B.T., Jaksa, M.B. & Mitchell, P.W. (2019). Ground response to rolling dynamic compaction. Institution of Civil Engineers, Geotechnique Letters.	

Principal Author

Name of Principal Author (Candidate)	Brendan Scott		
Contribution to the Paper	Performed site work, analysis and interpretation of site data, wrote manuscript.		
Overall percentage (%)	90		
Certification:	This paper reports on original research I conducted during the period of my Higher Degree by Research candidature and is not subject to any obligations or contractual agreements with a third party that would constrain its inclusion in this thesis. I am the primary author of this paper.		
Signature		Date	18/4/2019

Co-Author Contributions

By signing the Statement of Authorship, each author certifies that:

i. the candidate's stated contribution to the publication is accurate (as detailed above);

ii. permission is granted for the candidate in include the publication in the thesis; and

iii. the sum of all co-author contributions is equal to 100% less the candidate's stated contribution.

Name of Co-Author	Mark Jaksa		
Contribution to the Paper	Provided primary supervision and helped evaluate and edit the manuscript.		
Signature		Date	18/4/19

Name of Co-Author	Peter Mitchell		
Contribution to the Paper	Provided secondary supervision and helped evaluate and edit the manuscript.		
Signature		Date	16 Apr. 2019

Ground response to rolling dynamic compaction (Paper 3)

Abstract

Rolling dynamic compaction (RDC) is typically used for improving ground in situ or compacting fill in thick lifts. In many project applications, the effects of RDC are verified via testing that is undertaken pre- and/or post-compaction. This study presents results from a full-scale field trial that involved placing an earth pressure cell (EPC) and accelerometers at a depth of 0.7 m within a 1.5 m thick layer of homogeneous sandy gravel to measure the response to RDC in real-time. Double integration of acceleration-time data enabled settlement to be inferred, whilst the EPC measured the change in stress due to impact. The maximum change in vertical stress recorded over the 80 passes undertaken was approximately 1,100 kPa. During a typical module impact, the loading and unloading response occurred over a duration of approximately 0.05 seconds. The acceleration response of RDC was measured in three orthogonal directions, with the vertical accelerations dominant.

List of notation

d_{50}	particle size at per cent finer of 50%
g	free-fall acceleration (9.81 m/s^2)
$W_{elastic}$	elastic work done (energy imparted to ground that is recovered elastically)
$W_{plastic}$	plastic work done (energy imparted in ground that causes permanent settlement)
W_{total}	total work done (area under the load-displacement curve) = $W_{elastic} + W_{plastic}$
Δt	duration of applied load
$\delta_{elastic}$	elastic (rebound) settlement
$\delta_{plastic}$	plastic (permanent) settlement

4.1 Introduction

Rolling dynamic compaction (RDC) imparts energy to the ground through the use of a heavy, non-circular module that falls to impact the ground. A limitation of many past field investigations to verify the effects of RDC is that testing is typically performed pre- and/or post-compaction. Such investigations often serve their intended purpose for determining if a project specification has been met (or otherwise) but they do not capture the dynamic effects of a heavy module impacting the ground in real-time. This study has used a buried earth pressure cell (EPC) and accelerometers to better understand the ground response beneath the surface during the passage of an impact roller.

4.2 Background

Impact rollers with different module masses, shapes and drop heights, have been compared to predict the energy imparted into the ground (McCann 2015). A limitation with such a prediction is that a RDC module that is towed across the surface impacts the ground in a different manner to a dynamic compaction pounder that is a function of mass, drop height and vertical acceleration due to gravity. A RDC module, shown in Fig. 4.1, impacts the ground in a similar way to a falling hinged trap-door; the geometry and surface area of the module that is in contact with the ground is non-uniform; as is the impact velocity of the module when it contacts the ground.

In RDC applications, accelerometers have been placed on an impact roller to measure the ground surface response. Heyns (1998), and McCann and Schofield (2007) both noted that an increase in the magnitude of decelerations is commonly measured with increasing passes, as the surface soil stiffness increases. This finding is consistent with the work of Clifford (1978), who observed that the module drop height increases as the ground surface becomes harder; the cross-sectional area of the module that is in contact with the ground changes with drop height due to the geometry of the rounded corners and how far they embed in the ground. The energy imparted by the roller is spread over a smaller area as the stiffness of the surficial soil increases; this results in greater contact pressures being imparted to the soil with increasing passes. The use of module mounted accelerometers has proven useful in identifying less stiff near-surface soils that typically exhibit lower decelerations (McCann and Schofield 2007); however, there is no guarantee that measuring the response of an impact roller as it passes over the ground surface gives a true indication of the soil response below the surface. Inferring improvement due to RDC from surface measurements can be challenging given RDC typically disturbs the near-surface soils, which can be further complicated by sites containing inherent soil variability. Mooney and Rinehart (2007) carried out a field investigation using a smooth drum vibrating roller. They performed multiple passes across test areas comprising both heterogeneous and homogeneous soils. They found that soil heterogeneity presented significant challenges for interpreting instrumented roller data. This study overcomes previous limitations by attaching accelerometers to an EPC and burying them in homogeneous fill material to quantify the loading induced stress and ground deceleration beneath the ground surface, yet within the expected zone of influence of RDC.

4.2.1 Comparisons with dynamic compaction

Measuring the ground response of deep dynamic compaction has been studied by Mayne and Jones (1983), who attached an accelerometer to a 20.9 tonne pounder to monitor the deceleration upon impact with the ground surface after falling a distance of 18.3 m; the deceleration-time response of the impact blow occurred over a duration of only 0.05 seconds. Also of significance, the magnitude of decelerations recorded were in the order of 70-85g, and a trend of increasing magnitude with number of drops was observed. Clegg (1980) attached an accelerometer to a falling weight and found that the peak deceleration of the weight upon impact with the soil was directly related to the soil resistance, described as a combination of both soil stiffness and shearing resistance. Chow et al. (1990) developed a theoretical framework that was based on matching deceleration measurements of a dynamic compaction pounder impacting the ground using an accelerometer that was attached to the pounder near the centre of gravity. The one-dimensional model that was developed was similar to pile driving analyses where the impact velocity was obtained by integrating measured decelerations. Yu (2004) double integrated the acceleration-time response of a vertically falling plate to generate the load-displacement relationship, which was integrated to quantify the work done. Analysis of a load-displacement response due to impact was also undertaken by Jha et al. (2012) who investigated energy dissipation to quantify the elastic energy that was recovered during unloading of multi-phase cementitious materials. They plotted the load-displacement response for cementitious materials subjected to nano-indentation and determined the area under the loading and unloading curves and quantified the work done. Key aims of this study are to measure the loading induced stresses and displacements that soil particles beneath the ground surface experience, and to quantify the work done from measured force-displacement data.

4.3 Research test site

Fig. 4.1 shows a 4-sided 8-tonne impact roller (1,450 mm square and 1,300 mm wide module) that was used at a dedicated research site located at Monarto Quarries, approximately 60 km south-east of Adelaide, Australia. Whilst conducting a full-scale trial that is not associated with a client funded project is expensive, a research focussed trial provided an ability to control a number of variables that can often conceal the true effects of RDC. Significantly, natural soil was excavated to a depth of 1.5 m and replaced with homogeneous fill; a crushed rock with a maximum particle size of 20 mm that was readily available and locally produced at the quarry. Six equal lifts of 250 mm thickness were adopted; the material was placed using a Volvo L150E Loader, and was lightly compacted using a 60 kg vibrating plate and wheel rolling from the loader. The fill material was classified as a well-graded Sandy Gravel (GW) in accordance with the Unified Soil Classification System. The fill was tested for homogeneity through the use of particle size distribution and Proctor compaction testing; the results are given in Table 4.1.

Figure 4.1: 8-tonne 4-sided impact roller.

Table 4.1: Particle size distribution, compaction and field moisture test results of fill material

Material	d_{50} (mm)	Gravel size (%)	Sand size (%)	Fines (%)	Standard OMC (%)	Standard MDD (kN/m^3)	FMC (%)	Modified OMC (%)	Modified MDD (kN/m^3)
20 mm crushed rock	4.0	57	40	3	7.9	17.9	8.6	7.2	18.9

Note: d_{50} = particle size at percent finer of 50%; OMC = optimum moisture content; MDD = maximum dry density; FMC = field moisture content.

4.3.1 Earth pressure cells and accelerometers

Field trials undertaken by Avalle et al. (2009) and Scott et al. (2016) using the 4-sided impact roller have shown that a module impacting the ground directly above embedded instrumentation results in significantly higher ground decelerations being recorded, compared to when the module strikes the ground off-set from embedded instrumentation. A limitation of burying equipment at discrete locations is that it is not possible to capture the maximum ground response from every impact. However, a key advantage of this technique is that it does provide real-time data on dynamic pressures and accelerations that are imparted into the ground that other testing methods are unable to do.

A custom-built accelerometer cluster consisting of ±5g and ±16g accelerometers in the Z-plane to measure vertical acceleration, and ±5g accelerometers in the X- and Y-planes, to measure tilt perpendicular to, and in the direction of travel, respectively. A total of 80 passes were undertaken. The accelerometer cluster was attached to an EPC (230 mm diameter and 6 mm thick) that was buried at a depth of 0.7 m below the ground surface, and connected to a bespoke data acquisition system and Labview software program (refer Labview (2018)). The ability to capture an accurate ground response using EPCs and accelerometers relies heavily on adopting a sufficiently high sampling frequency. Given that displacement is to be quantified from the double integration of acceleration-time data, a sampling frequency of 4 kHz (twice that adopted by Avalle et al., 2009) was selected for this trial to ensure that the true peak pressure and ground deceleration could be accurately captured. As discussed by Thong et al. (2002), faster sampling rates can improve the accuracy of integration, but errors can increase with the duration of the time interval over which integration is undertaken.

4.4 Results and discussion

A single pass (No. 54 summarised in Table 4.2) was selected out of the 80 passes undertaken for analysis as it featured a high peak pressure and the largest vertical deceleration recorded. In Fig. 4.2 the module impact resulted in a measured peak pressure of 1,077 kPa at a depth of 0.7 m. It can be observed that the impulse pressure imparted to the ground was loaded and unloaded over a duration of approximately 0.05 seconds. Fig. 4.3 illustrates the vertical (Z-) acceleration-time response for the same pass shown in Fig. 4.2, whereby a downward (negative) acceleration first occurs as the soil is loaded. In response to loading, the soil resistance is mobilised, which results in an upward acceleration before the acceleration trace dampens and returned to zero less than 0.1 seconds after loading. Significantly, a peak deceleration (negative acceleration) of 21g was measured before the soil resistance was mobilised. Table 4.3 includes a summary of passes 1-10, as well as every fifth pass thereafter. As observed in Table 4.3, the magnitude of the peak downward acceleration was typically greater than the peak upward acceleration, this trend was more defined for impacts that generated large accelerations. Consequently, a shift in the baseline (zero) reading was undertaken that enabled readings of –21g and +6.3g to be measured using a ±16g accelerometer (range of 32g). Consistent with the findings of Mayne and Jones (1983), an increased number of passes generally resulted in larger accelerations (and peak pressures) being recorded. However, the variable location of the module landing on the ground surface relative to buried instrumentation, analysed and discussed by Scott et al. (2016), was also a contributing factor that would explain why some passes (e.g. pass 54) yielded much larger peak pressures and vertical accelerations than others.

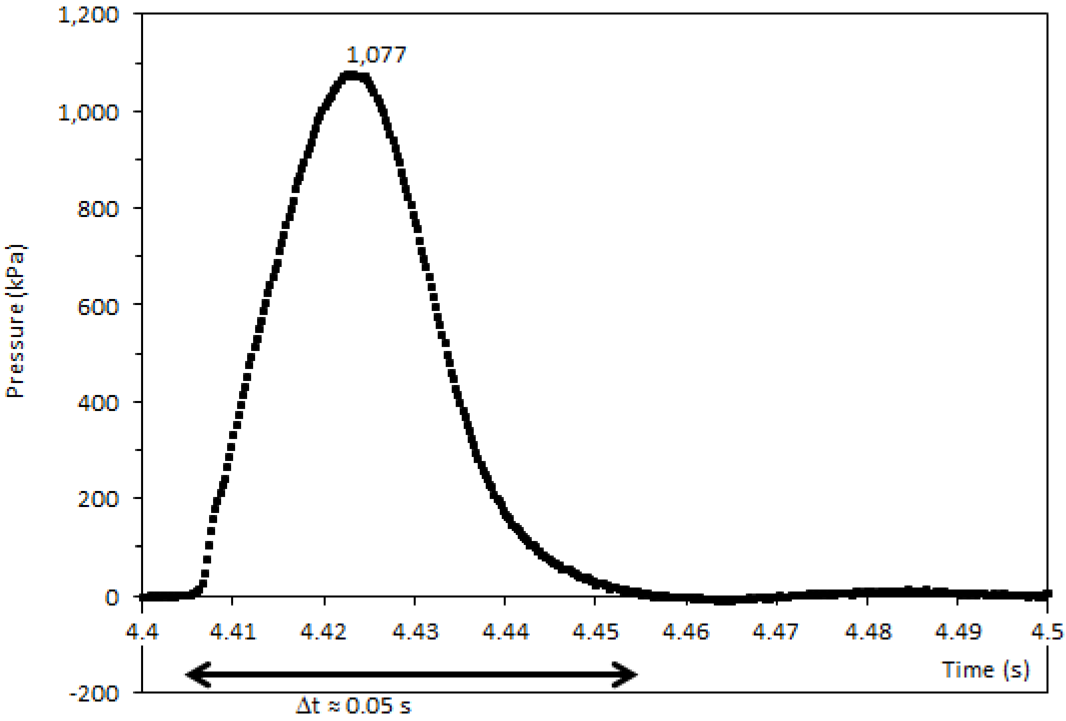

Figure 4.2: Pressure distribution at time of module impact

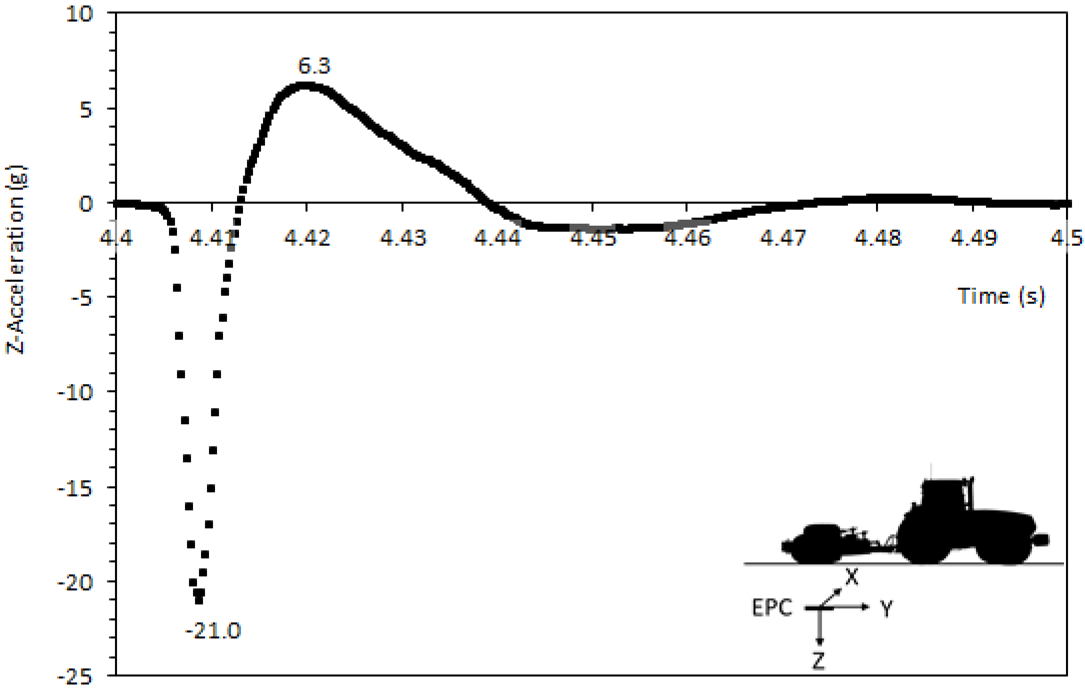

Figure 4.3: Z-acceleration response at time of module impact

Table 4.2: Summary of Pass No. 54 for test depth of 0.7 m

Pass No.	$\delta_{elastic}$ (mm)	$\delta_{plastic}$ (mm)	W_{total} (J)	$W_{elastic}$ (J)	$W_{plastic}$ (J)	Peak Pressure (kPa)	Δt (s)	Peak Dec. (g)	Peak Acc. (g)
54	4	5	254	36	218	1077	0.05	-21.0	6.3

Note: $\delta_{elastic}$ = rebound settlement; $\delta_{plastic}$ = permanent settlement; W_{total} = total area under load-displacement curve; $W_{elastic}$ = elastic work done; $W_{plastic}$ = plastic work done; Δt = duration of applied load; Peak Dec. = peak deceleration; Peak Acc. = peak acceleration.

Table 4.3: Summary of passes for test depth of 0.7 m

Pass No.	$\delta_{elastic}$ (mm)	$\delta_{plastic}$ (mm)	W_{total} (J)	$W_{elastic}$ (J)	$W_{plastic}$ (J)	Peak Pressure (kPa)	Impulse Δt (s)	Peak Dec. (g)	Peak Acc. (g)
1	2.0	0.5	13	9	4	230	0.07	-3.5	3.0
2	3	1	44	13	31	419	0.07	-5.5	3.8
3	3.5	0.5	35	25	10	371	0.08	-5.3	4.4
4	3	2	76	20	56	594	0.08	-4.6	2.5
5	6.5	0	108	53	55	656	0.07	-5.6	7.7
6	3	2	71	13	58	503	0.06	-11.6	5.2
7	3	2	64	20	44	550	0.08	-2.1	3.4
8	1	1	73	45	28	177	0.08	-1.3	0.6
9	2	1	22	6	16	258	0.05	-4.9	2.8
10	3	2	71	14	57	539	0.06	-8.5	3.9
15	3	2	56	15	41	490	0.08	-4.0	1.7
20	3	2	62	18	44	492	0.05	-9.6	4.8
25	2.5	1.5	35	14	21	324	0.06	-8.0	4.7
30	6	0.5	58	29	29	380	0.06	-10.5	**9.6**
35	2.5	1	22	7	15	272	0.05	-4.0	2.9
40	2	3	41	5	36	309	0.04	-6.6	4.4
45	2.5	0.5	12	4	8	166	0.05	-1.6	2.6
50	2	1	11	7	4	202	0.06	-1.8	1.7
55	3.5	2.5	98	24	74	680	0.05	-7.2	5.6
60	2.5	0.5	11	7	4	169	0.07	-2.4	2.5
65	3.5	**3.5**	177	14	163	873	0.05	**-13.2**	5.4
70	4	1.5	60	34	26	557	0.07	-4.9	3.8
75	1.5	6	136	18	118	731	0.07	-9.2	4.5
80	**7.5**	0.5	**249**	**59**	**190**	**1115**	0.05	-11.2	8.0

Note: $\delta_{elastic}$ = rebound settlement; $\delta_{plastic}$ = permanent settlement; W_{total} = total area under load-displacement curve; $W_{elastic}$ = elastic work done; $W_{plastic}$ = plastic work done; Δt = duration of applied load; Peak Dec. = peak deceleration; Peak Acc. = peak acceleration, peak values in ***bold****.*

Fig. 4.4 shows a plot of Y-acceleration (in the direction of travel of the roller) versus time. Of significance in this plot is the larger magnitude of the positive (compared to negative) Y-acceleration. It can be inferred that the direction of travel of the module influences the ground response, an expected result given the module drop is not solely in a vertical direction. Fig. 4.5 shows a plot of X-acceleration (perpendicular to the direction of travel) with time. Both positive and negative accelerations are approximately equal suggesting that the module landing directly over the centre of the cell produces a relatively symmetrical response in the direction across the test lane, this is not unexpected given the module only has a limited ability to move laterally within the trailer frame.

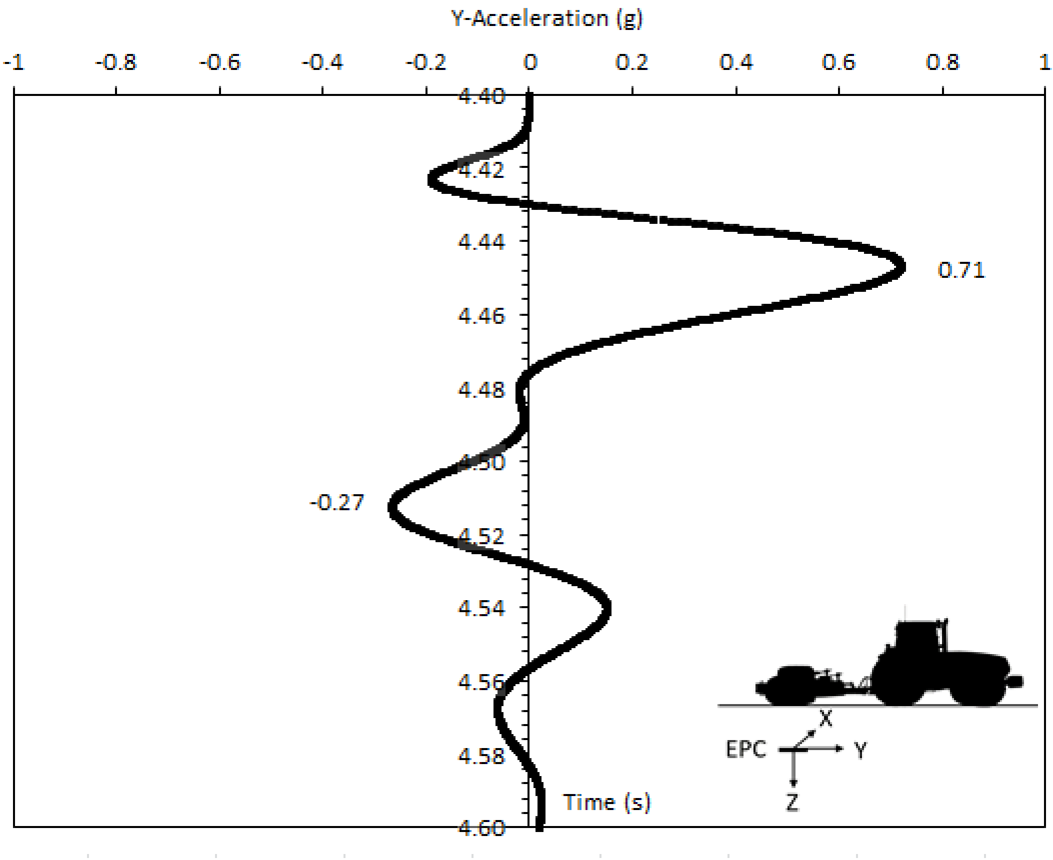

Figure 4.4: Y-acceleration response at time of module impact

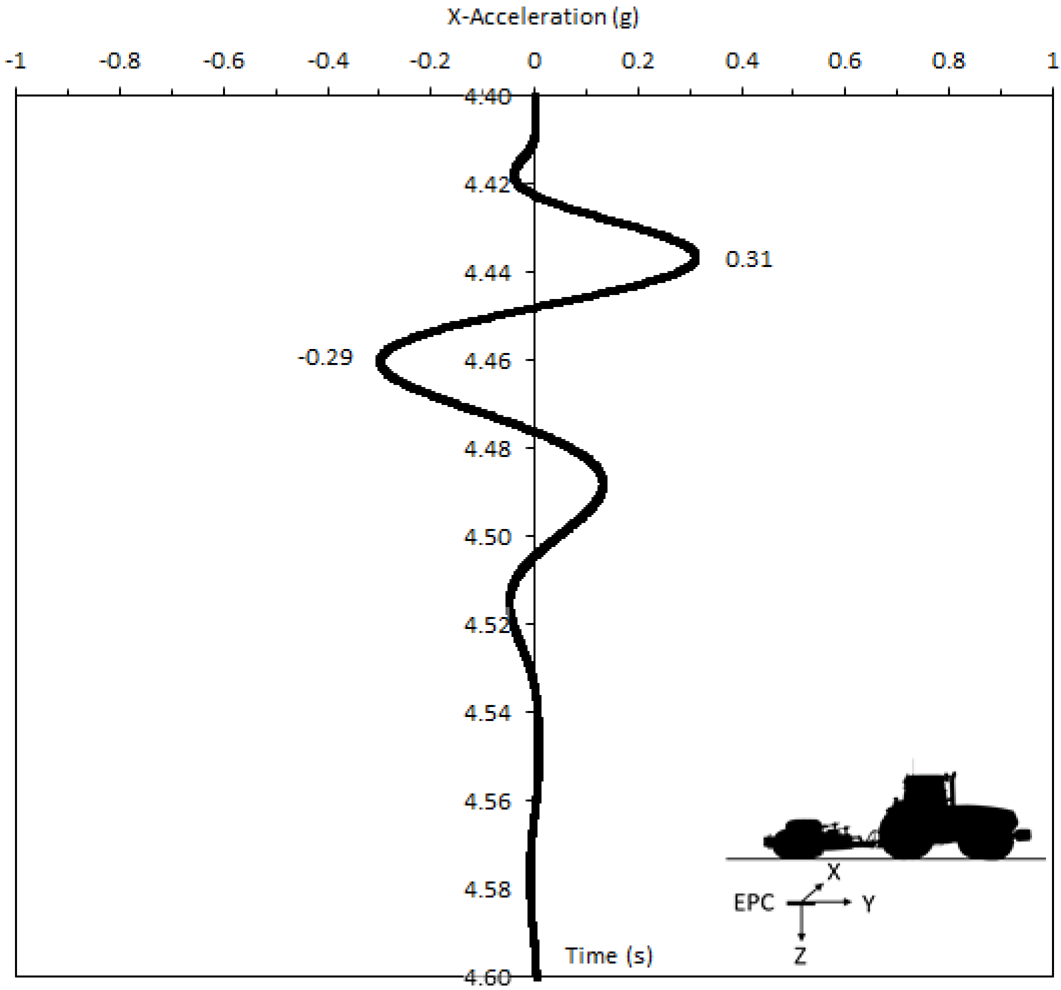

Figure 4.5: X-acceleration response at time of module impact

Fig. 4.6 shows the variation of Z-acceleration and Z-displacement of the soil with time in response to a single module impact, whereby displacement was calculated from double integration of the acceleration-time response. From Fig. 4.6, it is evident that approximately 9 mm total displacement occurred due to loading; however, upon unloading, the permanent displacement due to the single impact was 5 mm. The same impact blow is illustrated in Fig. 4.7, which shows the loading and unloading response of the soil due to a single pass of the impact roller at a measured depth of 0.7 metres beneath the ground surface. Force is determined by adopting the peak pressure at the time of impact and multiplying it by the plan area of the EPC. Displacement is evaluated from double integration of the acceleration-time response. In Fig. 4.7 the portion of the curve between points A and B represents the loading of the soil. The unloading portion of the curve is shown between points B and C. The distance between points A and C provides a measure of the permanent deformation of the soil. For a perfectly elastic soil response with no hysteresis, AB and BC would be coincidental. Area ABC yields the plastic work done and the area CBD represents the elastic work that has been recovered during unloading. The total work done comprises both recoverable (elastic) and permanent (plastic) components.

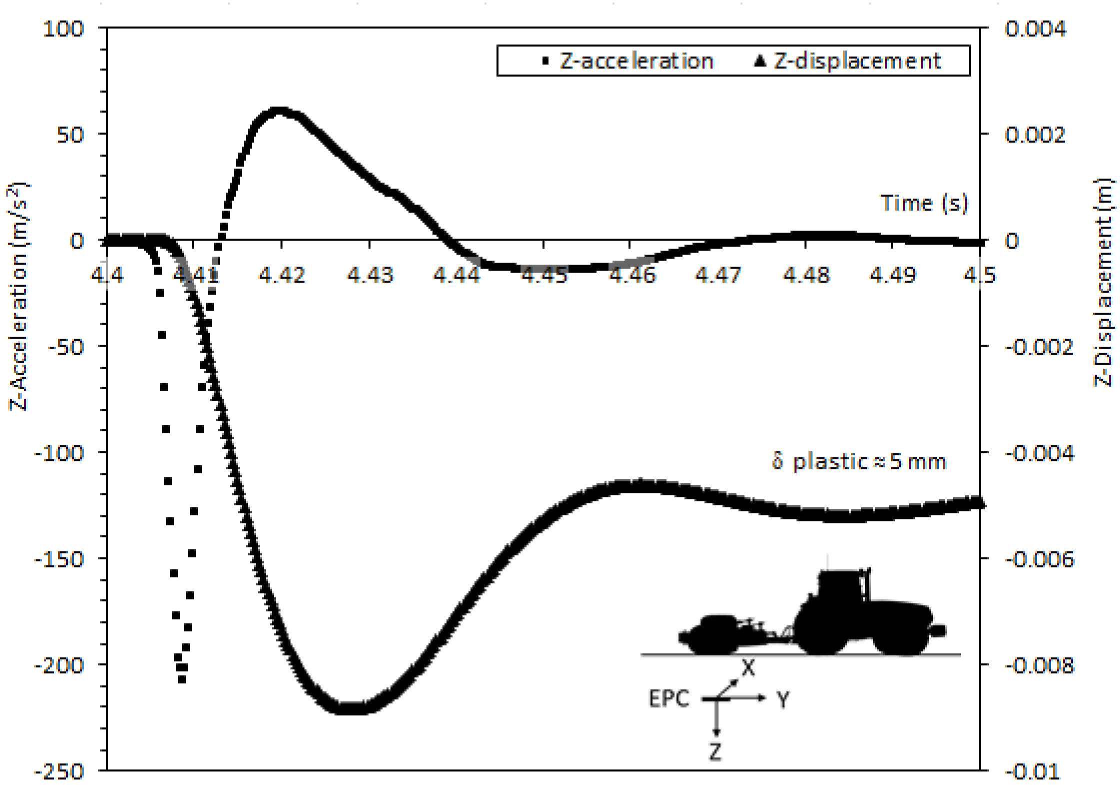

Figure 4.6: Z-acceleration and Z-displacement versus time

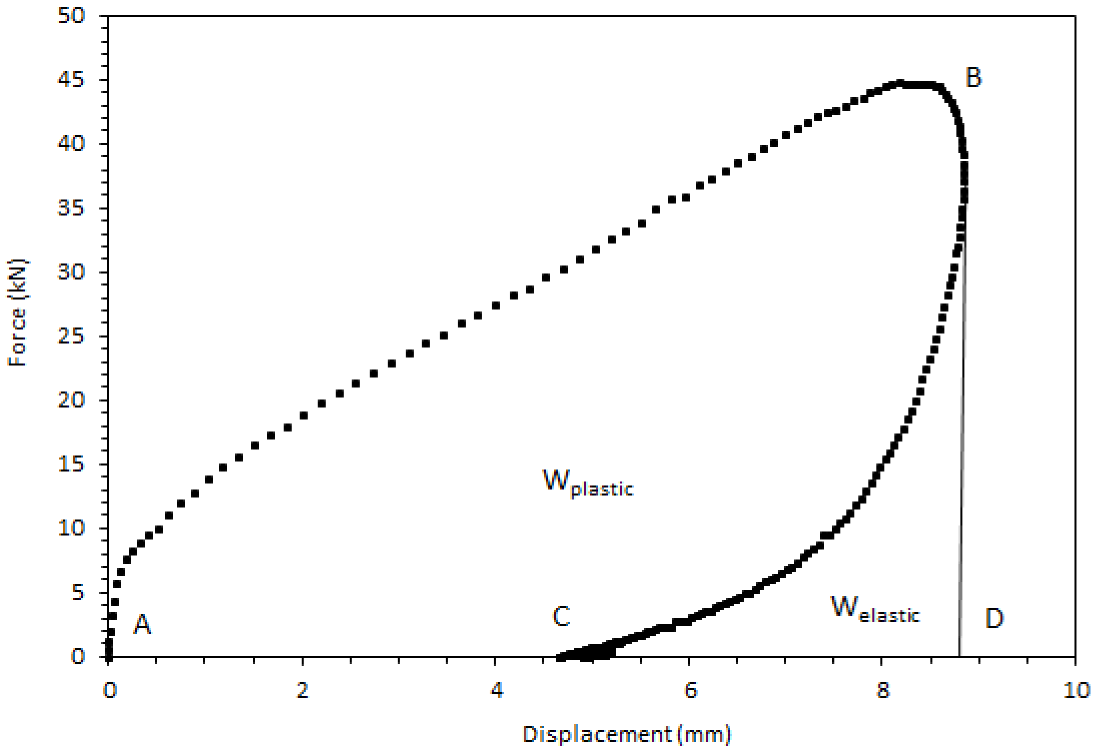

Figure 4.7: Force-displacement curve for a single pass

Fig. 4.8 shows the force-displacement response for consecutive module impacts (passes 1-10 inclusive, summarised in Table 4.3). As can be observed, there is a large variation in the shape and magnitudes of the force-displacement curves for individual passes. Pass 1 is close to an elastic impact where minimal work is done on the soil. The opposite is true for pass 10, which features a much larger area under the force-displacement curve.

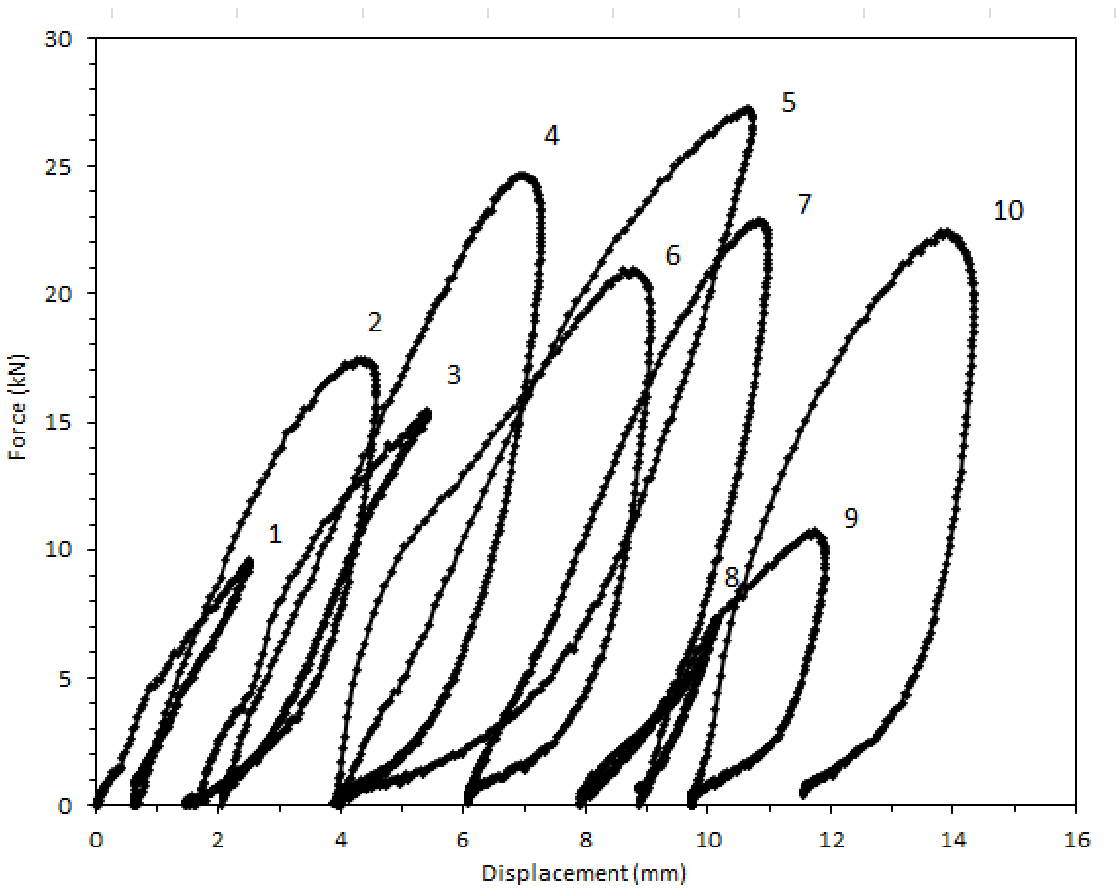

Figure 4.8: Force-displacement curves for consecutive passes (Pass Nos. 1-10)

4.5 Conclusions

To minimise soil variability, this study has captured the change in vertical stress due to RDC at a depth of 0.7 m beneath the surface using an earth pressure cell buried in a 1.5 m thick layer of homogeneous sandy gravel. The maximum change in vertical stress recorded over the 80 passes undertaken was approximately 1,100 kPa. During a typical module impact, the loading and unloading of the soil occurred over a duration of roughly 0.05 seconds. The acceleration response of a single module impact was also measured in three orthogonal directions at 0.7 m depth, with the vertical accelerations dominant. In project applications, there is typically a trade-off between layer thickness and the number of passes required to significantly improve ground to meet a certain specified criterion. Whilst the number of passes (80) undertaken in this study was greater than what would economically be undertaken in practice, the results from buried instrumentation indicate that 0.7 m is well within the depth range that can be significantly improved by RDC. Quantifying the dynamic behaviour of the soil beneath the ground surface in real-time emphasises that the uneven module geometry results in some passes imparting much greater pressure to the ground that others, this being a key reason why many passes are needed to ensure adequate coverage of a site.

4.6 Acknowledgements

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4.7 References

Avalle DL, Scott BT and Jaksa MB (2009). Ground energy and impact of rolling dynamic compaction – results from research test site. In Proceedings 17th International Conference on Soil Mechanics and Geotechnical Engineering, Vol. 3, Alexandria, Egypt, (eds M. Hamza, M. Shahien and Y. El-Mossallamy), vol. 3, pp. 2228–2231. Amsterdam, the Netherlands: IOS Press BV.

Chow YK, Yong DM, Yong KY and Lee SL (1990). Monitoring of dynamic compaction by deceleration measurements. Computers and Geotechnics, **10(3)**: 189-209.

Clegg B (1980). An impact soil test as alternative to California bearing ratio. In Proceedings 3rd Australia-New Zealand Conference on Geomechanics, Wellington, New Zealand: New Zealand Institution of Engineers, *pp. 225-230.* Wellington, New Zealand: New Zealand Institution of Engineers.

Clifford JM (1978). Evaluation of Compaction Plant and Methods for the Construction of Earthworks in Southern Africa. Dissertation in partial fulfilment of the requirements for the degree of Master of Science in Engineering, University of Natal, Durban, South Africa.

Heyns S (1998). Response analysis of an impact compactor. Report LGI98/013, Project No 020-DP, Pretoria, South Africa: Laboratory for Advanced Engineering Pty Ltd., University of Pretoria.

Jha KK, Suksawang N, Lahiri D and Agarwal A (2012). Energy-based analysis of nanoindentation curves for cementitious materials. ACI Materials Journal, **109(1)**: 81-90.

Labview (2018). http://www.ni.com/en-us/shop/labview.html (accessed 26/10/2018).

Mayne PW and Jones JS (1983). Impact stresses during dynamic compaction. Journal of Geotechnical Engineering, ASCE, **109(10)**: 1342-1346.

McCann K (2015). The use of impact compaction for the near surface compaction on dredged sand land reclamation projects. In Proceedings 12th Australia - New Zealand Conference on Geomechanics, pp. 1193-1200. Wellington, New Zealand: New Zealand Geotechnical Society.

McCann K and Schofield N (2007). Innovative methods in the in-situ determination of design parameters on heterogeneous sites subject to ground treatment using deep impact compaction. In Proceedings 10th Australia New Zealand Conference on Geomechanics, (eds J. Ameratunga, B. Taylor and M. Patten), Vol. 2, pp. 126-131. Brisbane, Australia: Australian Geomechanics Society.

Mooney MA and Rinehart RV (2007). Field monitoring of roller vibration during compaction of subgrade soil. Journal of Geotechnical and Geoenvironmental Engineering, ASCE, **133(3)**: 257-265.

Scott BT, Jaksa MB and Syamsuddin E (2016). Verification of an impact rolling compaction trial using various in situ testing methods. In Proceedings 5th International Conference on Geotechnical and Geophysical Site Characterisation, (eds B. M. Lehane, H. E. Acosta-Martínez and R. Kelly), pp. 735-740. Sydney, Australia: Australian Geomechanics Society.

Thong YK, Woolfson MS, Crowe JA, Hayes-Gill BR and Challis RE (2002). Dependence of inertial measurements of distance on accelerometer noise. Measurement Science and Technology, **13(8)**: 1163-1172.

Yu X (2004). Field evaluation of ground stiffness by static and dynamic tests. Electronic Journal of Geotechnical Engineering, **9(D)** http://www.ejge.com/2004/Ppr0442/Abs0442.htm (accessed 22/03/2019).

Chapter 5: Conclusions

Quantifying the ground response due to RDC, as well as the effects of towing speed, and the depth of improvement, will enable RDC to be applied and validated more appropriately for a range of applications and soil characteristics. A greater understanding of RDC will reduce design conservatism and construction costs; and importantly, reduce instances where the anticipated improvement did not occur. Furthermore, it will enable RDC to be used more effectively and with greater confidence in a range of applications. This will inevitably lead to more accurate assessments of the geotechnical properties of ground compacted using RDC, and hence, the optimised design of geotechnical systems such as pavements, foundations, dams, embankments and retaining structures.

5.1 Research Contributions

This research has added to the current knowledge of RDC and has addressed the five objectives of this thesis as follows:

1. This research has determined that towing speed influences the stress that is imparted into the ground. At towing speeds less than 9 km/h, the dynamic effects of the module are not maximised, compared with towing speeds of 10-12 km/h that were found to be optimal. At towing speeds above 12 km/h, higher stresses could occasionally be imparted into the ground, but the kinematics of the module impacting the ground changed if it was towed too quickly, causing the module to skip and jump from corner to corner, rather than the sides of the module falling to impact the ground in a predictable and reproducible manner.

2. This research proposes that the energy imparted to the ground due to RDC is a function of the work done, which is equal to the sum of the change in gravitational potential and kinetic energies. The energy that is delivered by a single impact is dependent upon towing speed. This research has refined the maximum estimated energy that is imparted to ground to between 22 kJ to 30 kJ for typical towing speeds of 9 and 12 km/h, respectively. This is in contrast to previous estimates for the 8-tonne 4-sided impact roller that predicted values of between 30 kJ to 54 kJ for the same towing speed range based on kinetic energy.

3. Understanding the depths beneath the surface that RDC is capable of improving in different soil conditions is a key criterion, particularly in applications for compacting in situ material (improving poor quality ground). This research has proposed a new term for RDC, defined as the effective depth of improvement (EDI), giving practitioners some guidance regarding what depths can be improved in different soil conditions. When compacting deep layers of placed fill material; the uncertainty regarding the depth of improvement should be less of a concern to practitioners, as the placed layer thickness can be designed to be limited to a depth that is well within the capability of the impact roller. This research also offers guidance as to the thickness of fill layers that can be adopted, via the use of another new term, defined as the maximum depth of improvement (MDI).

4. This research found that the formula for deep dynamic compaction first proposed by Menard and Broise (1975) could not be used directly for RDC without modification. However, modifications to this formula can be used to estimate the improvement depths for two distinctly different applications of RDC: improving ground in situ (using EDI), and compacting soil in thick layers (using MDI), respectively. Whilst these relationships are simplistic and have limitations, they provide reasonable estimates based on the field trials undertaken in this thesis and are in broad agreement with reported case studies that have used the 8-tonne, 4-sided impact roller over the past four decades.

5. Arguably, the greatest contribution to current knowledge from this body of work, is from capturing and analysing the in-ground response of RDC. It is imperative to understand how the ground responds to a single impact if there is any chance of trying to predict and understand what will happen after multiple impacts (as undertaken in project applications). The duration of the pressure impulse is significant; the time over which loading and unloading of the soil occurred was less than 0.05 seconds. The soil response due to RDC was also captured using accelerometers. Double integration of the acceleration-time response allowed displacements to be evaluated, whereby the loading and unloading response of the soil due to a single pass of the impact roller enabled recoverable (elastic) and permanent (plastic) components to be identified separately. Force was determined by adopting the peak pressure at the time of

impact and multiplying it by the plan area of the EPC. Plotting force against displacement enabled the in-ground response of RDC to be quantified in terms of work done, thereby giving a measure of the actual energy imparted to the ground at the measured depth.

5.2 Limitations of current research methods and existing RDC practices

An underlying aim of this research is to measure the in-ground response of RDC. To do so, instrumentation must obviously be buried in the ground. The single biggest limitation of using buried instrumentation is that it is not possible for an RDC module to land repeatedly on the same surface location relative to buried instrumentation that is placed at a fixed location. To overcome this issue, it was necessary to conduct many passes to determine trends and to measure the distance between the centre of the module and the centre of buried instrumentation (offset distance).

A large number of field test sites were used in this research, many of which were commercial project sites, giving the author opportunities to observe RDC in a variety of soil conditions, whilst also providing the author with large quantities of test data. What became apparent was that project data were often sufficient for proving conformance with a project specification; however, they were insufficient to answer specific research questions regarding how individual factors contributed to the performance of RDC. Inherent soil variability was the greatest issue that was masking results. At filled (or ‘made-up’) sites, this was, unsurprisingly, an even bigger issue. Despite attempts to quantify ground improvement using closely spaced boreholes and a suite of different in situ tests within close proximity, there was still uncertainty when comparing pre- and post-compaction data; the difference could be attributed to either soil variability, improvement using the impact roller, or a combination of the two factors. To isolate and quantify the effects of RDC, it was necessary to conduct tests in uniform soil conditions. This required significant financial support as it meant placing uniform fill material in significant quantities at sites where the costs of fill and earthmoving plant and equipment had to be covered. Adopting comprehensive field trials at dedicated research testing sites enabled targeted field trials of longer duration to be undertaken that were not possible at commercial sites where field testing programs had to be more efficient and time effective so as to not delay other site activities.

There are also a number of limitations associated with existing RDC practices that future research should consider. These limitations are further discussed in Appendix A, Section 3.2 but are summarised briefly as follows:

- When using RDC to compact thick layers, lengthy testing durations and/or the use of testing methods more suited to the compaction of thin layers can be problematic. Furthermore, the presence of oversized particles has the ability to constrain testing methods. Alternate methods of conformance testing that are appropriate for thick layers are a challenge;

- Small or restricted sites are unsuitable for RDC, particularly where the roller is unable to maintain an operating speed within the range of 9–12 km/h;

- Ground vibrations induced by RDC can be problematic if working close to adjacent movement sensitive infrastructure and can restrict its use;

- The variable depth to which ground improvement can be achieved is one of the biggest limitations on the use of RDC when improving in situ material, as a contingency plan may need to be implemented if ground improvement is not achieved to the required (or expected) depths;

- The variable depth of treatment of RDC also has the potential to cause damage to existing services, culverts or bridges (via load transfer) if an insufficient thickness of soil is not placed over such structures; and

- When working at sites with a shallow water table, there is the potential for the repeated dynamic loading of soil to induce increased pore water pressures, which can bring water to the surface if too many passes are applied within a short period of time. Best results are obtained when the site is not ‘over rolled’ and time is provided for pore water pressures to dissipate between sets of passes.

5.3 Future directions for industry

This research has illustrated the importance of towing speed. Consequently, there is a need to move away from the use of kinetic energy and/or gravitational potential energy to rate impact rollers for comparative or marketing purposes. Rating impact rollers using kinetic energy over-estimates the energy imparted into the ground and must be avoided. It is also counter-productive for the industry to rate impact rollers in terms of gravitational potential energy when specifications correctly dictate towing speed ranges that must be adopted in order for RDC to be most effective.

Some projects still adopt method specifications (this typically involves adopting a specified number of passes and not testing the soil post compaction). In applications where the impact roller is being used to improve in situ soil or compact thick layers, the focus should be on meeting the requirements of a performance specification. In future, the author predicts there will be a greater focus on quantifying the change in soil stiffness due to RDC, leading to increased testing and understanding of changes in soil modulus.

Impact roller module design was primarily developed during the period between the 1950s and 1970s in South Africa. As described by Clifford (1975) the impact roller was originally developed as there was a need to rapidly compact potentially collapsing sands in Southern Africa up to nominal depths of up to 3 metres using towing units with approximately 160-170 horsepower. Its success in improving the density of potentially collapsing sands resulted in the impact roller being used in different soils and applications as time progressed. Whilst improvements to module design have occurred since then, in recent years the development of the towing units have continued to increase, with modern equipment having significantly greater torque and horsepower than their 1970s counterparts. As such, the author believes there is scope to optimise and refine module design in the future.

5.4 Future research directions

The field testing for this research project was limited to the use of the standard (8-tonne) 4-sided impact roller. Preference was given to working with the same roller for the work conducted in this thesis; however, there is a need to test both the 8- and 12-tonne 4-sided modules at the same site in uniform soil conditions containing buried instrumentation. It is proposed both rollers would operate at the same speed to truly isolate the effect of module mass. Similarly, there is a need for full-scale testing of impact rollers with different numbers of sides in the same soil conditions using buried pressure cells and accelerometers to measure the ground response; this will provide a greater understanding of their similarities and differences.

In Chapter 3 of this thesis, there is scope to examine if there are advantages in refining and improving Equation 3.4 to include the change in kinetic energy term, ΔKE. Equation 3.4 retains the form of the original Menard and Broise (1975) equation, along with an empirical factor n to take into account soil type (as per dynamic compaction theory). This equation was augmented for RDC by multiplying by an energy ratio parameter, k, which varies with towing speed and is based on an estimation of ΔKE. Augmenting the original Menard and Broise (1975) equation was deliberate to allow practitioners to infer a depth of influence based on physical parameters associated with the module (mass m and drop height h) that can be quantified easily. It could be argued that incorporating the ΔKE term into Equation 3.4 may be logical and useful; however, the difficulty in accurately quantifying the change in kinetic energy is the reason why ΔKE was not included. Further research could aim to better quantify ΔKE, whilst it is recognised that there are energy losses due to friction and noise, their magnitude remains unknown.

It is acknowledged that equations developed for RDC in this thesis are simplistic, relying only on module mass, drop height, n value (soil type) and k value (taking into account that the energy imparted into the ground is not solely gravitational potential energy). The equations presented in this thesis do not include variables such as moisture content, number of passes and contact area of module with the ground. It is hoped that this work will inspire more refined assessments to be made in the future so that RDC can be compared more accurately with more traditional forms of compaction that have better predictive models. More accurate assessments of RDC will lead to greater knowledge and better informed decisions regarding circumstances that are appropriate for adopting this ground improvement technique, or otherwise. The effect of module shape (number of sides) and mass requires further investigation as the k value introduced in this paper, would not be applicable for the heavy duty (12-tonne) 4-sided roller, nor would it be applicable for impact rollers with 3- and 5-sided modules.

Whilst it is recognised that this thesis has included case studies of RDC working in uniform soil conditions that seldom occur in practice, it is hoped that the benefit of controlling soil variability in full-scale field trials can provide valuable information regarding the depths (and magnitude) that RDC can improve ground. Controlling soil variability is easy to do in a computer model, and comparatively easy in a laboratory environment, but neither captures the real-world environment in which ground improvement methods such as RDC are used. The author has witnessed RDC used at remote and challenging sites containing highly variable fill, where it was difficult to characterise and sub-sample representative soil conditions. In such instances where mixed or highly variable fill is present at marginal or difficult sites, field trials are recommended to quantify the limitations and capabilities of RDC.

Rigorous analysis of high speed photography to capture the changes in module velocity would significantly add to current knowledge and is arguably a reasonable way to quantify the frictional effects between module and soil that contribute to the work done. A fellow PhD student at The University of Adelaide is undertaking a quantitative assessment of high speed photography undertaken at one of the research intensive field full-scale trials, and is combining it with finite element modelling to predict the energy imparted into the ground; this work is progressing and is expected to support the findings summarised in this thesis that have quantified the energy imparted into the ground in terms of work done.

Rating an impact roller in terms of the energy that can be imparted to the ground surface under ideal conditions is highly theoretical; of greater importance is the actual in-ground response to RDC and how much work done is imparted into the soil at depth, and the resultant load-displacement response. Ultimately, RDC is a method used to achieve compaction, with the primary aim of reducing voids (inducing settlement) within a soil as a result of imparting mechanical energy into the ground. In future, there is a need to to quantify changes in stiffness with increasing RDC passes. The use of buried earth pressure cells captures compressive waves induced from the module; however, there is a need to also quantify the change in shear waves with increasing passes. To be able to do this effectively, a carefully planned and executed trial would include taking stiffness measurements not just pre- and post-compaction but after each pass to be able to quantify changes in shear wave speed with changes in void ratio.

In Chapter 2 of this thesis, the maximum imparted energy delivered to the ground surface by the 4-sided impact roller was found to lie in the range between 22 kJ and 30 kJ, for typical towing speeds of 9-12 km/h. In Chapter 4, the maximum work done that was measured by a 230 mm diameter EPC, was 250 J. Clearly, there is a large discrepancy between the external work applied to the soil surface, and, the internal work measured by a single EPC at a depth of 0.7 m below the ground surface. It is evident, that there is a need for further research to try and quantify the dissipation of internal work done on the soil over the influence zone of the impact roller, particularly given that the magnitudes of internal work and external work are substantially different. To be able to accurately quantify the dissipation of internal work done on the soil would require measurement of force and displacement over the influence zone of a single impact of the impact roller. Using current EPC technology, there are limitations with how close embedded EPCs can be spaced (both vertically and horizontally) for results to be considered a reliable representation of quantifying in situ soil stress. Whilst it may be possible that future advances in technology will make it easier to quantify the dissipation of work done that is imparted into the ground at full scale, initial endeavours to quantify this may be better achieved via numerical models, with calibration against full scale measurements such as those undertaken in this study.

There is a need to conduct rigorous vibration monitoring of RDC to determine appropriate safe distances for which RDC can safely operate in varying soil conditions. Studying the effects of vibrations induced from RDC is beyond the scope of this thesis, but is nonetheless important, as vibration effects can potentially limit the use of RDC in some instances. A series of charts that compare measurements of peak particle velocities, the industry standard for quantifying ground vibrations, with the distance from the impact roller will provide increased confidence regarding operational safe distances from structures of various types to prevent damage. The development of a ground vibration model (or similar) would enable ground vibrations to be predicted in a variety of applications and soil types. Together, these will enable RDC to be specified, for a particular application and soil conditions, with much more certainty than is currently the case.

There are three main focus areas for future research into RDC: full-scale field testing, numerical modelling and physical scale model testing. Research using numerical modelling is being undertaken by a fellow PhD student at The University of Adelaide, and has the obvious advantage of being able to conduct sensitivity analyses. In a computer model it is much easier to vary parameters such as soil type, moisture content, layer thickness, module shape or number of passes. However, computer modelling alone without calibration is of little value, therefore it is hoped that the output from this research (and future targeted full-scale field testing) will be of use to numerical modelling studies involving RDC.

Conducting research in a laboratory using a physical scale model is another future direction for research into RDC. A 1:13 scale model 4-sided impact roller has been constructed and is currently being tested and calibrated against full-scale results from this thesis at The University of Adelaide. Geometric and kinematic similarity is needed in order to obtain meaningful results from a scale model test; however, this method is showing promise in its developmental phase.

Research into RDC is still immature when compared to other compaction techniques such as conventional circular static and vibratory rolling, and, deep dynamic compaction. Given the complex nature of RDC, much research is still needed; it is hoped that this thesis will inspire further research into RDC so that our current knowledge and understanding of limitations into RDC can catch up to the aforementioned compaction techniques. The development of a compaction model that quantifies the performance of RDC (in terms of improvement in density, strength, stiffness or permeability) as a function of the characteristics of the compactor module (size, shape and number of passes, towing speed) and the geotechnical properties of underlying soil profile is the ultimate aim. This research has provided steps towards achieving this overarching aim.

Chapter 6: References

ASTM (2007). D 698: Standard test methods for laboratory compaction characteristics of soil using standard effort. ASTM International, West Conshohocken, PA, USA.

ASTM (2008). D 5195: Standard test methods for density of soil and rock in-place at depths below surface by nuclear methods. ASTM International, West Conshohocken, PA, USA.

ASTM (2009a). D 6913: Standard test methods for particle-size distribution (gradation) of soils using sieve analysis. ASTM International, West Conshohocken, PA, USA.

ASTM (2009b). D 1557: Standard test methods for laboratory compaction characteristics of soil using modified effort. ASTM International, West Conshohocken, PA, USA.

ASTM (2010a). D 2216: Standard test methods for laboratory determination of water (moisture) content of soil and rock by mass. ASTM International, West Conshohocken, PA, USA.

ASTM (2010b). D 4318: Standard test methods for liquid limit, plastic limit, and plasticity index of soils. ASTM International, West Conshohocken, PA, USA.

Avalle DL (2004). Ground improvement using the “square” impact roller – case studies. In Proceedings of the 5th International Conference on Ground Improvement Techniques, Kuala Lumpur, Malaysia, pp. 101-108.

Avalle DL (2007) Trials and validation of deep compaction using the “square” impact roller. Symposium Advances in Earthworks, Australian Geomechanics Society, Sydney, Australia, pp. 63-69.

Avalle DL and Carter JP (2005). Evaluating the improvement from impact rolling on sand. In Proceedings of the 6th International Conference on Ground Improvement Techniques, Coimbra, Portugal, pp. 153-160.

Avalle D and Grounds R (2004). Improving pavement subgrade with the "square" impact roller. 23rd Annual Southern African Transport Conference, Pretoria, South Africa, pp. 44-54.

Avalle DL and Mackenzie RW (2005). Ground improvement of landfill site using the “square” impact roller. Australian Geomechanics, **40(4)**: 15-21.

Avalle DL, Scott BT and Jaksa MB (2009). Ground energy and impact of rolling dynamic compaction – results from research test site. In Proceedings 17th International Conference on Soil Mechanics and Geotechnical Engineering, Vol. 3, Alexandria, Egypt, pp. 2228-2231.

Avalle D and Young G (2004). Trial programme and recent use of the impact roller in Sydney. Earthworks Seminar, Australian Geomechanics Society, Adelaide, Australia, 5pp.

Avsar S, Bakker M, Bartholomeeusen G and Vanmechelen, J (2006). Six sigma quality improvement of compaction at the New Doha International Airport Project. Terra et aqua, **103**: 14-22.

Berry AD (2001). Development of a volumetric strain influence ground improvement prediction model with special reference to impact compaction. Dissertation submitted in partial fulfilment of the requirements of the degree of Master of Engineering, University of Pretoria, Pretoria, South Africa.

Bradley AC, Jaksa MB, Kuo YL. Examining the kinematics and energy of the four-sided impact roller. Proceedings of the Institution of Civil Engineers – Ground Improvement, 2019, 172 (4): 297-304.

Charles JA, Burford D and Watts KS (1981). Field studies of the effectiveness of dynamic consolidation. In Proceedings of the 10th International Conference on Soil Mechanics and Foundation Engineering, Stockholm, Sweden, 3: 617-622.

Chen Z, Xu C, Ye G and Shen C (2014). Impact Roller Compaction of Dry Sand in Laboratory Tests. In Proceedings Geo-Shanghai, Ground Improvement and Geosynthetics, Shanghai, China, pp. 258-269.

Chow YK, Yong DM, Yong KY and Lee SL (1990). Monitoring of dynamic compaction by deceleration measurements. Computers and Geotechnics, **10(3)**: 189-209.

Clegg B (1980). An impact soil test as alternative to California bearing ratio. In Proceedings 3rd Australia-New Zealand Conference on Geomechanics, New Zealand Institution of Engineers, Wellington, New Zealand, pp. 225-230.

Clifford JM (1975). An introduction to impact rollers. National Institute for Road Research, Internal report RP/2/75, South Africa, pp. 1-30.

Clifford JM (1978). Evaluation of Compaction Plant and Methods for the Construction of Earthworks in Southern Africa. Dissertation in partial fulfilment of the requirements for the degree of Master of Science in Engineering, University of Natal, Durban, South Africa.

Clifford JM (1980). The development and use of impact rollers in the construction of earthworks in southern Africa. CSIR Report 373, National Institute for Transport and Road Research Bulletin 16, Pretoria, South Africa, pp. 1-53.

Clifford JM and Coetzee SD (1987). Coal and discard stockpiling with an impact roller. In Proceedings of the International Conference on Mining and Industrial Waste Management, Johannesburg, South Africa, pp. 75-79.

Clifford JM and Bowes G (1995). Calculating the Energy delivered by an Impact Roller. A trilogy of Papers for the Sept. 1995 Lecture Tour and International Seminars to commemorate the 10th Anniversary of the BH 1300 Standard Impact Roller, Paper Two.

Dave TN and Dasaka SM (2011). A review on pressure measurement using earth pressure cell. International Journal of Earth Sciences and Engineering, **4(6)**: 1031-1034.

Ellis CI (1979). Pavement engineering in developing countries. Transport and Road Research Laboratory, TRRL Supplementary Report 537, Crowthorne, Berkshire, 35pp.

Fadum RE (1948). Influence values for estimating stresses in elastic foundations. In Proceedings of the 2nd International Conference ISSMFE, Rotterdam, Netherlands, 3: 77-84.

Geokon (2007). Instruction Manual Model 3500, 3510, 3515, 3600 Earth Pressure Cells. Geokon Incorporated, Lebanon, USA, 24pp.

Halliday D, Resnick R and Walker J (1993). Fundamentals of Physics, 4th Edition. John Wiley & Sons, Incorporated, Canada, pp. 182-250.

Hamidi B, Nikraz H and Varaksin S (2009). A review of impact oriented ground improvement techniques. Australian Geomechanics **44(2)**: 17-24.

Heyns S (1998). Response analysis of an impact compactor. Report LGI98/013, Project No 020-DP, Pretoria, South Africa: Laboratory for Advanced Engineering Pty Ltd., University of Pretoria.

Jha KK, Suksawang N, Lahiri D and Agarwal A (2012). Energy-based analysis of nanoindentation curves for cementitious materials. ACI Materials Journal, **109(1)**: 81-90.

Kim K (2010). Numerical simulation of impact rollers for estimating the influence depth of soil compaction. Dissertation in partial fulfilment of the requirements for the degree of Master of Science, Texas A&M University, Texas, USA

Labview (2018). http://www.ni.com/en-us/shop/labview.html (accessed 26/10/2018).

Leonards GA, Holtz RD and Cutter WA (1980). Dynamic compaction of granular soils. Journal of Geotechnical Engineering Division ASCE **106(1)**: 35-44.

Lukas RG (1980). Densification of loose deposits by pounding. Journal of Geotechnical Engineering Division ASCE **106(4)**: 435-446.

Lukas RG (1995). Dynamic compaction. Geotechnical Engineering Circular No. 1, U.S. DOT, Publication No. FHWA-SA-95-037, Federal Highway Administration, Washington, D.C.

Mayne PW and Jones JS (1983). Impact stresses during dynamic compaction. Journal of Geotechnical Engineering, ASCE, **109(10)**: 1342-1346.

Mayne PW, Jones JS and Dumas JC (1984). Ground response to dynamic compaction. Journal of Geotechnical Engineering ASCE **110(6)**: 757-774.

McCann K (2015). The use of impact compaction for the near surface compaction on dredged sand land reclamation projects. In Proceedings 12th Australia - New Zealand Conference on Geomechanics, New Zealand Geotechnical Society, Wellington, New Zealand, pp. 1193-1200.

McCann K and Schofield N (2007). Innovative methods in the in-situ determination of design parameters on heterogeneous sites subject to ground treatment using deep impact compaction. In Proceedings 10th Australia New Zealand Conference on Geomechanics, Australian Geomechanics Society, Vol. 2, Brisbane, Australia, pp. 126-131.

Menard L and Broise Y (1975). Theoretical and practical aspects of dynamic consolidation. Geotechnique, **25(1)**: 3-18.

Mooney MA and Rinehart RV (2007). Field monitoring of roller vibration during compaction of subgrade soil. Journal of Geotechnical and Geoenvironmental Engineering, ASCE, **133(3)**: 257-265.

National Instruments (2019) http://www.ni.com/en-us/shop/labview.html (accessed 03/05/2019).

Nazhat Y (2013). Behaviour of sandy soil subjected to dynamic loading. Thesis submitted in fulfilment of the requirement for the degree of Doctor of Philosophy, University of Sydney.

Ranasinghe RATM, Jaksa MB, Kuo YL and Pooya Nejad F (2017). Application of artificial neural networks for predicting the impact of rolling dynamic compaction using cone penetrometer test results. Journal of Rock Mechanics and Geotechnical Engineering, **9(2)**: 340-349.

Rinehart RV and Mooney MA (2009). Measurement of Roller Compactor Induced Triaxial Soil Stresses and Strains. Geotechnical Testing Journal, **32(4)**: 347-357.

SA (Standards Australia) (1997) AS 1289.6.3.3: Methods of testing soils for engineering purposes – Soil strength and consolidation tests – Determination of the penetration resistance of a soil – Perth sand penetrometer test. Standards Australia, Sydney, Australia.

Salgado R and Yoon S (2003) Dynamic cone penetration test (DCPT) for subgrade assessment. Joint Transportation Research Program, West Lafayette, IN, USA, Report FHWA/IN/JTRP-2002/30.

Scott BT and Jaksa MB (2008). Quantifying the influence of rolling dynamic compaction. In Proceedings of the 8th Australia New Zealand Young Geotechnical Professionals Conference, New Zealand Geotechnical Society, Wellington, New Zealand, pp. 199-204.

Scott BT and Jaksa MB (2012). Mining applications and case studies of Rolling Dynamic Compaction. In Proceedings of the 11th Australia New Zealand Conference on Geomechanics, Australian Geomechanics Society, Melbourne, Australia, pp. 961-966.

Scott BT, Jaksa MB and Kuo YL (2012). Use of proctor compaction testing for deep fill construction using impact rollers. International Conference on Ground Improvement and Ground Control, Wollongong, Australia, pp. 1107-1112.

Scott BT and Jaksa MB (2014). Evaluating rolling dynamic compaction of fill using CPT. 3rd International Symposium on Cone Penetration Testing, Las Vegas, USA, pp. 941-948.

Scott BT and Jaksa MB (2015). The effectiveness of rolling dynamic compaction – a field based study. In: Indraratna B, Chu J, Rujikiatkamjorn C, eds. Ground Improvement Case Histories: Compaction, Grouting and Geosynthetics. Kidlington, Oxford: Elsevier, pp. 429-452, doi: 10.1016/B978-0-08-100698-6.00014-3.

Scott BT, Jaksa MB and Syamsuddin E (2016). Verification of an impact rolling compaction trial using various in situ testing methods. In Proceedings 5th International Conference on Geotechnical and Geophysical Site Characterisation, Australian Geomechanics Society, Sydney, Australia, pp. 735-740.

Scott BT, Jaksa MB and Mitchell PW (2020). Influence of towing speed on the effectiveness of Rolling Dynamic Compaction. Journal of Rock Mechanics and Geotechnical Engineering, **12(1):** 126-134, doi: 10.1016/j.jrmge.2019.10.003.

Scott BT, Jaksa MB and Mitchell PW (2019). Depth of influence of Rolling Dynamic Compaction. Institution of Civil Engineers, Ground Improvement, doi: 10.1680/jgrim.18.00117.

Scott BT, Jaksa MB and Mitchell PW (2019). Ground response to Rolling Dynamic Compaction. Institution of Civil Engineers, Geotechnique Letters, **9(2):** 99-105. doi: 10.1680/jgele.18.00208.

Scott BT and Suto K (2007). Case study of ground improvement at an industrial estate containing uncontrolled fill. In Proceedings of the 10th Australia New Zealand

Conference on Geomechanics, Australian Geomechanics Society, Vol. 2, Brisbane, Australia, pp. 150-155.

Slocombe BC (2004). Dynamic Compaction. Ground Improvement 2nd Ed. Moseley, MP and Kirsch, K, eds. Spon Press, New York, pp. 93-118.

Thong YK, Woolfson MS, Crowe JA, Hayes-Gill BR and Challis RE (2002). Dependence of inertial measurements of distance on accelerometer noise. Measurement Science and Technology, **13(8)**: 1163-1172.

Weiler WA and Kulhawy FH (1982). Factors affecting stress cell measurements in soil. Journal of Geotechnical Engineering, **108(12)**: 1529-1548.

Whiteley RJ and Caffi P (2014). Evaluating the effectiveness of rolling impact compaction at a brownfield site with high and low frequency seismic surface waves and geotechnical testing. Near Surface Geophysics **12**: 405-414.

Wolmarans CH and Clifford JM (1975). An evaluation of the CSIR impact roller. 6th Regional Conference for Africa on Soil Mechanics and Foundation Engineering, Durban, South Africa, pp. 33-39.

Yu X (2004). Field evaluation of ground stiffness by static and dynamic tests. Electronic Journal of Geotechnical Engineering, **9(D)** http://www.ejge.com/2004/Ppr0442/Abs0442.htm (accessed 22/03/2019).

Appendix A: Book Chapter

Book Chapter

Scott, B.T. & Jaksa, M.B. (2015). The effectiveness of rolling dynamic compaction – a field based study. In B. Indraratna, J. Chu, & C. Rujikiatkamjorn (Eds.), *Ground Improvement Case Histories: Compaction, Grouting and Geosynthetics*, pp. 429-452, Kidlington, Oxford: Elsevier. doi: 10.1016/B978-0-08-100698-6.00014-3.

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Name of Principal Author (Candidate)	Brendan Scott		
Contribution to the Paper	Performed site work, analysis and interpretation of site data, wrote manuscript.		
Overall percentage (%)	85		
Certification:	This paper reports on original research I conducted during the period of my Higher Degree by Research candidature and is not subject to any obligations or contractual agreements with a third party that would constrain its inclusion in this thesis. I am the primary author of this paper.		
Signature	[redacted]	Date	18/4/2019

Co-Author Contributions

By signing the Statement of Authorship, each author certifies that:

i. the candidate's stated contribution to the publication is accurate (as detailed above);

ii. permission is granted for the candidate in include the publication in the thesis; and

iii. the sum of all co-author contributions is equal to 100% less the candidate's stated contribution.

Name of Co-Author	Mark Jaksa		
Contribution to the Paper	Assisted with site work; provided primary supervision and helped to evaluate and edit the manuscript.		
Signature	[redacted]	Date	18/4/19

The effectiveness of rolling dynamic compaction – a field based study

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Abstract

Rolling Dynamic Compaction (RDC) is a soil improvement technique, which involves a heavy non-circular module (impact roller) that rotates about a corner as it is towed, causing the module to fall to the ground and compact it dynamically. Whilst conventional circular rollers are able to compact layer thicknesses typically up to 500 mm, thicker layers are able to be compacted using RDC due to the dynamic effect of the module, which yields a greater depth of influence. When combined with the ability to compact ground efficiently, by means of its faster operating speed (9-12 km/h) when compared to conventional circular rollers, RDC can be a productive and cost-effective option in many different earthwork applications. However, the depth of influence of RDC can vary significantly depending on the soil type, moisture content, loose layer thickness or number of passes adopted.

Applications of RDC as well as verification techniques that can be used to quantify ground improvement are presented. A featured case study investigates the zone of influence of a 4-sided ‘impact roller’ that was measured in a systematic fashion in the field by means of a number of earth pressure cells that were buried at varying depths beneath the ground surface and measuring the in situ stress over a range of module passes. In addition, a variety of in situ tests were performed including penetrometer, field density and geophysical testing to measure density improvement, again as a function of the number of module passes. The field measurements conducted on mine tailings indicated that the depth of improvement due to RDC exceeded 2 m below the ground surface. At a depth of 1.5 m, RDC imparted soil stresses of approximately 150 kPa into the ground; positive pressure readings were also measured by earth pressure cells buried up to 3.85 m below the ground surface, indicating that the actual zone of influence (for which there is improvement) extends beyond this depth.

Keywords: impact, roller, rolling, dynamic, compaction, applications, field, trials, verification.

1. Introduction

Ground improvement is a fundamental and essential part of civil construction; an increasing number of new technologies and ground improvement methods have been developed and implemented to assist the geotechnical engineer in providing cost-effective solutions for construction on marginal or difficult sites.

The available methods and techniques to improve the geotechnical characteristics of soils are described in detail by Terashi & Juran (2000), Munfakh & Wyllie (2000) and Phear & Harris (2008). The general consensus from the aforementioned authors is that ground improvement using surface dynamic compaction techniques such as RDC can be successfully undertaken to improve a soil's shear strength and stiffness, or reduce its permeability. Of the available methods, compaction is arguably the simplest and most prevalent ground improvement technique, and involves increasing the density of the ground by means of mechanically applied energy such as static compaction, which employs drum, padfoot, sheepsfoot and tyre rollers, or dynamic compaction, which makes use of vibratory rollers and plates, rammers, heavy tamping, vibroflotation and rolling dynamic compaction (Hausmann 1990).

The advantage of dynamic compaction is that it enables ground to be improved to a much greater depth (>10 m as compared to 0.3 m for static compaction), with the depth of improvement dependent upon the energy applied (Mayne et al. 1984). Lukas (1995) suggests that when compared to other ground improvement techniques, dynamic compaction is one of the most cost effective, but its use is limited by the large ground vibrations it induces, so is not suitable on small sites or adjacent to buildings and other infrastructure.

RDC was originally developed by Aubrey Berrangé in South Africa in the late 1940s, but its value was not fully appreciated until the mid-1980s. Since then RDC has been successfully implemented worldwide with different module designs having 3, 4, and 5 sides, as shown in Figures 1, 2 and 3, respectively. RDC involves towing heavy (6-12 tonnes) non-circular modules, which rotate about a corner and fall to impact the ground. RDC can compact thicker layers due to a greater depth of influence beneath the ground surface, which is derived from a combination of a heavy module mass, the shape of the module and the speed at which it is towed, typically in the range of 9-12 km/h. In addition, RDC is unique in that it is able to compact large areas of open ground at depth, both effectively and efficiently because of its faster operating speed and thicker lifts compared to conventional circular drum rollers. Due to the combination of kinetic and potential energies, RDC has demonstrated improvement to more than 1 m below the ground surface and greater than 3 m in some soils (Avalle & Carter 2005); far deeper than conventional static or vibratory rolling (Clegg & Berrangé 1971, Clifford 1976, 1978a, 1978b), which is generally limited to depths of less than 0.5 m.

The ability to compact thick layers can make RDC a productive and cost-effective option for many different earthwork projects and applications. This view is supported by Pinard (1999) who stated that in most open-field situations, RDC is able to compact soil, crushed rock and landfill waste cost-efficiently and to greater depths when compared to other available compaction methods. As a result, RDC has been used in land reclamation applications, projects that either require the compaction of non-engineered fill in situ, or alternatively, compaction of thickly placed loose layers of fill in bulk earthworks. RDC has also been used in the agricultural sector to reduce water loss, and in mining applications to improve haul roads and construct tailings dams. Additional details on applications of RDC are presented in Section 3 of this chapter.

Quantifying the effectiveness of RDC via field-based trials has been the focus of different researchers over the years, including Avalle & Carter (2005), Avalle (2007a), Avalle et al. (2009) and Jaksa et al. (2012). Field-based research typically involves a team of professional operators and technicians spending days diligently preparing a test pad, undertaking testing before and after rolling to seek to quantify the effect, however, as noted by Avalle (2007a) there are challenges associated with verification due to the ability of RDC to compact thick layers that often include large (over-size) particles. Further details on verification techniques used to quantify the effectiveness of RDC are presented in Section 4, and by means of an example case study in Section 5.

Figure 1. 3-sided RDC module (Landpac).

Figure 2. 4-sided RDC module (Broons).

Figure 3. 5-sided RDC module (Infratech).

2. RDC and Compaction Theory

The underlying theory of compaction applies to RDC. In simple terms, an impact roller applies mechanical energy used to reduce air voids and rearrange soil particles to increase density, which results in a reduction in the void ratio within a soil. As is the case for compaction with conventional circular drum rollers, in order to achieve the maximum dry density, an optimum amount of moisture is required; if too little or too much moisture is present, a reduction in dry density will result. A unique relationship between moisture content and dry density is generated for a given soil type and compactive effort. A key difference between RDC and conventional circular drum rollers is in the compactive effort applied, akin to the modified and standard proctor compaction tests, respectively. To highlight the difference in compactive effort, both modified and standard proctor compaction curves, performed on the same soil, are presented in Figure 4.

It can be observed that the ‘maximum dry unit weight’ for the modified test is higher than that resulting from the standard test, and corresponds to a lower optimum moisture content. A summary of the test results is included in Table 1. Figure 5 shows the particle size distribution for the soil sample that was subjected to both laboratory test methods. The sample tested consisted of fine-to-medium grained sand (containing 3% clay-sized, 96% sand-sized and 1% gravel-sized particles).

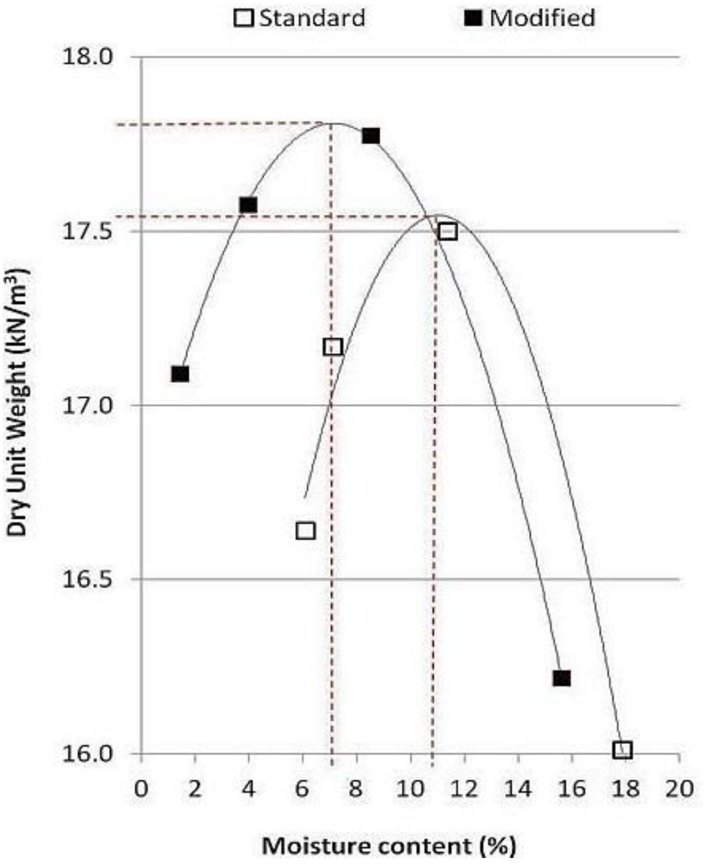

Figure. 4. Standard and modified proctor test results on the same soil.

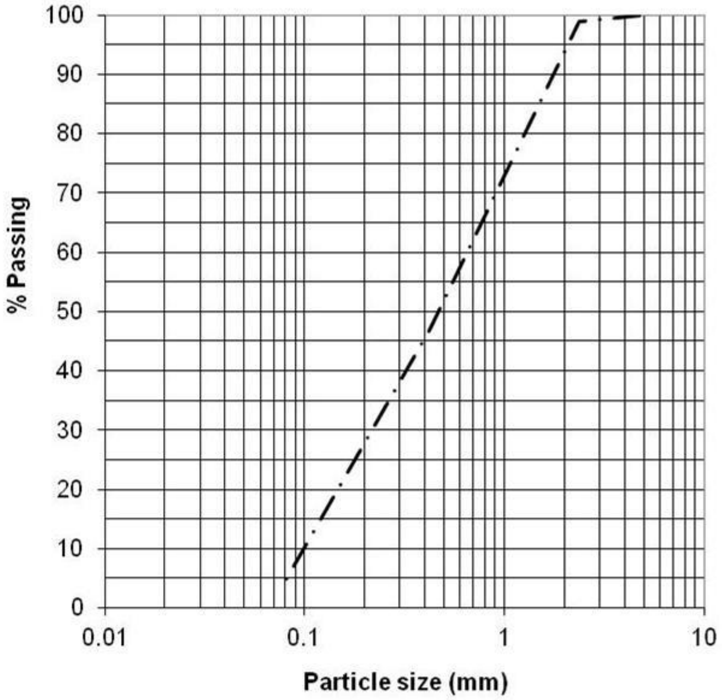

Figure 5. Particle size distribution of tested soil.

Table 1. Comparison of standard and modified Proctor test results

Laboratory Test	Standard Proctor	Modified Proctor
Maximum dry unit weight: kN/m^3	17.6	17.8
Optimum moisture content	~ 11%	~ 7%

As Coduto et al. (2011) explain, the term 'maximum dry unit weight' is somewhat misleading, because the standard and modified tests have two different maxima. However, as they describe, this term can best be thought of as 'the greatest dry unit weight that can be achieved for that particular compactive effort'. Changes in field compactive effort can significantly affect the relationship between moisture content and dry unit weight. For this reason, as observed by Scott et al. (2012), the use of RDC typically results in a target moisture content lower than the optimum moisture content (determined from the standard proctor test) in order to achieve the corresponding maximum dry unit weight.

The ability of RDC to compact material in thicker lifts and at lower moisture contents (when compared to the optimum) has the potential for significant time and cost advantages. However, it is important to understand which baseline laboratory test is more representative to the field compactive effort that is proposed; a decision often based on the loads to be supported, which in turn affects the compaction equipment to be used to ensure an appropriate dry unit weight will be achieved. The soil type, moisture content and compacted layer thickness are all factors that affect density results and are often varied depending upon the target specification required (typically a percentage of the maximum dry density) relative to either the standard or modified proctor test. It should be noted that there is no 'magic formula' that converts standard and modified compaction results, as the relationship between the two is unique for each soil type.

The authors' experience has demonstrated that, for cases where the standard proctor test is used, impact rollers are likely to achieve the desired dry unit weight criterion (depending on the soil type and moisture content) in loosely placed layer thicknesses up to 1,500 mm. If an additional moisture range is also included as part of a project specification (e.g. in the case of deep fills where hydro-compression is of concern) then consideration needs to be given as to how representative the baseline laboratory test chosen will be for RDC. An earthworks contractor will inevitably aim to optimize site compaction by selecting an optimal combination of both compactive effort and moisture content range, bearing in mind that the contractor will also be optimizing against a third criterion (i.e. cost), thereby avoiding increased compactive effort and the need for additional moisture, wherever possible.

3. Applications of RDC

RDC has been used successfully in many earthwork applications, including general civil construction works (Avalle 2004a), roads (Jumo & Geldenhuys 2004), airports and land reclamation projects, as well as in agriculture, where it has been used to compact soil in irrigated areas to reduce soil permeability (Avalle 2004b). Others include the compaction of sites with non-engineered fill, such as industrial land (Scott & Suto 2007) or brownfield sites (Avalle & Mackenzie, 2005). Typical applications may involve the improvement of poor quality ground in situ or the compaction of thickly placed layers for embankments or for in-filling deep excavations.

The ability of RDC to identify weak (low density) areas or soft spots (zones of high moisture content in clayey soils) that can then be replaced or reworked, reduces the potential for differential settlements resulting from subgrade soils that have inadequate stiffness. The ability of RDC to improve the uniformity and density of subgrade soils makes RDC highly suitable as a proof roller, a view supported by Avalle (2006), who showed that improved haul roads can reduce the likelihood of rock spillage from haul trucks, thereby reducing the potential for damage to other haul road vehicles. The authors have witnessed the ability of RDC to detect soft spots in mining haul roads,

The use of RDC is becoming more prevalent in the mining sector, where large earthmoving equipment capable of hauling and placing high material volumes quickly, complements the ability of RDC to compact large volumes efficiently. As described by Scott & Jaksa (2012), the authors have observed the effective use of RDC for the compaction of bulk earthworks of mine spoil materials; the use of thick layers which enabled large particle sizes to be used, facilitating greater recycling of mine spoil materials with a reduced need to screen large quantities of oversized particles. As well as haul roads, the authors have observed RDC used on pit floors and tip heads to aid in the break down and rubbilisation of large surface rocks that are potentially hazardous to haul truck tyres and therefore costly for mine operators in terms of replacement cost and potential loss of production if spare tyres are not readily available.

3.1 Thick Lift Compaction

Deep fills have been traditionally constructed by compacting soil in thin layers using relatively small particle sizes placed in a highly controlled manner. Field density tests are typically undertaken in each layer to confirm performance specifications of placed fill. The determination of field density testing using a nuclear density gauge, is the current industry standard, and involves determining in situ density at discrete locations within a depth of 300 mm below the tested surface. This method is ideally suited for the verification of fill that has been placed in relatively thin layers using conventional static or vibrating drum rollers, as the maximum test depth of the nuclear density gauge is comparable to the influence depth of the aforementioned rollers.

The ability of RDC to compact material in larger quantities is an obvious advantage over compacting fill in thin layers; however, as noted by Avalle (2007a), there are challenges associated with verification. The authors have participated in several field trials across Australia where it was found that RDC could achieve compaction of layers between 500-1500 mm thick, depending upon the soil type, moisture content, number of applied passes and specified target dry density ratio. Verification of RDC using field density testing typically requires excavation through compacted material down to targeted bench levels to measure fill density and confirm the depth and extent of ground improvement. Scott & Suto (2007) used this method to help quantify ground improvement using RDC and correlated other in situ test methods with density testing. They cited limitations such as lengthy test durations and the difficulty with the testing process for mixed soils, particularly where oversized particles are present. Pinard (1999) discussed similar issues and also identified the large ratio between the volume of material tested to that compacted and the poor correlation between laboratory and field results (in heterogeneous soils). The presence of oversized particles has the ability to constrain testing methods (and project specifications), making this a key area to be addressed in an impact rolling trial.

3.2 Limitations of RDC

Whilst RDC has the ability to improve a variety of soil types in a range of applications, not all site conditions lend themselves to using RDC. Small or restricted sites are unsuitable, where the roller is not able to maintain an operating speed within the range of 9–12 km/h. Clifford & Bowes (1995) predicted the impact energy of the square impact roller and concluded that the speed of the module striking the ground was the most significant parameter contributing to the energy imparted by the module.

Due to dynamic effects, ground vibrations induced by RDC can be problematic if working close to adjacent infrastructure and can restrict its use. The authors recently observed an impact rolling trial (the results from which are yet to be published) that involved the use of RDC adjacent to historic infrastructure and therefore highly sensitive to vibrations and ground settlement. Vibration monitoring was undertaken to ensure that allowable peak particle velocities commensurate with cosmetic (if any) damage to historic buildings were not exceeded (typically 2 to 3 mm/s). The aim of the trial was to determine how close the module could traverse so that the structural integrity of the nearby building was not compromised. The measurements of the vibration monitoring at a site consisting of non-engineered fill resulted in a buffer distance being recommended by the authors. In this particular case, a safe (buffer) distance of 50 m was employed, but this distance is site specific, and depends upon the condition and construction type of adjacent infrastructure, as well as the rate of vibration decay, which depends upon a number of factors, such as the ground characteristics and conditions, and the mass and operating speed of the impact roller.

Vibration monitoring undertaken by Avalle (2007b) yielded similar findings and proposed a simple expression for obtaining an initial estimate of the potential magnitude of peak particle velocity (measured in mm/s), equal to $100/D$, where D was the distance in metres from an 8-tonne, 4-sided impact roller used in this body of work. The aforementioned vibration trial undertaken by the authors confirmed this expression proposed by Avalle (2007b) as being reasonable, but recommends caution for widespread use, given the number of variables involved. A site-specific trial is the most appropriate and safest way to determine how problematic vibrations induced by RDC might be to adjacent infrastructure.

Careful assessment of the suitability of RDC is needed, particularly for marginal or difficult sites. Whilst capable of compacting soils at moisture contents less than optimum, like other compaction techniques, RDC relies on sufficient moisture within the soil mass to attain a density in reasonable proximity to the maximum dry density. As observed in Figure 4, the attainable dry density can reduce significantly if too much or, as more commonly observed by the authors, too little moisture is present. There is a misconception among practitioners that RDC can successfully compact soils to achieve a high density at low moisture contents that are significantly dry of the optimum moisture content. As discussed in Section 2, compaction theory is valid, and target moisture ranges are still required to be met, albeit the moisture contents may be slightly lower due to the greater compactive effort imparted by RDC.

In applications where deep layers of imported fill material are being compacted cost benefits can still be obtained whilst limiting the layer thicknesses to well within the capability of the machine, however, the variable depth to which ground improvement can be achieved is one of the biggest limitations on the use of RDC when improving in situ material, as a back-up plan may need to be implemented if ground improvement is not achieved to the required (or expected) depths. The variable depth of treatment of RDC also has the potential to cause damage to existing services, culverts or bridges (via load transfer) if an insufficient thickness of soil is not placed over such structures. It is recommended by the authors that at least 1.5 m of soil cover is required to prevent damage in most applications.

In the authors' experience, careful assessment (e.g. the use of a RDC trial) is highly recommended in soil conditions where non-engineered fill material is present, particularly if the site contains large oversized material. Depending upon the nature and depth of the material it may be able to be rubbilised and compacted, however, there is also the potential for it to bridge underlying soil that would otherwise be improved, as found by Scott & Suto (2007).

When working at sites with a shallow water table, there is the potential for the repeated dynamic loading of soil to induce increased pore water pressures, which can bring water to the surface if too many passes are applied within a short period of time. The authors have observed RDC successfully used at sites with a shallow water table (i.e. within a depth of 1 to 2 m from the ground surface). The best results are obtained when the site is not 'over rolled' and time is provided for pore water pressures to dissipate between sets of passes. The authors found that by using sets of no more than 6 passes and then rolling other parts of site for a period of one hour (or utilising lunch breaks) obtained successful results.

Cases have also been observed by the authors where the high energy impacts of RDC have caused existing inter-particle bonds to break within weakly cemented sands at low in situ moisture contents, which actually resulted in negative improvement in soil density.

4. Verification of RDC

The depth of influence of RDC varies, depending upon factors such as the soil material type, moisture, groundwater conditions and the applied input energy (number of passes). The influence depth is typically a measure of the depth to which the imposed load from the module quantitatively affects the soil. This can vary considerably due to inherent differences between sites and interpretation on how the magnitude of improvement is both defined and quantified. For example, Avalle & Carter (2005) reported a depth of improvement to approximately 1.4 m in Botany Sands, whereas Avalle (2007a) reported a depth of 7 m in calcareous sands. Both used the cone penetration test (CPT) to quantify the depth of improvement as a result of RDC. Scott & Jaksa (2014) also used the CPT as a key site investigation technique to quantify the zone of influence of ground improvement using RDC. There have been varying results as to what the depth of influence of RDC is for different soil conditions. There is currently little published information on predicted depths of treatment for varying soil conditions, and it is often up to the project engineer to predict if the use of RDC will improve the ground sufficiently for the desired project application. To determine whether ground improvement using RDC will be a cost-effective option, it is commonplace to undertake a trial.

4.1 Testing Methods for Verifying RDC

Due to the ability of RDC to compact thick layers, alternative testing strategies may be appropriate depending upon site conditions. As discussed in this section, one of the key aims of a field trial should be to determine the most appropriate testing regime for any particular project or site. Avalle (2004) and Scott & Jaksa (2008) discuss a number of testing methods used prior to, and after RDC to quantify ground improvement. As explained by Avalle (2004) there is no simple rule that outlines which testing methods should be adopted or what the scope and nature of a field trial should be, as this depends on several factors such as site conditions, budget, efficiency, risk mitigation and available equipment.

Common testing methods associated with the use of RDC applications include intrusive techniques such as dynamic cone penetration (DCP) testing; cone penetration testing (CPT), Marchetti flat plate dilatometer (DMT), field density testing (either via the use of a nuclear density gauge, or less commonly used, the sand replacement method). Non-intrusive (surface methods) are also widely used in RDC applications to measure ground response, including the use of plate load tests, accelerometers, the Clegg hammer, and light-weight falling deflectometer. Seismic (geophysical) techniques are also becoming more widely used in RDC applications, such as the multi-channel analysis of surface waves (MASW) technique as used by Scott & Suto (2007) and Whiteley & Caffi (2014), the spectral analysis of surface waves (SASW) method, as used by Jaksa et al. (2012), and the continuous surface wave system (CSWS) method used by Bouazza & Avalle (2006).

Observational techniques (visual and audible) are common, particularly in proof rolling applications. The measurement of ground deformation via surface settlement monitoring is a commonly used technique. Depending upon the application, permeability, infiltration testing or vibration monitoring (when working adjacent to existing infrastructure) are also appropriate. In situ stress measurement via the use of earth pressure cells has also been used by the authors as described in the case study presented in Section 5. Soil sampling for laboratory tests such as particle size distribution, Atterberg limits, moisture content, and standard or modified proctor compaction testing is common practice.

4.2 Field Trials

This section presents a field trial where the use of RDC for thick lift compaction was assessed. A test pad was constructed to assist in the determination of the optimal number of passes, moisture content, and range of loose layer thicknesses that could be compacted using RDC, as well as to determine verification techniques that were appropriate, given the site conditions.

RDC was used to proof roll the subgrade prior to placement of any fill material to ensure there were no observable soft spots that required remediation prior to commencement of placed fill. The test pad was constructed such that 9 impact rolling lanes could be rolled. This enabled three separate zones of 10, 20 and 30 passes to be constructed that would allow testing after rolling to be undertaken simultaneously in the center of each zone. Given that one of the key objectives of this trial was to determine the thickness of fill that could be compacted under various compactive efforts, the height of the placed fill varied in thickness from 0.5–1.5 m. Whilst the construction of the test pad took time and effort, from both surveying and dozer operation, it enabled all post-compaction testing to be conducted in an efficient and effective manner. Figure 6 shows a diagram of the test pad, both in plan and elevation.

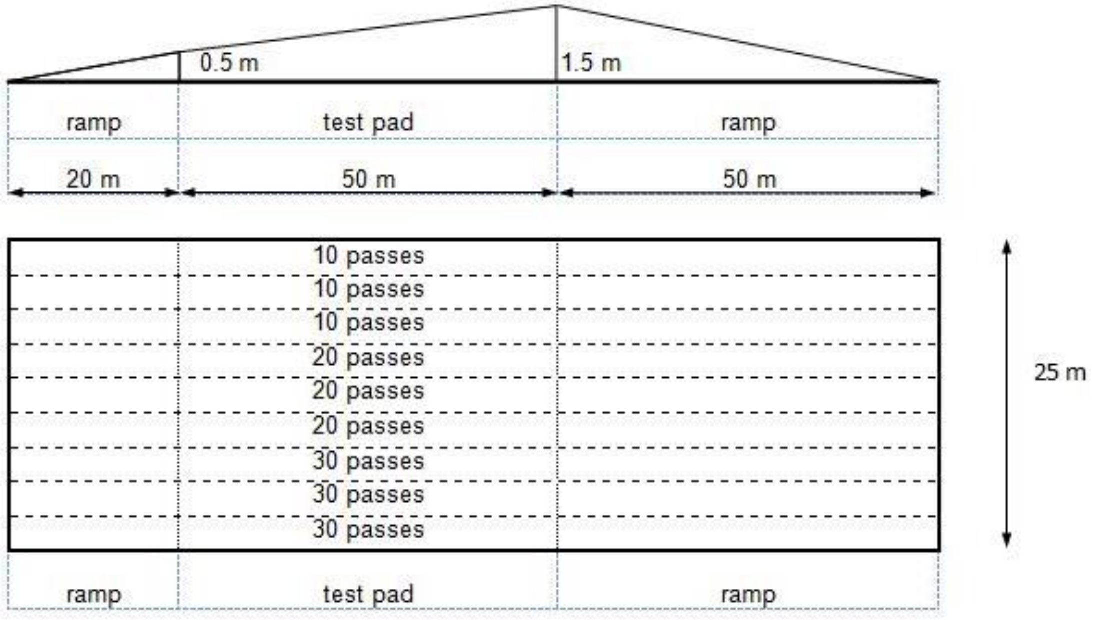

Figure 6. Test pad layout in plan and elevation.

The total length of the test pad, including ramps, was approximately 120 m; the actual area over which the testing was undertaken was in the order of 25 m by 50 m. Allowing 25 m at each end of the test pad for the impact roller to turn around and reach normal operating speed by the time it reached the ramp areas, a nominal area of 170 m long by 25 m wide was cordoned off and used for the trial. It was estimated that approximately 2500 m^3 of material was used for the compaction trial; sufficiently large to be representative of an embankment that was proposed. The construction of the test pad and the results that ensued, enabled more than one unique solution to be developed for the site, giving the Contractor the ability to determine an optimum compacted layer thickness based on the material, compactive effort and scheduling of plant and equipment, so as to maximise efficiency of site operations.

5. Case Study

The case study presented summarizes a RDC trial whereby the underlying objective was to determine an efficient relationship between the number of passes, placed loose layer thickness, moisture content and corresponding dry density ratio that could be achieved. RDC was achieved using an 8-tonne, 4-sided impact roller and the water table was located at a significant depth below the excavated bench level.

A test pad approximately 4 m high was constructed in three lifts. The trial was conducted as a staged process with one lift placed, rolled and tested each day. The ability of the site to work 24 hours per day and utilize large loaders, excavators and haul trucks made the staged trial possible in a short timeframe, as the time to place significant earthwork volumes (even for a trial) should not be underestimated. Allowing for windrows on the sides and ramps at either end the test pad, it was estimated that at least 5,000 m^3 of material was used in the trial.

Whilst adopting multiple layers for the trial added extra time, it did mean that the compaction trial could address one of the key concerns for the large scale operation; to determine if a target density of 95% of maximum modified dry density could be achieved, not only for a single layer, but also in the second and third layers placed above. Undertaking the trial in this manner was then representative of the construction of the tailings dam that was proposed, whilst it also enabled the depth of influence of the impact roller to be investigated.

This site contractors had the advantage of previously working with RDC for the construction of haul roads (albeit using different material); so had a preference for adopting a layer thickness that would complement the operational efficiency of other equipment on site, even if it meant that the placed layer thickness was less than what the roller was capable of compacting to achieve the specified performance criteria. Given the contractors had a preference for fewer passes and less thick layers, this enabled a trial pad to be constructed that featured layer thicknesses no greater than 1,500 mm and a maximum of 16 passes applied, with intermediate testing undertaken to provide representative results for varying numbers of passes over a range of depths.

In order to measure the zone of influence and effectiveness of the impact roller a test pad was constructed in three separate lifts of 1,200, 1,530 and 1,460 mm, as illustrated in Figure 7, which also shows the locations of embedded earth pressure cells (discussed later). The test pad was constructed by haul trucks end-tipping loose material adjacent to the pad, whereby a loader and excavator subsequently spread the material over the pad. The placement process caused the soil to be partly compacted by the self-weight of the plant; however, this method was deemed representative of the proposed construction method, therefore was consistent with the general aim of the trial to be as representative as possible given the site conditions.

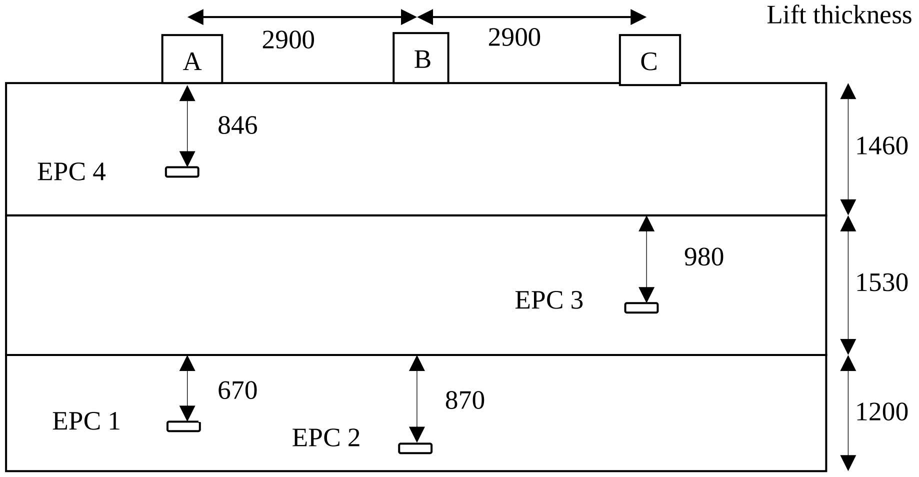

Figure 7. Cross-sectional view of test pad including EPC locations (all dimensions shown in mm).

Verification of RDC was undertaken using a combination of surveying of surface settlements, soil sampling and conducting a series of laboratory tests (e.g. particle size distribution, hydrometer test, Atterberg limits, standard and modified proctor tests) to characterize the soil. In situ tests were performed at intervals of eight passes to quantify soil conditions with changes in compactive effort. The in situ tests undertaken included field density measurements, the spectral analysis of surface waves (SASW) geophysical technique and dynamic cone penetration tests (DCPs) to measure and infer changes in density as a function of the number of module passes. Surface settlement monitoring was undertaken to quantify the change in surface level with number of passes. Earth pressure cells (EPCs) were installed at different depths to measure dynamic pressures to assist in quantifying the depth of influence and stress distribution induced by RDC.

Figure 8 shows the average grading curve obtained from 9 particle size distribution tests. The test pad was constructed using coarse, iron magnetite tailings that are a by-product of a consistent rock crushing process; the grading curve produced is fairly typical of well-graded sand with some gravel; 6% clay sized, 80% sand sized and 14%

gravel sized fractions, respectively. The Atterberg limits tests (liquid limit ~22%; plastic limit ~11%) and the particle size distributions suggest that the material is consistent with well-graded sand (SW) with some clay fines of low plasticity. The average field moisture content was ~5%. Triaxial and direct shear testing was carried out to further characterize engineering properties of the tailings material. The results are summarized in Table 2. The high density is consistent with crushed magnetite.

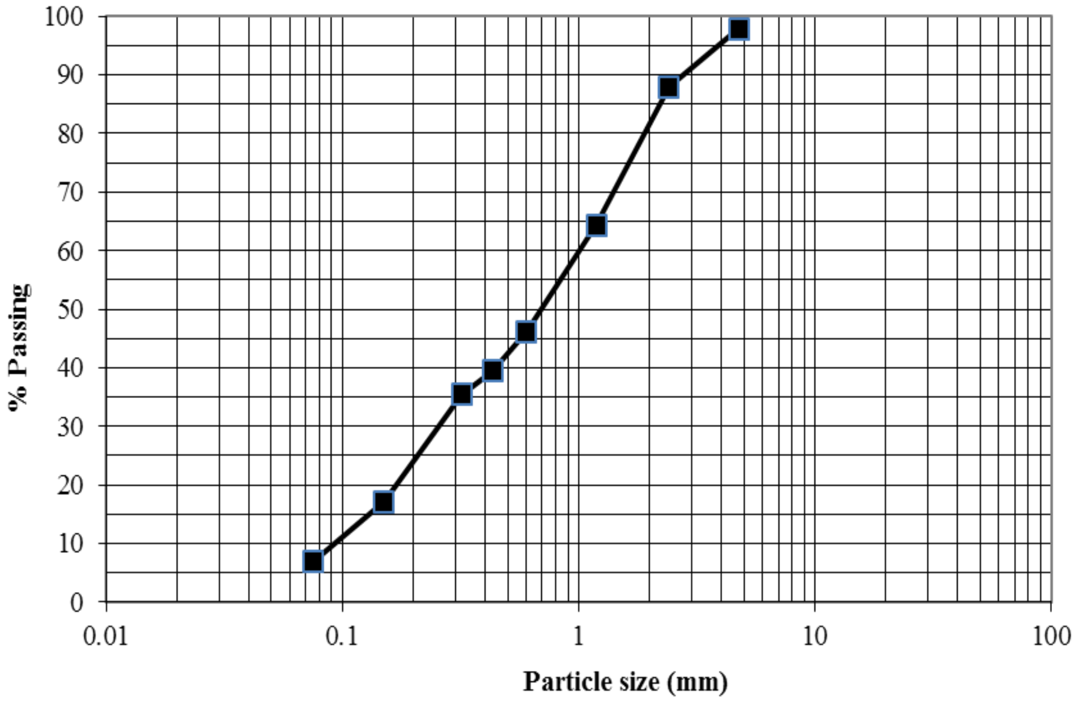

Figure 8. Average particle size distribution of test pad material.

Table 2. Summary of laboratory test results for key soil parameters

Cohesion (kPa)	7
Internal angle of friction (°)	37
Elastic shear modulus (MPa)	6

Figure 9 shows a plot of the average modified dry density ratio versus depth below ground surface after 8 passes and was used to determine the depth at which the target dry density ratio (95% with respect to modified compaction) was expected to be achieved. From this figure, it can be estimated that the effective depth for 8 passes is just over 1.2 m (i.e. 8 passes of the impact roller will achieve a dry density ratio of 95%, provided that the placed layer thickness does not exceed about 1.3 m).

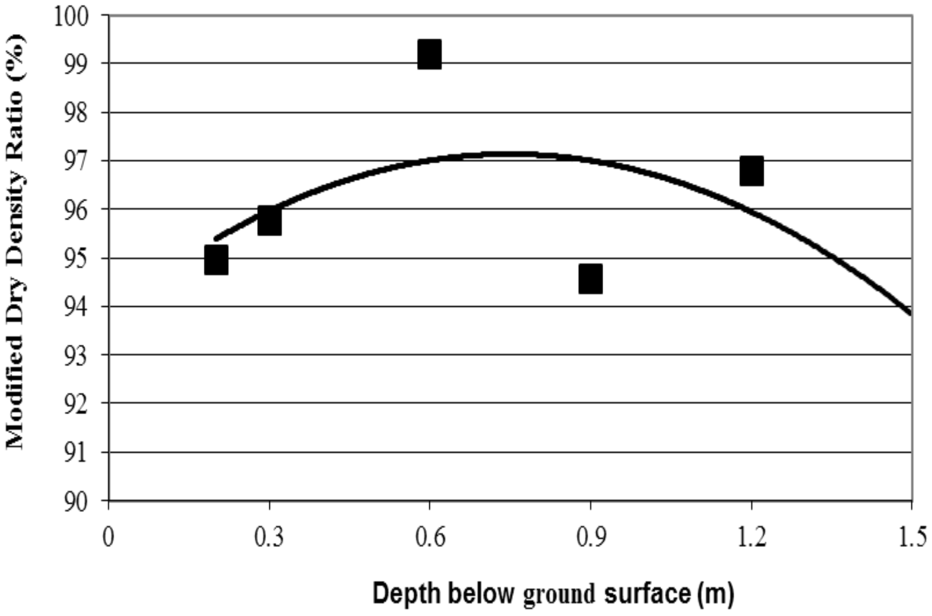

Figure 9. Modified dry density ratio versus test depth after 8 passes.

The SASW technique was used in conjunction with DCPs to assess the improvement with depth at the same location using two different methods at intervals of eight passes. Typical results are shown in Figure 10, where it can be observed that an increased number of passes results in an increase in shear modulus between depths of 0.5–2.1 m. This is an indication of increased soil density. Below a depth of 2.1 m results were inconclusive due to insufficient data.

Figure 11 summarises the number of DCP blows per 50 mm penetration versus test depth below the ground surface. It can be observed that the test results confirm a noticeable increase in the number of blows with a greater number of passes. As each test was terminated at a depth of 850 mm due to the physical limit of the equipment, it was not possible to determine the depth of influence solely using this test, however Figure 11 suggests that RDC is effective in improving the in situ density of the tailings material from a depth of 0.3 m to beyond the penetrometer depth of 0.85 m.

It is evident from Figures 10 and 11 that there is little, if any, improvement of the near-surface soils with increasing passes. This can be attributed to the module causing the near-surface soils to displace laterally and heave rather than being compacted; this occurs in cases where the near-surface soils have insufficient bearing capacity to withstand the stresses imparted by the module. As it typically loosens and disturbs near-surface soils, RDC is unsuitable as a finishing roller.

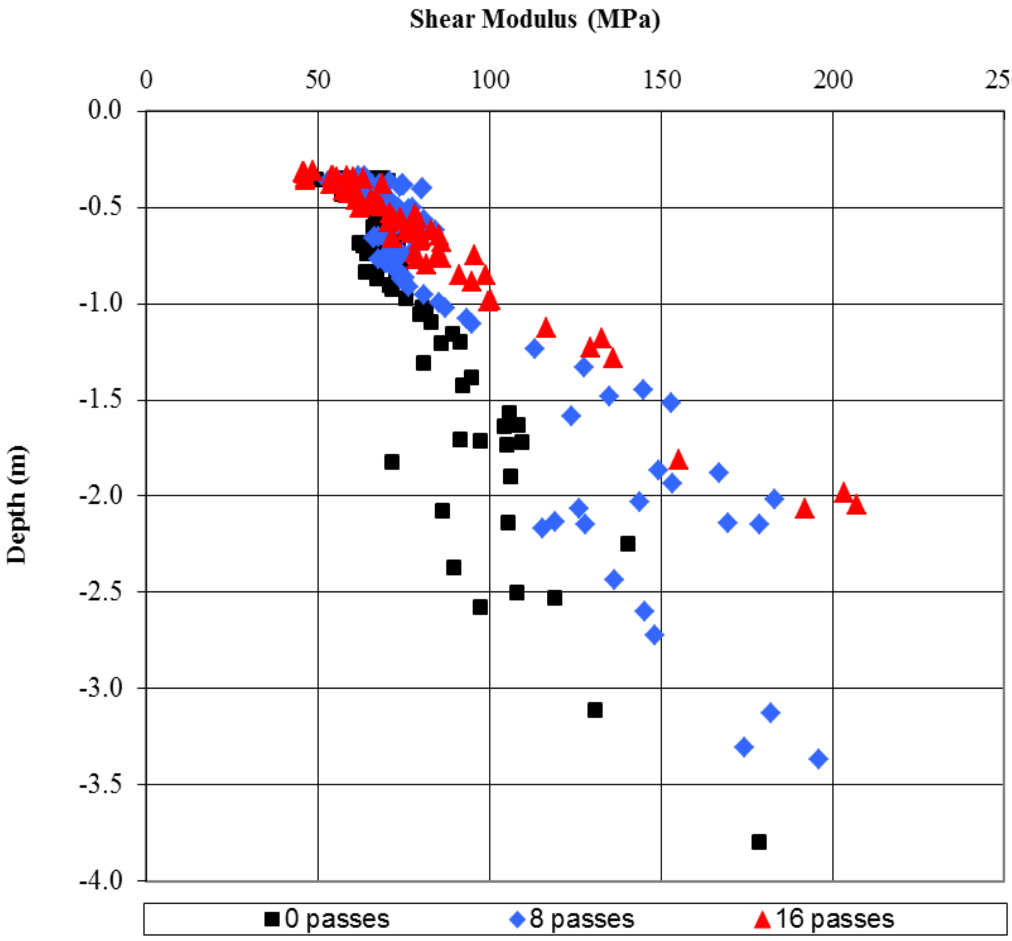

Figure 10. SASW test results for varying numbers of passes.

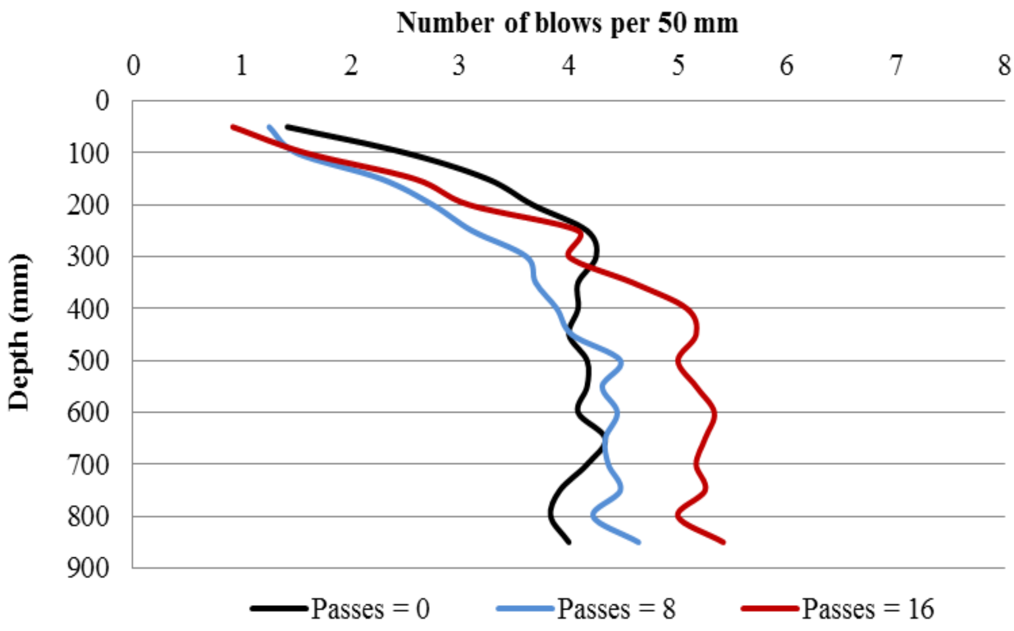

Figure 11. Results of dynamic cone penetrometer tests.

Settlement of the ground surface as a result of varying numbers of impact roller passes was determined from survey measurements of the ground surface at 0, 8 and 16 passes. Due to the undulating nature of the ground surface after rolling, a consistent approach of determining settlement was adopted by always measuring the surface at the lowest point left by the impact rolling module. The average settlement presented in Figure 12 was determined by averaging surface measurements across all three lifts. Figure 12 shows that the majority of settlement occurred within the first 8 passes; with a comparatively small magnitude of the total settlement (17%) occurring in the second set of 8 passes.

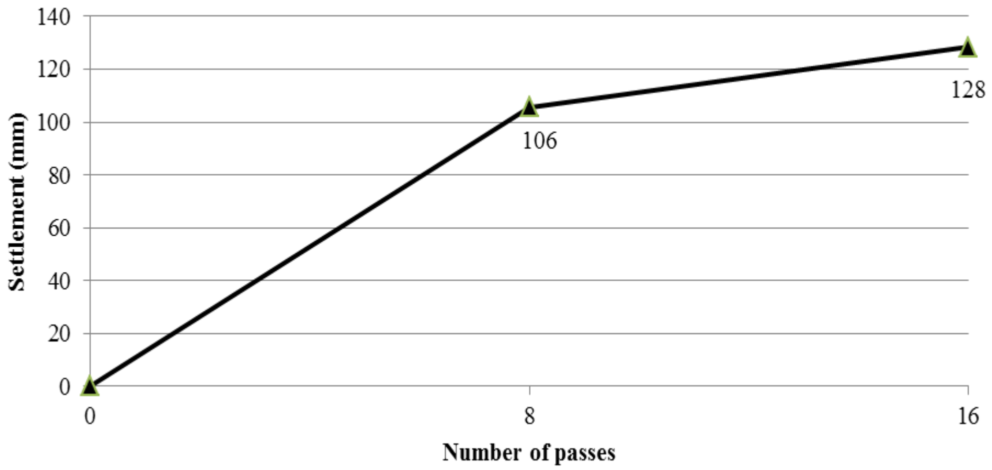

Figure 12. Average settlement versus number of passes.

A total of 4 Geokon 3500 earth pressure cells (EPCs) were buried at different depths and used to measure the dynamic pressures imparted by RDC. The locations of the EPCs (in cross section) were shown previously in Figure 7. EPCs 1, 2 and 3 were separated by a half-turn of the roller (2.9 m) in the forward direction of travel and were installed at various vertical depths below locations A, B and C, respectively. EPC 4 was located directly above EPC 1 at location A, but was separated vertically to prevent stress shadowing effects as discussed by Rinehart & Mooney (2009) who used EPCs to measure stresses imparted into the ground due to circular, static and vibratory rollers. The EPCs were installed at each depth using an excavator to create a trench. After installation the soil was then replaced in the trench by the excavator and was compacted lightly by means of its bucket. This process attempted to replicate the virgin construction of each lift. The EPCs were connected to a data acquisition system and a laptop to continuously record the pressures induced by the impact roller. Measurements from the EPCs were acquired at a sampling frequency of 2 kHz (i.e. one sample every 0.0005 seconds). That sampling frequency proved appropriate to balance conflicting requirements; on the one hand to detect the sudden increase in pressure caused by the roller striking the ground and, on the other, without generating overly excessive quantities of data.

An indication of the depth of influence can be obtained by analysing the variation in peak pressure (resulting from a strike of the roller) with depth. To develop that relationship, data from all three lifts were used. As shown in Figure 7, two EPCs were installed when compacting Lift 1, three for Lift 2, and four for Lift 3, together providing pressure readings at 9 different depths below the rolled surface, as the test pad was progressively constructed.

An example of data obtained from an EPC is shown in Figure 13, where a direct impact is measured by the impact roller striking the ground immediately above the buried EPC; a single large peak of over 200 kPa is recorded. Two smaller peaks are also measured either side of the main peak, at intervals of approximately half of one-second, which corresponds to the module striking the ground each quarter revolution before and after the location of the EPC. In this particular pass, the two adjacent peaks were readily visible; however all other peaks were barely detectable since the pressure dissipates rapidly through the soil as the impacts occur farther away.

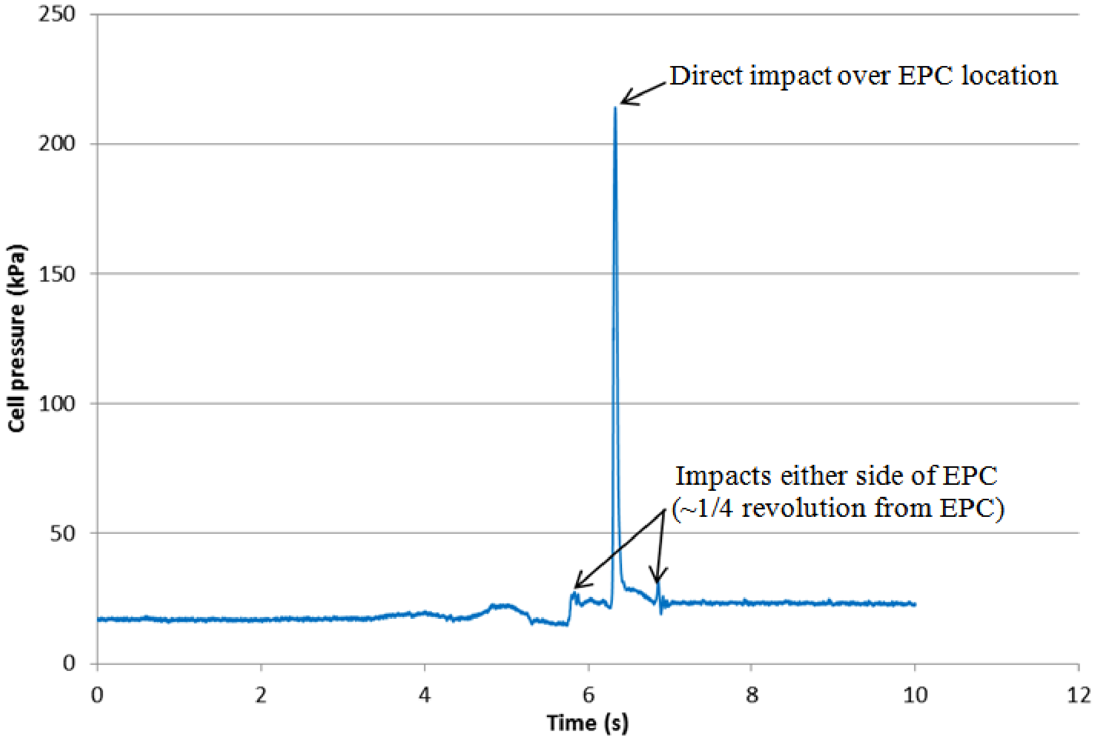

Figure 13. Example results obtained from direct impact over an EPC.

Figure 14 shows the measured peak pressures averaged over all of the EPCs plotted against depth below ground. Only peak pressures corresponding to module impacts striking the ground directly over an EPC were used to develop this and the remaining figures. The plot shows that the highest pressure reading obtained in the field trial was 600 kPa at 0.7 m depth. The pressure then quickly dissipated, decreasing by over 50% to around 260 kPa at 1 m depth. By 2 m depth the pressure had again halved to 120 kPa. The deepest EPC, located 3.85 m below ground, measured a pressure due to the roller of 38 kPa. That value was nearly equivalent to the static pressure of the impact roller at the surface, suggesting that, even at that depth, the roller was having some measurable influence.

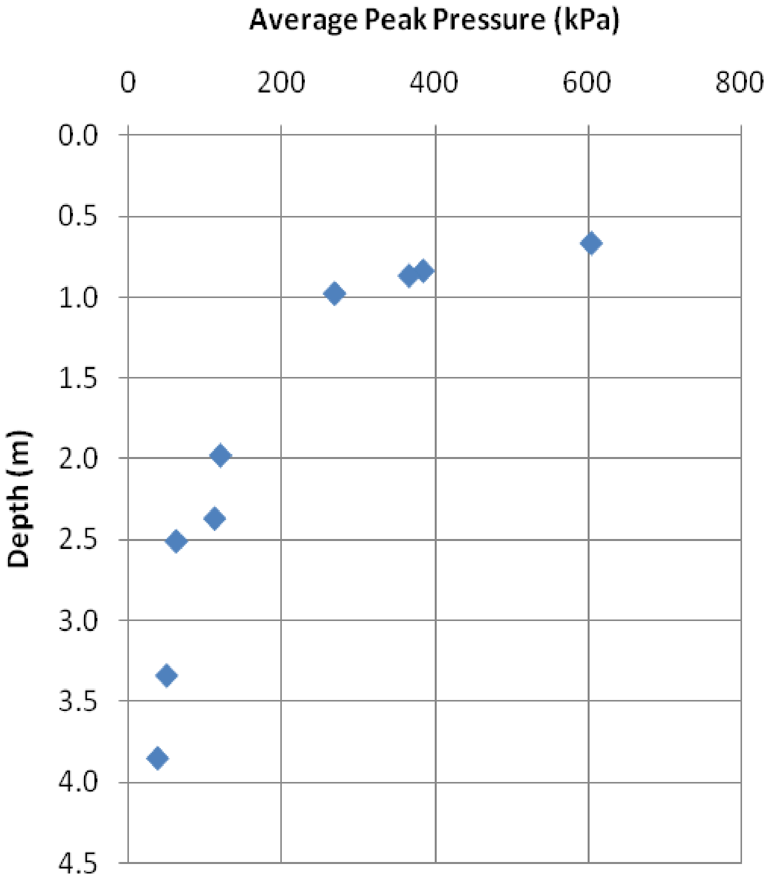

Figure 14. Average peak pressure versus depth below ground.

The pressure measurements from all lifts and EPCs were combined to produce a cross-section showing the zone of influence in the plane perpendicular to the direction of travel. Figure 15 shows a summary contour plot of peak pressure imparted by the impact roller with depth after 16 passes of the impact roller. It can be observed that the highest pressure readings recorded (> 150 kPa) were located within the upper 1.5 m from the surface, supporting other test data from this trial that suggested most of the quantifiable ground improvement occurs within this zone. Even the deepest pressure cell (buried at a depth of 3.85 m below the ground surface) registered positive pressure readings due to the impact roller, suggesting that the zone of influence extended beyond this depth.

The results of the compaction trial indicated that the target dry density ratio (95% of maximum modified dry density) can be expected to be achieved after a minimum of 8 passes on a loose lift thickness of tailings material of 1,200 mm.

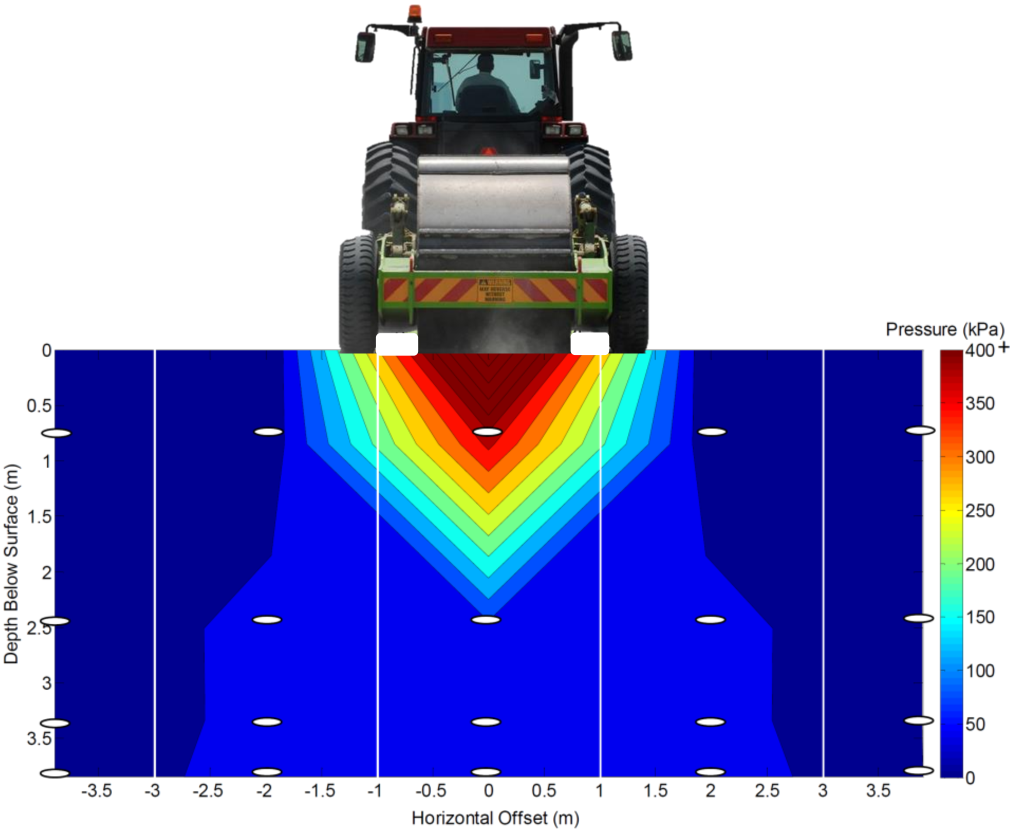

Figure 15. Pressure contours with depth after 16 passes perpendicular to direction of travel.

5. Final Comments

Whilst RDC is a simple and effective ground improvement technique, there is a need to understand the basic principles which govern its compaction of soil. As RDC can be used in a wide range of applications, it is important to understand that there is not a ‘one size fits all’ approach, and each site needs to be treated individually. The involvement of an experienced geotechnical engineer will be of great benefit, as they will be able to realize the advantages of RDC, whilst also recognize its limitations, which is particularly important at marginal or difficult sites.

Whilst the ability to compact material in large volumes effectively and efficiently is a significant advantage of RDC, there are challenges associated with verification. The use of a field trial can be a useful way to determine the appropriateness of RDC at a particular site. One of the key aims of a field trial should be to determine the most appropriate testing regime for any particular project or site, which depends on factors such as the target specification, site conditions, budget, efficiency, risk mitigation and available equipment. Other aims of a field trial should include determining the number of passes required, the range of moisture contents that are appropriate, and the depth of influence or range of loose layer thicknesses that can be compacted using RDC.

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References

Avalle, D. L. (2004a). Ground improvement using the ‘square’ impact roller – case studies. *Proc. 5th Int. Conf. on Ground Improvement Techniques, Kuala Lumpur,* pp. 101–108.

Avalle, D. L. (2004b). Use of the impact roller to reduce agricultural water loss. *Proc. 9th Australia New Zealand Conf. on Geomechanics, Auckland,* pp. 513–518.

Avalle, D. L. & Carter, J. P. (2005). Evaluating the improvement from impact rolling on sand. *Proc. 6th Int. Conf. on Ground Improvement Techniques, Coimbra, Portugal,* 8pp.

Avalle, D. L. & Mackenzie, R. W. (2005). Ground improvement of landfill site using the “square” impact roller. *Australian Geomechanics*, Vol. 40, No. 4, pp. 15-21.

Avalle, D. L. (2006). Reducing haul road maintenance costs and improving tyre wear through the use of impact rollers. *Mining for tyres conference, Perth,* 5pp.

Avalle, D. L. (2007a). Trials and validation of deep compaction using the “square” impact roller. *Symposium - Advances in Earthworks, Sydney,* Australian Geomechanics Society, 6pp.

Avalle, D. L. (2007b). Ground vibrations during impact rolling. *Proc. 10th Australia - New Zealand Conf. on Geomechanics, Brisbane,* Vol. 2, pp. 42-47.

Avalle, D. L., Scott, B. T. & Jaksa, M. B, (2009). Ground energy and impact of rolling dynamic compaction – results from research test site, *Proc. XVII Int. Conf. on Soil Mechanics and Geotech. Engrg.,* Alexandria, Egypt, Vol. 3, pp. 2228–2231.

Bouazza, A. & Avalle, D. L. (2006). Verification of the effects of rolling dynamic compaction using a continuous surface wave system, *Australian Geomechanics,* Vol. 41, No 2, pp. 101-108.

Clegg, B. & Berrangé, A. R. (1971). The development and testing of an impact roller, *The Civil Engineer in South Africa*, Vol. 13, No. 3, pp. 65–73.

Clifford, J. M. (1976). Impact rolling and construction techniques. *Proc. ARRB Conf.*, Vol. 8, pp. 21–29.

Clifford, J. M. (1978a). The impact roller – problems solved. *The Civil Engineer in South Africa*, Vol. 20, No. 12, pp. 321–324.

Clifford, J. M. (1978b). *Evaluation of Compaction Plant and Methods for the Construction of Earthworks in Southern Africa*. Diss. Masters Thesis, University of Natal, South Africa, 308pp.

Clifford, J. M. & Bowes, G. (1995). Calculating the Energy delivered by an Impact Roller. *A trilogy of Papers for the Sept. 1995 Lecture Tour and Int. Seminars to commemorate the tenth anniversary of the BH 1300 Standard Impact Roller,* Paper Two, pp 1-15.

Coduto, D.P., Yeung, M.R., Kitch, W.A. (2011). *Geotechnical Engineering: Principles and Practices, 2nd ed.* Pearson Higher Education Inc., Upper Saddle River, NJ, 794pp.

Hausmann, M. R. (1990). *Engineering Principles of Ground Modification, McGraw-Hill,* New York, 632pp.

Jaksa, M. B., Scott, B. T., Mentha, N. L., Symons, A. T., Pointon, S. M., Wrightson, P. T. & Syamsuddin, E. (2012). Quantifying the zone of influence of the impact roller. *Int. Symposium on Recent Research, Advances and Execution Aspects of Ground Improvement Works, Brussels, Belgium,* Vol. 2, pp. 41–52.

Jumo, I. & Geldenhuys, J. (2004). Impact compaction of subgrades-experience on the Trans-Kalahari Highway including continuous impact response (CIR) as a method of quality control. *Proc. 8th Conf. on Asphalt Pavements for Southern Africa,* Paper 19.

Lukas, R. G. (1995). Dynamic compaction, *Geotechnical Engineering Circular No 1, Report.* FHWA-SA-95-037, 105pp.

Mayne, P. W., Jones, J. S. & Dumas, J. C. (1984). Ground response to dynamic compaction. *Journal of Geotechnical Engineering, ASCE,* Vol. 110, No. 6, pp. 757-774.

Munfakh, G. A. & Wyllie, D. C. (2000). Ground Improvement Engineering – Issues and Selection. *Proc. Int. Conf. on Geological and Geotechnical Engineering, GeoEng2000, Melbourne,* 27pp.

Phear, A. G. & Harris, S. J. (2008). Contributions to Géotechnique 1948–2008: Ground improvement. *Géotechnique,* Vol. 58, No. 5, pp. 399–404.

Pinard M. I. (1999). Innovative developments in compaction technology using high energy impact compactors. *Proc. 8th Australia New Zealand Conf. on Geomechanics, Hobart,* Vol. 2, pp. 775–781.

Rinehart, R. V. & Mooney, M. A. (2009). Measurement of roller compactor induced triaxial soil stresses and strains. *Geotechnical Testing Journal,* Vol. 32, No. 4, pp. 347–357.

Scott, B. T & Suto, K. (2007). Case study of ground improvement at an industrial estate containing uncontrolled fill. *Proc. 10th Australia New Zealand Conf. on Geomechanics, Brisbane,* Vol. 2, pp. 150-155.

Scott, B. T. & Jaksa, M. B. (2008). Quantifying the influence of rolling dynamic compaction. *Proc. 8th Young Geotechnical Professionals Conf., Wellington, New Zealand,* pp. 199-204.

Scott, B. T. & Jaksa, M. B. (2012). Mining applications and case studies of Rolling Dynamic Compaction. *Proc. 11th Australia New Zealand Conf. on Geomechanics, Melbourne,* pp. 961-966.

Scott, B. T. & Jaksa, M. B., Kuo, Y. L. (2012). Use of Proctor compaction testing for deep fill construction using impact rollers. *Int. Conf. on Ground Improvement and Ground Control, Wollongong,* Australia, pp. 1107-1112.

Scott, B. T. & Jaksa, M. B. (2014). Evaluating rolling dynamic compaction of fill using CPT. *3rd Int. Symposium on Cone Penetration Testing,* Las Vegas, USA, pp. 941-948.

Terashi, M. & Juran, I. (2000). Ground Improvement-State of the Art. *Proc. Int. Conf. on Geological & Geotechnical Engineering, GeoEng2000, Melbourne,* Vol. 1, pp. 461-519.

Whiteley, R. J. & Caffi, P. (2014). Evaluating the effectiveness of rolling impact compaction at a brownfield site with high and low frequency seismic surface waves and geotechnical testing. *Near Surface Geophysics*, Vol. 12, pp. 405–414.

Appendix B: Conference Paper 1

Conference Paper

Scott, B.T., Jaksa, M.B. & Kuo, Y.L. (2012). Use of proctor compaction testing for deep fill construction using impact rollers. *International Conference on Ground Improvement and Ground Control, Wollongong, Australia*, pp. 1107-1112.

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Principal Author

Name of Principal Author (Candidate)	Brendan Scott		
Contribution to the Paper	Performed site work, analysis and interpretation of site data, wrote manuscript, acted as corresponding author, presented paper.		
Overall percentage (%)	90		
Certification:	This paper reports on original research I conducted during the period of my Higher Degree by Research candidature and is not subject to any obligations or contractual agreements with a third party that would constrain its inclusion in this thesis. I am the primary author of this paper.		
Signature		Date	18/4/2019

Co-Author Contributions

By signing the Statement of Authorship, each author certifies that:

i. the candidate's stated contribution to the publication is accurate (as detailed above);

ii. permission is granted for the candidate in include the publication in the thesis; and

iii. the sum of all co-author contributions is equal to 100% less the candidate's stated contribution.

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Contribution to the Paper	Helped to evaluate and edit the manuscript		
Signature		Date	18/4/19

Use of proctor compaction testing for deep fill construction using impact rollers

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Rolling Dynamic Compaction (RDC) is a generic term associated with densifying ground using non-circular (impact) rollers. RDC is suited to deep fill applications because of the ability to compact ground efficiently by means of its faster operating speed (10-12 km/h) and greater depth of influence when compared to conventional circular rollers. Whilst conventional circular rollers are able to compact layer thicknesses typically in the range of 200-500 mm, thicker layers are able to be compacted using RDC. This paper discusses performance based specifications and the applicability of both the standard and modified proctor compaction tests to RDC. For projects where impact rollers are used, the modified proctor test is strongly recommended as the energy imparted onto the soil is more representative than the standard test.

Keywords: proctor, compaction, impact, roller

1 Introduction

This paper is concerned with a specific type of dynamic compaction, known as rolling dynamic compaction (RDC), which involves densifying the ground using heavy (6 to 12 tonne) non-circular modules (of three, four or five sides), that rotates about a corner as they are towed, causing the module to impact the ground and compact it dynamically. Three different module designs that are available throughout the world are shown in Figure 1. Due to the combination of kinetic and potential energies, and the relatively large mass of the module, RDC is able to compact the ground to greater depths than its static and vibrating roller counterparts, and more efficiently because of its greater speed – 12 km/h compared with 4 km/h using traditional rollers (Pinard 1999).

Figure 1(a). RDC module: 3-sided (Landpac)

Figure 1(b). RDC module: 4-sided (Broons)

Figure 1(c). RDC module: 5-sided (Landpac)

2 Compaction of deep filling

Deep fills have been traditionally constructed by compacting soil in thin layers using relatively small particle sizes placed in a highly controlled manner. Field density tests are typically undertaken in each layer to confirm performance specifications of the placed fill. The determination of field density testing using a nuclear density gauge (Standards Australia 2007), is the current industry standard, and involves determining the in situ density at discrete locations within the top 300 mm from the surface. This method is ideally suited for the verification of fill density that has been placed in relatively thin layers (lifts) using conventional static or vibrating drum rollers (where thin layers comparable to the influence depth of the nuclear density gauge are generally adopted). However, in RDC applications involving thicker lifts, verification using field density testing typically requires excavation through compacted material down to targeted bench levels to verify fill density. The ability of an impact roller to compact material in larger quantities is an obvious advantage over compacting fill in thin layers; however, as noted by Avalle (2007), there are challenges associated with verification. This paper discusses performance based specifications that are established on field density test results and discusses the applicability of both the standard proctor (Standards Australia 2003a) and modified proctor (Standards Australia 2003b) compaction tests to RDC.

3 Standard and modified proctor compaction tests

In order to determine the suitability of standard and modified proctor compaction tests to RDC, it is pertinent to highlight the difference in the imparted energy between the two test methods. As noted in Table 1, the modified test imparts approximately 4.5 times the energy (2703 kJ/m^3) per unit volume as the standard test (596 kJ/m^3).

Table 1. Comparison of imparted energy for standard and modified proctor tests.

Test	Standard Proctor	Modified Proctor
Hammer weight	2.7 kg	4.9 kg
Drop height	300 mm	450 mm
Energy imparted per blow	7.94 J	21.62 J
No. of soil layers	3	5
No. of blows per layer	25	25
Energy imparted per unit volume	596 kJ/m^3	2703 kJ/m^3

As detailed in Coduto et al. (2011), the standard test was developed by R. R. Proctor in the 1930s as a means for modelling and assessing compacted fills using compaction equipment of that era. During the 1940s and 1950s, fills compacted using the standard test no longer provided adequate support for trucks and aircraft traffic that were increasing in both size and frequency. To address this issue, the U.S. Army Corps of Engineers developed the modified test in 1958 that used a higher compactive effort to better model heavier compaction equipment that was then needed to compact fills to support heavier and more frequent trucks and aircraft traffic. Since 1958, increases in the size and frequency of trucks and aircraft traffic have continued; compaction equipment has also evolved with larger and heavier rollers used today compared to over 50 years ago, yet the modified test has continued to stand the test of time. Of greater interest (or concern) however, is that the standard test as developed by R. R. Proctor approximately 80 years ago, continues to be widely referred to, despite much of today's modern compaction equipment bearing little resemblance (in terms of energy imparted per unit volume) to that used during the 1930s.

Whether the performance criteria for a particular project are a function of the standard or modified proctor compaction test is often dictated by what is written in the project specification, a decision usually made at the discretion of the project engineer. It is commonly accepted that the modified test is used where fills involving heavy compaction equipment will be required in order to support large loads, such as roads and runways; with the standard test used for fills involving other applications where lower loads are expected and hence, lower dry unit weights are required. It is the experience of the authors that a number of specifications written around the use of heavy compaction equipment (such as impact rollers) commonly refer to key performance criteria relative to the standard proctor test. Virtually all compaction specifications include the criterion of achieving a minimum dry unit weight; in some instances the moisture content is also specified within a certain range. In cases where both dry unit weight and moisture content are used as specification criteria, it is critical to understand what laboratory baseline test (modified or standard) is more representative of the field compactive effort, which is a function of the weight and type of roller, number of passes and lift thickness that is used.

Figure 2 shows the particle size distribution for a soil sample that was subjected to both laboratory test methods. A comparison of standard and modified proctor test results on the same soil is shown in Figure 3. For this example (hereby referred to as Site A) the materials consisted of fine to medium grained sand (containing 3% clay-sized, 96% sand-sized and 1% gravel-sized particles). It can be observed that the 'maximum dry unit weight' for the modified test is slightly higher (~1.5%) than that resulting from the standard test, which corresponds to a lower optimum moisture content. A summary of the test results for Site A is included in Table 2.

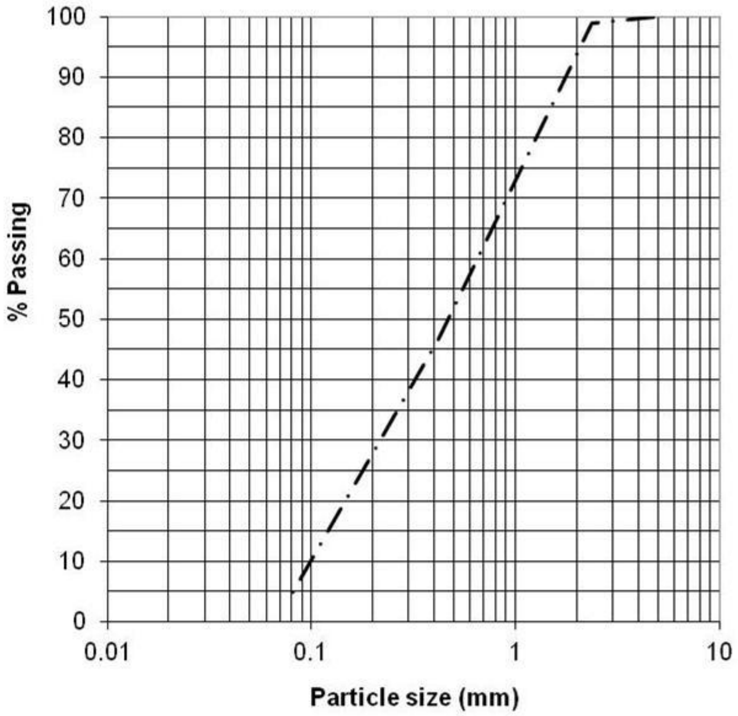

Figure 2. Particle size distribution for Site A

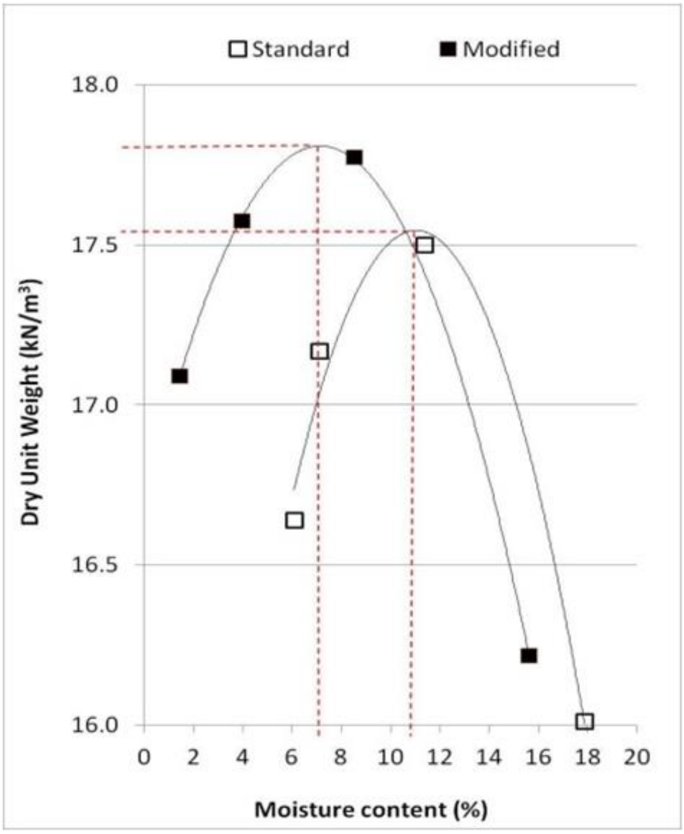

Figure 3. Comparison of standard and modified proctor test results for Site A

Table 2. Comparison of standard and modified proctor test results for Site A.

Test	Standard Proctor	Modified Proctor
Maximum dry unit weight	17.6 kN/m^3	17.8 kN/m^3
Optimum moisture content	~ 11%	~ 7%

Figure 4 shows the particle size distribution for a different material taken from Site B; a comparison of standard and modified proctor test results is shown in Figure 5. At this site, the material consisted of iron tailings (containing 6% clay-sized, 80% sand-sized and 14% gravel-sized particles); it can be observed that the ‘maximum dry unit weight’ for the modified test is approximately 8% higher than that resulting from the standard test; with the optimum moisture content for the modified test slightly slower than that from the standard test. A summary of the test results is included in Table 3.

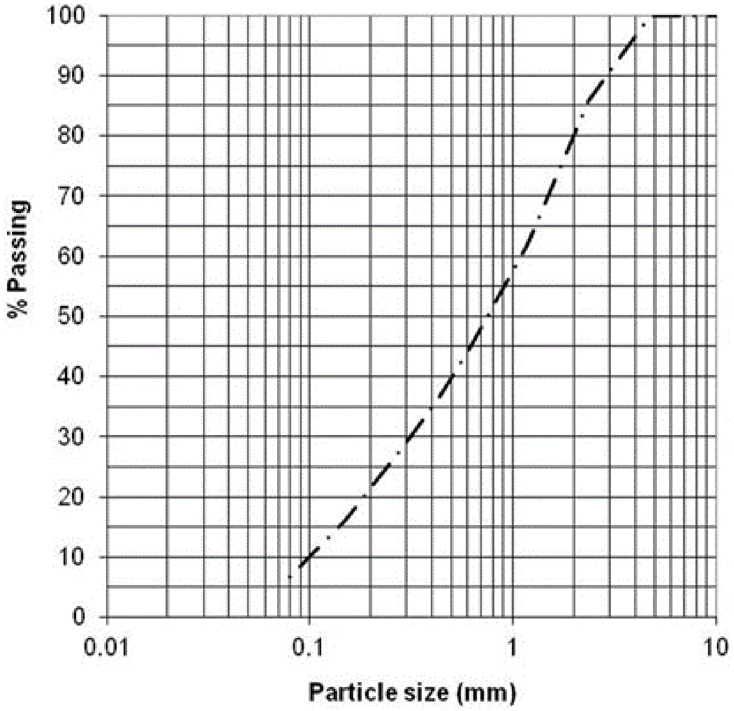

Figure 4. Particle size distribution for Site B

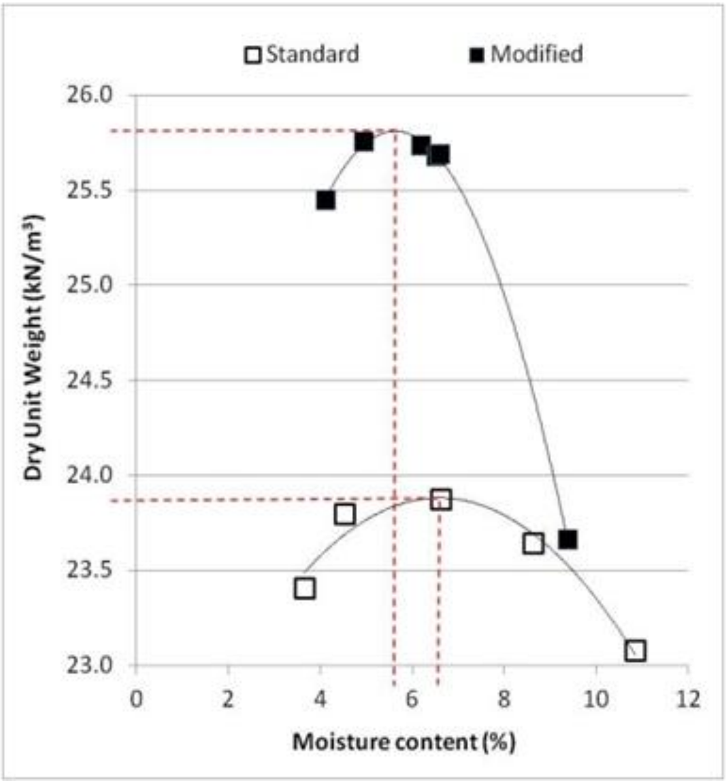

Figure 5. Comparison of standard and modified proctor test results for Site B

Table 3. Comparison of standard and modified proctor test results for Site B.

Test	Standard Proctor	Modified Proctor
Maximum dry unit weight	23.9 kN/m^3	25.8 kN/m^3
Optimum moisture content	~ 6.5%	~ 5.6%

For both Sites A and B, two values for 'maximum dry unit weight' were presented in Tables 2 and 3, respectively; as Coduto et al. (2011) explain this term is somewhat misleading, because the standard and modified tests have two different 'maximums'. However, as they describe, this term can best be thought of as 'the greatest dry unit weight that can be achieved for that particular compactive effort'. As the two examples in this paper show (on different materials that have somewhat comparable particle size distributions but obvious differences in mineral composition and specific gravity) changes in field compactive effort can significantly change the relationship between moisture content and dry unit weight. Additionally, there is no magic relationship that converts standard and modified compaction results, as the relationship between the two is unique for each soil type.

For the purposes of comparison, Table 4 presents the target moisture content range for Sites A and B assuming specification criteria of at least 98% of SMDD (maximum dry density with respect to the standard proctor compaction test); with Table 5 assuming specification criteria of at least 95% of MMDD (maximum dry density with respect to the modified proctor compaction test). It can be observed from Tables 4 and 5 that for the case of Site B, minimal change in target moisture content would have occurred; however, the target moisture range for Site A was significantly different depending on which laboratory baseline test was used. It must be stressed at this point that both Sites A and B consist of coarse grained soils that contain minimal fines content, so they are less sensitive to changes in moisture content and can be compacted over a wider moisture range than fine grained soils. The latter case is beyond the scope of this paper.

Table 4. Specification of 98% of maximum standard dry unit weight for Sites A and B.

Location	Site A	Site B
Maximum dry unit weight	17.6 kN/m^3	23.9 kN/m^3
Target dry unit weight (98% SMDD)	17.2 kN/m^3	23.4 kN/m^3
Corresponding (target) moisture range	7 – 15%	~3 – 10%

Table 5. Specification of 95% of maximum modified dry unit weight for Sites A and B.

Location	Site A	Site B
Maximum dry unit weight	17.8 kN/m^3	25.8 kN/m^3
Target dry unit weight (95% MMDD)	16.9 kN/m3	24.5 kN/m3
Corresponding (target) moisture range	~2 – 14%	~3 – 9%

The authors' experience has demonstrated that, for cases where the standard test is used, impact rollers are likely to achieve the desired dry unit weight criterion in thick lifts (depending on the soil type, adequate dry unit weights may be achieved in layer thicknesses up to 1,500 mm). If an additional moisture range is also included as part of a project specification (e.g. in the case of deep fills where hydro-compression is of concern) then consideration needs to be given as to how representative the baseline laboratory test chosen will be of impact rolling. The contractor will inevitably use the test results to optimize the site compaction by selecting an optimal combination of both compactive effort and moisture content range, bearing in mind that the contractor will also be optimizing against a third criteria (cost), thereby avoiding increased compactive effort and the need for additional moisture wherever possible.

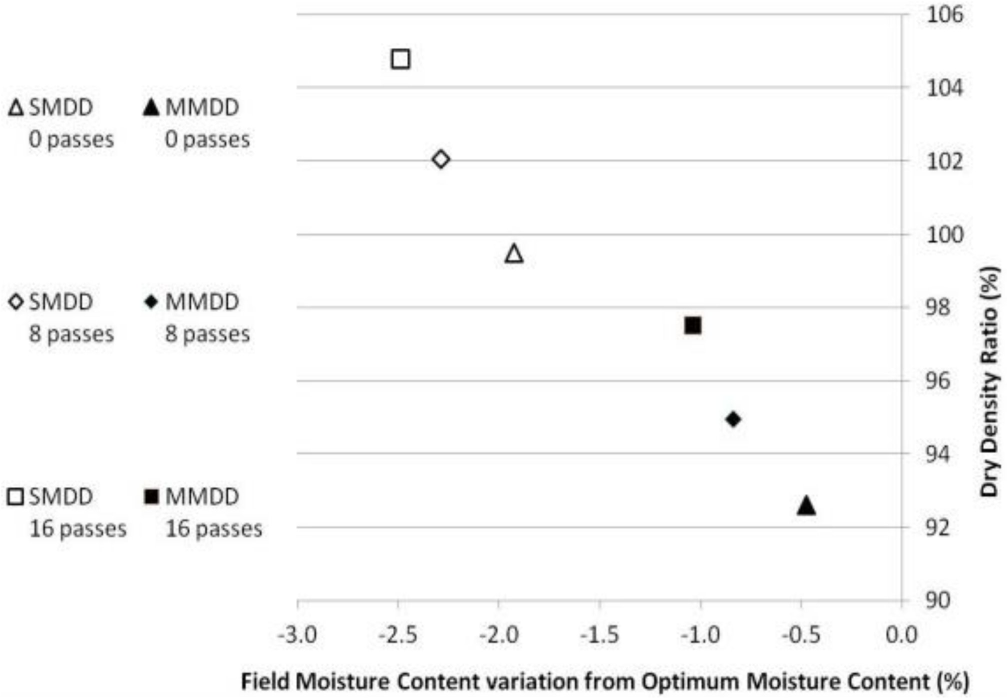

Figure 6. Dry density ratio versus field moisture content, dry of optimum, for increasing compactive effort at Site B.

Figure 6 shows an example of field density measurements taken after 0, 8 and 16 passes of an impact roller at Site B compared against both standard and modified proctor compaction tests (expressed as a ratio of maximum dry density) and field moisture content dry of optimum. This figure shows that, with increasing passes of the roller, the dry density ratio increases, corresponding to a reduced field moisture content. The difference in field moisture content compared to the optimal moisture content obtained from both test methods clearly shows that the modified test better models the density versus moisture content relationship, as it is more representative of the compactive effort being imparted into the ground than the standard test. Clifford and Bowes (1995) determined the theoretical energy imparted by RDC based on kinetic energy theory. Ongoing research by the authors is aiming to validate such theory against measured field data so that predictions can be made to determine the required energy needed to improve soils of different types.

4 Conclusions

RDC is unique in that it is able to compact large volumes of soil effectively and efficiently. The ability to compact material in thicker lifts and at lower moisture contents (when compared to the optimum) has the potential for significant time and cost advantages. When determining which proctor compaction test method to use, it is important to understand which laboratory test is more representative to the field compactive effort that is proposed; a decision often based on the loads to be supported, which in turn affects the compaction equipment to be used to ensure adequate dry unit weights will be achieved. In the case where impact rollers are proposed, use of the modified test is strongly recommended as the energy imparted onto the soil is more representative than the standard test.

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References

Avalle, D.L. (2007). Trials and validation of deep compaction using the “square” impact roller, *Symposium - Advances in Earthworks, Sydney,* Australian Geomechanics Society, 6pp.

Clifford, J.M. and Bowes G. (1995). Calculating the energy delivered by an Impact Roller. *A trilogy of Papers for the September 1995 Lecture Tour and International Seminars to commemorate the tenth anniversary of the BH 1300 Standard Impact Roller,* Paper Two, pp 1-15.

Coduto, D.P., Yeung, M.R., Kitch, W.A. (2011). *Geotechnical Engineering: Principles and Practices,* 2nd ed. Pearson Higher Education Inc., Upper Saddle River, NJ.

Pinard, M.I. (1999). Innovative developments in compaction technology using high energy impact compactors. *Proceedings, 8th Australia New Zealand Conference on Geomechanics, Hobart,* Australian Geomechanics Society, Vol. 2, 775-781.

Standards Australia, (2003a). Methods of testing soils for engineering purposes – soil compaction and density tests – determination of the dry density/moisture content relation of a soil using standard compactive effort, *AS 1289.5.1.1,* Sydney.

Standards Australia, (2003b). Methods of testing soils for engineering purposes – soil compaction and density tests – determination of the dry density or moisture content relation of a soil using modified compactive effort, *AS 1289.5.2.1,* Sydney.

Standards Australia (2007). Methods of testing soils for engineering purposes – soil compaction and density tests – determination of field density and field of a soil using a nuclear surface moisture - density gauge – direct transmission mode, *AS 1289.5.8.1*, Sydney.

Appendix C: Conference Paper 2

Conference Paper

Scott, B.T. & Jaksa, M.B. (2008). Quantifying the influence of rolling dynamic compaction. *Proceedings 8th Young Geotechnical Professionals Conference, Wellington, New Zealand,* pp. 199-204.

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Name of Principal Author (Candidate)	Brendan Scott		
Contribution to the Paper	Wrote manuscript, acted as corresponding author, presented paper.		
Overall percentage (%)	95		
Certification:	This paper reports on original research I conducted during the period of my Higher Degree by Research candidature and is not subject to any obligations or contractual agreements with a third party that would constrain its inclusion in this thesis. I am the primary author of this paper.		
Signature		Date	18/4/2019

Co-Author Contributions

By signing the Statement of Authorship, each author certifies that:

i. the candidate's stated contribution to the publication is accurate (as detailed above);

ii. permission is granted for the candidate in include the publication in the thesis; and

iii. the sum of all co-author contributions is equal to 100% less the candidate's stated contribution.

Name of Co-Author	Mark Jaksa		
Contribution to the Paper	Provided primary supervision and helped evaluate and edit the manuscript.		
Signature		Date	18/4/19

Quantifying the influence of rolling dynamic compaction

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Keywords: compaction, ground, improvement, impact, rolling

Abstract

Rolling dynamic compaction (RDC) is a commonly used ground improvement technique. A key feature of RDC is the ability to provide deep layer compaction when compared to conventional rollers. This greater zone of influence makes it a productive and cost-effective option in earthworks applications. Whilst RDC has been used successfully on many projects in Australia and overseas in applications such as roads, airports, construction and land reclamation projects, there are cases where the expected ground improvement has not occurred. There is a lack of information indicating what the zone of influence of the roller is, and how much input energy is required for different soil conditions. The methods of testing the effectiveness of RDC need improvement. Relationships are needed that relate the input energy and the ground improvement that can be expected for different soil types.

1. Introduction

Rolling dynamic compaction (RDC) consists of a non-circular module of 3, 4 or 5 sides, that rotates about its corners as it is towed, causing it to fall to the ground and compact it dynamically. A square impact rolling module is shown in Figure 1. A cross section of this 4-sided module, which is concrete filled and encased with steel, is shown in Figure 2. The module is towed at a speed typically in the range of 10-12 km/h (Pinard 1999).

Figure 1. 4-sided impact roller

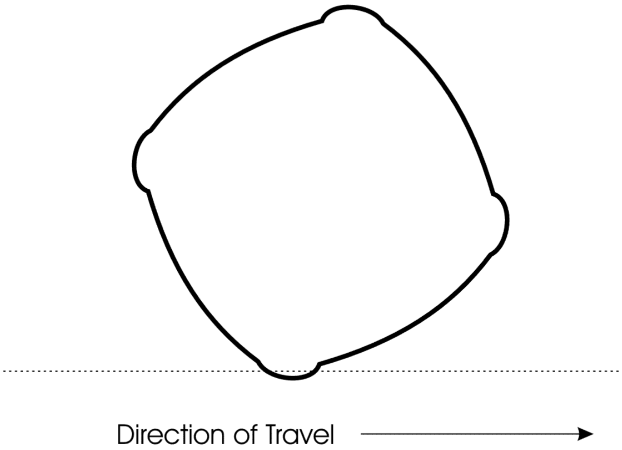

Figure 2. Cross-section of 4-sided module

2. Need for ground improvement

One of the major functions of geotechnical engineering is to design, implement and evaluate ground improvement schemes for civil engineering infrastructure projects. Since the 1970s an increasing number of new technologies and ground improvement methods have been developed and implemented to assist the geotechnical engineer in providing cost-effective solutions for construction on marginal or difficult sites. The available methods and techniques to improve the geotechnical characteristics of soils are described in detail by Terashi & Juran (2000), Munfakh & Wyllie (2000) and Munfakh (2003). The general consensus from the aforementioned authors is that ground improvement using surface dynamic compaction techniques such as RDC can be successfully undertaken to improve a soil's shear strength and stiffness, or reduce its permeability.

RDC has been used successfully in many earthworks applications in Australia and overseas including the improvement of poor quality ground in situ, the compaction of thick layers for in-filling deep excavations, the proof rolling of road and subgrade materials and the compaction of reclaimed land. In recent years, RDC has been used to construct haul roads in the mining industry, as well as in agriculture, where it is used to compact soil in irrigated areas to reduce soil permeability and conserve water.

3. What is the depth of influence of RDC?

RDC has demonstrated improvements in soil density to depths of more than one metre below the ground surface for clay soils and 2-3 m or more in sands (Avalle, 2004, Avalle & Carter, 2005). This zone of influence is far deeper than conventional static or vibratory rolling techniques (Clegg & Berrangé 1971, Clifford 1976, 1978), which are generally limited to depths of less than 0.5 m. This ability to provide deep layer compaction, as well as its relatively fast operating speed (when compared to conventional rollers) makes RDC a productive and cost-effective option in earthworks applications. This view is supported by Pinard (1999) who stated that in most open-field situations, RDC is able to compact soil, crushed rock and landfill waste cost-efficiently and to greater depths when compared to other available compaction methods.

Whilst RDC has the proven ability to improve a variety of soil types, for example sand (Figure 3) and clay (Figure 4), not all site conditions lend themselves to using RDC. Small or restricted sites are not suitable, as the roller is not able to maintain an operating speed in the vicinity of 10-12 km/h. Clifford & Bowes (1995) predicted the impact energy of the square roller and concluded that the speed of the module striking the ground was the most significant parameter contributing to the energy imparted by the impact roller. In the author's experience, careful assessment (e.g. the use of an impact rolling trial) is highly recommended in soil conditions where non-engineered fill material is present, particularly if the site contains large oversized material; depending upon the nature and depth of the material it may be able to be broken down and compacted, however, there is also the potential for it to bridge underlying soil that would otherwise be improved (Scott & Suto 2007). Cases have also been observed where the high energy impacts of RDC have caused existing inter-particle bonds to break within the soil; hence careful assessment of the suitability of RDC is needed in such soil conditions.

The depth of influence of RDC varies, depending upon factors such as the soil material type, moisture, groundwater conditions and the input energy (Avalle 2004). There is currently little information on predicted depths of treatment for varying soil conditions, and it is often up to the project engineer to predict if the use of RDC will improve the ground sufficiently for the project application. This prediction as to whether to adopt RDC for ground improvement at a site, may or may not prove to be cost-effective, as RDC has the potential to save significant time and construction costs (or otherwise). In applications where deep layers of imported fill material are being compacted it is common for cost benefits to still be obtained whilst limiting the layer thicknesses to well within the capability of the machine, however, the variable depth to which ground improvement can be achieved is one of the biggest limitations on the use of RDC when improving in situ material, as a back-up plan may need to be implemented if ground improvement is not achieved to the required (or expected) depths. The variable depth of treatment using RDC also has the potential to cause damage to existing services, culverts or bridges (via load transfer) if an insufficient thickness of soil is not placed over such structures. Broons (2008) recommends that at least 1.5 metres of soil cover is required to prevent such damage, however, further research is warranted to verify or refine this requirement.

4. How is ground improvement using RDC verified?

There are currently no guidance documents to provide the engineering profession with recommended testing methods to use for various soil conditions so that appropriate decisions and assessments can be made on the ground improvement undertaken by RDC. Whilst the latest edition of the Australian Earthworks Code, AS 3798 (Standards Australia 2007) now recognises deep compaction by impact rolling as an alternative procedure for earthworks, it offers little guidance as to how to determine if ground improvement has been achieved, only stating that “trial programs may be required to develop the most appropriate testing regime for any particular project or site". As explained by Avalle (2004) there is no simple rule that outlines what the scope and nature of trial programs should be, as this depends on factors such as budget, efficiency, risk and site conditions.

Field density testing (in order to comply with AS 3798) is commonly undertaken to verify thick lift filling or ground improvement using RDC. The determination of field density testing using a nuclear surface moisture-density gauge (Standards Australia 1995), is the current industry standard, and involves determining the in situ density at discrete locations within 300 mm below the tested surface, making it an ideal testing method where conventional surface compaction techniques and relatively thin layers (lifts) are used. However, RDC applications involving thicker lifts or where surface improvement of in situ ground is undertaken, verification using field density testing requires excavation through compacted material to the desired test levels. Scott & Suto (2007) used this method to help quantify ground improvement using RDC, and cited limitations such as lengthy test durations and the difficulty with the testing process for mixed soils, particularly where oversized particles are present.

The cone penetration test (CPT) involves statically pushing a cone penetrometer and associated drilling rods into the ground and continuously recording the resistance to penetration mobilised in the soil (Lunne et al. 1997). The CPT has been shown to be one of the most accurate in situ test methods available in routine geotechnical engineering practice (Jaksa et al. 1997), and has been successfully used in RDC applications to verify the ground conditions prior to, and after impact rolling. Avalle & Carter (2005) reported the verification of RDC in sandy soils; with improvement evident to at least 3 metres below the ground surface (refer Figure 3). Budget constraints, availability of equipment and the presence of heterogeneous fill material often dictate as to whether the CPT can be used to verify impact rolling applications.

For sites containing significant quantities of mixed soils or oversized particles that are not conducive to traditional (intrusive) geotechnical investigation methods, the use of seismic methods is becoming increasingly common. The use of seismic methods such as MASW (Multi-Channel Analysis of Surface Waves) and CSWS (Continuous Surface Wave System) as reported by Scott & Suto (2007) and Avalle & Mackenzie (2005), respectively, enable correlations of Young's modulus to be made from measuring seismic velocity. Avalle & Mackenzie (2005) reported the verification of RDC in a clay landfill capping overlying refuse using CSWS; with improvement evident to approximately 2 metres below the ground surface (refer Figure 4). Budget constraints and the use of highly specialised equipment are factors that may limit the use of seismic methods to verify RDC.

The use of on-board sensing equipment to measure density, stiffness, subgrade strength or modulus based on the response of the roller as it travels across the ground surface is becoming increasingly common. This technology (known as Intelligent Compaction or Continuous Compaction Control) was first used on vibrating drum rollers the mid-1990s to help identify soft spots and to create more uniform pavement and subgrade layers (Petersen & Peterson 2006). Similar technology, known as the Continuous Impact Response (CIR) system, has recently been introduced into RDC applications and is discussed in detail by McCann & Dix (2007) and Landpac (2008). The CIR system involves measuring ground decelerations from accelerometers that are placed on the impact rolling module. With increasing passes, ground decelerations increase as the soil density and stiffness increase. A GPS system is employed to spatially monitor the movements of the impact roller, thereby enabling soft spots to be identified from both ground decelerations and spatial data. Due to the inherent heterogeneity of soils in terms of their material properties and moisture contents, technology such as Intelligent Compaction and CIR will become more prevalent in the future, and are good examples of how advances in technology are helping to improve confidence in achieving uniform compaction.

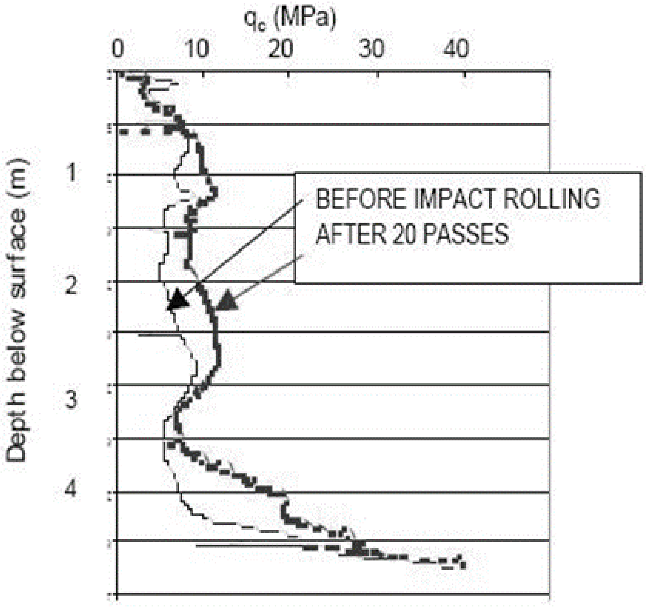

Figure 3. Verification using CPT (Avalle & Carter 2005)

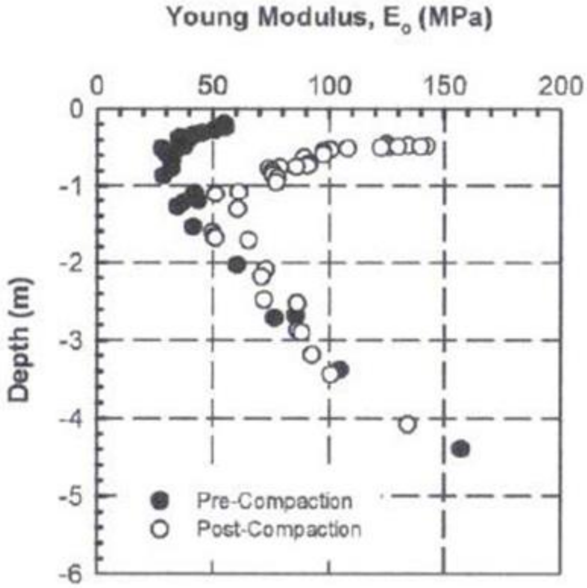

Figure 4. Verification using seismic methods (Avalle & Mackenzie 2005)

Measuring surface settlements is commonly adopted; this can be undertaken in a number of ways, ranging from the use of accurate robotic total station equipment to the use of simple string lines and tape measures (Avalle 2004). Whilst settlement monitoring output can generally be obtained in an efficient and cost-effective manner, care needs to be taken to account for the effect of surface undulations caused by the periodic impacts of the module on the ground (as observed in Figure 1). Such surface undulations can typically have up to 200-300 mm height difference between the high and low points, meaning that if accurate surface settlements are to be obtained, a grader and smooth-drum roller are often required to produce a finished level surface. Alternatively, embedded steel plates can be placed beneath the surface to help overcome the effect of surface undulations. This method has been adopted in recent trials undertaken by the authors, whereby central vertical tell-tale rods of variable lengths can be bolted to the steel plates prior to embedment to measure settlement at various depths below the ground surface. The use of magnetic extensometers installed within boreholes has also been trialled for this purpose, and is the more promising method for determining settlement in targeted soil layers, especially as installing and removing embedded steel plates can become quite cumbersome when placed greater than 300 mm below the ground surface.

Further to the methods discussed previously, Avalle (2004) offers a comprehensive list of testing methods that have been adopted prior to, and after impact rolling to quantify ground improvement. As stated by Avalle (2004) the different test methods chosen often depend on factors such as the geotechnical engineer’s preference of field testing methods and experience with impact rolling, available testing equipment, budget constraints, site location and ground conditions. It is the author’s opinion that site specific field trials are the most appropriate and efficient way of assessing factors and considerations such as: will RDC be suitable for the site conditions? How many passes are required? What testing methods are appropriate to quantify and validate the performance of RDC? With a large variation in current approaches, there is a need for some direction and guidance.

5. Need for further research into RDC

Currently, a key limitation that restricts the use of RDC is the reluctance by the engineering profession to specify the use of impact rolling. This is largely due to the theory behind RDC generally not being well understood, particularly as the use of RDC is often guided by intuition, or based on experience in similar soils and applications. Whilst RDC is a commonly used technique to improve poor or marginal ground, there is little published information on what the zone of influence is for different soil types, or to indicate what testing methods should be adopted to quantify its effectiveness.

In order to develop, calibrate and validate a suitable model for RDC applications, field and laboratory measurements are needed in a variety of site conditions. A database containing testing data from previous RDC projects is being used to assist with this research; however, further field testing and measurements are required to complement existing data. This will involve conducting field testing both prior to, and after impact rolling to compare and evaluate a number of different testing methods. Commonly specified testing methods on impact rolling projects (such as those discussed in Section 4), as well as in situ permeability and porewater pressure testing will be trialled in a variety of soil conditions. Laboratory tests to classify soil types and to determine shear strength and compressibility parameters will also be undertaken so that accurate and efficient testing and verification techniques and protocols can be recommended to quantify the improvement of RDC in the field.

To determine the zone of influence of RDC on different soil conditions, commonly used testing methods will be combined with instrumentation that is embedded into the ground to quantify the zone of influence of RDC. The transfer of energy of the impact rolling module to the underlying ground will be measured at various depths, using load cells and accelerometers that will be embedded into the ground. The impact roller will pass over the embedded instrumentation whereby the force measured in the load cell, and the ground deceleration measured using accelerometers can be used to determine the energy recorded. By measuring the energy at various depths below ground level, and for differing soil types, it will enable the zone of influence of the roller to be quantified.

6. Conclusions

Although RDC has been used on many projects in Australia and overseas, there is little published information quantifying what the zone of influence is, or how much energy is required in order to improve soils of different types. There is also little guidance on how RDC should be verified to quantify its effectiveness.

It is anticipated that the outcomes of this work will enable RDC to be applied and validated more appropriately for a range of soil conditions. More accurate assessments of RDC, as well as improved testing regimes, are expected to reduce design conservatism and construction costs. In addition, perhaps most significantly, quantifying the effectiveness of RDC in terms of the energy imparted into the ground and the zone of influence for various soils will lead to a greater understanding of its theory, which will enable RDC to be used more effectively and with greater confidence in a range of engineering applications.

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References

Avalle, D.L. (2004). Impact Rolling in the Spectrum of Compaction Techniques and Equipment. *Earthworks Seminar Proceedings, Adelaide,* Australian Geomechanics Society, 4pp.

Avalle, D.L. & Carter, J.P. (2005). Evaluating the Improvement from Impact Rolling on Sand. *6th International Conference on Ground Improvement Techniques, Coimbra, Portugal,* 8pp.

Avalle, D.L. & Mackenzie, R.W. (2005). Ground improvement of landfill site using the “square” impact roller, *Australian Geomechanics,* Vol. 40, No. 4, 15-21.

Broons (2008). Website: http://www.broons.com/, accessed 25 July 2008.

Clegg, B. & Berrangé, A.R. (1971). The Development and Testing of an Impact Roller. *The Civil Engineer in South Africa*, Vol. 13, No. 3, 65–73.

Clifford, J.M. (1976). Impact Rolling and Construction Techniques. *Proceedings ARRB Conference,* Vol. 8, 21–29.

Clifford, J.M. (1978). *Evaluation of Compaction Plant and Methods for the Construction of Earthworks in Southern Africa,* Masters Thesis, University of Natal, South Africa, 308 pp.

Clifford, J.M. & Bowes G. (1995). Calculating the Energy delivered by an Impact Roller. *A trilogy of Papers for the September 1995 Lecture Tour and International*

Seminars to commemorate the tenth anniversary of the BH 1300 Standard Impact Roller, Paper Two, pp 1-15.

Jaksa, M.B., Brooker, P.I. & Kaggwa, W.S. (1997). Inaccuracies Associated with Estimating Random Measurement Errors. *Journal of Geotechnical and Geoenvironmental Engineering*, ASCE, Vol. 123, No. 5, 393–401.

Landpac (2008). Website: http://www.landpac.co.za/, accessed 25 July 2008.

Lunne, T., Robertson, P.K. & Powell, J.J.M. (1997). *Cone Penetration Testing in Geotechnical Engineering Practice*, Blackie Academic and Professional, New York.

McCann, K. & Dix, S. (2007). Engineered impact compaction of un-engineered fills. *Earthworks Symposium, Sydney*, Australian Geomechanics Society, 83-92.

Munfakh, G.A. & Wyllie, D.C. (2000). Ground Improvement Engineering - Issues and Selection. *Proceedings International Conference on Geological and Geotechnical Engineering, GeoEng2000, Melbourne*, Vol. 1, 333-359.

Munfakh, G.A. (2003). Ground Improvement in Transportation Projects: From Old Visions to Innovative Applications. *Ground Improvement*, Thomas Telford, Vol. 7, No. 2, 47-60.

Petersen, L. & Peterson, R. (2006). *Intelligent Compaction and In-Situ Testing at Mn/DOT TH53*. Minnesota Department of Transportation, Report No. MN/RC-2006-13, Minnesota.

Pinard, M.I. (1999). Innovative Developments in Compaction Technology Using High Energy Impact Compactors. *Proceedings, 8th Australia New Zealand Conference on Geomechanics, Hobart*, Australian Geomechanics Society, Vol. 1, 775-781.

Scott, B.T. & Suto, K (2007). Case study of ground improvement at an industrial estate containing uncontrolled fill. *Proceedings 10th Australia - New Zealand Conference on Geomechanics, Brisbane*, Vol. 2, 150-155.

Standards Australia (1995). Soil Compaction and Density Tests – Determination of Field Density and Field Moisture Content of a Soil Using a Nuclear Surface Moisture-Density Gauge – Direct Transmission Mode, *AS 1289.5.8.1*, Sydney, NSW.

Standards Australia (2007). Guidelines for earthworks for commercial and residential developments, *AS 3798,* Sydney, NSW.

Terashi, M. & Juran, I. (2000). Ground Improvement-State of the Art. *Proceedings International Conference on Geological & Geotechnical Engineering, GeoEng2000, Melbourne,* Vol. 1, 461–519.

Appendix D: Conference Paper 3

Conference Paper

Scott, B.T. & Jaksa, M.B. (2014). Evaluating rolling dynamic compaction of fill using CPT. Proceedings *3rd International Symposium on Cone Penetration Testing, Las Vegas, USA*, pp. 941-948.

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Publication Details	Scott, B.T. & Jaksa, M.B. (2014). Evaluating rolling dynamic compaction of fill using CPT. 3rd International Symposium on Cone Penetration Testing, Las Vegas, USA, pp. 941-948.

Principal Author

Name of Principal Author (Candidate)	Brendan Scott		
Contribution to the Paper	Performed site investigation, interpreted data, wrote manuscript, acted as corresponding author, presented paper.		
Overall percentage (%)	95		
Certification:	This paper reports on original research I conducted during the period of my Higher Degree by Research candidature and is not subject to any obligations or contractual agreements with a third party that would constrain its inclusion in this thesis. I am the primary author of this paper.		
Signature	[redacted]	Date	18/4/2019

Co-Author Contributions

By signing the Statement of Authorship, each author certifies that:

i. the candidate's stated contribution to the publication is accurate (as detailed above);

ii. permission is granted for the candidate in include the publication in the thesis; and

iii. the sum of all co-author contributions is equal to 100% less the candidate's stated contribution.

Name of Co-Author	Mark Jaksa		
Contribution to the Paper	Provided primary supervision and helped evaluate and edit the manuscript		
Signature	[redacted]	Date	18/4/19

Evaluating rolling dynamic compaction of fill using CPT

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Abstract

Rolling Dynamic Compaction (RDC) is a ground improvement technique that involves compacting soil using a non-circular roller. Whilst conventional circular rollers are able to compact layer thicknesses typically in the range of 200 mm to 500 mm, thicker layers are able to be compacted using RDC. However, the depth of influence of RDC can vary significantly depending on the soil type, moisture content, loose layer thickness and number of passes. This paper focusses on how cone penetration testing was used during a compaction trial as a key site investigation technique to determine the zone of influence of RDC at a site involving quartzose and carbonate sand fill. The results presented quantify the increase in cone tip resistance with depth and illustrates how a number cone penetration tests (CPTs) were used to evaluate changes in soil strength due to increased roller passes, changes in moisture content or placed loose layer thickness.

1 Introduction

Rolling dynamic compaction (RDC) is a generic term associated with densifying the ground using a heavy (6-12 tonne) non-circular roller module of 3, 4 or 5 sides, that rotates about its corners as it is towed, causing the module to fall to the ground and compact it dynamically. A square impact rolling module is shown in Figure 1. A key advantage of RDC is the ability to provide deep layer compaction when compared to circular static and vibrating drum rollers. RDC can compact thicker layers due to a greater depth of influence beneath the ground surface, which is derived from a combination of a heavy module mass, the shape of the module and the speed at which it is towed, typically in the range of 9-12 km/h. The ability to compact thick layers can make RDC a productive and cost-effective option for earthwork projects; however, as noted by Avalle (2007) there are challenges associated with its verification. This paper discusses how the cone penetration test (CPT) was used as a key site investigation technique to quantify the zone of influence of ground improvement using RDC. The CPT rig used in the project is shown in Figure 2.

2 Verification of RDC and the use of the CPT

Whilst RDC has been used successfully on many projects in Australia and overseas in applications such as roads, airports and construction and land reclamation projects, there have been varying results as to what the depth of influence of RDC is for different soil conditions. The CPT has been used successfully on a number of RDC projects in Australia, including Avalle & Carter (2005), who reported on the verification of RDC in sandy soils using the CPT; with improvement evident in plots of cone tip resistance (qc) between depths of approximately 0.5-3.0 m below the ground surface. In a paper by Kelly (2000) plots of qc versus depth below the ground surface also were provided for reclaimed sand deposits; based on their results, improvement was most evident between depths of 0.5-2.6 m below the ground surface; with Kelly quoting influence to depths of 5 m below the surface. In the same paper, increases in qc to depths of 4 m in in situ sandy soils were reported from CPTs undertaken pre- and post-RDC; improvement was most evident between depths of 0.6-1.5 m.

When compacting thick layers with RDC it is not uncommon for large sized particles (such as concrete and rock fragments) to be present within heterogeneous fill. As reported by Avalle & Grounds (2004) this can cause loss of continuous data and a need for relief drilling where refusal was met due to high cone tip resistance. They found that the usefulness of the CPT to verify ground improvement using RDC was limited within heterogeneous fill due to the presence of large hard particles; as such only intermittent plots of cone tip resistance could be obtained making it difficult to determine if there was an indication of strength gain with increasing roller passes. Their work suggests that budget constraints, availability of equipment and the presence of heterogeneous fill material often dictate whether the CPT can be used to verify impact rolling applications. However, to quote Lunne et al. (1997), “the CPT has been found to be one of the best methods to monitor and document the effect of deep compaction due to the continuous, reliable and repeatable nature of the data”. This paper focusses on a compaction trial where CPTs were successfully used to quantify the depth of improvement of RDC.

Figure 1. 4-sided impact rolling module

Figure 2. CPT rig undertaking post compaction testing

3 Case study

An earthworks trial was undertaken on a remote site in Australia comprising predominantly quartzose and carbonate sand fill. Key objectives of the earthworks trial were to optimise the number of roller passes, loose lift layer thickness and moisture content of the fill, to achieve a dry density ratio of at least 90% of maximum modified dry density.

Despite the site of the compaction trial being located a 2-day drive from the nearest capital city; a specialist CPT contractor was engaged to carry out CPTs using a 10 cm^2 electric cone penetrometer. As shown in Figure 2, the CPT rig used was a tracked vehicle, making it ideal for traversing the disturbed undulating surface that remains after RDC. Figure 2 clearly shows the undulating sandy surface created by the RDC process. Given that the earthworks trial was undertaken in very hot weather conditions approaching 40°C, moisture conditioning of the fill material was challenging. CPTs were undertaken through the full thickness of placed fill and to a minimum of 2 m into the underlying natural soil to help assess the variability of the placed fill material and quantify the improvement of soil strength with increased roller passes.

The fill material consisted of a mix of locally excavated sand (quartzose and carbonate with a varying proportion of carbonate cementation) that was blended with red-brown sandy clay, silty sand and clayey sand material that was also sourced from site. The fill material was fairly typical of ‘Pindan’ sands that are common in the Kimberley and Pilbara regions of Western Australia. Based on the dozens of laboratory particle size distribution tests that were undertaken on the blended fill material, sand-sized particles typically varied between 60-85% by mass; the remaining fraction (15-40% by mass) consisted of fine-grained material, implying that there were no gravel-sized particles (or larger). Figure 3 shows a typical particle size distribution curve for the placed fill material. Atterberg limits testing indicated that the fine-grained component contained either non-plastic fines, or fines of low plasticity (liquid limit ~20% and plasticity index ~15%). The natural field moisture content of the fill typically varied between 4-9%. However, as RDC is less effective if the soil is too dry of the optimum moisture content, moisture conditioning of the fill prior to placement was undertaken. The thickness of the compacted fill was 1 m. The natural soil underlying the placed fill consisted of stiff to hard silty clay. Groundwater was not encountered within a depth of 5 m below the placed fill.

Figure 4 shows a typical result comparing qc before and after rolling. An increase in soil shear strength was quantified by increasing cone tip resistances in the sandy fill layer and to a depth of approximately 0.75 m into the underling natural clay (total depth of 1.75 m). The fill and natural soil interface at a depth of 1 m below the ground surface was clearly identified in the CPTs. Figure 5 shows a number of CPT plots that were superimposed to help quantify soil variability. Figures 4 and 5 are examples of a robust site investigation using CPTs to quantity the effectiveness of RDC to address the key project aims of optimising the number of roller passes and determining an appropriate layer thickness by quantifying the vertical zone of influence of RDC. In many ways this work is no different to previous work undertaken by Avalle & Carter (2005) and Kelly (2000) and so is not a large focus of this technical paper.

Figure 6 shows a typical plot of cone tip resistance versus depth after the same number of passes. The key variable between the two locations (ignoring spatial variability which would be inherently present) was the moisture conditioning of the sandy fill before placement. As can be observed in Figure 6, the fill placed with no additional moisture yielded quite poor results below a depth of 0.7 m when compared to the soil with moisture conditioning. Nuclear density and sand replacement tests that were conducted on site also confirmed the presence of loose sandy fill below 0.7 m, however, the CPT was used as a preferred method of quantifying the lateral extent of the issue because of its efficiency and ability to obtain real-time continuous data with depth. This was a key early finding that helped to guide the remainder of the compaction trial.

In Figure 4, the shape of the profile of cone tip resistance versus depth is unusual for a surface compaction ground improvement technique such as RDC. Typically, the near surface soils (e.g. 0.3 m) are disturbed with little evidence of improvement, below this depth increases in cone tip resistance are expected, which would steadily decrease down to some depth of influence (assuming uniform soil conditions). In Figure 4, there is an increase in cone tip resistance below a depth 0.7 m that is unlikely to be attributed to RDC, given that the sandy fill layer is approximately 1 m thick. The fact that this phenomenon was observed in the CPT plots before and after compaction suggests that is likely to be either a function of the fill placement method (this fill may have received more traffic compaction from trucks or dozers during placement), or, it is a case of the cone tip sensing a soil interface (layer boundary). The latter is discussed by Ahmadi & Robertson (2005) where they found that a soil interface could be measured up to 15 cone diameters ahead of the depth of the cone, depending upon the strength of the soil. For the 10 cm^2 (35.7 mm diameter) cone used on this project, it is therefore possible for the interface between the sandy fill and stiff-to-hard clay to be sensed within a depth of 0.5 m from the layer boundary. It is interesting to note that this phenomenon was not observed to the same extent for the case of the soil with no moisture added in Figure 6. However, this is not inconsistent with the findings of Ahmadi & Robertson (2005) who also indicated that in soft (loose) soils the soil interface could be sensed as little as 1 cone diameter ahead of the depth of the cone.

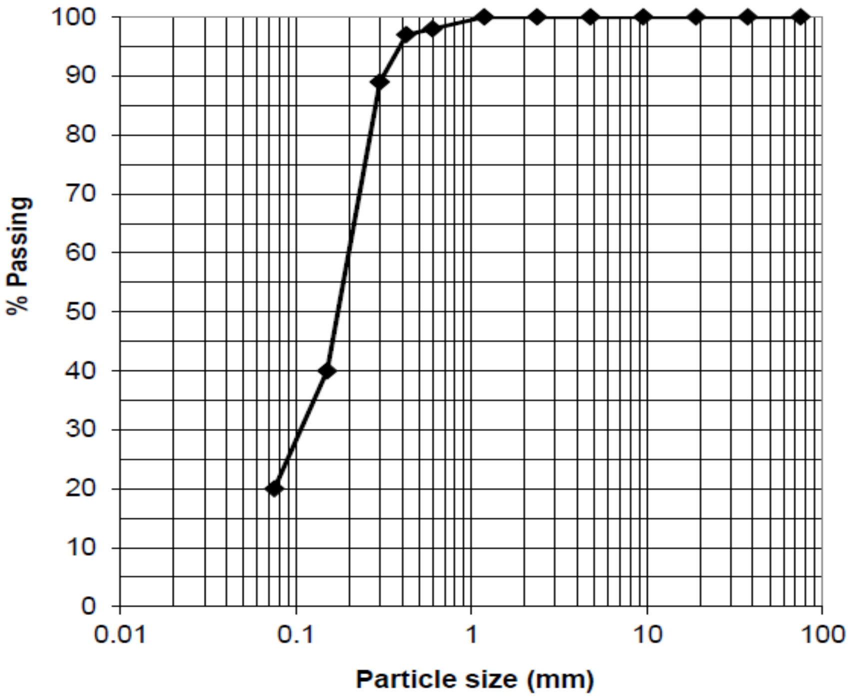

Figure 3. Typical particle size distribution curve for sandy fill material

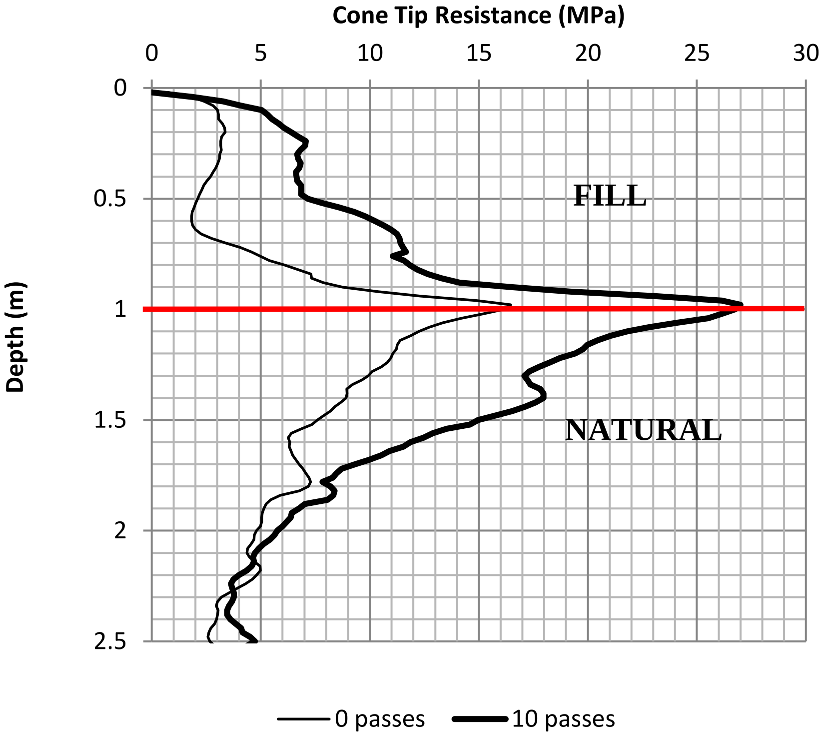

Figure 4. Typical plot of cone tip resistance (qc) versus depth before and after compaction

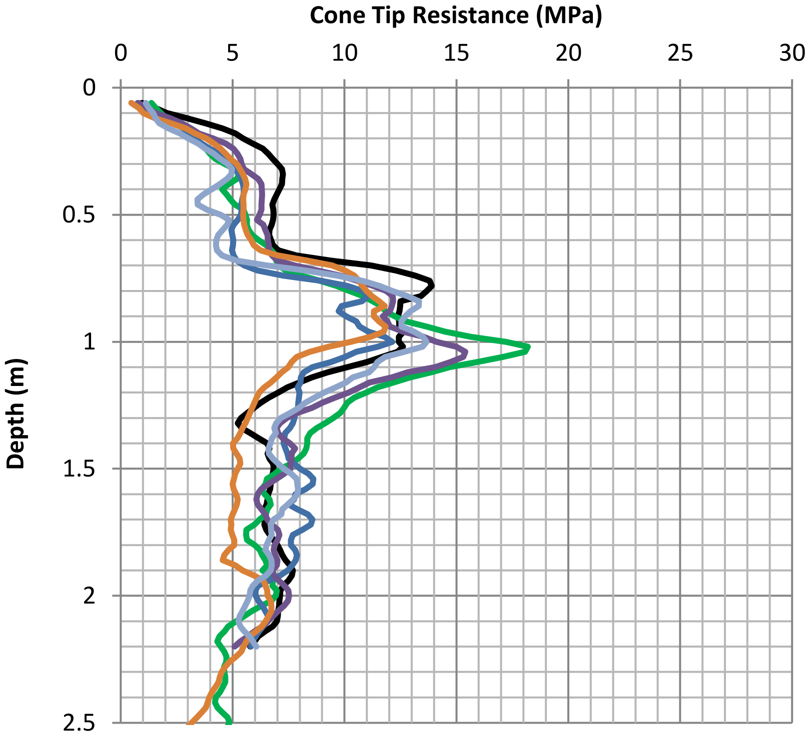

Figure 5. Comparing CPT results to determine compacted fill variability

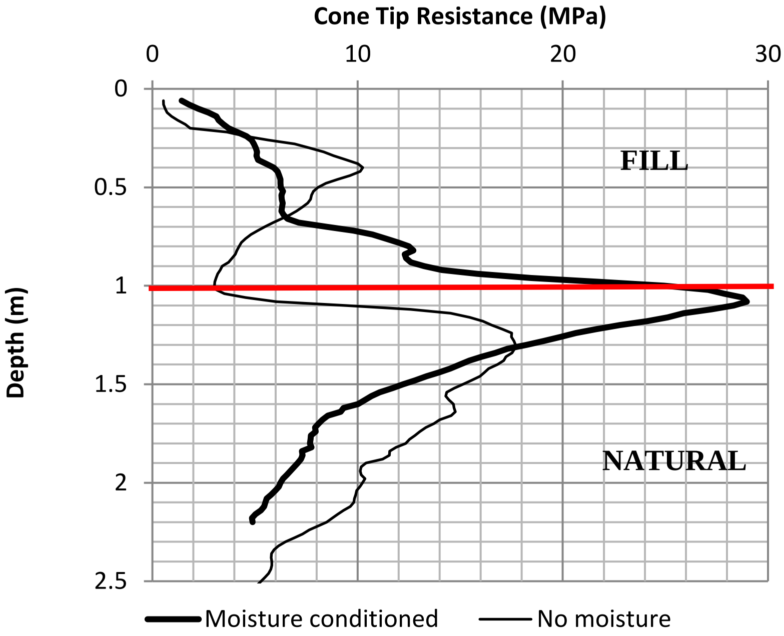

Figure 6. Comparing moisture conditioned and non-moisture conditioned soil after compaction

4 Zone of influence of RDC and the use of the CPT

Rather than focussing on the results of the compaction trial, the remainder of this technical paper discusses how the CPT was used to determine not just the vertical extent of RDC, but also the lateral zone of influence. In order to quantify lateral effects, five closely spaced CPTs were undertaken, as illustrated in Figure 7 and summarised in Table 1.

The distance between impact rolling lanes is typically 2.3 m; CPTs 1-4 were equally spaced at a distance of 1.15 m apart. CPT 5 was located a distance of 3 m from CPT 4 in an area that was uncompacted but close enough to the other locations to be deemed typical of 0 passes, so that spatial variability was minimised. CPTs 1 and 3 were located at the centre of the impact rolling lane (centre of module imprint that remained on the ground surface after rolling). CPTs 2 and 4 were located on the wheel paths of the trailer that tows the module. In Figure 1 it can be observed that the module (width of 1.3 m) is narrower than the track distance between the trailer tyres. In RDC applications it is common for a 'wheel path to wheel path' rolling pattern to be adopted (rather than a module-to-module pattern) as it is thought that there is an overlap between locations of module impacts between adjacent impact rolling lanes; however, this has never been quantified (published). Therefore, a key aim was to quantify the difference in cone tip resistances between CPT locations to determine, not only the vertical depth of influence, but also any lateral effects due to RDC.

Figure 7. Location plan of CPTs

Table 1. Description of CPT locations

CPT Location	Comment
1	Centre of middle lane after 10 passes (both adjacent lanes also subjected to 10 passes)
2	Wheel path between middle lane (10 passes) and outside edge lane (10 passes)
3	Centre of edge lane after 10 passes (only one adjacent lane subjected to 10 passes)
4	Wheel path of outside edge lane
5	Uncompacted area 3 m beyond edge lane (0 passes).

The results from CPT locations 1, 3 and 5 are summarised in Figure 8, where it can be observed that the greatest improvement in cone tip resistance (and therefore soil shear strength) is in the middle lane (CPT 1), as expected. In the edge lane (CPT 3), which has also been subjected to 10 passes, there is quantifiable improvement in cone tip resistance to a depth of approximately 1.3 m when compared to zero passes, but less improvement than in the middle lane. The results from CPT locations 2, 4 and 5 are summarised in Figure 9, whereby it can be observed that there was greater improvement in cone tip resistance at the location in the wheel path between the middle and edge lanes (CPT 2) than at the location in the wheel path to the edge lane only (CPT 4).

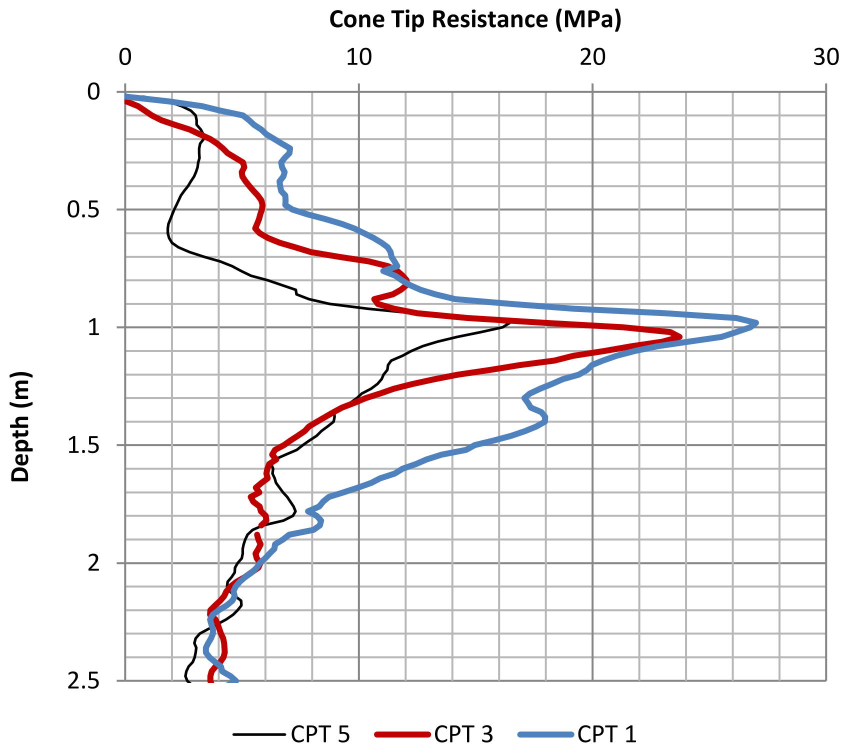

Figure 8. 0 passes versus 10 passes in edge lane versus 10 passes in middle lane

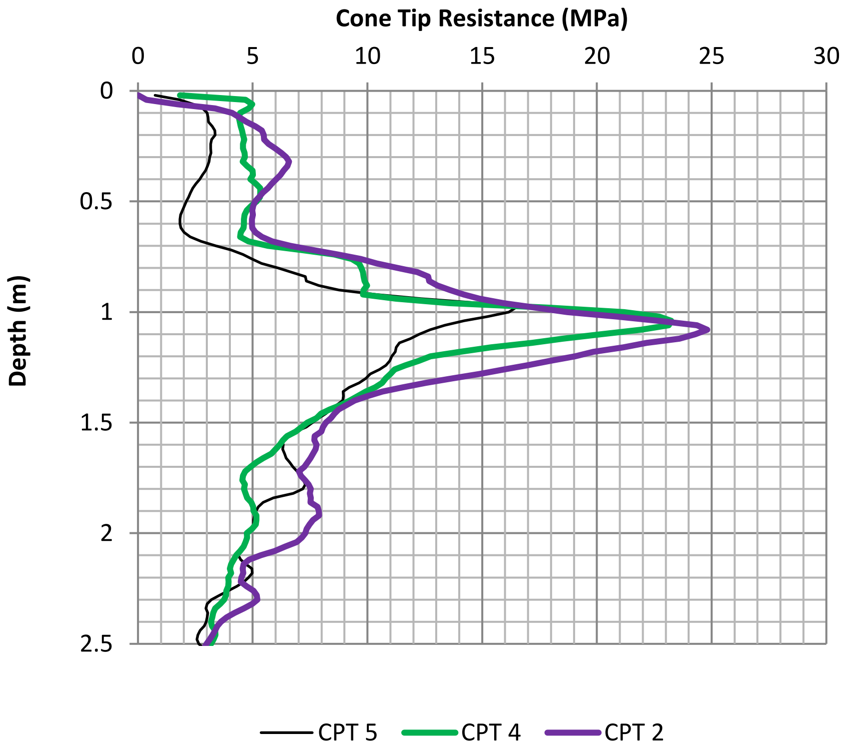

Figure 9. 0 passes versus wheel path to edge lane versus wheel path to edge/middle lane

To further quantify the improvement at each test location, the percentage change in cone tip resistance (from 0 passes) has been plotted with depth as shown in Figure 10. In this figure the values of cone tip resistance have been averaged and plotted over 100 mm depth intervals. This graph shows the evidence of a lateral zone of influence with wheel path locations (CPT 2 and CPT 4) yielding results not dissimilar to that of the edge lane (CPT 3) despite the module not impacting directly above these test locations. It is also clear from this analysis that the greatest increase in cone tip resistance and vertical depth of influence was for the middle lane (CPT 1), which benefited from both adjacent lanes being subjected to 10 passes, as well as 10 passes directly in that lane.

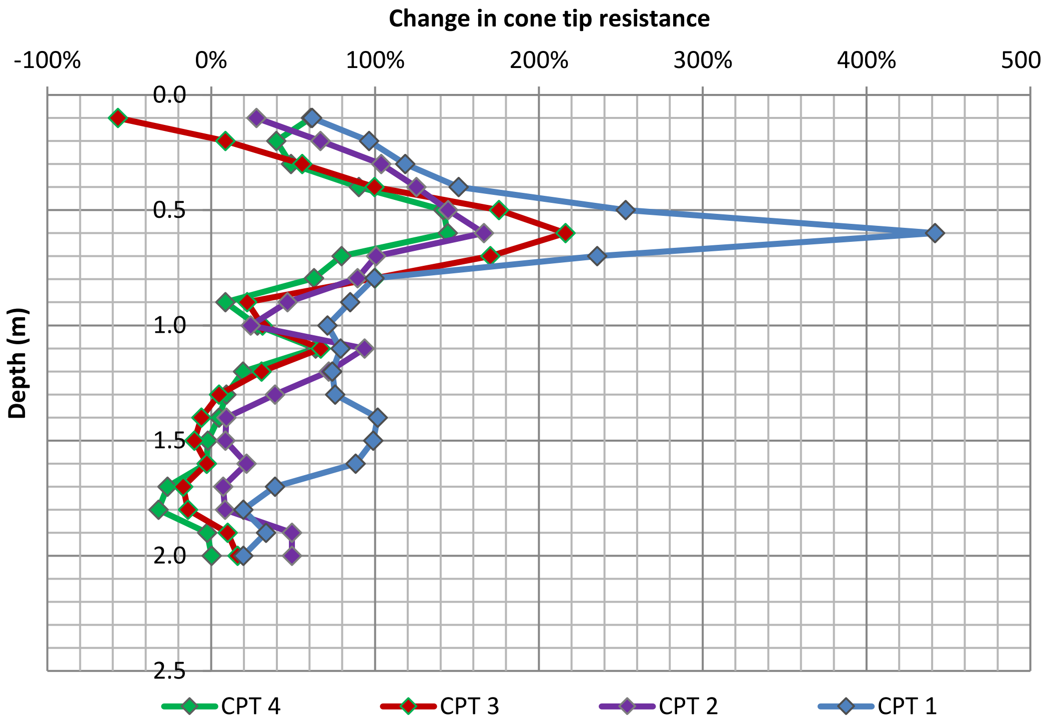

Figure 10. Percent changes in cone tip resistance versus depth below ground surface for CPTs 1-4

5 Conclusions

The case study presented in this paper demonstrates that the use of modern in situ testing methods such as the CPT help to quantify and validate the effects of RDC in a thick lift compaction application. The CPT was shown to be an efficient and preferred test method for quantifying the ground improvement by comparing values of cone tip resistance before and after rolling. Furthermore, the zone of influence of RDC was able to be quantified by analysing a series of closely-spaced CPTs which confirmed both vertical and lateral effects. Quantifying lateral effects of RDC using CPT is significant, as it confirms the appropriateness of a wheel path to wheel path rolling pattern which is commonly adopted in many earthworks applications.

Acknowledgements

The authors wish to acknowledge Mr. Stuart Bowes and the staff at Broons for their assistance with accessing and undertaking site work referred to within this paper. The authors also wish to acknowledge Mr. Andrew Russell and the staff from Golder Associates for allowing the additional CPTs referred to in Section 4 of this paper to be performed (solely for research purposes) and for providing access to test data. Research and technical staff from the School of Civil, Environmental and Mining Engineering at the University of Adelaide are also acknowledged for their valuable assistance.

References

Ahmadi, M.M. and Robertson, P.K. (2005). Thin layer effects of the CPT qc measurement. *Canadian Geotechnical Journal*, 42(5): 1302-1317.

Avalle, D.L. and Carter, J.P. (2005). Evaluating the Improvement from Impact Rolling on Sand. *6th International Conference on Ground Improvement Techniques, Coimbra, Portugal*, 8pp.

Avalle, D. and Grounds, R. (2004). Improving Pavement Subgrade with the ‘Square’ Impact Roller. *Proceedings 23rd Southern African Transport Conference, Pretoria,* 44-54.

Avalle, D.L. (2007). Trials and validation of deep compaction using the “square” impact roller. *Symposium - Advances in Earthworks, Sydney,* Australian Geomechanics Society, 6pp.

Kelly, D.B. (2000). Deep in-situ ground improvement using high energy impact compaction (HEIC) technology. *Proceedings International Conference on Geological and Geotechnical Engineering, GeoEng2000, Melbourne,* 6pp.

Lunne, T., Robertson, P.K. and Powell, J.J.M. (1997). *Cone Penetration Testing in Geotechnical Engineering Practice,* Blackie Academic and Professional, New York, 159-163.

Appendix E: Conference Paper 4

Conference Paper

Scott, B.T. & Jaksa, M.B. (2012). Mining applications and case studies of rolling dynamic compaction. *Proceedings 11th Australia New Zealand Conference on Geomechanics, Melbourne, Australia*, pp. 961-966.

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Principal Author

Name of Principal Author (Candidate)	Brendan Scott		
Contribution to the Paper	Performed site work, analysis and interpretation of site data, wrote manuscript, acted as corresponding author, presented paper.		
Overall percentage (%)	95		
Certification:	This paper reports on original research I conducted during the period of my Higher Degree by Research candidature and is not subject to any obligations or contractual agreements with a third party that would constrain its inclusion in this thesis. I am the primary author of this paper.		
Signature	[redacted]	Date	18/4/2019

Co-Author Contributions

By signing the Statement of Authorship, each author certifies that:

i. the candidate's stated contribution to the publication is accurate (as detailed above);

ii. permission is granted for the candidate in include the publication in the thesis; and

iii. the sum of all co-author contributions is equal to 100% less the candidate's stated contribution.

Name of Co-Author	Mark Jaksa		
Contribution to the Paper	Provided primary supervision and helped evaluate and edit the manuscript		
Signature	[redacted]	Date	18/4/19

Mining applications and case studies of rolling dynamic compaction

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Abstract

Rolling Dynamic Compaction (RDC) is a generic term associated with densifying the ground using a non-circular roller. The application and use of RDC in the mining industry is increasing because of its ability to compact ground efficiently by means of a faster operating speed (10-12 km/h) and compaction of thicker layers than conventional circular rollers. Whilst conventional rollers are able to compact fill in layers up to 400 mm, thicker layers are able to be adopted using RDC for the construction of tailings dams and mining haul roads. Increased layer thicknesses enable larger particle sizes to be used, therefore greater reuse of mine spoil material can be undertaken with a reduced need to screen out large quantities of oversized materials. As well as demonstrating how RDC has been used effectively for the compaction of bulk earthworks at two different mine sites, this paper also discusses various aspects and factors associated with conducting a compaction trial on mine spoil materials.

Keywords: compaction, impact, roller, ground, improvement, mining

1. Introduction

Rolling Dynamic Compaction (RDC) is a generic term associated with densifying the ground using a non-circular roller module of 3, 4 or 5 sides, that rotates about its corners as it is towed, causing it to fall to the ground and compact it dynamically. A square impact rolling module is shown in Figure 1.

The use of RDC is increasing in the mining industry for applications such as proof rolling and construction of mining haul roads. Subjected to traffic movements by heavy haul trucks and other earthmoving equipment, the condition of haul roads can rapidly decline over time. The ability of RDC to gain an increase in strength of compacted material (thus increasing the bearing capacity) means that haul roads are more capable of supporting imposed stresses from heavy mining earthmoving equipment. The ability of RDC to detect weak (low density) areas or soft spots (zones of high moisture content in clayey soils) that can then be replaced or reworked reduces the potential for differential settlements to occur as a result of subgrade soils that do not have adequate stiffness. As explained by Avalle (2006), the ability of RDC to improve the uniformity and density of subgrade soils and haul roads makes it highly suitable as a proof roller. Improved haul roads greatly reduce the stress on haul truck frames and suspension, resulting in less rolling resistance, greater surface uniformity and reduced tyre temperatures, factors that all help to increase tyre life. As discussed by Avalle (2006), there is also reduced likelihood of rock spillage from haul trucks, thereby reducing the potential for damage to other haul road vehicles. As well as haul roads, RDC has been used on pit floors and tip heads (Broons 2012) to help break down and rubbilise large surface rocks that are potentially hazardous to haul truck tyres and therefore costly for mine operators in terms of replacement cost and potential loss of production if spare tyres are not readily available.

A current focus area of research by the authors of this paper is on low permeability covers that are constructed over mine waste materials. Covers or capping layers are typically used to reduce the percolation of surface water through to mine waste that could lead to environmental hazards. The application of RDC to create a low permeability cover in mining applications is similar to previously documented cases where RDC has been used in landfill environments, such as the case study described by Avalle and Mackenzie (2005). Due to space constraints, examples and applications of RDC for rubbilising rock and creating low permeability capping layers are beyond the scope of this paper, and are topics of future papers.

2. Thick lift compaction of mine spoil materials

The focus of this paper is to present two case studies that demonstrate how RDC has been used effectively in the compaction of bulk earthworks of mine spoil materials. In particular, the ability of RDC to compact thick layers (500 mm or more) and use larger particle sizes that are commonly encountered in mining environments is discussed in examples where thick lift compaction was used for the construction of tailings dams and embankments. Greater recycling of mine spoil materials can be undertaken with a reduced need to screen out large quantities of oversized materials.

Deep fills have been traditionally undertaken by compacting soil in thin layers using relatively small particle sizes placed in a highly controlled manner; shallow density tests are typically undertaken in each layer to confirm performance specifications of the placed fill. Whilst conventional rollers can satisfactorily compact fill in layers up to 400 mm loose lift thickness, as quoted in AS 3798 "Guidelines on earthworks for commercial and residential developments" (Standards Australia 2007a); RDC can typically achieve thick lift compaction in layers in the vicinity of 500-1500 mm depending upon the material composition, number of passes applied and specified target density ratio. AS 3798 recognises the ability of impact rolling for deeper compaction, suggesting that "alternative testing strategies may be appropriate" and that "trial programs may be required to develop the most appropriate testing regime for any particular project or site". This paper presents examples of trial programs and test methods via two case studies that are discussed in Section 3.

On mining sites where large earthmoving equipment are capable of moving and placing significant volumes quickly, having the ability to compact large volumes in a timely and efficient manner is an obvious advantage of RDC because of its ability to compact ground efficiently by means of a faster operating speed (10-12 km/h) and compaction of thicker layers than conventional circular drum rollers that rely on either static weight, kneading or vibratory action.

3. Case studies

Particle size distribution tests were performed as per AS 1289.3.6.1 (Standards Australia 2009) for both sites; typical results for each are shown in Figure 2. Site A consisted of tailings material that was fairly typical of a well graded sand with some gravel; 6% clay-sized, 80% sand-sized and 14% gravel-sized fractions, respectively. Conversely, Site B consisted of drag line spoil that was more variable; with 12% clay-sized, 16% sand-sized, 34% gravel-sized fractions, with the remaining 38% cobble- or boulder-sized particles. For Site B, the laboratory determined values of particle size distribution exhibited greater variability than for Site A.

Figure 1: 8-tonne square impact roller

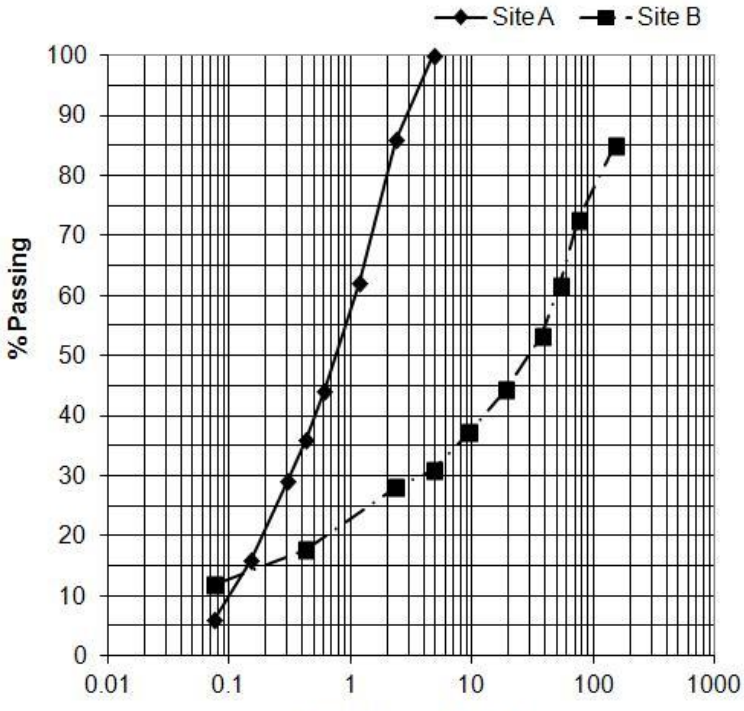

Figure 2: Typical particle size distributions for Sites A and B

The obvious differences in materials dictated that two quite different compaction trials were undertaken. For each case, the underlying objective of both compaction trials was similar; to determine an efficient relationship between the number of passes, layer thickness, moisture content and corresponding dry density ratio that could be achieved. For both sites, a 4-sided 8-tonne impact roller (as shown in Figure 1) was used. At both sites, the water table was located a significant depth below the excavated bench level. Some noteworthy differences and factors that affected each compaction trial are discussed in greater detail in the following sections.

3.1 Design and construction of test pad areas

For the compaction trial at Site A, a test pad approximately 3.6 metres high was constructed (in three lifts of 1200 mm) such that a plan area of approximately 8 m wide by 30 m long was available for testing at the top of the third lift (sufficiently wide so that 3 impact rolling lanes could be rolled to enable testing to occur in the middle lane so that it is representative of a larger scale operation and the effect of rolling adjacent lanes can be taken into account). The trial was conducted as a staged process with one lift placed, rolled and tested each day. The ability of the mine site to work 24 hours a day and utilise large loaders, excavators and haul trucks made the staged trial possible in a short timeframe, as the time to place significant earthwork volumes (even for a trial) should not be underestimated. Allowing for windrows on the sides and ramps at either end the test pad, it was estimated that at least 2500 m^3 of material was used for the trial. Whilst adopting multiple layers for the trial did add extra time, it did mean that the compaction trial could address one of the key concerns for the large scale operation; to determine if a target density could be achieved not only in a single layer, but also on the second and third layers placed above. Undertaking the trial in this manner was then representative of the construction of the tailings dam that was proposed.

The mine had the advantage of previously working with the impact roller for the maintenance of haul roads (albeit on slightly different material). The mine had a preference for adopting a layer thickness that would complement the operational efficiency of other equipment on site; based on these criteria, a maximum layer thickness of 1200 mm was adopted; intermediate testing was undertaken to provide representative results for varying number of passes over a range of depths.

For the compaction trial undertaken at Site B, a single layer, but much larger test pad in plan area, was adopted. The test pad was designed to be sufficiently wide so that 9 impact rolling lanes could be rolled; this enabled three separate zones of 10, 20 and 30 passes to be constructed that could allow testing after rolling to occur in the middle of each zone simultaneously. Given that one of the key objectives of this trial was to determine the thickness of fill that could be compacted for various compactive efforts, the height of the placed fill was benched so that it varied in thickness from 0.5 m through to 1.5 m. Whilst this process took some time and effort from both the surveyor and the dozer operator it did enable all post-compaction testing to be conducted in an efficient manner. Figure 3 shows the trial pad in plan and elevation. Whilst the total length (including ramps) was approximately 120 metres, the actual pad on which the testing was undertaken was of the order of 25 m x 50 m. To allow the impact roller to turn around and reach normal operating speed by the time it reached the ramp areas a nominal area of 170 m long by 25 m wide was cordoned off and used for the trial. It was estimated that approximately 2500 m^3 of material was used for the compaction trial; sufficiently large to be representative of a large embankment (supporting settlement sensitive infrastructure) that was proposed.

For both sites, the impact roller was used to proof roll the sub grade prior to placement of any fill material to ensure there were no soft spots that required rectification prior to commencement of placed fill.

3.2 How was ground improvement using RDC verified?

At Site A, verification of RDC was undertaken using a combination of surveying of surface settlements, soil sampling, as well as a set of in situ tests that was performed after different numbers of passes of the impact roller to determine changes in the soil density profile. The in situ tests undertaken included penetrometer testing, field density testing and geophysical testing. For sites containing significant quantities of mixed soils or oversized particles (such as Site B) the use of traditional (intrusive) geotechnical investigation methods can be problematic (or a test of patience) if effective refusal is met prior to reaching the target test depth. Geophysical techniques are becoming increasingly common in such applications; methods such as MASW (Multi-channel Analysis of Surface Waves) and CSWS (Continuous Surface Wave System) as reported by Scott & Suto (2007) and Avalle & Mackenzie (2005), respectively, enable correlations of Young’s modulus to be made from measurements of seismic velocity. At Site A, the Spectral Analysis of Surface Waves (SASW) geophysical technique was used successfully and complemented the other techniques used.

At Site B, verification was determined from combining surface settlement, penetrometer and field density test data. All testing was undertaken at the completion of rolling, with care taken to ensure the correct number of passes was applied to each test lane. Whilst suitable from a geotechnical perspective, geophysical testing was not undertaken at this site as it would have been problematic due to the noise that reverberated off the pit walls from a large number of vehicles that were working at the bottom of a pit floor where the test pit was located. Geophysical testing methods typically rely on geophones, which are sensitive devices that are used to record energy waves passing through soil; however, at Site B such signals would have been overwhelmed by local noise sources, rendering this technique unsuitable for this particular site.

Further to the methods discussed, Avalle (2004) offers a comprehensive list of testing methods that have been adopted prior to, and after impact rolling to quantify ground improvement. As explained by Avalle (2004) there is no simple rule that outlines which testing methods should be adopted or what the scope and nature of trial programs should be, as this depends on factors such as site conditions, budget, efficiency, risk and available equipment.

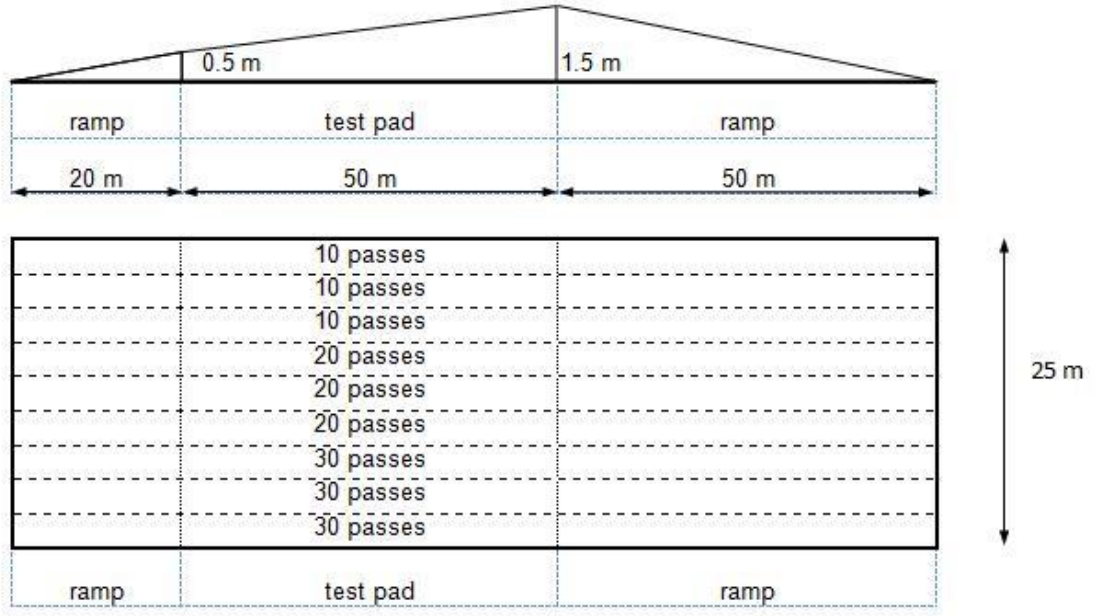

Figure 3: Elevation and plan schematic of trial pad for Site B

3.3 Discussion of test results

The relationship between dry density ratio and layer thickness was established for varying numbers of passes. The results from density tests undertaken after varying numbers of passes of the impact roller at Sites A and B are shown in Figures 4 and 5, respectively, along with polynomial curves of best fit to the measured data. It is interesting to note that the project specifications referred to modified and standard Proctor compaction tests respectively; space restricts detailed discussion on this topic. However, it is noteworthy that for Site B dry density ratios greater than 100% were measured, indicating that field compactive effort (a function of the number of passes and lift thickness) is greater than the compactive effort imparted by the standard Proctor test under laboratory conditions. For Site A, the results of the compaction trial indicate that the target dry density ratio (95% compaction with respect to maximum modified dry density) can be expected to be achieved after 6 passes on layers up to 900 mm; or 10 passes on layers up to 1100 mm thick. For Site B, the results of the compaction trial indicate that the target dry density ratio (98% compaction with respect to maximum standard dry density) can be expected to be achieved after 10 passes on layers up to 850 mm thick; or 30 passes on layers up to 1000 mm thick. The true benefit of increasing the number of passes occurs at intermediate depths. As shown in Figure 4, within 600 mm from the surface only a small number of passes were needed to meet the project specification for Site A; conversely, below a certain depth (e.g. depths greater than 1000 mm for Site B as shown in Figure 5) the specified density ratio was not obtained despite increasing compactive effort. Based on the results obtained, more than one unique solution could be presented to the mine operators, from which they could then assess the benefits for themselves (taking into account their site conditions) of adopting increasing passes or thinner layers.

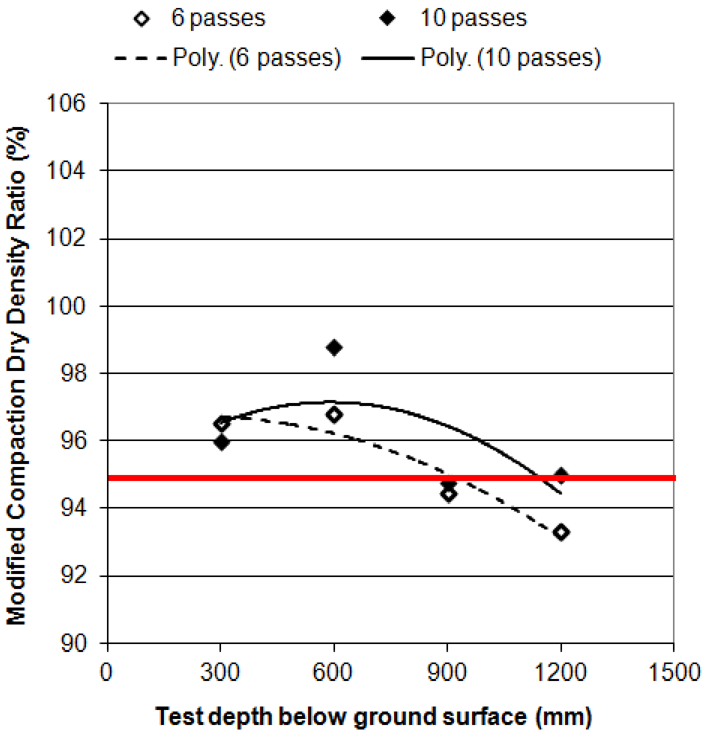

Figure 4: Dry density ratio versus test depth for Site A after 6 and 10 passes, respectively

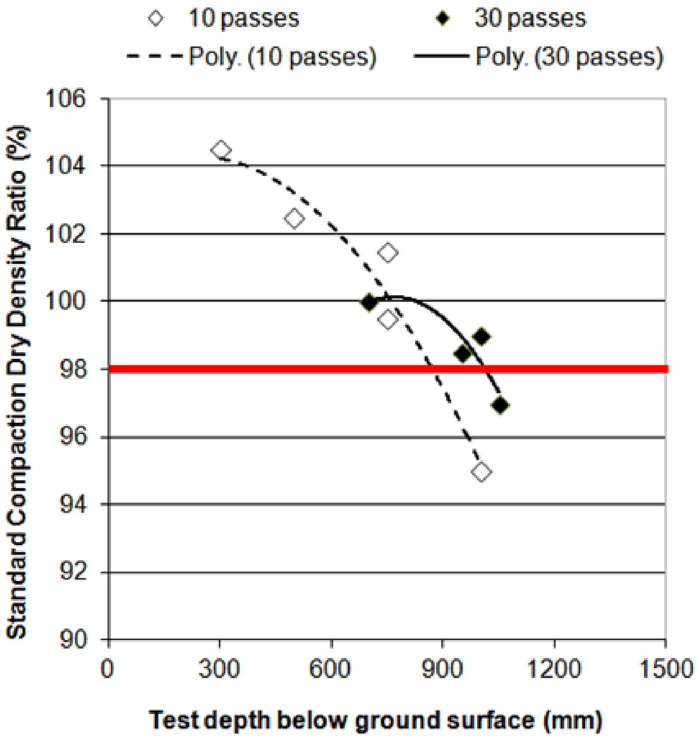

Figure 5: Dry density ratio versus test depth for Site B after 10 and 30 passes, respectively

4. Thick lift compaction using RDC and AS 3798

It is the experience of the authors that, as most performance based specifications nominate a target density ratio, field density testing is commonly undertaken to verify thick lift filling using RDC. The determination of field density testing using a nuclear density gauge (Standards Australia 2007b), is the current industry standard, and involves determining the in situ density at discrete locations within 300 mm below the tested surface, making it an ideal testing method where conventional surface compaction techniques and relatively thin layers (lifts) are used. However, in RDC applications involving thicker lifts such as at Sites A and B, verification using field density testing required excavation through compacted material to targeted bench levels across the test pad to determine the zone of influence. Scott & Suto (2007) used this method to help quantify ground improvement using RDC and correlated other test methods with density testing; they cited limitations such as lengthy test durations and difficulty with the testing process for mixed soils, particularly where oversized particles are present. Pinard (1999) discussed similar issues and also identified the large ratio between volume of material tested to that compacted and poor correlation between laboratory and field results (in heterogeneous soils) as further issues. The presence of oversized particles has the ability to constrain testing methods (and project specifications), making this a key area to be addressed in an impact rolling trial.

The ability of an impact roller to compact larger quantities of oversized material is an obvious advantage over compacting fill in thin layers; however, as noted by Avalle (2007) there are challenges associated with verification. Project specifications that follow the AS 3798 (Standards Australia 2007a) guidelines, that the maximum allowable particle size should not exceed two-thirds of the compacted layer thickness, are routinely used. As explained by Mostyn and Ervin (2007) it is not uncommon to see earthworks specifications that reference AS 3798 by stipulating a minimum relative compaction, whilst also allowing coarse material (greater than 20% retained on a 37.5 mm sieve) to be used via the specification of a maximum particle size. AS 3798 would define Site B (47% and 15% retained on 37.5 mm and 150 mm sieves, respectively), as a "coarse material" that is to be compacted to a method specification rather than a density ratio. Compaction testing in accordance with AS 1289 (Standards Australia, 2003a and 2003b) allows for correction of oversized material provided that it contains no more than 20% of particles coarser than 37.5 mm. Where coarse material (such as mining spoil) is used for filling, it is not uncommon for the post-compaction quantity of coarse material to exceed these limits. For such coarse material, testing in accordance with AS 1289 is not valid because the test does not give reliable results in circumstances where rock-to-rock contact limits the compaction that can be achieved in the compaction mould. Whilst this was recognised as a limitation, density testing on a sub-set of the material with less than 20% passing 37.5 mm was undertaken to provide a guide to the density requirements.

As Mostyn and Ervin (2007) reinforce in their paper, the objective of AS 3798 is to provide guidance to those responsible for, or involved in the design, specification and control testing of earthworks for commercial and residential developments. Just as AS 3798 recommends that suitably qualified geotechnical professionals need to be consulted for fill depths greater than 5 metres, similar input and guidance from experienced geotechnical personnel is also required when conducting trials and verification of deep compaction using RDC.

5. Conclusion

Australian Standard AS 3798 recognises deep compaction by impact rolling as an alternative procedure for earthworks, stating that trial programs may be required to develop the most appropriate testing regime for any particular project or site. This paper presents the results from two impact rolling trials that investigated the ability of RDC to compact mine spoil materials in thick lifts. Whilst the objectives of both trials was to identify an efficient relationship between the number of passes, layer thickness, moisture content and corresponding density that could be achieved, this paper discusses the application of AS 3798 to thick lift compaction using RDC and provides different approaches and guidance (by means of examples) of trial pad construction and verification test methods that could be applied to similar sites.

Acknowledgements

The authors are grateful to the staff at Broons Hire (SA) Pty Ltd for their support and without whose assistance this research would not have been possible. Special mention must go to Stuart Bowes and Bruce Constable from Broons for their assistance with accessing and undertaking site work. Thanks must also go to technical and research staff from the School of Civil, Environmental and Mining Engineering at the University of Adelaide for their valuable assistance.

References

Avalle, D.L. (2004). Impact rolling in the spectrum of compaction techniques and equipment. *Earthworks Seminar Proceedings, Adelaide,* Australian Geomechanics Society, 4pp.

Avalle, D.L. & Mackenzie, R.W (2005). Ground improvement of landfill site using the "square" impact roller, *Australian Geomechanics,* Vol. 40, No. 4.

Avalle, D.L. (2006). Reducing haul road maintenance costs and improving tyre wear through the use of impact rollers. *Mining for tyres conference, Perth,* 5pp.

Avalle, D.L. (2007). Trials and validation of deep compaction using the "square" impact roller. *Symposium - Advances in Earthworks, Sydney,* Australian Geomechanics Society, 6pp.

Broons (2012). Project reports – Mining, <http://broons.com/impact/>, (Jan. 15 2012).

Mostyn G.R. & Ervin, M.C. (2007). AS3798-2007 Guidelines on earthworks for commercial and residential developments – recent revisions. *Symposium - Advances in Earthworks, Sydney,* Australian Geomechanics Society, 5 pp.

Pinard, M.I. (1999). Innovative developments in compaction technology using high energy impact compactors. *Proceedings, 8th Australia New Zealand Conference on Geomechanics, Hobart,* Australian Geomechanics Society, Vol.2, 775-781.

Scott, B.T. & Suto, K. (2007). Case study of ground improvement at an industrial estate containing uncontrolled fill. *Proceedings 10th Australia - New Zealand Conference on Geomechanics, Brisbane,* Australian Geomechanics Society, Vol. 2, 150-155.

Standards Australia, (2003a). Methods of testing soils for engineering purposes – soil compaction and density tests – determination of the dry density/moisture content relation of a soil using standard compactive effort, *AS 1289.5.1.1,* Sydney.

Standards Australia, (2003b). Methods of testing soils for engineering purposes – soil compaction and density tests – determination of the dry density or moisture content relation of a soil using modified compactive effort, *AS 1289.5.2.1*, Sydney.

Standards Australia (2007a). Guidelines for earthworks for commercial and residential developments, *AS 3798,* Sydney.

Standards Australia (2007b). Methods of testing soils for engineering purposes – soil compaction and density tests – determination of field density and field of a soil using a nuclear surface moisture - density gauge – direct transmission mode. *AS 1289.5.8.1*, Sydney.

Standards Australia (2009). Methods of testing soils for engineering purposes – soil classification tests – determination of the particle size distribution of a soil – standard method of analysis by sieving, *AS 1289.3.6.1*, Sydney.

Appendix F: Conference Paper 5

Conference Paper

Scott, B.T., Jaksa, M.B. & Syamsuddin, E. (2016). Verification of an impact rolling compaction trial using various in situ testing methods. *Proceedings 5th International Conference on Geotechnical and Geophysical Site Characterisation,* Gold Coast, Australia, pp. 735-740.

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Publication Details	Scott, B.T., Jaksa, M.B. & Syamsuddin, E. (2016). Verification of an impact rolling compaction trial using various in situ testing methods. Proceedings 5th International Conference on Geotechnical and Geophysical Site Characterisation, Gold Coast, Australia, pp. 735-740.

Principal Author

Name of Principal Author (Candidate)	Brendan Scott		
Contribution to the Paper	Performed site work, analysis and interpretation of site data, wrote manuscript, acted as corresponding author, presenting author.		
Overall percentage (%)	90		
Certification:	This paper reports on original research I conducted during the period of my Higher Degree by Research candidature and is not subject to any obligations or contractual agreements with a third party that would constrain its inclusion in this thesis. I am the primary author of this paper.		
Signature		Date	18/4/2019

Co-Author Contributions

By signing the Statement of Authorship, each author certifies that:

i. the candidate's stated contribution to the publication is accurate (as detailed above);

ii. permission is granted for the candidate in include the publication in the thesis; and

iii. the sum of all co-author contributions is equal to 100% less the candidate's stated contribution.

Name of Co-Author	Mark Jaksa		
Contribution to the Paper	Provided primary supervision and helped evaluate and edit the manuscript.		
Signature		Date	18/4/19

Name of Co-Author	Erfan Syamsuddin		
Contribution to the Paper	Assisted with site work, analysis of geophysical test data presented in Figure 6.		
Signature		Date	18/4/2019

Verification of an impact rolling compaction trial using various in situ testing methods

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Abstract

Rolling Dynamic Compaction (RDC) involves a heavy non-circular module that rotates and falls to impact the ground dynamically; it has a greater depth of influence compared to conventional circular rollers. The depth of influence to which an impact roller can compact soil is known to vary, and is dependent upon factors such as soil type, moisture content and applied input energy, thus verification of impact rolling is particularly important to quantify the extent to which soil has been improved. This paper compares before and after compaction test results using three in situ testing methods, field nuclear density, dynamic cone penetrometer (DCP) and spectral analysis of surface waves (SASW), as well as the ground response due to RDC using earth pressure cells, accelerometers and surface settlement measurements used during the compaction trial.

1. Introduction

Rolling dynamic compaction (RDC) improves ground through the use of a heavy, non-circular module that imparts energy into the soil as it falls to impact the ground. This dynamic effect results in a greater depth of influence than circular rollers, with depths of improvement found to range from more than 1 m below the ground surface to greater than 3 m in some soils (Avalle & Carter 2005) depending upon factors such as soil type, moisture content and compactive effort. RDC disturbs the ground surface leaving an undulating surface; this is a function of the surface geometry of the face of the module as it impacts the ground. As a result, whilst RDC can improve ground at depth it can make the surface soil less dense requiring a conventional circular roller to compact the near surface soil. The aim of the field trial described in this paper was to investigate the extent of ground improvement using various techniques to allow comparison between in situ testing methods undertaken before and after compaction, as well as collecting real-time data during the trial to further understand the ground response to RDC.

2. Scope of compaction trial

In this study, a field trial was conducted using a Broons BH-1300 4-sided impact roller (Fig. 1) at Monarto Quarries, located approximately 60 km south-east of Adelaide, South Australia. The trial pad was constructed by excavating a 1.5 m depth of natural soil and replacing it with 20 mm crushed rock material. Six equal lifts of 250 mm thickness were adopted; each lift was lightly compacted in a uniform manner using a vibrating plate compactor and wheel rolling from a Volvo L150E Loader that was used to place the material.

Figure 1. Broons BH-1300 4-sided impact roller used in compaction trial.

2.1. Soil type

To minimize the effects of soil variability, a homogeneous soil was used for this trial; locally produced crushed rock with a maximum particle size of 20 mm; the material was classified as a well-graded Sandy Gravel (GW) in accordance with the Unified Soil Classification System.

The soil was tested for homogeneity through the use of particle size distribution testing, and both Standard and Modified Proctor compaction laboratory tests. As shown in Figure 2, the optimum moisture content for the Modified Proctor test was 11.3%, corresponding to a maximum dry density of 19.7 kN/m^3. For the Standard Proctor test, the optimum moisture content was 13.3% and the maximum dry density 18.8 kN/m^3.

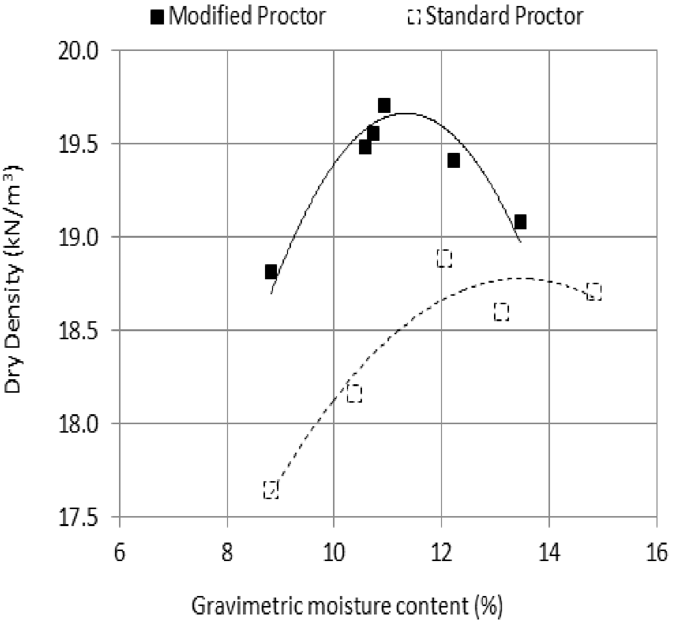

Figure 2. Modified and Standard Proctor compaction curves for 20 mm quarry material.

2.2. *In situ testing methods*

The soil type being compacted dictates (to some extent) what in situ testing methods are appropriate. Other factors that influence the choice of testing method include, time, cost and the availability of testing equipment. Further discussion on testing methods commonly used with RDC is given by Scott & Jaksa (2008). In this trial, field density testing using a nuclear density gauge, dynamic cone penetration (DCP) testing, and geophysical testing using the spectral analysis of surface waves (SASW) technique were undertaken before and after compaction. The aforementioned methods were chosen primarily because they were readily available given the university owns the equipment.

2.3. Ground response

Rinehart & Mooney (2007) successfully used Geokon 3500 earth pressure cells (EPC) in a field trial to measure the loading induced pressures due to static and vibratory circular drum rollers. Based on their success, the same cells were adopted for the present field trial to measure the pressure imparted into the soil due to RDC, as they are commercially available and capable of measuring dynamic loads.

Accelerometers have, in the past, been fixed to falling weights to monitor the deceleration upon impact with the ground surface in deep dynamic compaction applications, as reported by Mayne & Jones (1983). Clegg (1980) used the analogy of a compaction hammer, describing the peak deceleration when it is brought to rest on the soil being directly related to the resistance provided by the soil due to its stiffness and shearing resistance.

Module mounted accelerometers have also been used to measure the ground surface response from a 3-sided impact roller as reported by McCann & Schofield (2007) who stated that the magnitude of the deceleration increased with compactive effort. Whilst this technique provides useful information at the surface, there is no guarantee that measuring the ground surface response gives a true indication of what is happening at depth, especially at sites where there is inherent soil variability. For the purposes of this trial it was decided to attach accelerometers to the buried EPCs to quantify the ground deceleration produced at targeted depths within the expected depth of influence of the roller.

A custom-built accelerometer cluster was attached to each EPC consisting of ±5 g accelerometers in the X and Y planes to measure tilt, as well as the Z plane to measure vertical acceleration. An additional ±16 g accelerometer was used in the vertical plane as the magnitude of peak vertical acceleration was uncertain at the test depths of 0.7 m and 1.1 m. The EPCs and accelerometers were connected to a custom-built data acquisition system and Labview software program. The ability to capture an accurate ground response using EPCs and accelerometers relies heavily on adopting a sufficiently high sampling frequency. A sampling frequency of 4 kHz was selected for this trial to ensure that the true peak pressure and ground deceleration could be accurately captured.

3. Results

3.1. Surface settlement monitoring

Surface settlement monitoring is a quick and simple test method that is commonly used when working with RDC to identify local soft spots that may require additional compaction, or excavation and replacement. From the authors' experience, unexpected results can be obtained with surface settlement monitoring if a grader cuts into the surface between passes (rather than just smoothing off high points of the undulating surface profile) or if targeted coordinates are blindly surveyed without taking into account the nature of the undulating surface. However, provided a consistent approach is undertaken that takes into account the undulating surface left by the impact roller, it is possible to determine how many passes are needed until effective refusal is met. In this trial, local low points from each module face that contacted the ground were surveyed, with the average surface settlement plotted every 5 passes (typically) as shown in Figure 3. A trend line fitted through the measured data indicates that effective refusal was met after approximately 70 passes. This was largely a function of the loosely placed condition of the soil, as it was subjected to minimal traffic compaction from the loader used to place the material.

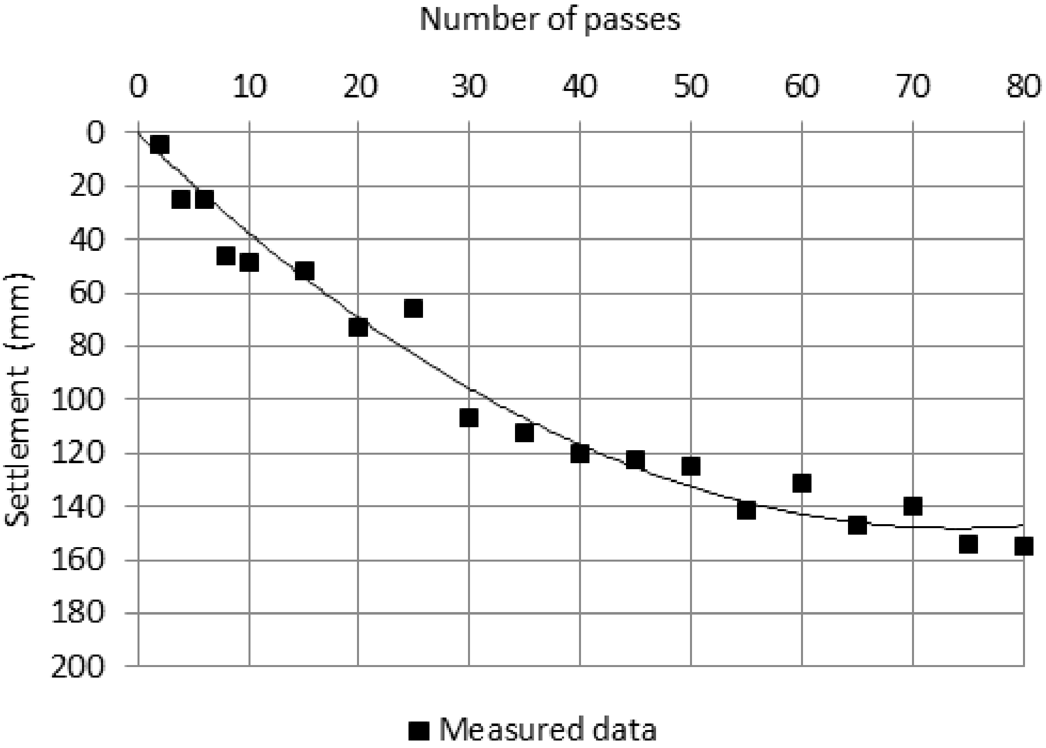

Figure 3. Summary of surface settlement with trend line through the measured data points.

3.2. Density

A nuclear density gauge was used to measure field density before and after compaction. The variation of dry density with depth is summarised in Figure 4, whereby it can be observed that the post compaction dry densities were greater than the pre compaction densities over the full depth of the trial pad, suggesting that the depth of influence of RDC was beyond 1.5 m. The maximum dry density achieved was measured to be 19.0 kN/m^3 at a depth of 0.55 m; corresponding to dry density ratios of 96.5% and 101%, with respect to the Modified and Standard Proctor tests, respectively.

The advantage of the nuclear density test is that it provides a measure of soil's dry density ratio, often specified in earthwork projects. The largest disadvantage is that the gauge's source rod length is limited to a maximum of 300 mm, meaning excavation of compacted material is required to test greater depths. For a dedicated trial this was not a major concern; however, for a project site the time needed for testing and the need to excavate to targeted depths and re-compact after testing can slow progress. Scott & Suto (2007) used this method to help quantify ground improvement using RDC, and cited limitations such as lengthy test durations and the difficulty with the testing process for mixed soils, particularly where oversized particles were present.

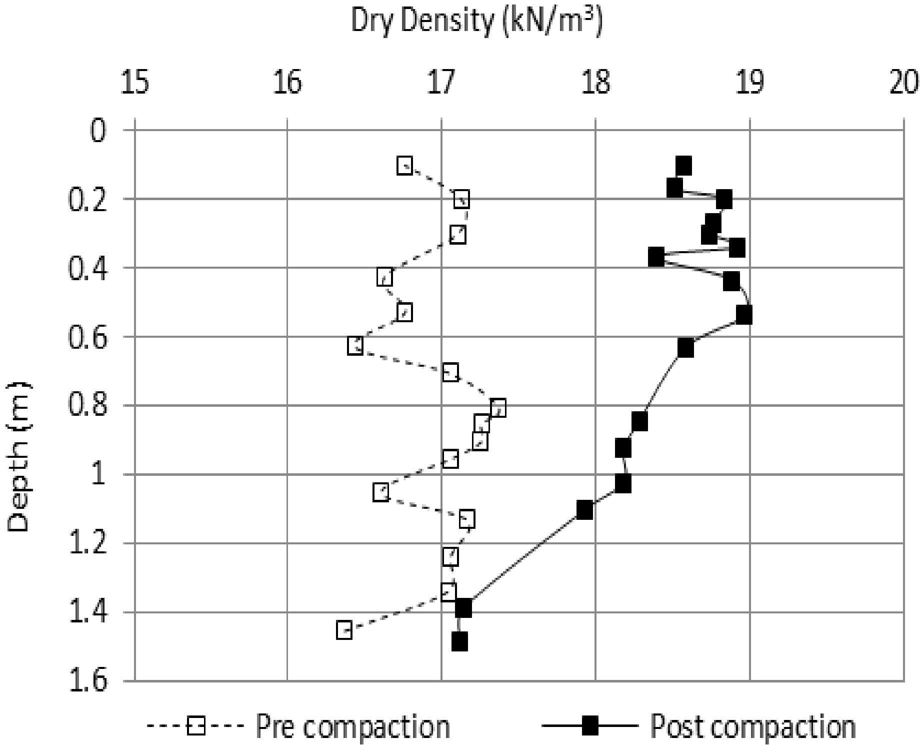

Figure 4. Dry density versus depth from field density testing.

3.3. Dynamic cone penetrometer

DCP test results indicated a greater number of blows were required after compaction for each 100 mm increment between depths of 0.2 m to 1.8 m, as shown in Figure 5. At a depth of 0.1 m, disturbance of near surface soil due to RDC resulted in a negative improvement for reasons discussed in Section 1, as shearing of the soil had occurred as described by Clegg (1980) and discussed in Section 2.3. DCP testing was terminated at a depth of 1.8 m due to limit of equipment, with the results suggesting that the impact roller influenced the ground beyond this depth.

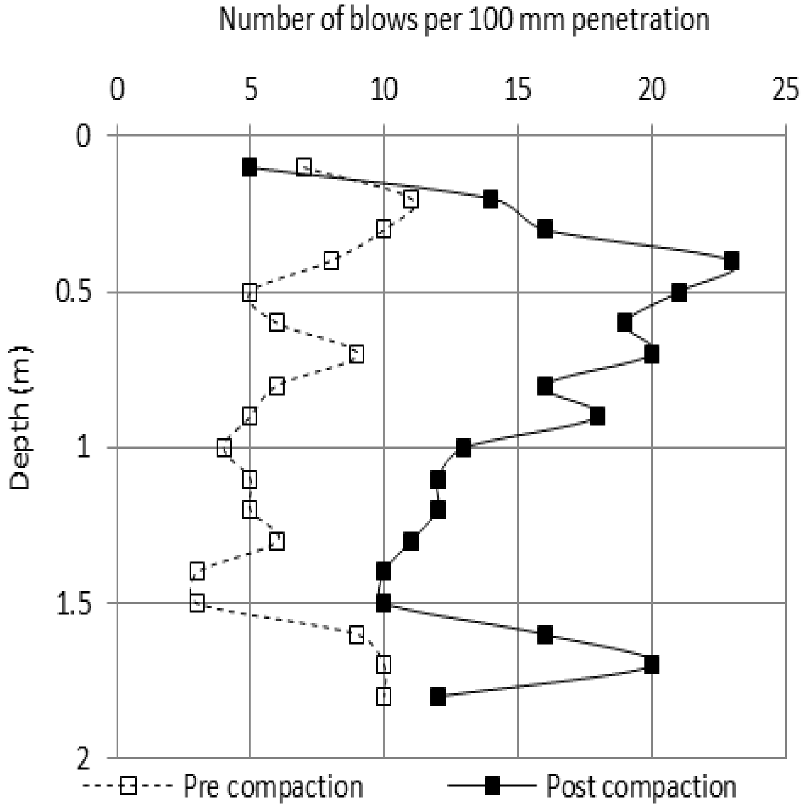

Figure 5. DCP pre and post compaction results.

DCP testing is simple, low cost and uses portable equipment; however, it is a test that can be limited by the presence of large particles. This was found to be the case at this site where refusal was occasionally met on gravel-sized particles greater than the rod diameter (16 mm), in which case, the test was terminated and a substitute test performed. Whilst reasonable results from this trial were obtained due to the relatively homogeneous nature of the soil used in this trial, placing heavy reliance on DCP data without the use of other in situ testing methods is not recommended, particularly at sites containing oversized particles and heterogeneous fill. For example, Whiteley & Caffi (2014) reported difficulty in comparing pre- and post-compaction DCP test results in fill material containing crushed rock.

3.4. SASW testing

Non-intrusive SASW testing was undertaken before and after compaction. At this site, six receivers (geophones) were placed on the ground surface and a sledgehammer used to generate the wave energy. As shown in Figure 6, the results indicate that the 4-sided impact roller was able to improve the shear wave velocity for the full 1.5 m thickness of crushed rock material used for the trial, as well as a further 0.5 m thickness of the underlying natural soil. Below a depth of 2 m, the shear wave velocity profiles converged, suggesting this was the depth to which RDC could improve this site.

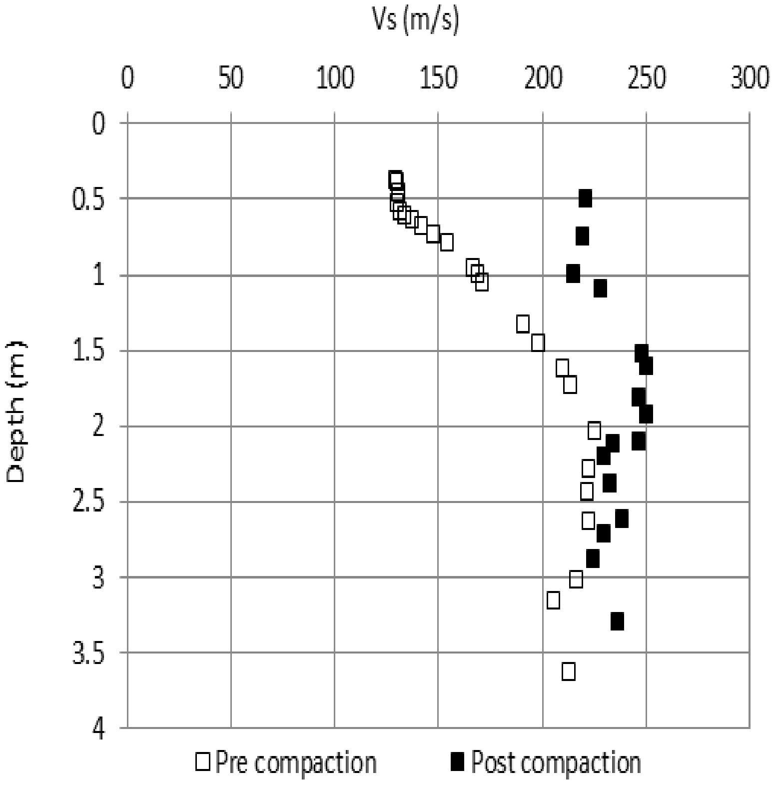

Figure 6. Shear wave velocity versus depth from SASW testing.

3.5. Earth pressure cells and accelerometers

The measured peak pressure recorded for each pass of the impact roller, 80 no. in total, is displayed in Figure 7. There is no clear relationship between number of passes and measured peak pressure, except to observe that the largest peak pressures were recorded between passes 50 to 80, suggesting that the maximum peak pressure may increase with the number of passes. The peak vertical ground deceleration for each pass is presented in Figure 8. Again, no clear trend exists between the number of passes and the peak ground deceleration measured, suggesting other factors have a greater effect, as this was an unexpected result (refer Section 2.3).

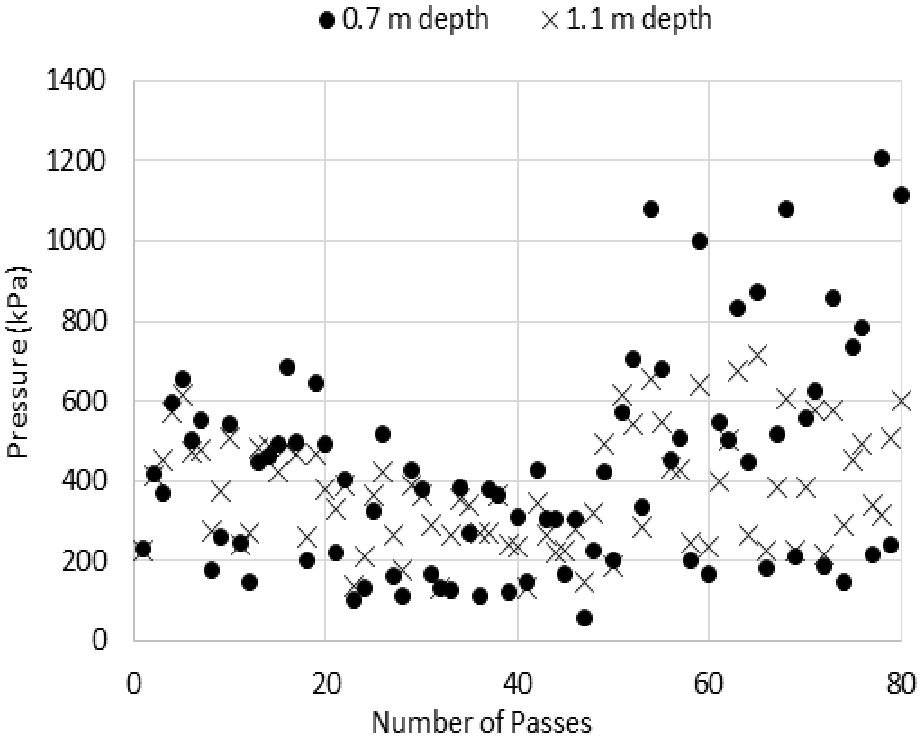

Figure 7. Measured peak pressure for each pass of the impact roller.

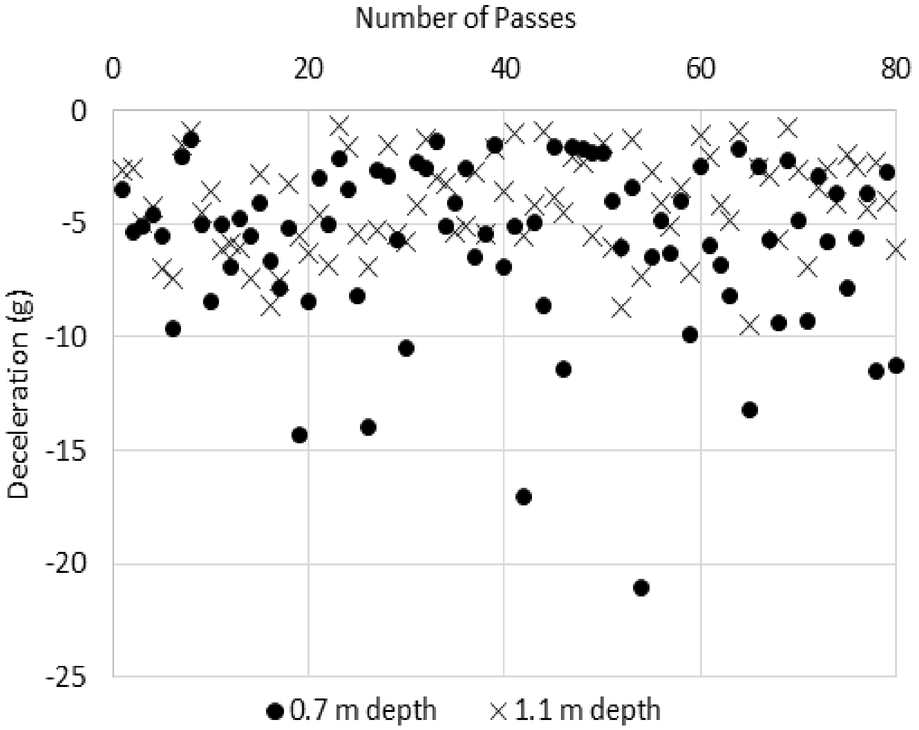

Figure 8. Measured peak deceleration for each pass of the impact roller.

A limitation of using buried instrumentation in RDC applications is that it is not possible for the impact roller module to land in exactly the same location each time relative to the instrumentation in the ground. Avalle et al. (2009) attempted to do this by adopting the same at-rest starting location and operating speed; however it was found that the reproducibility of impacts could not be controlled due to other variables, such as the condition of the ground surface, soil moisture content, density and how quickly the operator changed through the gears and accelerated. For this trial, the same methodology undertaken by Avalle et al. (2009) was adopted, where the effects of non-direct impacts were taken into account by measuring the distance between the centre of the EPC and the centre of the module face.

A correlation between measured peak pressure and vertical ground deceleration is shown in Figure 9. At a depth of 0.7 m, greater peak pressures and vertical ground decelerations were recorded than at a depth of 1.1 m, an expected result which supports a general trend of increasing ground deceleration with increasing peak pressure.

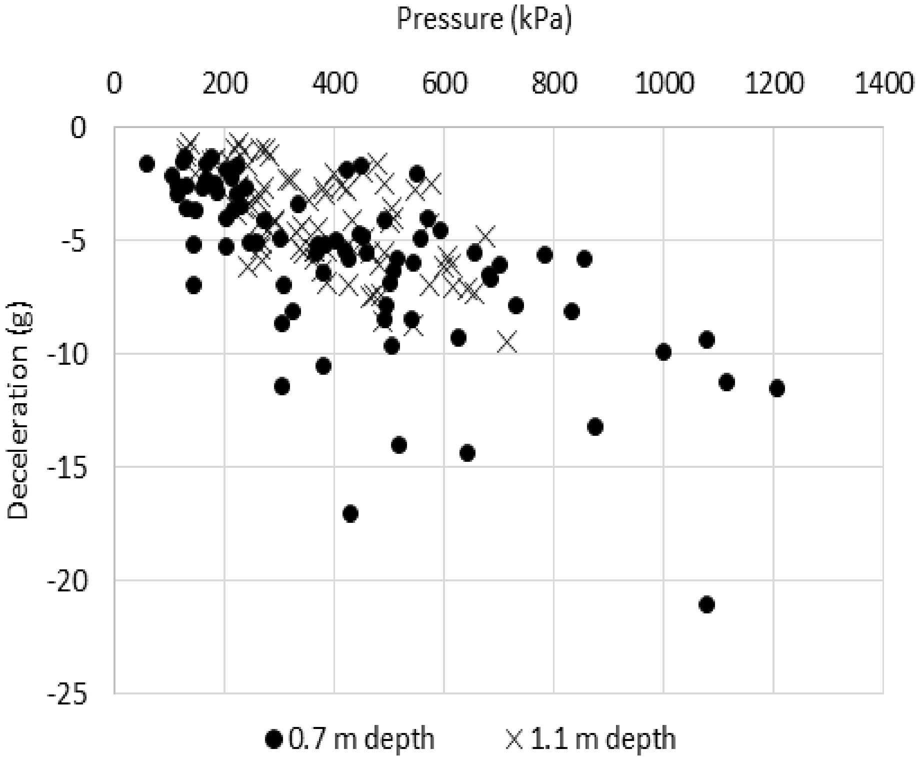

Figure 9. Correlation between measured peak pressure and deceleration.

The distribution of peak pressure with offset distance is shown in Figure 10, where it can be observed that the highest pressures corresponded to offset distances between +100 mm to +650 mm. The physical location where the module landed on the ground relative to the fixed position of the buried instrumentation was found to be critical in terms of both the peak pressure recorded and ground deceleration (Fig. 11) produced. Figure 12 summarises the same results using a heat map to illustrate which parts of the contact face of the 4-sided impact roller produced the highest peak pressures and ground decelerations. As observed in this figure, the pressure distribution beneath the contact face as it impacts the ground is non-uniform. Maximum peak pressures and ground decelerations are associated with red, intermediate values in yellow and lower values with blue colours.

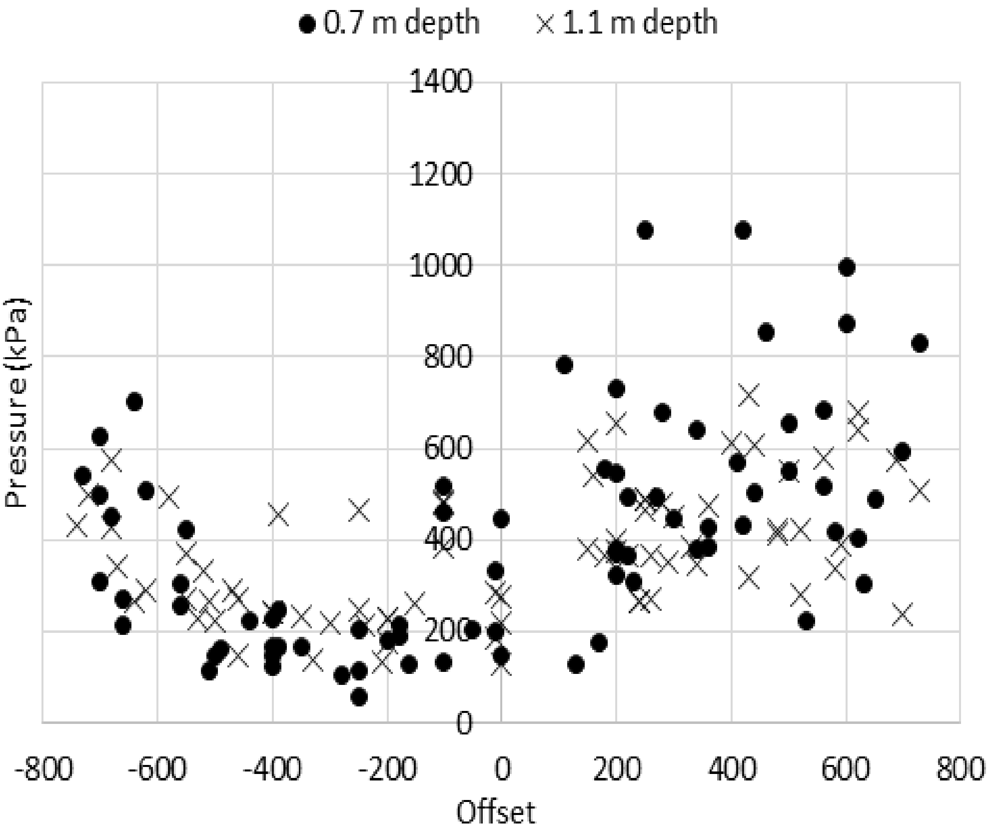

Figure 10. Distribution of peak pressure with offset distance.

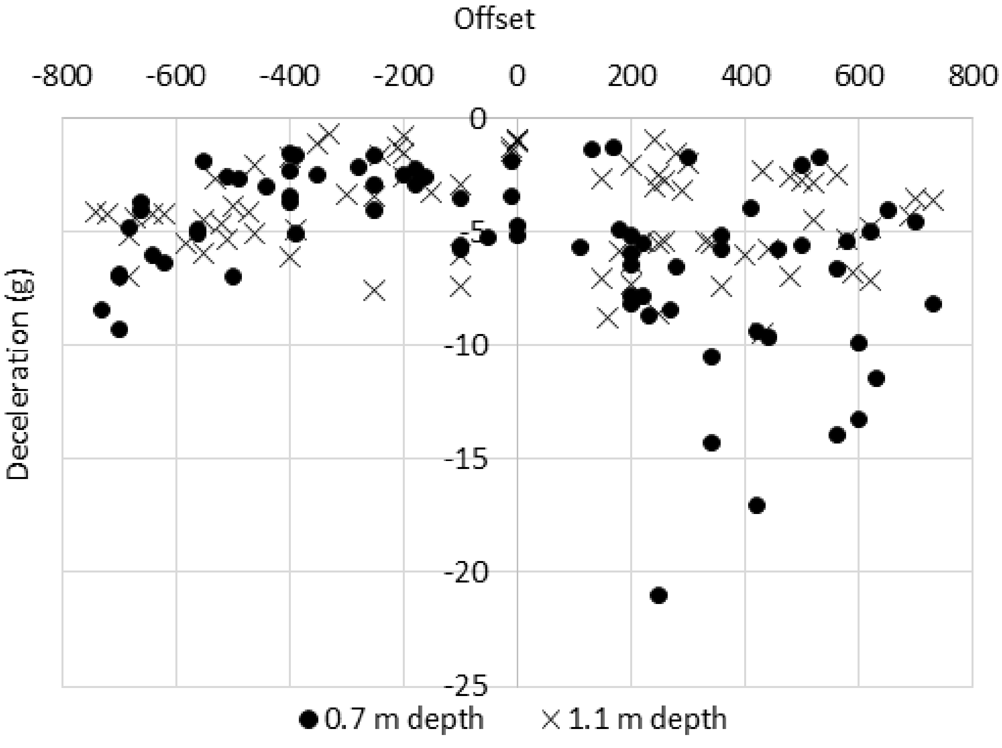

Figure 11. Distribution of peak deceleration with offset distance.

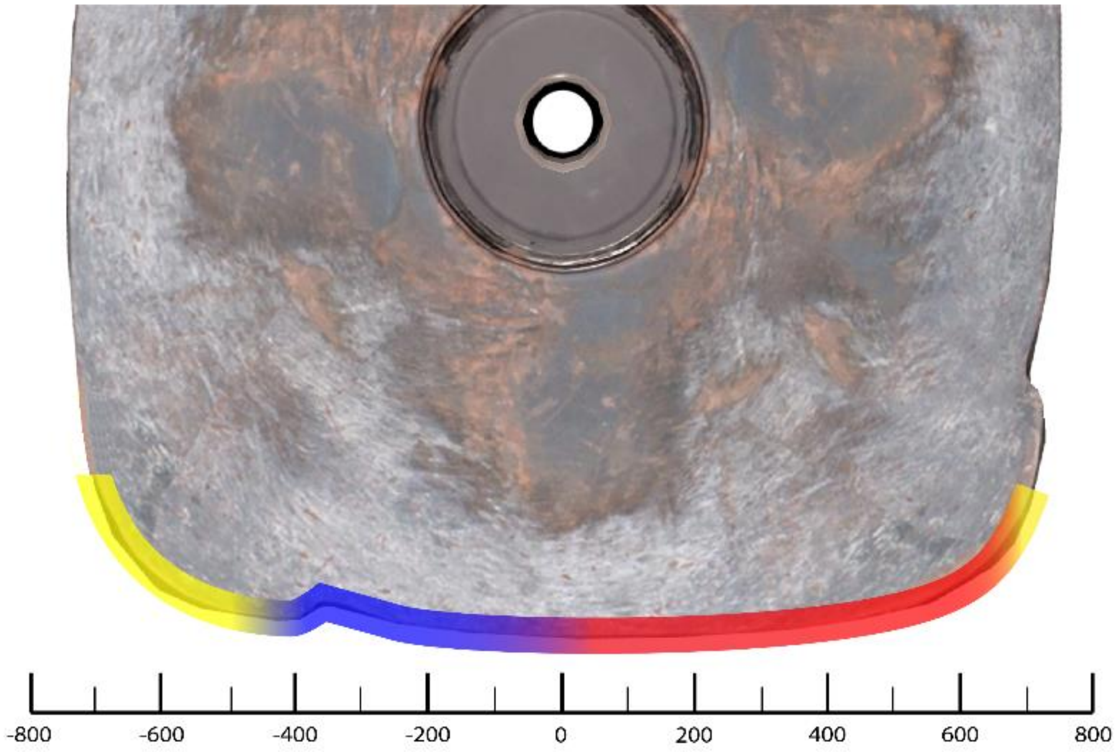

Figure 12. Heat map for 4-sided impact roller indicating the most influential parts of the contact surface that produced maximum peak pressure and peak ground deceleration.

The findings from this trial generally agree with Avalle et al. (2009) who found that the zone of maximum impact was located at offset distances from 0 mm to +400 mm from the centre of the roller. However, the results from this trial should be considered as being more reliable, largely due to the instrumentation used to measure load. This trial used thin EPCs that produce a much more reliable measurement of in situ soil stress than the bulky load cell used by Avalle et al. (2009) and which is significantly stiffer than the surrounding soil.

Whilst it is not possible to capture the maximum ground response from each and every impact, by burying equipment into the ground at discrete locations; this technique does provide real-time information of dynamic pressures and accelerations in the ground that other testing methods are unable to do.

4. Conclusions

This field based study was conducted using well-graded 20 mm quarry material to minimise the effects of soil variability. The fill material was placed to a depth of 1.5 m and compacted using a 4-sided impact roller. From testing undertaken pre- and post-compaction, ground improvement was quantified using three different in situ testing methods: DCP testing, field density testing using a nuclear density gauge and geophysical testing using the SASW method. Comparison of the three in situ testing methods adopted in this trial showed good agreement with each other.

All three in situ testing methods used in this trial indicated that the depth of influence of RDC was greater than the depth of fill material (1.5 m). As the results from field density and DCP tests were limited in depth due to limit of equipment, the SASW test method was able to provide the best estimate for the depth of improvement of RDC in this trial; approximately 2 m.

The use of earth pressure cell and accelerometers buried at depths of 0.7 m and 1.1 m, well within the depth of influence of the roller for this soil as quantified by the different in situ testing methods undertaken in this trial, found that a slight upward trend existed between the number of passes and peak pressure. There was also a weak upward trend between peak pressure and vertical deceleration. Significantly, both peak vertical deceleration and peak pressure imparted into the ground were dependent upon offset distance or, specifically, which part of the module face struck directly over the buried earth pressure cell.

Apart from a faster operating speed than circular rollers, one of the key reasons why RDC is able to improve ground to greater depths is due to the geometry of the contact face that gives rise to a non-uniform pressure distribution beneath the module. That is, there are regions on the surface of the roller that impart significantly greater pressures into the ground than other parts of the contact face. This is one of the key reasons why many passes are needed to ensure adequate coverage of a site.

Whilst the buried instrumentation used in this trial has been customised primarily for research purposes, and is unlikely to be adopted for widespread use on ground improvement projects using RDC, recent advances in technology allow the soil response subject to dynamic loading to be more accurately captured than ever before.

Further analysis of real-time data and future field trials will continue to advance knowledge and understanding in this area.

Acknowledgements

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References

Avalle, D.L. & Carter, J.P. 2005. Evaluating the improvement from impact rolling on sand, *Proc. 6th Int. Conf. on Ground Improvement Techniques,* Coimbra, Portugal, 153-160.

Avalle, D.L., Scott, B.T. & Jaksa M.B. 2009. Ground energy and impact of rolling dynamic compaction – results from research test site. *Proc. 17th Int. Conf. Soil Mechanics and Geotechnical Engineering,* Alexandria, Egypt, Vol. 3: 2228-2231.

Clegg. B. 1980. An impact soil test as alternative to California Bearing Ratio. *Proc. 3rd Australia New Zealand Conf. on Geomechanics,* Wellington, New Zealand, 225-230

Mayne, P.W. & Jones, J. S. 1983. Impact stresses during dynamic compaction, *Journal of Geotechnical Engineering,* 109(10): 1342-1346.

McCann, K. & Schofield, N. 2007. Innovative methods in the in situ determination of design parameters on heterogeneous sites subject to ground treatment using deep impact compaction. *Proc. 10th Australia New Zealand Conf. on Geomechanics,* Brisbane, Australia, Vol. 2: 126-131.

Rinehart, R.V. & Mooney, M.A. 2009. Measurement of roller compactor induced triaxial soil stresses and strains, *Geotechnical Testing Journal*, 32(4): 347-357.

Scott, B.T & Suto, K. 2007. Case study of ground improvement at an industrial estate containing uncontrolled fill. *Proc. 10th Australia New Zealand Conf. on Geomechanics,* Brisbane, Australia, Vol. 2: 150-155.

Scott, B.T. & Jaksa, M.B. 2008. Quantifying the influence of rolling dynamic compaction, *Proc. 8th Young Geotechnical Professionals Conf.*, Wellington, New Zealand, 199-204.

Whiteley, R.J. & Caffi, P. 2014. Evaluating the effectiveness of rolling impact compaction at a brownfield site with high and low frequency seismic surface waves and geotechnical testing, *Near Surface Geophysics*, 2014(12): 405-414.

Appendix G: Conference Paper 6

Conference Paper

Avalle, D.L., Scott, B.T., & Jaksa, M.B. (2009). Ground energy and impact of rolling dynamic compaction - results from research test site. *Proceedings of the 17th International Conference on Soil Mechanics and Geotechnical Engineering, Cairo, Egypt*, Vol. 3, pp. 2228-2231.

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Principal Author

Name of Author (Candidate)	Brendan Scott		
Contribution to the Paper	Performed site work, analysis and interpretation of site data, co-wrote manuscript.		
Overall percentage (%)	40		
Certification:	This paper reports on original research I conducted during the period of my Higher Degree by Research candidature and is not subject to any obligations or contractual agreements with a third party that would constrain its inclusion in this thesis. I am the primary author of this paper.		
Signature		Date	18/4/2019

Co-Author Contributions

By signing the Statement of Authorship, each author certifies that:

i. the candidate's stated contribution to the publication is accurate (as detailed above);

ii. permission is granted for the candidate in include the publication in the thesis; and

iii. the sum of all co-author contributions is equal to 100% less the candidate's stated contribution.

Name of Co-Author	Derek Avalle		
Contribution to the Paper	Performed site work, analysis and interpretation of site data, co-wrote manuscript.		
Signature		Date	18/02/2019

Name of Co-Author	Mark Jaksa		
Contribution to the Paper	Helped to evaluate and edit the manuscript		
Signature		Date	18/4/19

Ground energy and impact of rolling dynamic compaction – results from research test site

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B.T. Scott & M.B. Jaksa, The University of Adelaide, Australia

Abstract

As a major component of research activities at Sydney and Adelaide Universities into various aspects of rolling dynamic compaction as performed with the “square” impact roller, an experimental test site has been established. The test site is approximately 100 m by 50 m, and is part of a larger industrial property in Wingfield, South Australia. Geologically, the site comprises approximately 1-2 m of non-engineered fill, overlying estuarine deposits. The primary objectives of the work at the test site relate to quantifying the effects of the impact roller in terms of energy delivered to the ground and the ground response. Impact rollers with solid 4-sided modules of mass 8 t and 12 t are utilised. A monitoring and testing regime has been developed that includes physical measurements of energy on and below the impact module, surface settlement and sub-surface layer compression measurements. Early results from the testing programme provide a basis for understanding and developing the relationship of delivered to transmitted energy for the particular impact modules used at this site, the dissipation of energy through the ground and the effects on the various strata at depth due to module mass and number of passes (or energy input). The output from this study will form the basis for modelling ground conditions at this site and the effects of the impact rolling. The data thus generated will support further studies into numerical modelling of rolling dynamic compaction and the ongoing programme of testing at other sites with different geological characteristics.

Keywords: rolling, dynamic, compaction, impact, energy

1. Introduction

The use of dynamic force for ground improvement is ages old. Practitioners and researchers have long sought after a formula to predict and verify its effects; however, such a solution remains elusive. With the inherent heterogeneity of ground conditions and varying methods for the application of dynamic compaction, the solution remains empirical. The use of impact rolling is often guided by intuition, or based on experience in similar soils and applications. Although there is little published information on what the zone of influence is, or how many passes are required for different soil types, it is known that certain combinations of ground conditions and dynamic compaction combine to good effect, resulting in improved foundation solutions.

Research initiatives at both Sydney and Adelaide Universities are focussing specifically on impact rollers and their characteristics in relation to their energy input and the corresponding ground response. Commencing in 2007, work has been continuing at a test site in Adelaide, South Australia.

2. The "square" impact roller

"Square" impact rollers have been in use for several decades, primarily for the purposes of ground improvement. Also known as "rolling dynamic compaction", the technique involves a non-circular impact module (as shown in Figure 1) that is towed at speeds typically in the range of 9-12 km/h, which results in the impact rolling module striking the ground approximately twice per second. The impact roller is usually towed using a four-wheel drive tractor, as shown in Figure 2. Trials that have been undertaken by the authors have shown that towing speeds slower than 9 km/h can result in insufficient momentum to keep the module turning over without sliding, whilst towing speeds faster than 12 km/h often result in an uncomfortable ride for the operator and may cause the module to bounce about within the trailer support frame, resulting in increased wear and tear on mechanical components.

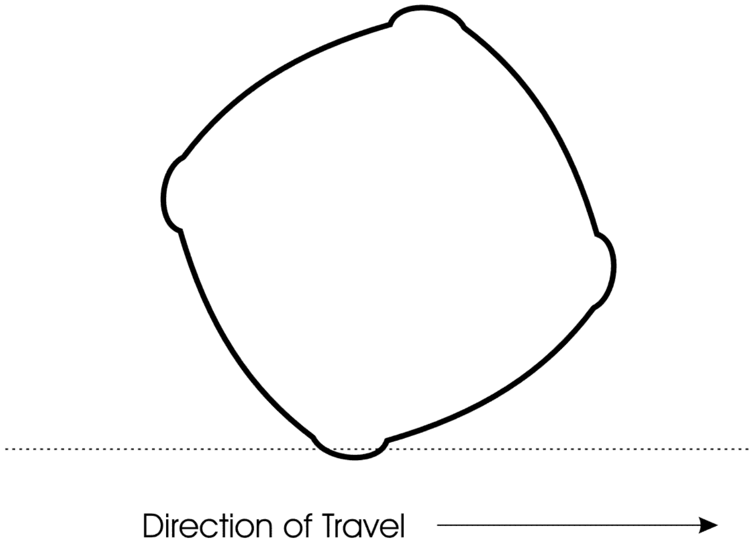

Figure 1. Cross-section of the "square" impact module.

Figure 2. Impact rolling in progress.

The module is connected to the frame by a system of linkage arms that allow the module freedom of movement within its frame and linkages. Once the tow unit commences forward movement, the module is dragged forward and begins to rotate due to friction and soon reaches its operating speed. The energy delivered to the ground results in ground modification. Dependent on the prevailing ground conditions and the characteristics of the impact roller, the effects are measurable by means such as surface settlement, or a relative gain in compaction or soil strength.

A description of rolling dynamic compaction is given by Scott and Jaksa (2008), and they provide several references as background to the subject.

3. Test site conditions

The test site is part of an industrial property in Wingfield, to the north of the city of Adelaide. The site is approximately 100 m long (north-south) and 50 m wide, and is bounded by a main road to the south, an industrial site to the east, a railway line to the north and open ground to the west. The site lies in an area that is typically characterised by estuarine deposits, comprising sands, silts and clays. The land levels at the test site have been raised by man-made fill to facilitate future industrial development.

Eight boreholes were drilled across the site to depths of between 4 m and 6 m. Fill was encountered in each of the boreholes to depths ranging between 1.6-2.2 m. The fill generally consisted of very stiff to hard sandy clay with some gravel. Underlying the fill, natural soils consisting of grey and brown silty clay were encountered in each of the boreholes. The natural clay layers were generally of a firm to stiff consistency; however, some softer zones were encountered below the water table, which was located at approximately 3 m below the ground surface.

4. Instrumentation, testing and selected results

The objectives of the testing programme include the measurement of impact energy on the impact rolling module (input energy), and the measurement of energy that is imparted by the module into the ground (output energy). Also of interest are the dissipation of output energy as a function with depth, and the settlement of soil layers below the surface, as these factors help to identify the zone of influence of the roller.

The testing programme undertaken to date has included the installation of instrumentation on the impact module to measure input energy, the placement of instrumentation in the ground at or below the ground surface to measure output energy, and the measurement of settlements before and after rolling both at the surface and at depth, as described in further detail below.

4.1 Instrumentation of the impact module

The impact module is constructed of thick steel plate and completely filled with concrete, to form a solid block. The instrumentation of the impact rolling module will consist of accelerometers mounted within the steel plate forming the module "skin". At this stage, one accelerometer has been mounted on the side of the module and a wireless transmitter and receiver are being used to collect the output during operation, as shown in Figure 3. Two trials of the system have been undertaken to date, which have demonstrated the satisfactory operation of the data transmission. Further work is planned to embed multiple accelerometers within the module, and these results will be reported in due course.

Figure 3. Transmitter and accelerometer device mounted directly onto impact module.

4.2 Energy delivered to the ground

The output energy that is imparted to the ground is measured using a 1,000 kN load cell with 250 mm square x 20 mm thick top and bottom steel plates. Two accelerometers capable of withstanding accelerations up to 50 g were fixed to the underside of the top plate. The load cell was embedded in the ground in the centreline of the impact module path, with the top plate of the load cell flush with the ground surface, and the bottom plate of the load cell placed on bricks to provide a firm base reaction. The load cell system is illustrated in Figure 4.

A sampling frequency of 2,000 samples per second was adopted to capture the load and accelerometer data. Sampling frequencies in the range of 200 to 10,000 samples per second were trialled; however, the adopted sampling frequency was found to adequately capture the peak load and acceleration readings without acquiring unnecessarily large quantities of data. The data acquisition system used was linked to a laptop computer.

Load and acceleration data were recorded over a 10 second period, which captured the roller approaching, passing over and moving away from the load cell that was embedded in the test lane. Figure 5 shows the variation in the load as the impact roller passes over the embedded load cell. In Figure 5, the load that is imparted from the module to the ground occurs over a time of approximately 0.1 seconds. The magnitude of the peak load is approximately 137 kN, corresponding to an imposed bearing pressure of approximately 2,200 kPa over the contact area of the load cell. After impact, the load cell reading does not return exactly to 0 kN, suggesting that plastic deformation has occurred. Settlement of the load cell (and supporting bricks and soil beneath) was verified by survey measurements taken on the top plate of the load cell both before and after impact.

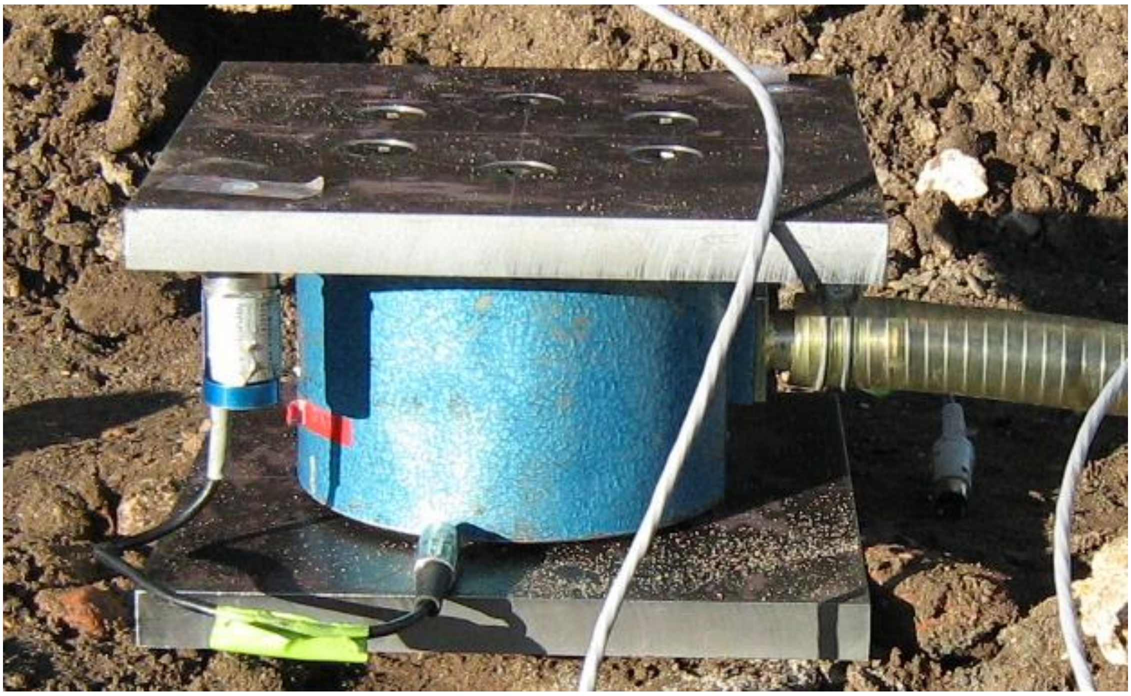

Figure 4. Load cell with accelerometers prior to embedment in the ground.

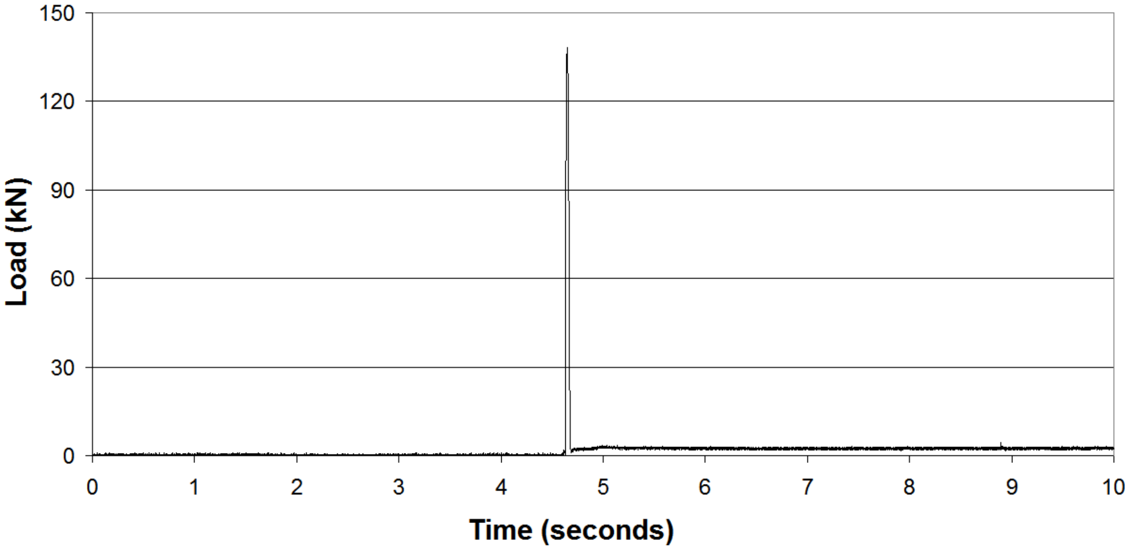

Figure 5. Measured load as the impact roller passes over embedded instrumentation.

Figure 6 shows the variation in measured acceleration as the roller approaches, impacts and then moves away from the embedded load cell. In Figure 6, as the impact roller passes over the load cell there is a large acceleration (downwards movement of the load cell), followed by a large deceleration (upwards) as the soil provides a reaction against the initial downward movement of the load cell. The field trials conducted at the test site to date indicate that a more rigid soil response is recorded with an increasing number of passes; this supports the findings of Landpac (2008) that the ground deceleration increased as the soil stiffness and density increased. In Figure 6, small accelerations are evident at approximately half-second intervals either side of the peak reading, indicating that ground accelerations have been recorded as the rolling module impacts the ground as it approaches and then moves away from the embedded load cell. These findings generally support the findings of Avalle (2007) who analysed the magnitude of ground vibrations as a function of the distance from impact rolling.

Field trials undertaken to date have proven that a module impacting the ground directly above embedded instrumentation results in significantly higher ground decelerations being recorded, compared to when the module strikes the ground off-set from the embedded instrumentation. Testing to date indicates that even small off-set distances can produce large discrepancies in the magnitude of decelerations measured by embedded instrumentation. Trials were undertaken to determine if the reproducibility of impacts could be controlled. Despite attempts at controlling the operating speed and using the same at-rest starting location, field testing verified that getting the module to land in precisely the same location is not possible, as it is dependent on a number of variables such as the ground conditions (moisture, compaction), how quickly the tractor operator changes through the gears and accelerates, as well as the operating speed of the towing unit.

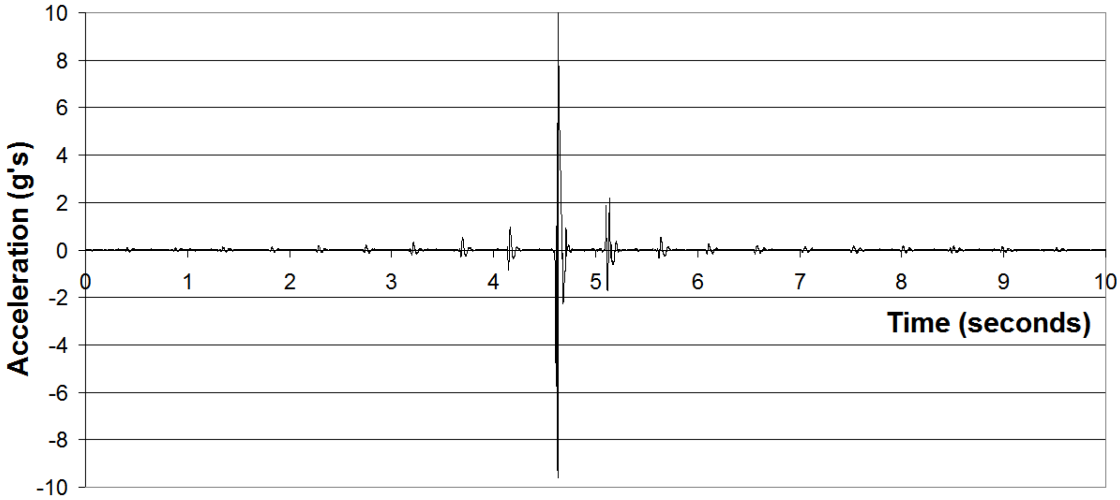

Figure 6. Measured acceleration as the roller passes over embedded instrumentation.

As the reproducibility of impacts could not be controlled, it was decided to measure the off-set distance from the centre of the module to the centre of the load cell to determine if there was a relationship with the peak load recorded (refer Figure 7). Similarly, the peak deceleration was measured and plotted against the off-set distance (Figure 8). The results of both Figures 7 and 8 indicate that there is a large discrepancy in the values of both peak load and deceleration, depending upon where the impact rolling module hits the ground relative to the embedded instrumentation. The highest values were recorded when the module struck the ground at a distance within 400 mm of the centre of the module's impact surface. This appears to be a function of the geometry of the impact rolling face, with the zone of maximum impact noted in Figure 9. These results indicate that the pressure distribution underneath the module impact is non-uniform.

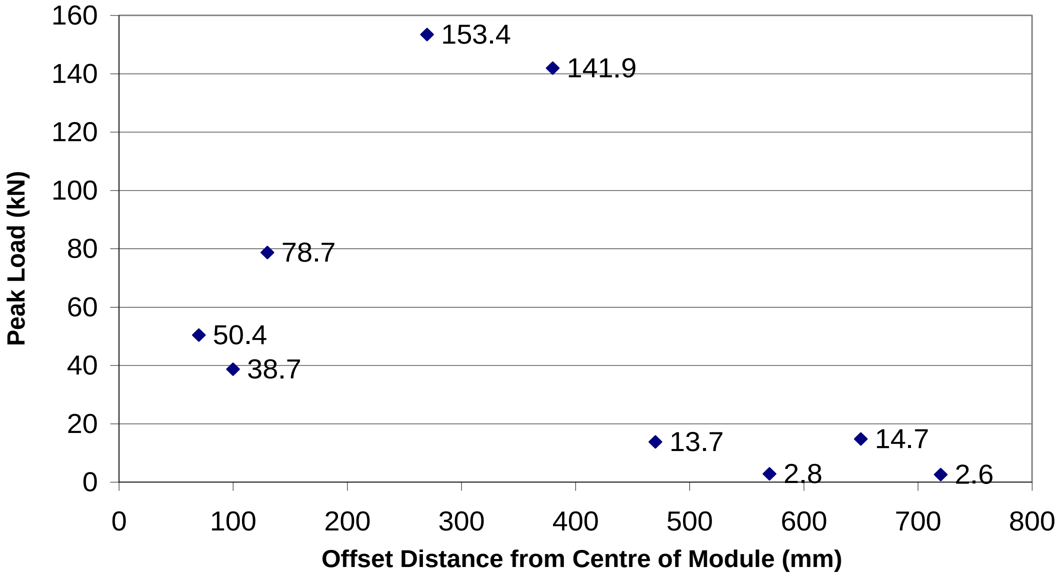

Figure 7. Peak load versus off-set distance from centre of module.

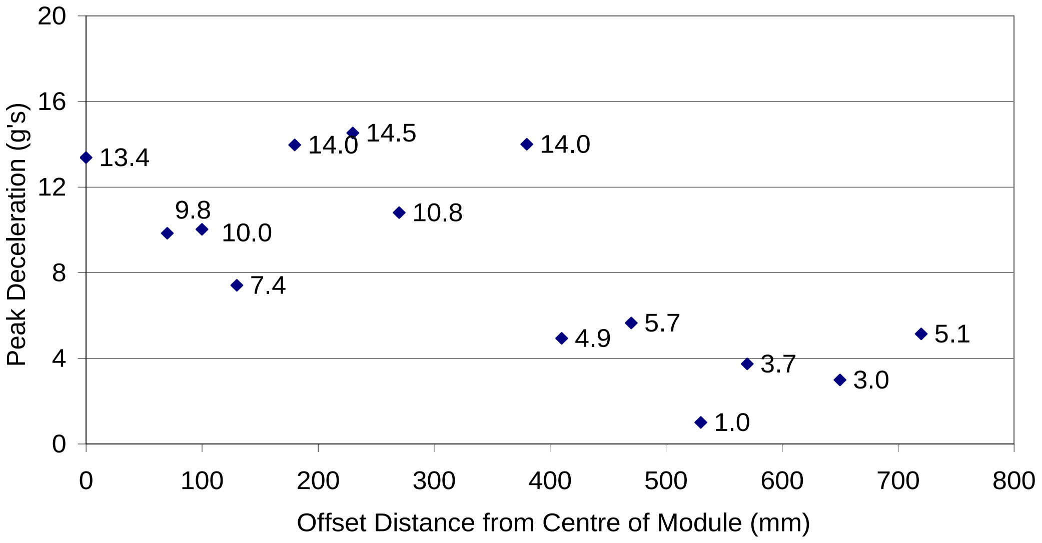

Figure 8. Peak deceleration versus off-set distance from the centre of the module.

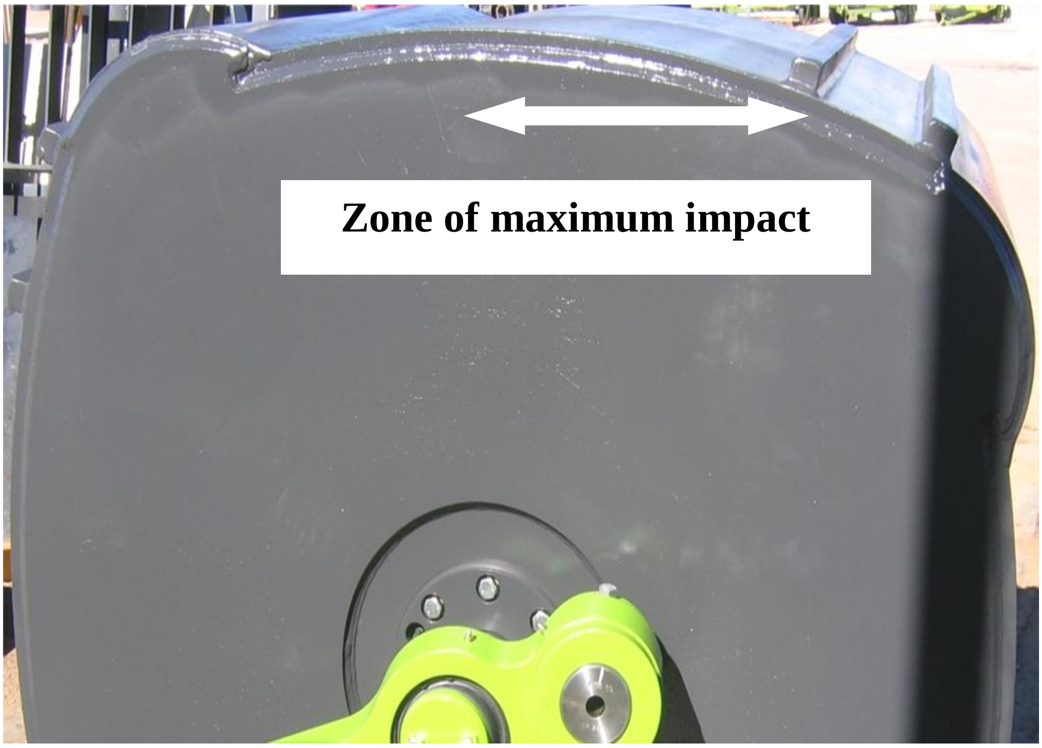

Figure 9. Geometry of impact rolling module face.

Trials have also been undertaken to determine typical distances that are required in order to get the impact roller up to its operating speed from a standing start. Trials undertaken to date indicate that a distance of approximately 20 m may be required. This generally supports the findings of Scott and Suto (2007), who reported that ground near the perimeter of a fenced site could not be improved as successfully as the rest of site due to access-related issues that reduced the towing speed of the module. This in turn, supports the theory proposed by Clifford and Bowes (1995), who suggested that the higher the velocity of the module upon impacting the ground, the greater the energy that is imparted, hence the more ground improvement that can be expected.

4.3 Measurement of surface and subsurface deformation

Measuring surface settlement is a commonly adopted technique for verifying ground improvement with an impact roller, as data can generally be obtained in an efficient and cost-effective manner. However, care needs to be taken to account for the effect of surface undulations caused by the periodic impacts of the module on the ground. Depending upon the soil conditions, surface undulations can typically have up to a 200-300 mm height difference between the high and low points, meaning that if accurate surface settlements are to be obtained, a grader and smooth-drum roller are often required to produce a finished level surface for surveying.

In order to measure settlement of soil layers below the ground surface embedded steel plates with central vertical tell-tale rods were buried beneath the surface. This method proved successful for measuring settlements within near surface layers, and proved to be a useful way to overcome the effect of surface undulations; however, installing and removing embedded steel plates became quite cumbersome when placed greater than 300 mm below the ground surface.

To measure settlements within layers at greater depths, magnet extensometers comprising three ring magnets were installed in each of four boreholes across the site. Within each borehole, the first magnetic extensometer (Magnet 1) was installed in the fill layer, the second (Magnet 2) near the fill/natural soil interface and the third (Magnet 3) in the natural soil layer below the water table. The results of settlement data after 18 passes of the impact roller at one of the borehole locations is given in Table 1.

Table 1. Measured settlements at various depths below ground surface

Measuring Technique	Depth below ground surface (m)	Settlement relative to site datum (mm)
Steel Plate	0.1	20
Magnet 1	0.8	10
Magnet 2	1.9	5
Magnet 3	3.1	5

Whilst the magnitude of settlements recorded in the soil layers at depth were small (presumably due to the thick layer of very stiff to hard clay fill at the site), this method appears promising for determining settlement in targeted soil layers at depth.

5. Future work

To determine the zone of influence of rolling dynamic compaction in different soil conditions, commonly used testing methods will be combined with instrumentation that is embedded deeper into the ground, in addition to the ongoing development of the input energy system mounted on the impact module. The transfer of energy of the impact rolling module to the underlying ground will be measured at various depths, using earth pressure cells and accelerometers that will be embedded into the ground. The impact roller will pass over the embedded instrumentation whereby the pressure and ground deceleration measured using accelerometers can be used to determine the energy recorded. Measurement of the energy at various depths below ground level for differing soil types will enable the zone of influence of the impact roller to be quantified.

6. Conclusions

There is little published information quantifying what the zone of influence is, or how much energy is required in order to improve soils of different types using dynamic means. It is anticipated that the outcomes of the current research programmes will enable rolling dynamic compaction to be applied and validated more appropriately for a range of soil conditions. In addition, quantifying the effectiveness of rolling dynamic compaction in terms of the energy imparted into the ground and the zone of influence for various soils will lead to a greater understanding of its theory, which will enable impact rollers to be used more effectively and with greater confidence in a range of engineering applications.

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References

Avalle, D.L. 2007. Ground vibrations during impact rolling. Proceedings of the 10th Australia New Zealand Conference on Geomechanics, Australian Geomechanics Society, Brisbane, Vol. 2, 42-47.

Clifford, J.M. & Bowes G. 1995. Calculating the Energy delivered by an Impact Roller. A trilogy of Papers for the Sept. 1995 Lecture Tour and International Seminars to commemorate the 10th anniversary of the BH-1300 Impact Roller, Paper 2, pp 1-15.

Landpac, 2008. Website http://www.landpac.co.za/, accessed 6 April 2008.

Scott, B. & Jaksa, M. 2008. Quantifying the influence of rolling dynamic compaction. Proceedings of the 8th Australia New Zealand Young Geotechnical Professionals Conference, New Zealand Geotechnical Society, Wellington, New Zealand, pp. 199-204.

Scott, B.T & Suto, K. 2007. Case study of ground improvement at an industrial estate containing uncontrolled fill. Proceedings of the 10th Australia New Zealand Conference on Geomechanics, Australian Geomechanics Society, Brisbane, Vol. 2, 150-155.

Appendix H: Copies of published journal papers

Scott, B.T., Jaksa, M.B. & Mitchell, P.W. (2020). Influence of towing speed on effectiveness of rolling dynamic compaction. *Journal of Rock Mechanics and Geotechnical Engineering, 12(1): 126-134.*
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Scott, B.T., Jaksa, M.B. & Mitchell, P.W. (2019). Depth of influence of rolling dynamic compaction. *Ground Improvement, Institution of Civil Engineers.*
https://doi.org/10.1680/jgrim.18.00117

Scott, B.T., Jaksa, M.B. & Mitchell, P.W. (2019). Ground response to rolling dynamic compaction. *Geotechnique Letters, Institution of Civil Engineers, 9(2): 99-105.*
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Full Length Article

Influence of towing speed on effectiveness of rolling dynamic compaction

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ABSTRACT

The influence of towing speed on the effectiveness of the 4-sided impact roller using earth pressure cells (EPCs) is investigated. Two field trials were undertaken; the first trial used three EPCs placed at varying depths between 0.5 m and 1.5 m with towing speeds of 9–12 km/h. The second used three EPCs placed at a uniform depth of 0.8 m, with towing speeds of 5–15 km/h. The findings from the two trials confirmed that towing speed influences the pressure imparted to the ground and hence compactive effort. This paper proposes that the energy imparted to the ground is best described in terms of work done, which is the sum of the change in both potential and kinetic energies. Current practice of using either kinetic energy or gravitational potential energy should be avoided as neither can accurately quantify rolling dynamic compaction (RDC) when towing speed is varied.

1. Introduction

Improving the ground is a fundamental and essential part of civil construction. Compaction is a prevalent ground improvement technique that involves increasing the density of soil by means of mechanically applied energy to increase shear strength and stiffness or reduce permeability. This paper is concerned with rolling dynamic compaction (RDC) which involves traversing the ground with a non-circular roller. Typical module designs have 3, 4 or 5 sides. As the module rotates, it imparts energy to the soil as it falls and impacts the ground. More introductory information pertaining to RDC is included in Scott and Jaksa (2015) and Ranasinghe et al. (2017).

At filled sites containing significant soil variability, it can be difficult to quantify the effect of a single variable. Similarly, the inherent soil heterogeneity of natural ground can also influence results, often making it hard to quantify the effect of towing speed alone. To overcome this limitation, two compaction trials that used homogeneous soil conditions are described in this paper. Both trials used buried earth pressure cells (EPCs) and were undertaken at a dedicated research site. Whilst replacing natural soil with fill material and conducting full-scale trials are expensive exercises, particularly where the trial is not part of a client funded project, having full control over a site enabled variables other than towing speed to be held constant. The aim of this paper is to determine the influence, if any, of towing speed on the energy imparted to the ground.

The impact roller was originally developed in South Africa with the intention of improving the properties of granular soils, in particular to identify and improve collapsing sands within 3 m below the ground surface in southern Africa (Clifford, 1978). Wolmarans and Clifford (1975) described a case study of compacting Kalahari (collapsing) sand in Rhodesia where at least 25 passes were required; layers were able to be compacted in thicknesses of up to 1.5 m and still achieve the target density. Clifford (1975) stated that the impact roller is not a finishing roller, as it over-compacts the near-surface soils, often requiring the upper 0.1–0.2 m to be compacted by rollers used for surfacing works. Ellis (1979) described that one of the main advantages of RDC was to compact cohesionless soils in thick layers; however, he cited a disadvantage that in loose soils, the near-surface soil is disturbed by RDC and must be compacted by other machines, agreeing with the results of Clifford (1975).

The typical operating speed range of the 4-sided impact roller, as shown in Fig. 1, is 9–12 km/h. Clifford (1980) stated that one of the difficulties encountered with RDC is the need for rollers to be operated at their optimum speed to ensure that sufficient energy is generated for each impact blow. In cases where the towing speed is slower than the typical range, or the module slides across the surface, Clifford (1980) found that adding a capping layer of

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Fig. 1. 4-sided RDC module (Broons).

material containing a granular/cohesive mixture could reduce lateral shearing effects and aided traction of the module for typical towing speeds. Clifford (1978) described a case study where an insufficiently thick capping layer was adopted which resulted in individual impact blows punching through to the underlying dredged fill; the site was also divided into a series of small working areas in which the roller was unable to maintain a towing speed within the typical range. According to Clifford (1978), both factors cause a reduction in speed and are the key reasons that better results could not be obtained.

Clifford (1980) discussed that there is an upper speed limit beyond which an impact blow is not delivered by the face of the module. At towing speeds greater than the typical range, Clifford (1980) stated that the roller can spin as a circular mass and only contact the ground with its corners, a condition that should be avoided. Avsar et al. (2006) described the compaction of a 22-km^2 reclamation area for the new Doha International Airport Project. They identified towing speed as one of the most important indicators that directly influenced the in situ dry density that could be achieved; an optimum towing speed of the 4-sided roller for that project was found to be 11 km/h. Chen et al. (2014) conducted a laboratory investigation on a scale model impact roller device in loose dry sand, by examining the effect of module weight, size and towing speed. They used a Chinese cone penetration test to confirm that towing speed was one of the most important factors contributing to the effectiveness of the impact roller. The aforementioned cases generally support the concept that towing speed influenced the effectiveness, as did the findings of Scott and Suto (2007), who stated that ground near the perimeter of a fenced site could not be improved as successfully as the rest of site due to access-related issues that reduced the towing speed of the module. This paper presents the findings of two full-scale field trials that were undertaken to quantify the effect of towing speed for the 4-sided impact roller.

2. Testing methodology

Each time the module of an impact roller strikes the ground, a pressure wave is created that travels through the soil from the surface. A key aim of the trial is to measure the loading-induced stresses below the ground due to RDC. EPCs allow real-time measurements of stresses imparted to the ground. Rinehart and Mooney (2009) successfully used Geokon Model 3500 semiconductor type EPCs in a field trial to measure dynamic loading induced from vibratory circular drum rollers. They used 100 mm-diameter cells that were 10 mm thick with normal stress measurement ranges of 250 kPa, 400 kPa and 1000 kPa. The same type of cells were selected to measure the pressure imparted into the soil due to RDC, albeit 230 mm-diameter cells of 6 mm thickness with a normal stress measurement range of 6000 kPa to capture the expected higher loads from the impact roller.

It has been well documented by researchers (e.g. Weiler and Kulhawy, 1982; Rinehart and Mooney, 2009) that a buried cell can influence localised stress fields and therefore any measurements may not be representative of the true loading-induced stresses. They discussed that errors can be minimised via the choice of pressure cell design, by undertaking calibration and by the use of correct field placement techniques. Given the challenges associated with measuring in situ stress accurately, it was important to characterise the uncertainty in the measurement techniques adopted. A whole system calibration was performed both pre- and post-testing, whereby the worst-case scenario was a difference of 8.5%. This magnitude of error is generally consistent with that reported by Dave and Dasaka (2011) who compared different calibration techniques for EPCs and stated that pressure cell output could be considered reliable within an error of approximately 10%. The dynamic frequency response (peak capture) was affected by the data acquisition rate and any internal filtering used in the signal path. The data acquisition rate selected was 2000 samples per second, and the filter used was set at 800 Hz. Fast Fourier transform analysis of the data indicated that the fundamental frequency of impulses due to RDC was less than 800 Hz, confirming that the peak values were not attenuated by the adopted filter.

2.1. Trial A

A field trial was undertaken at Monarto Quarries, located approximately 60 km southeast of Adelaide, South Australia. The test site was primarily chosen because there was access to earthmoving equipment, and importantly, homogeneous quarry material was used for the field trial. An area within the quarry where the ground was flat, close to material stockpiles, yet away from quarry operations was chosen for the trial. Natural soil was removed to a depth of 1.75 m, over a plan area that was 10 m long and 5.5 m wide. Three Geokon Model 3500 EPCs were buried at nominal depths of 0.5 m, 1 m and 1.5 m within the quarry fill material that was placed in seven lifts of 250 mm thickness. Bedding sand was placed immediately below and above each pressure cell to ensure horizontal placement and to prevent gravel sized particles of the fill material from damaging the cells. Each lift was wheel-rolled using a Volvo L150E loader; a vibrating plate compactor was used to compact soil within 250 mm from each EPC to prevent possible damage.

2.1.1. Material classification

The fill material placed for the trial was a crushed rock with a maximum particle size of 20 mm that was readily available and locally produced. A summary of the particle size distribution and Proctor compaction test results for Trial A is given in Table 1. For Trial A, particle size distribution (ASTM D6913-04(2009), 2009) results are the average of nine tests, and the standard (ASTM D698-12, 2012) and modified (ASTM D1557-12, 2012) Proctor compaction results are the average of three curves. The field moisture content (ASTM D2216-10, 2010) reported is the average of nine tests undertaken. Atterberg limit testing (ASTM D4318-10, 2010) confirmed that the fines consisted of clay of low plasticity. According to the Unified Soil Classification System (USCS), the fill material used for this compaction trial could be described as well-graded gravel (GW).

The aim of Trial A undertaken in August 2012 was to measure the loading-induced stress at three different depths for 40 passes in total; 10 passes of the roller were conducted at each of the towing speeds of 9, 10, 11 and 12 km/h. Towing speed was controlled via the control panel in the towing unit (i.e. tractor) but was subsequently validated by dividing the distance between EPCs by the

Table 1
Particle size distribution, compaction and field moisture test results of 20 mm crushed rock fill material for Trials A and B.

Trial	d_{50} (mm)	Gravel size (%)	Sand size (%)	Fines (%)	Standard OMC (%)	Standard MDD (kN/m^3)	FMC (%)	Modified OMC (%)	Modified MDD (kN/m^3)
A	4	57	40	3	7.9	17.9	8.6	7.2	18.9
B	3.5	58	38	4	12.6	19.2	9.6	10	19.8

Note: d_{50} = particle size at percent finer of 50%; OMC = optimum moisture content; MDD = maximum dry density; FMC = field moisture content.

time interval between the peak pressures that were measured. Three EPCs were used to measure the pressure imparted to the ground, each offset by one-half of one revolution of the module (2.9 m) in the forward direction of travel. Avalle et al. (2009) used buried instrumentation to capture the ground response of the 4-sided impact roller and their work found that the time during which the impulse load occurred was less than 0.1 s. They found that a sampling frequency of 2 kHz was sufficient to capture the rapid increase in pressure caused by impact from RDC and this same sampling frequency is adopted for the field trial presented in this paper. The selection of thin EPCs used in the present trial provides a much more reliable measurement of in situ soil stress than the bulky load cell used by Avalle et al. (2009), which is significantly stiffer than the surrounding soil.

2.1.2. Assessment of EPC results

Fig. 2 presents example results of the measured pressures versus time for a single pass of the impact roller travelling across the test site. The order in which the three traces were recorded is a function of the physical placement of the EPCs in the ground; 1.5 m depth located farthest left, 1 m depth in the middle and 0.5 m farthest right. The largest peak pressure was observed for the EPC buried at 0.5 m depth, whereas the deeper pressure cells at 1 m and 1.5 m depths recorded smaller impulses, indicating that the pressure imparted into the soil reduces in magnitude and increases in area with greater depth, as expected. Fig. 3 highlights a single impact blow measured by an EPC, where a loading-induced peak pressure of 648 kPa was recorded at 0.5 m depth. Fig. 3 demonstrates the dynamic nature of RDC and the importance of adopting a 2 kHz sampling frequency is evident from the individual data points shown, given that the loading and unloading phases occur over a time period of approximately 0.045 s.

Fig. 4 presents the relationship between the measured peak pressures versus depth for each of the towing speeds examined, with an increasing trend between the peak pressure and towing speed evident for all depths measured, and a decrease in pressure with depth, as one would expect. As can be observed from these results, a clear relationship exists between measured pressure and towing speed, with the slowest speed of 9 km/h yielding the lowest pressures, and progressively increasing with greater speed. Fig. 5 presents the results of the measured peak pressure plotted against offset distance for all depths, whereby the offset distance is defined as the distance between the centre of the module and the centre of the buried EPC. From this figure, it can be observed that, at shallow depths, offset distance has a large influence on the peak pressure recorded. However, with increasing depth, the effects of offset distance are less pronounced, suggesting a greater radial effect away from the centre of impact as depth increases. For an EPC depth of 0.5 m, offset distances between −100 mm and 400 mm generated the greatest pressures, apart from an anomalous result at an offset of −275 mm, and two other offsets that coincide with the corners of the module (−650 mm and 650 mm). This finding is generally consistent with Avalle et al. (2009), who found that the zone of maximum impact was located from 0 mm to 400 mm from the centre of the module. In order to further examine the effects of towing speed, an additional field trial was undertaken.

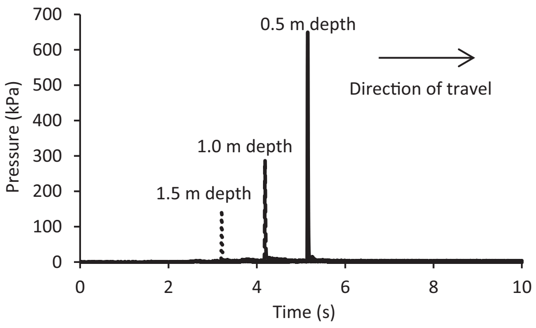

Fig. 2. Example results for a single pass of the impact roller over buried EPCs.

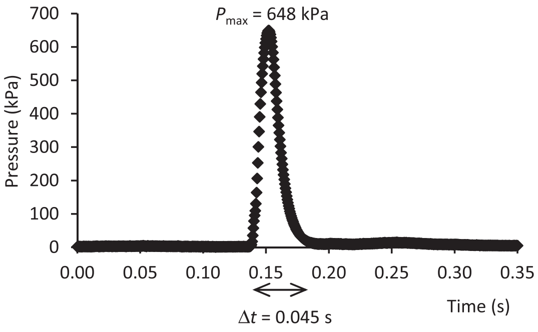

Fig. 3. Measured impulse pressure at 0.5 m depth.

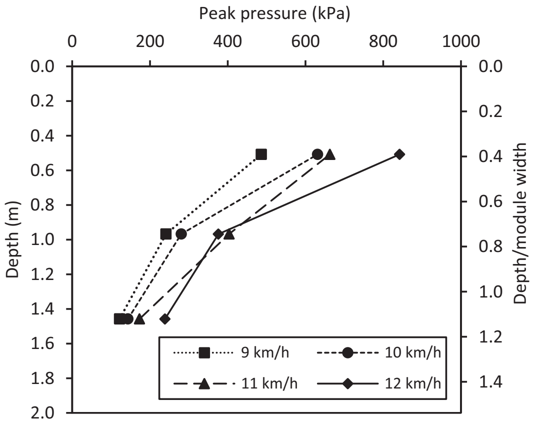

Fig. 4. Measured peak pressure increasing with towing speed.

2.2. Trial B

Field Trial B was undertaken at Monarto Quarries during August 2014, albeit at a different location from Trial A. Natural soil was removed to a depth of 1.2 m, over a plan area 12 m long and 3 m wide. Three Geokon Model 3500 EPCs were placed at a constant depth of 0.8 m. Quarry fill material was placed in six equal lifts of

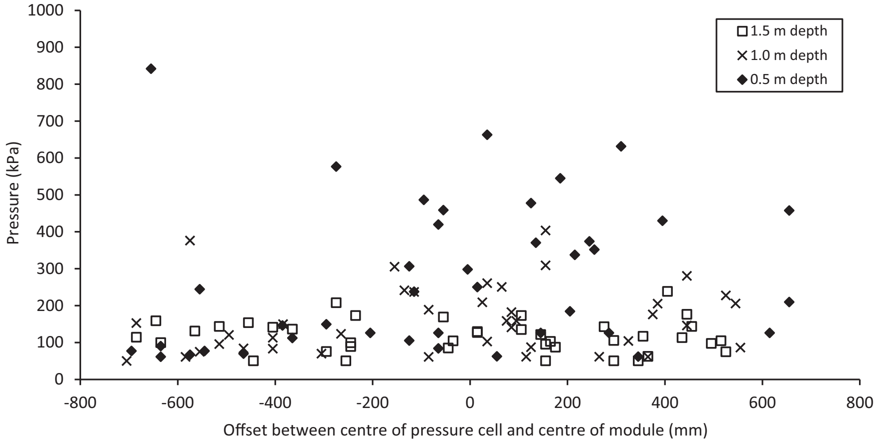

Fig. 5. Non-uniform pressure distribution measured at 0.5 m, 1 m and 1.5 m depths.

200 mm thickness, with each lift again being wheel-rolled using a Volvo L150E loader and a vibrating plate compactor used to compact soil within 200 mm from each EPC. The aim of the field trial was to measure the loading-induced stress at a single depth for 100 passes in total; 35 passes of the roller were conducted at a towing speed of 12 km/h prior to comparative EPC measurements being undertaken to achieve effective refusal. Five passes were conducted at each of the following towing speeds and in the following order: 12, 10, 8, 6, 9, 7, 5, 11, 14, 13 and 15 km/h, respectively. Due to time constraints, no EPC measurements were recorded between passes 90 and 100.

2.2.1. Material classification

The fill material placed for the trial was a crushed rock with a maximum particle size of 20 mm that was readily available on site. A summary of the particle size distribution (ASTM D6913-04(2009), 2009) and standard (ASTM D698-12, 2012) and modified (ASTM D1557-12, 2012) Proctor compaction test results for Trial B is given in Table 1. The test results indicate that the material is similar to that used in Trial A; however, there are differences which can be attributed to the two-year interval between trials, different weather conditions at the time of testing, and the material being sourced from different parts of the quarry. For Trial B, the particle size distribution results are the average of seven tests, and the standard and modified Proctor compaction curves were generated using a minimum of five data points each; both laboratory compaction curves were generated five times. The field moisture content reported is the average of 30 tests undertaken. According to the USCS, the fill material is again classified as well-graded gravel (GW). Atterberg limit testing confirmed that the fines consisted of clay of low plasticity.

Density measurements and other in situ tests were not undertaken during either field trial presented in this paper. However, the authors carried out in situ test from pre- and post-compaction in very similar soil conditions as this study during a separate field trial that was also conducted at Monarto Quarries. The results have been published in Scott et al. (2016). It is acknowledged that only undertaking pre- and post-compaction testing provides limited information regarding changes in soil state with increasing compactive effort; however, such testing regimes are common as they are effective at determining whether a project specification has been met, or otherwise. A recently published paper by Scott et al. (2019) captured the ground response of a single module impact in real-time using buried EPCs and accelerometers.

2.2.2. Assessment of EPC results

Fig. 6 presents the minimum, maximum and average peak pressures that were recorded at varying towing speeds. As mentioned above, five passes were conducted at each target towing speed, with each pass traversing over three EPCs at a uniform depth of 0.8 m, resulting in 15 data points per towing speed. It can be observed that at towing speeds lower than 9 km/h, significantly lower pressure is imparted to the soil. The maximum pressure (1220 kPa) was recorded at a towing speed of 14 km/h and the highest average peak pressure (646 kPa) at a towing speed of 11 km/h. Large pressure variations were measured for the same towing speed due to limitations of using EPCs that are buried at fixed locations. The location of the centre of the module landing on the ground surface relative to the centre of a buried EPC is variable. As discussed by Avalle et al. (2009), this variability is something unable to be controlled (despite some attempts at trying to do so). As discussed by Scott et al. (2016), whilst the module is nominally a “square”, the sides have curved features, and this results in a non-uniform pressure distribution and is a key contributing factor why some passes yielded much larger peak pressures for the same towing speed than others.

Fig. 7 presents the same data set, plotted instead with peak pressure versus offset distance. Adjacent speeds have been combined to yield 30 data points for each line. It can be observed that, for increasing towing speed, greater pressure is imparted to the ground up to 11–12 km/h. For speeds of 13–14 km/h, the shape of the pressure versus offset relationship is in contrast to the other towing speeds, indicating that the corners of the module impart the greatest pressure. This suggests that the behaviour of the module changes with increasing towing speed, which is consistent with the

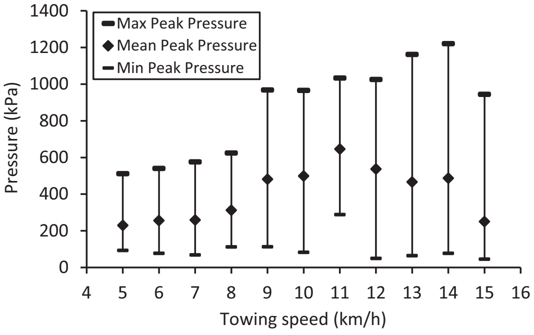

Fig. 6. Minimum, maximum and average peak pressures for varying towing speeds.

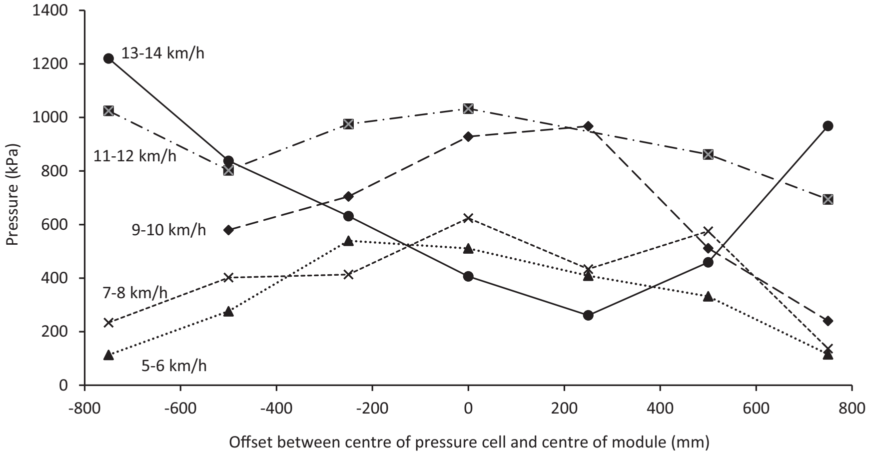

Fig. 7. Large variation in peak pressure for varying offset distances and towing speeds.

findings of Clifford (1980) as discussed earlier. In contrast, at slower speeds, the module face produces the greatest impact. Fig. 8 shows a plot of the peak pressure versus normalised time for the odd-numbered towing speeds. The largest peak pressure (1160 kPa) was recorded at a towing speed of 13 km/h.

To confirm the observations from the pressure cell data, a number of qualitative behaviours were observed; at lower towing speeds, the blows were delivered by the face of the module, which maintained a regular contact pattern with the ground. At faster speeds, the blows were delivered towards the corners, and the module was observed to skip along the surface from corner to corner, which is again consistent with the findings from Fig. 7 and Clifford (1980). The spacing between successive blows of the roller module was also monitored and physically measured on site. The module imprint length was measured to be significantly larger than the physical face length (1450 mm) of the module for towing speeds greater than 13 km/h as indicated in Fig. 9, implying non-uniform rotation and skipping behaviour. Bradley et al. (2019) used high-speed photography that captured the kinematics of the 4-sided module at 1000 frames per second. The field work undertaken by Bradley et al. (2019) is highly relevant to the field work of this study even though the two field trials had different aims and motivations and were undertaken on separate (adjacent) test areas within the Monarto Quarries site. There are strong similarities between the two; both field trials were held concurrently, allowing the same 4-sided impact roller to be used and fill material from the same stockpile to be used. The study by Bradley et al. (2019) captured the motion and estimated the kinematic profile of the module during impact to estimate the energy imparted to the ground (23 kJ ± 4 kJ) for a constant towing speed of 10 km/h that was adopted during the trial.

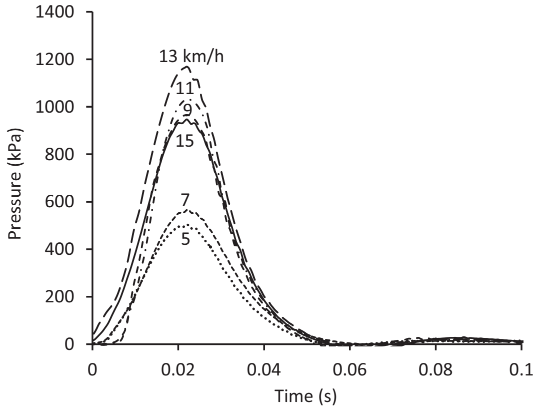

Fig. 8. Duration of pressure impulse not greatly influenced by towing speed.

3. Discussion

In this paper, towing speed refers to the horizontal motion of the towing unit, whereas rotational velocity refers to the angular velocity of the module. To quantify the difference between the two, Clifford and Bowes (1995) presented theoretical analyses from independent mathematicians who predicted the change in rotational velocity of the module as it falls to impact the ground. They claimed that towing speed was more significant than other factors such as module mass or lift height. Whilst the use of load cells is referenced in their paper, no experimental results were included to confirm their findings. Clifford and Bowes (1995) used high-speed photography to support their calculations regarding the change in angular velocity of the module during the lifting and falling phases of each impact for a constant towing speed. They explained that a key reason why the angular velocity of the module is not constant (unlike the towing speed) is due to the double-spring-linkage system on the 4-sided impact roller. Clifford and Bowes (1995) explained that the module velocity is slowed during the lifting phase as the springs of the double-linkage system are compressed. This causes the module to lag a little behind the towing frame that is travelling at a constant speed. During the impact phase, the springs are then discharged which cause the module to move faster than the towing frame as the spring energy is released. Whilst no results of the high-speed photography were presented in their paper, they claimed that the spring energy resulted in a decrease in rotational velocity during lifting, and an increase in module velocity during the falling phase. They found that the magnitude of change in module rotational velocity was inconsistent and was dependent upon soil surface irregularities. Their calculations proposed that the energy delivered by the 4-sided roller during a single impact can be described by kinetic energy, estimated to be up to 50 kJ, depending upon their assumptions made regarding the velocity of the module upon impact with the ground, v_f.

McCann (2015) used 3- and 5-sided modules and presented an alternative viewpoint, stating that the magnitude of the gravitational potential energy provides a reasonable estimate of the energy delivered by the 3-sided roller. McCann (2015) cited the work of Heyns (1998) who undertook both theoretical and empirical analyses. Heyns (1998) placed an accelerometer on the axle of a 3-

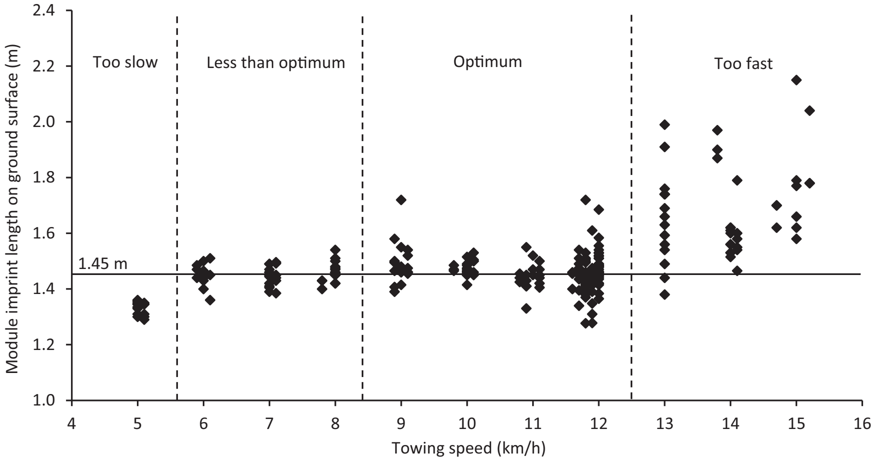

Fig. 9. Inconsistent module imprint length on ground surface with increasing towing speed.

sided impact roller to measure the magnitude of the peak deceleration of the module as it impacted the ground. Heyns (1998) used dynamic compaction theory from Mayne and Jones (1983) to infer the energy imparted to the ground based on the measured peak deceleration. Whilst good agreement between estimated and measured accelerations was noted by Heyns (1998), both are fundamentally based on dynamic compaction theory. The use of this theory without modification for RDC applications is questionable and requires further research. Heyns (1998), cited by Berry (2001), observed that an increase in towing speed resulted in an increase in energy imparted to the ground, but it was not the major component of the energy for towing speeds tested between 9 km/h and 14 km/h. After losses were taken into account, Heyns (1998) concluded that the magnitude of the gravitational potential energy, PE_g (Eq. (1)), was a reasonable estimate for the energy delivered by the 3-sided roller to the ground. If this theory is applied to a 4-sided impact roller with a module mass, m, of 8-tonne and a maximum module drop height, h, of 0.15 m, the estimated energy imparted to the ground would be approximately 12 kJ.

$$PE_g = mgh \tag{1}$$

where g is the gravitational acceleration.

Clearly, there is a need for further research as this finding is in stark contrast with that of Clifford and Bowes (1995) who estimated the energy for a single impact using total kinetic energy, KE (Eq. (2)), based on an 8-tonne module mass, m, and a module landing velocity, v_f, that was assumed to be greater than the towing speed.

$$KE = \frac{1}{2}mv_f^2 \tag{2}$$

The fact that Clifford and Bowes (1995) analysed a 4-sided roller and Heyns (1998) analysed a 3-sided roller may, to some extent, explains the disparity in results. The standard 4-sided impact roller, as shown in Fig. 1, consists of a single 8-tonne module that is 1300 mm wide, 1450 mm high and rotates with the aid of a double-spring-linkage system. The standard 3-sided impact roller, as shown in Fig. 10, consists of twin 6-tonne modules that are each 900 mm wide and 2170 mm high that rotate about a fixed axle with the aid of a hydraulic accumulator. The concept of energy storage upon lifting and release on impact theoretically increases the potential energy imparted to the ground; however, there is little, if any, published information that quantifies the magnitude of the energy that can be stored and released by either the double-spring-linkage system or the hydraulic accumulator.

Fig. 10. 3-sided RDC module (source: Landpac.com).

In an attempt to quantify the effects of the spring-linkage system, Clifford and Bowes (1995) analysed the change in angular velocity of the module before and after impact. They did not, however, quantify the contribution of spring energy in terms of the potential energy imparted to the ground. Whilst differences in impact roller configuration may account for some of the disparity in the estimates provided by Heyns (1998) and Clifford and Bowes (1995), there is clear disagreement as to whether the use of potential energy or kinetic energy provides more accurate estimates. It is also apparent that research is required to determine the effects of the double-spring-linkage system and the hydraulic accumulator to be able to accurately quantify the total potential energy delivered by the 4- and 3-sided impact rollers, respectively.

From both field trials undertaken, it is evident that the towing speed of the module influences the pressure imparted to the ground, suggesting that gravitational potential energy alone does not accurately capture the ground response of RDC. Whilst Heyns (1998) found that towing speed influenced the energy imparted to the ground at towing speeds higher than the typical range, these findings present compelling evidence that the magnitude of the energy imparted to the ground is a function of towing speed, even within the typical operating range of 9–12 km/h. Clifford and Bowes (1995) argued that module speed was a critical parameter, and that the continuous rolling action must be more beneficial than the equivalent falling weight that relied solely on gravitational potential energy. However, the magnitude of peak pressures measured in the ground with changes in towing speeds strongly suggests that the use of total kinetic energy does not accurately describe it either. If it did, greater changes in pressure would have been evident with varying speed. The observations indicate that total kinetic energy overestimates the contribution of towing speed, and therefore does not provide a reliable estimate of the energy imparted to the ground. Combining the findings of past research and the trials presented in this paper, the energy imparted to the ground appears to be a function of both potential and kinetic energies. To determine the magnitude of energy imparted to the ground by a single blow, it is necessary to analyse the potential and kinetic energy before and after impact in more detail, which is addressed below.

3.1. *Energy imparted by RDC*

In order to estimate the energy imparted to the ground as a consequence of RDC, the conclusions from the high-speed photography undertaken by Clifford and Bowes (1995) are adopted. They indicated that, when compared to the average, the module velocity decreased by 10–20% during the lifting phase of the module, and increased by 10–20% during the falling phase. The module frame is towed at a relatively constant speed, therefore the speed of the module after impact with the ground is slower than that prior to impact, but is not zero as implied by Clifford and Bowes (1995) for their use of total kinetic energy to be correct. For calculation purposes, a module mass, m, has a velocity increase of $+10\%$ prior to impact, v_i, and a velocity decrease of -10% after impact, v_f, when compared to the average. These correspond to lower bound values stated by Clifford and Bowes (1995), to determine the work done due to the change in kinetic energy, W_ke, which is equal to ΔKE, as defined using Eq. (3). The results are presented in Table 2.

$$W_\mathrm{ke} = \Delta KE = \frac{1}{2}mv_i^2 - \frac{1}{2}mv_\mathrm{f}^2 \tag{3}$$

The change in potential energy, ΔPE_g, is equal to the work done due to gravity, W_g, therefore, the module falling to the ground surface can be described by Eq. (4), in which the module drop height after impact, h_2, is equal to zero; hence for an 8-tonne mass, m, and a lift height (h_1) of 0.15 m, $\Delta PE_\mathrm{g} \approx 12$ kJ.

$$W_\mathrm{g} = \Delta PE_\mathrm{g} = mgh_1 - mgh_2 \tag{4}$$

It should be emphasised that Eq. (4) gives the maximum potential energy that can be delivered to the ground. This energy will not be delivered with every impact as the full gravitational potential energy will only be reached when the module is compacting soil that is hard enough to allow the full lift height to be achieved. It is noted that using high-speed photography will also capture changes in module velocity due to the spring-linkage system, or due to energy losses in the system (such as frictional forces that act between the module and the ground surface). The net work done, W, as described by Eq. (5), is a combination of both the change in potential and kinetic energies, as work is being done against gravity, as well as inertia and frictional resistive forces, and is considered a more appropriate means to describe the energy delivered by RDC, rather than relying solely on gravitational potential or total kinetic energy.

Table 2
Predicted change in kinetic energy based on high-speed photography by Clifford and Bowes (1995).

v (km/h)	v (m/s)	v_i (m/s)	v_f (m/s)	ΔKE (kJ)
8	2.22	2.44	2	7.8
9	2.5	2.75	2.25	10
10	2.78	3.06	2.5	12.5
11	3.06	3.36	2.75	14.9
12	3.33	3.67	3	17.8
13	3.61	3.97	3.25	20.8

Note: v = speed of towing unit.

$$W = \Delta PE + \Delta KE \tag{5}$$

The high-speed photography approach used by Clifford and Bowes (1995) quantified the spring energy in terms of a change in module rotational velocity as the springs are compressed and subsequently released. However, spring energy, as defined by Halliday et al. (1993), is a form of potential energy, therefore the contribution of the dual springs in the linkage system should, more appropriately, be quantified in terms of potential energy.

3.2. *Contribution of the spring-linkage system*

The double-spring-linkage system consists of two springs: a large outer spring and a smaller inner spring that fits within the internal diameter of the larger spring. To determine the contribution of each of the springs to the energy imparted by the module, the stiffness of both springs was determined. Each spring was placed separately in a large compression machine whereby the load versus displacement response was quantified. The maximum compression of the dual springs was governed by the limiting compression distance of the outer spring, as both springs compress together in the towing frame. The force in the spring is determined using Hooke's law in Eq. (6), where the spring force, F_s, is a function of the spring stiffness, k, and the compression distance of the spring, x:

$$F_\mathrm{s} = -kx \tag{6}$$

Based on Halliday et al. (1993), the work done by a spring, W_s, can be determined by

$$W_\mathrm{s} = \int_{-x_\mathrm{max}}^{0} F_\mathrm{s}\mathrm{d}x = \frac{1}{2}kx_\mathrm{max}^2 \tag{7}$$

where x_max is the maximum spring compression. Using Eq. (7), it is possible to determine the work done, W_s, by both the inner and outer springs with varying spring compression distances up to the maximum (limiting) compression, x_max. Whilst having different spring stiffnesses, k, both the inner and outer springs compress by the same magnitude in the double-linkage mechanism, the work done by the springs is equal to the change in spring potential energy, ΔPE_s, as described by

$$W_\mathrm{s} = \Delta PE_\mathrm{s} = \left(\frac{1}{2}kx_\mathrm{max}^2\right)_\mathrm{inner} + \left(\frac{1}{2}kx_\mathrm{max}^2\right)_\mathrm{outer} \tag{8}$$

The outer spring was found to contribute 84% of the work done by the dual springs combined, due to the larger spring stiffness ($k = 370$ N/mm), compared to the inner spring ($k = 70$ N/mm). As observed in Fig. 11, the work done by the springs is approximately 5 kJ at the maximum spring compression. This is the maximum energy that the springs are able to deliver, but the full potential energy of the springs will not be delivered with every blow, as both the geotechnical properties of the ground and the undulating surface profile significantly affect the behaviour of the module.

A summary of the work done with varying speed is presented in Fig. 12. It is observed that the change in gravitational and spring potential energies is constant for all speeds. The maximum spring energy is more likely to be realised at faster towing speeds; however, further research involving more direct measurement techniques is needed to confirm this. As stated previously, the change in kinetic energy, as quantified by Clifford and Bowes (1995), accounts

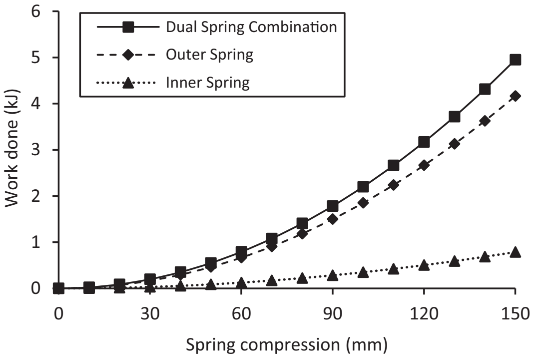

Fig. 11. Energy contribution of the dual springs in the linkage system of the 4-sided impact roller.

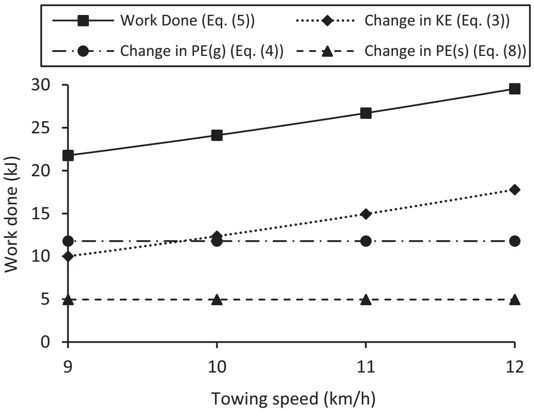

Fig. 12. Increasing energy for typical towing speeds of the 4-sided impact roller.

for spring effects and this is supported by Fig. 12, where $\Delta PE_S < \Delta KE$. Without taking into account the spring energy contribution twice, the total work done is equal to the sum of the change in gravitational potential, and kinetic energies (Eq. (5)). This yields values of total work done between 22 kJ and 30 kJ for typical towing speeds of 9 km/h and 12 km/h, respectively. For the same speeds, Clifford and Bowes (1995) predicted 30 kJ–54 kJ, respectively, using Eq. (2) and assuming that the spring-linkage system increases the landing velocity of the module by 10%. The predicted energy that is imparted to the ground by Bradley et al. (2019) does support the assumptions made by Clifford and Bowes (1995) regarding the relationship between towing speed and module velocity that were used in this study to estimate the change in kinetic energy. Bradley et al. (2019) quantified the change in energy due to a single module impact from high-speed photography, and estimated that the energy imparted to the ground due to a single module impact was 23 kJ (±4 kJ) for a towing speed of 10 km/h, consistent with the findings of this study.

4. Conclusions

This paper examined the effect of towing speed on the energy imparted to the ground from the 4-sided impact roller. This involved combining theory from Halliday et al. (1993), observations from two full-scale field trials, high-speed photography by Clifford and Bowes (1995), and estimates of energy imparted to the ground for the 3-sided roller by Heyns (1998). The maximum imparted energy delivered to the ground by the 4-sided impact roller was found to lie in the range between 22 kJ and 30 kJ, for typical towing speeds of 9–12 km/h.

It is proposed that the energy imparted by RDC to the ground needs to be considered in terms of work done, which is due to the change in both potential and kinetic energies. Current practice of describing the energy imparted to the ground using total kinetic energy should be avoided as it overestimates the energy imparted to the ground. Describing the energy via the use of gravitational potential energy should also be avoided, but for a different reason; it is counter-productive for the impact rolling industry to develop specifications stipulating target towing speeds when the rollers are described solely in terms of their gravitational potential energy.

The change in potential energy is derived from a combination of both gravitational and spring energies for the 4-sided impact roller. The values presented in this paper for the potential energy delivered by the springs (5 kJ) and gravitational potential energy (12 kJ) are the maximum values that are theoretically possible. However, they are not values that will be achieved with every impact, as favourable ground conditions are needed for the full potential energy to be delivered. The change in kinetic energy is a function of the friction between the module and the ground surface. Quantifying the friction at the module–soil interface is extremely difficult to evaluate theoretically, as it depends on several variables associated with the module, such as the roughness of the module face in contact with the ground, the presence of wear plates or anti-skid bars, the contact area between the module and soil, and the towing speed. Properties relating to the ground are also significant, with soil type, grading, moisture content, density, elastic modulus and surface geometry all providing different frictional resistance, which makes it complex and extremely difficult to estimate the energy needed to overcome friction as it is material-dependent.

If the energy imparted to the ground was only due to potential energy, then it would be theoretically independent of towing speed and would be limited to a maximum value of 17 kJ. The findings of this research confirm that towing speed does influence the energy imparted to the ground. There is, therefore, a need for specifications to detail a target towing speed range for RDC. Based on the authors' experiences, the optimum speed will vary depending on site conditions. To optimise the use of the 4-sided impact roller, a towing speed range of 10–12 km/h is recommended, which is consistent with the findings of the field trials reported in this paper.

Declaration of Competing Interest

The authors wish to confirm that there are no known conflicts of interest associated with this publication and there has been no significant financial support for this work that could have influenced its outcome.

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References

ASTM D6913-04(2009). Standard test methods for particle-size distribution (gradation) of soils using sieve analysis. West Conshohocken, PA, USA: ASTM International; 2009.

ASTM D2216-10. Standard test methods for laboratory determination of water (moisture) content of soil and rock by mass. West Conshohocken, PA, USA: ASTM International; 2010.

ASTM D4318-10. Standard test methods for liquid limit, plastic limit, and plasticity index of soils. West Conshohocken, PA, USA: ASTM International; 2010.

ASTM D698-12. Standard test methods for laboratory compaction characteristics of soil using standard effort. West Conshohocken, PA, USA: ASTM International; 2012.

ASTM D1557-12. Standard test methods for laboratory compaction characteristics of soil using modified effort. West Conshohocken, PA, USA: ASTM International; 2012.

Avalle DL, Scott BT, Jaksa MB. Ground energy and impact of rolling dynamic compaction – results from research test site. In: Proceedings of the 17th International Conference on Soil Mechanics and Geotechnical Engineering, Vol. 3, Alexandria, Egypt; 2009. p. 2228–31.

Avsar S, Bakker M, Bartholomeeusen G, Vanmechelen J. Six sigma quality improvement of compaction at the New Doha International Airport Project. Terra et Aqua 2006;103:14–22.

Berry AD. Development of a volumetric strain influence ground improvement prediction model with special reference to impact compaction (MS Thesis). Pretoria, South Africa: University of Pretoria; 2001.

Bradley AC, Jaksa MB, Kuo YL. Examining the kinematics and energy of the four-sided impact roller. Proceedings of the Institution of Civil Engineers – Ground Improvement 2019;172(4):297–304.

Chen Z, Xu C, Ye G, Shen C. Impact roller compaction of dry sand in laboratory tests. In: Proceedings of Geo-Shanghai, Ground Improvement and Geosynthetics, Shanghai, China; 2014. p. 258–69.

Clifford JM. An introduction to impact rollers. Internal report RP/2/75. National Institute for Road Research; 1975.

Clifford JM. Evaluation of compaction plant and methods for the construction of earthworks in southern Africa (MS Thesis). Durban, South Africa: University of Natal; 1978.

Clifford JM. The development and use of impact rollers in the construction of earthworks in southern Africa. CSIR Report 373. Pretoria, South Africa: National Institute for Transport and Road Research; 1980.

Clifford JM, Bowes G. Calculating the energy delivered by an impact roller. A trilogy of Papers for the Sept. 1995 Lecture Tour and International Seminars to commemorate the 10th Anniversary of the BH 1300 Standard Impact Roller, Paper Two. 1995.

Dave TN, Dasaka SM. A review on pressure measurement using earth pressure cell. International Journal of Earth Sciences and Engineering 2011;4(6):1031–4.

Ellis CI. Pavement engineering in developing countries. TRRL Supplementary Report 537. Crowthorne, Berkshire, UK: Transport and Road Research Laboratory; 1979.

Halliday D, Resnick R, Walker J. Fundamentals of physics. 4th ed. John Wiley & Sons; 1993. p. 182–250.

Heyns S. Response analysis of an impact compactor. Report LGI98/013, Project No 020-DP. Pretoria, South Africa: Laboratory for Advanced Engineering Pty Ltd., University of Pretoria; 1998.

Mayne PW, Jones JS. Impact stresses during dynamic compaction. Journal of Geotechnical Engineering 1983;109(10):1342–6.

McCann K. The use of impact compaction for the near surface compaction on dredged sand land reclamation projects. In: Proceedings of the 12th Australia New Zealand Conference on Geomechanics. Wellington, New Zealand: New Zealand Geotechnical Society; 2015. p. 1193–200.

Ranasinghe RATM, Jaksa MB, Kuo YL, Pooya Nejad F. Application of artificial neural networks for predicting the impact of rolling dynamic compaction using cone penetrometer test results. Journal of Rock Mechanics and Geotechnical Engineering 2017;9(2):340–9.

Rinehart RV, Mooney MA. Measurement of roller compactor induced triaxial soil stresses and strains. Geotechnical Testing Journal 2009;32(4):347–57.

Scott BT, Suto K. Case study of ground improvement at an industrial estate containing uncontrolled fill. In: Proceedings of the 10th Australia New Zealand Conference on Geomechanics. Brisbane, Australia: Australian Geomechanics Society; 2007. p. 150–5.

Scott BT, Jaksa MB. The effectiveness of rolling dynamic compaction – a field based study. In: Indraratna B, Chu J, Rujikiatkamjorn C, editors. Ground Improvement Case Histories: Compaction, Grouting and Geosynthetics. Kidlington, Oxford: Elsevier; 2015. p. 429–52.

Scott BT, Jaksa MB, Syamsuddin E. Verification of an impact rolling compaction trial using various in situ testing methods. In: Proceedings of the 5th International Conference on Geotechnical and Geophysical Site Characterisation. Sydney, Australia: Australian Geomechanics Society; 2016. p. 735–40.

Scott B, Jaksa M, Mitchell P. Ground response to rolling dynamic compaction. Géotechnique Letters 2019;9(2):99–105.

Weiler WA, Kulhawy FH. Factors affecting stress cell measurements in soil. Journal of Geotechnical Engineering 1982;108(12):1529–48.

Wolmarans CH, Clifford JM. An evaluation of the CSIR impact roller. In: Proceedings of the 6th Regional Conference for Africa on Soil Mechanics and Foundation Engineering, Durban, South Africa; 1975. p. 33–9.

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Depth of influence of rolling dynamic compaction

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The depth of influence of rolling dynamic compaction (RDC) was investigated in a field trial using a four-sided impact roller. Earth pressure cells (EPCs) were placed at varying depths at a site consisting of homogeneous soil conditions. EPCs measured pressures imparted by RDC at 3·85 m depth; however, the largest magnitudes of pressure were confined to the top 2 m beneath the ground surface. These results were complemented by field density data, penetrometer and geophysical testing. A number of published case studies using the 8 t four-sided impact roller, for either improving ground in situ or compacting soil in thick layers, are summarised in this paper. Finally, equations are presented that predict first, the effective depth of improvement, appropriate for determining the depth to which the ground can be significantly improved in situ, and, second, the depth of major improvement for RDC, appropriate for thick-layer compaction.

Notation

D	depth of soil compacted due to gravitational potential energy (m)
d_{50}	particle size at 50% per cent finer
$\boldsymbol{g}$	free-fall acceleration (9·81 m/s^2)
h	maximum module drop height (m)
k	ratio of energy imparted to the ground divided by the gravitational potential energy
m	module mass (t)
n	empirical factor in depth of improvement equation
r	reduction factor for determining the depth of major improvement
v	towing speed (m/s)
v_{f}	module velocity after impacting the ground (m/s)
v_{i}	module velocity prior to impacting the ground (m/s)
$\Delta\mathrm{KE}$	change in kinetic energy (kJ)

1. Introduction

There is an increasing need for civil engineers to provide cost-effective solutions for construction on marginal or difficult sites. In particular, an understanding of the advantages and limitations of ground-improvement options is essential to ensure that technically feasible and constructible solutions are adopted. Compaction is a prevalent ground-improvement technique that aims to increase the density of soil by applying mechanical energy to increase soil strength and decrease differential and total settlements within a desired depth range beneath the ground surface. This paper is concerned with a specific type of dynamic compaction known as rolling dynamic compaction (RDC), which involves traversing the ground with a non-circular roller. Typical module designs have three, four or five sides. As the module rotates, it imparts energy to the soil as it falls to impact the ground. High-energy impact compaction and high impact energy dynamic compaction are alternative names found in different parts of the world, or used by different contractors, for RDC.

When compared with circular drum rollers, RDC can compact thicker layers due to a greater depth of influence beneath the ground's surface. This is derived from a combination of a heavy module mass, the shape of the module and the speed at which it is towed; typically in the range of 9–12 km/h. Depths of improvement for RDC have been found to vary significantly and the factors that affect it are not fully understood. The depth of influence of RDC is often quantified by comparing in situ test results before and after compaction. However, at sites containing significant soil variability, the use of pre- and post-compaction testing can be problematic. To overcome this limitation, this paper describes a compaction trial where earth pressure cells (EPCs) were placed at different locations beneath the ground surface in homogeneous soil conditions to quantify the depths to which RDC improves the ground.

2. Background

Published case studies involving standard four-sided impact rollers that have improved the ground in situ and have compacted soil in thick layers are summarised in Tables 1 and 2, respectively. In addition to the referenced published articles, the authors reviewed dozens of unpublished reports on the use of a four-sided 8 t roller in a variety of soil conditions. Their findings are in general agreement with the improvement depths and layer thicknesses summarised in Tables 1 and 2, respectively. It is clear from Tables 1 and 2 that the depth of improvement of RDC varies significantly depending on the soil material type. It is reasonable to conclude that RDC has a greater depth of influence in granular soils than in clays. It is also evident that the thickness of compacted layers is less than the depth of improvement in the same soil type, as the compacted layer thickness is typically tailored to meet a target specification.

While not summarised in these tables, other variables such as moisture content, groundwater conditions and the number of passes applied also affect the depth to which ground can be improved using RDC. When reviewing Tables 1 and 2, it is important to note that the target specification, the testing methods used to quantify improvement and the interpretation of how the depth of improvement is both defined and quantified vary between the listed references, making it difficult to draw definitive conclusions as to the maximum improvement depth or layer thickness possible. In current practice, it is often the responsibility of the project engineer to predict whether the use of RDC will improve the ground sufficiently for the desired project application. The variable and unknown depth of influence of RDC is a key reason why this ground-improvement technique is not used more commonly, and highlights why further research is needed.

Kim (2010) performed finite-element simulations on impact rollers of different shapes with the aim of determining the stress distribution and influence depth, which was defined as the depth at which the vertical stress decreased to one-tenth of the applied stress at the surface. In that study, the module mass, diameter and width of each roller were held consistent; only the shape and number of sides varied. This study identified that the influence depth is a function of both the contact area and applied stress, with greater contact area and surface contact pressures resulting in increased depths of influence. A key limitation of this study, given the definition of influence depth adopted, was that the surface contact stresses modelled for impact rolling were not verified using field test results. Significantly, Kim's analysis illustrated stress wave propagation to depths much greater than those typically influenced by static loading. Nazhat (2013) analysed the behaviour of sand

Table 1. Improvement depths for compacting in situ

Reference	Soil type	Improvement depth: m
Clifford (1978)	Sand	>2·5
Clifford (1978)	Sand	>2·0
Avalle and Young (2004)	Fill (clay)	1·0
Avalle (2004)	Fill (sand)	>2·0
Avalle and Grounds (2004)	Fill (mixed)	1·5
Avalle and Mackenzie (2005)	Fill (clay)	2·0
Avalle and Carter (2005)	Fill (sand) over natural sand	3·0
Avalle (2007)	Fill (sand)	2·5
Scott and Suto (2007)	Fill (gravelly clay)	1·5
Whiteley and Caffi (2014)	Fill (mixed)	1·5
Scott and Jaksa (2014)	Fill (clayey sand) over natural clay	1·75

Table 2. Thickness of compacted layers

Reference	Soil type	Layer thickness: m
Wolmarans and Clifford (1975)	Sand	1·5
Wolmarans and Clifford (1975)	Clay	0·6
Clifford (1980)	Clay	0·5
Clifford and Coetzee (1987)	Fill (coal discard material)	0·5
Avalle and Grounds (2004)	Fill (gravel)	1·0
Avalle (2007)	Sandy clay/clayey sand	0·7
Scott and Jaksa (2012)	Fill (mixed)	1·0
Scott and Jaksa (2014)	Fill (clayey sand)	1·0

subjected to dynamic loading, and identified compaction shock bands by way of the use of high-speed photography and image correlation techniques from laboratory-based testing. As explained by Nazhat (2013), it is evident that improvements in the ability to measure and quantify dynamic effects are helping to increase knowledge of unseen processes beneath the ground surface; however, it is clear that more research is needed to fully understand the kinematic behaviour of soils subjected to dynamic loading.

3. Dynamic compaction

Dynamic compaction is a ground-improvement technique that usually employs a large crane to lift a heavy tamper, which is then dropped onto the ground in a regular grid pattern. Menard and Broise (1975) improved the mechanical characteristics of fine saturated sands using this method, and were the first to propose a relationship between the thickness to be compacted, D, the pounder mass, m, and the drop height, h, as given by

1. $$D = \sqrt{mh}$$

Menard and Broise (1975) observed that greater depths of improvement could be achieved for partially immersed soils than for soils completely out of water. The initial density and grading were factors that influenced the time taken to reach a liquefied state, after which the low-frequency, high-amplitude vibrations from dynamic compaction caused the sand particles to be reorganised into a more dense state. In subsequent years, this theory was applied to a wider range of soil conditions, including unsaturated soils, and it was found that in many cases the maximum depth of influence was less than that predicted by Equation 1. A number of different authors, including Leonards *et al.* (1980), Lukas (1980, 1995) and Charles *et al.* (1981), investigated the variation of an empirical factor (n) with different soil conditions and for varying drop heights, h, and pounder masses, m. The general consensus is that n varies with different soil conditions, with lower values for fine-grained soils and larger values for coarse-grained soils, resulting in varying estimations for the depth of improvement, as per Equation 2.

2. $$D = n\sqrt{mh}$$

Alternatively, Equation 2 can be re-written as shown in Equation 3. In this form, the right-hand side of the equation is a function of gravitational potential energy, mgh, and the material characteristics, described by the parameter n.

3. $$D = \sqrt{\frac{n^2}{g}(mgh)}$$

The value of n was investigated in detail by Mayne *et al.* (1984), who collated data from over 120 sites and found that n typically varied between 0·3 and 0·8, but could be as high as 1·0 in some instances. As explained by Mayne *et al.* (1984) and Lukas (1995), the variation in predicted depth of improvement is not simply a function of the tamper weight and drop height, but is also influenced by other variables such as the tamper surface area, total energy applied, contact pressure of the tamper, efficiency of the dropping mechanism, initial soil conditions and groundwater levels.

Applying Equation 2 to the range of plotted values for n (0·3–0·8) in Mayne *et al.* (1984) to an 8 t four-sided impact roller, using the maximum physical drop height of the module that is available on a flat surface ($h = 0{\cdot}15$ m), the depth of improvement predicted would be in the range of 0·33–0·88 m. Hamidi *et al.* (2009) applied Equation 2 to RDC and indicated that the use of this equation was subject to controversy as larger depths of improvement have been reported. Table 1 confirms the use of dynamic compaction formulae as under-estimating the improvement depths that are achievable using RDC. While the application of deep dynamic compaction theory to RDC without modification is not suitable, the use of a more appropriate n value does warrant further investigation, as both dynamic compaction theory and Table 1 indicate that soil type is a key variable that influences the depth of improvement.

For dynamic compaction applications, Slocombe (2004) defines the ‘effective depth of influence’ as being the maximum depth at which significant improvement is measureable. The ‘zone of major improvement’ is typically half to two-thirds of the effective depth of influence. As explained by Slocombe (2004), these terms have been adopted in the UK but may have alternative meanings in different parts of the world.

Impact rolling is routinely undertaken in unsaturated soils, whereby the application of mechanical energy expels air from the voids to reduce the void ratio. Within the influence depth of RDC, repeated loading-induced stresses imparted into a granular soil are sufficient to cause a permanent rearrangement of soil particles, resulting in increased density and soil settlement. Below the influence depth, the soil remains elastic and does not undergo volume change. Berry (2001) developed an elastoplastic model to determine the depth to which there was permanent deformation using surface settlement as the main input parameter. While Berry’s model did not quantify the energy to achieve a particular surface settlement, it was observed that a depth of three times the module width was considered appropriate for a three-sided impact roller. At sites with a shallow water table, it is possible for the high-amplitude and low-frequency vibrations associated with RDC to induce pore pressures to rise to the surface. In order to prevent liquefaction from occurring, the number of passes is typically limited to allow pore-water pressures to dissipate. Rather than competing with, impact rollers are often used to complement deeper ground-improvement techniques that leave soils within the top 2 m of the surface in a disturbed and weakened condition. Avsar *et al.* (2006) describe an example of a large land reclamation project whereby impact rolling successfully complemented deeper ground-improvement techniques.

In the work described in this paper, the depth to which RDC improves the ground measured in full-scale field trials in homogeneous soil conditions. The measured data were compared with predictions based on dynamic compaction theory to determine the relevance of this approach to RDC applications.

4. Field trial to determine depth of improvement

A field trial was conducted using a Broons BH-1300 8 t four-sided impact roller (Figure 1) at the Iron Duke mine located on the Eyre Peninsula in South Australia during June 2011. The test pad was constructed in three separate lifts, as illustrated in Figure 2, which also shows the locations of embedded EPCs in plan and elevation. The test pad was constructed using haul trucks, end tipping loose tailings material in stockpiles where a loader and excavator subsequently spread the material over the test pad. The placement process caused the soil to be partially compacted by the self-weight of the plant; however, this method was deemed representative of the proposed construction method for the mine site and therefore was consistent with the generic aim of the field compaction trial to be as representative as possible given the site constraints. As well as undertaking the trial for research purposes, to determine the depth of influence, there was a need to ascertain the layer thickness that could be placed to achieve a target density of 95% of maximum modified dry density for future projects at the mine.

Figure 1. 8 t four-sided impact roller

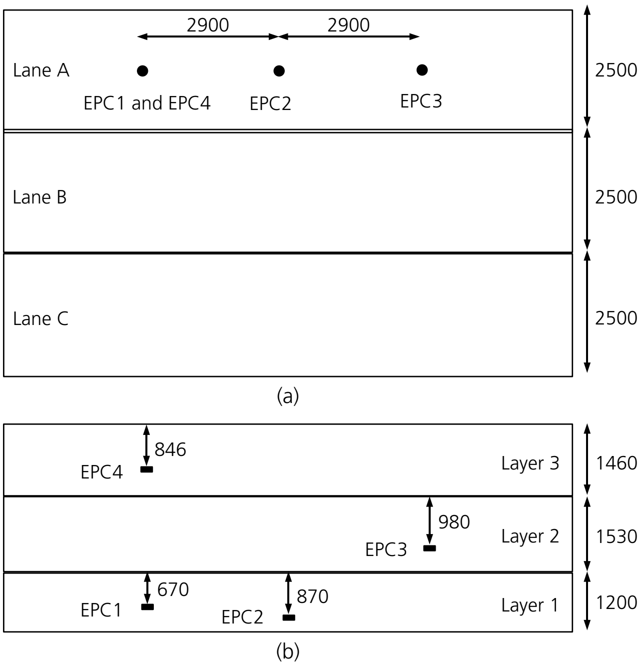


Figure 2. (a) Plan and (b) elevation views of test pad including EPC locations (all dimensions in mm)

4.1 Material classification

The test pad was constructed using iron magnetite tailings, which are a by-product of a consistent rock-crushing process. In order to classify and determine the compaction characteristics of the tailings, particle-size distribution tests were performed, as well as standard and modified compaction tests, the results of which are summarised in Table 3. The particle-size distribution (ASTM, 2009a) results are the average of nine tests and the standard (ASTM, 2007) and modified (ASTM, 2009b) Proctor compaction results are the average of three curves. The large dry unit weights are a consequence of the sand-sized particles consisting of crushed magnetite. The field moisture content (FMC) (ASTM, 2010a) reported is the average of 15 tests undertaken. Atterberg limit testing (ASTM, 2010b) confirmed that the fines consisted of clay of low plasticity (plastic limit 11% and liquid limit 22%). According to the Unified Soil Classification System, the fill material used for this compaction trial could be described as a well-graded sand (SW).

4.2 EPCs

Four Geokon model 3500 (230 mm diameter, 6 mm thick) EPCs were used to measure the dynamic pressures imparted by RDC. As shown in Figure 2, the initial lift (1200 mm thick containing buried EPC1 and EPC2) was first compacted; this was repeated for the second lift of 1530 mm (containing EPC3) and the third and final lift (1460 mm containing EPC4). In plan, the EPCs were placed one-half of one rotation of the roller apart (2·9 m) from each other in the forward

Table 3. Particle-size distribution, compaction and field moisture test results

Material	d_{50}: mm	Gravel: %	Sand: %	Fines: %	Standard optimum moisture content (OMC): %	Standard maximum dry unit weight: kN/m^3	FMC: %	Modified OMC: %	Modified maximum dry unit weight: kN/m^3
Magnetite tailings	0·7	14	80	6	6·6	23·9	5·1	5·7	25·8

d_{50}, particle size at per cent finer of 50%

direction of travel. The EPCs were connected to a bespoke data-acquisition system and the Labview software program (National Instruments, 2019). A sampling frequency of 2 kHz (i.e. one sample every 0·0005 s) was adopted to capture sudden increases in pressure caused by the module impacting the ground. Prior to compaction, the EPCs were used to measure the self-weight of the impact rolling module for the roller in an 'at rest' condition, centred above each EPC. The measured pressures were compared to predictions using Fadum's chart (Fadum, 1948) using elastic theory, the results of which are shown in Figure 3. The measured pressures followed the same general trend, but were less than the predicted pressures; the difference between the predicted and measured values was an average of 38% over the depths measured. The most likely explanation for this is that the non-uniform shape of the module face impacting the ground does not produce a uniform pressure distribution and this is exacerbated for shallow EPC depths. A towing speed of 10·5 km/h was selected for all 16 passes that were conducted on each layer. The staged construction process resulted in the dynamic pressure imparted by RDC to be measured at nine different depths.

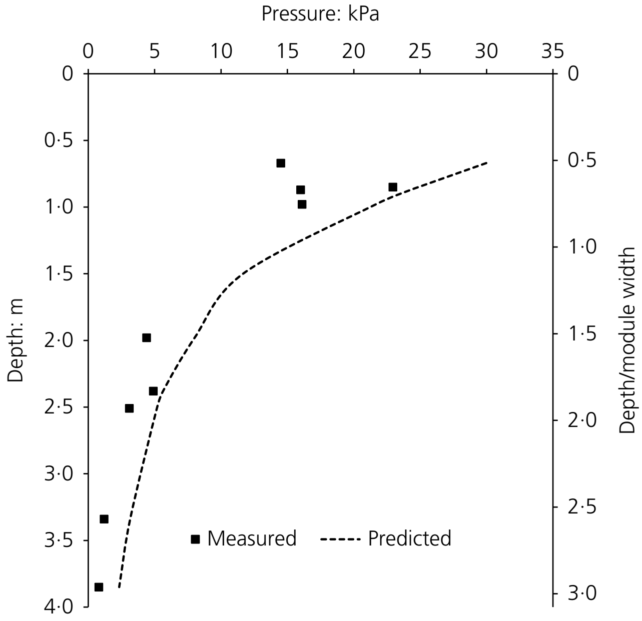


Figure 3. Measured and predicted pressures against depth for impact roller at rest

4.3 In situ testing

Various in situ testing methods were performed after 0, 8 and 16 passes to quantify soil improvement with increasing compactive effort. The in situ tests were undertaken in the centre of lane A in layer 3, as shown in Figure 2. The tests conducted included field density measurements (ASTM, 2008), the spectral analysis of surface waves (SASW) geophysical technique and dynamic cone-penetration (DCP) tests to measure and infer changes in density as a function of the number of module passes. SASW testing was conducted using a GDS Instruments surface wave system using six 4·5 Hz geophones spaced at 1 m intervals with a sledge hammer source impacting a metal strike plate 1 m from the first geophone. DCP testing was undertaken in accordance with the procedure described in AS 1289.6.3.3 (SA, 1997). Verification of RDC was also undertaken using settlement monitoring to quantify the change in ground surface level with the number of passes. This was achieved using a level and staff to measure settlement at nine points across the test pad in adjacent low points in the undulating surface, as is the normal practice. Due to space constraints, a discussion of testing methods generally employed to verify RDC is not presented here. They are however, discussed in detail by Avalle and Grounds (2004) and Scott and Jaksa (2008).

5. Results of the field trial

This section provides details of the results obtained from the field trial; specifically those obtained from the EPCs, in situ and geophysical testing and settlement monitoring.

5.1 EPC data

Figure 4 illustrates the results obtained for a typical pass of the impact roller traversing over the first lift of the test pad, where EPC1 and EPC2 were buried at depths of 0·67 and 0·87 m, respectively. As expected, the shallower EPC recorded the greatest pressure. Figure 5 presents the variation of measured peak pressure with depth, where it is observed that peak pressures greater than 100 kPa were recorded at depths above 2·0 m. The EPC results generally supported other test data that indicated that most of the quantifiable ground improvement occurred within 2 m of the surface. Even the deepest EPC (buried at a depth of 3·85 m below the ground surface) registered positive pressure readings due to the impact roller, suggesting that the depth to which RDC had an influence

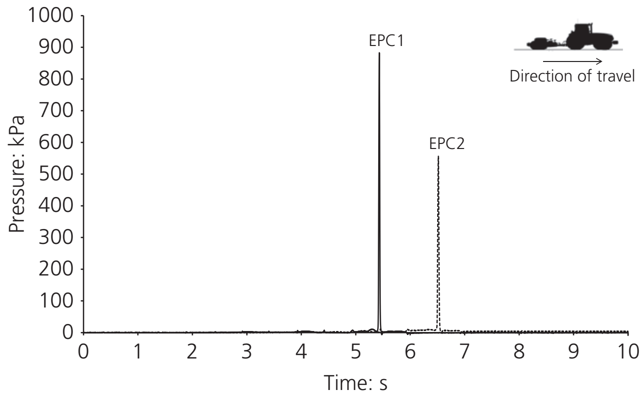


Figure 4. Example results of pressure against time for a single pass of the impact roller: lift 1 containing EPC1 and EPC2

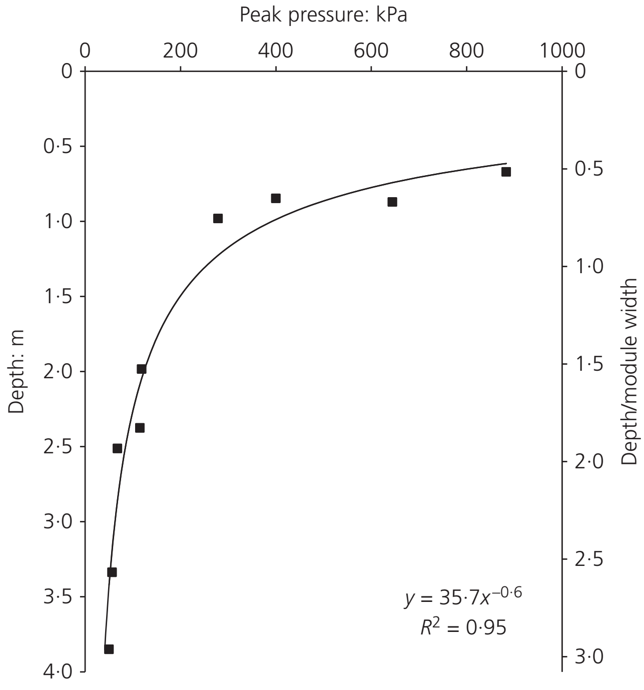


Figure 5. Measured peak pressure against depth with trend line fitted to data

extended beyond this depth. While the fitted trend line illustrates a good fit to the measured data, extrapolating for shallower than the measured depths is not recommended. A limitation of using EPCs is that they should not be placed at or close to the ground surface due to the high probability of damaging the sensors, with the manufacturer's guidelines recommending that no heavy equipment be used over the cells unless at least 500 mm of material is placed above them (Geokon, 2007). Figure 6 illustrates the measured peak pressures, plotted on a log scale, that were recorded by each EPC as the impact roller traversed directly above (lane A) and in the lanes adjacent to the buried EPCs, representing lateral offset distances of 2·5 and 5·0 m. For a lateral offset of 2·5 m, a maximum peak pressure was measured at a depth of 2·0 m. For a lateral offset of 5·0 m, all measured peak pressures were considered negligible. Further information on the lateral influence of RDC is discussed by Scott and Jaksa (2014).

5.2 In situ test results

Figure 7 compares the average modified dry density ratio in accordance with ASTM (2009b) against depth after eight passes. From the trend line fitted to the data, it is estimated that eight passes will achieve a dry density ratio of 95%, provided that the layer thickness does not exceed 1·2 m. Due to time constraints on site, density testing was not undertaken after 16 passes.

The SASW technique was used in conjunction with DCP tests to assess the improvement with depth at intervals of eight passes. Results for layer 2 are shown in Figure 8, where it can be observed that an increased number of passes resulted in an increase in shear modulus between depths of 0·5 and 2·1 m; this is an indication of increased soil density. Below a depth of 2·1 m the results were inconclusive due to insufficient data.

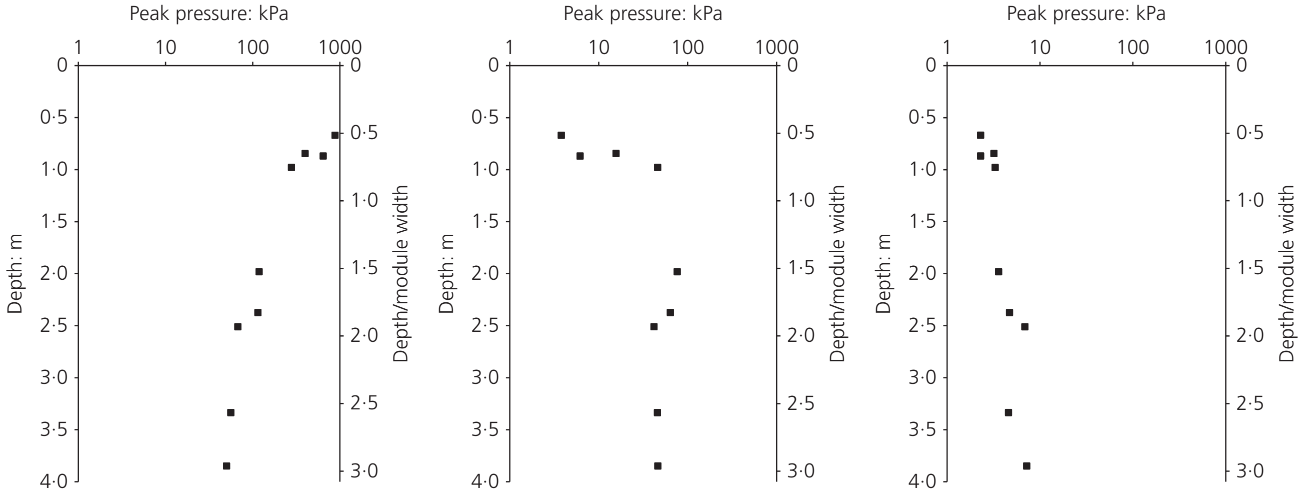
Figure 9 summarises the number of DCP blows per 50 mm penetration with respect to depth below the ground surface. The tests were terminated at penetration depths of 850 mm due to the limited length of the penetrometer. Salgado and Yoon (2003) found that increasing blow counts are indirectly related to an increase in soil dry density. An increase in blow count is evident with a greater number of passes to depths of between 0·3 m and beyond the 0·85 m limit of the penetrometer. Loosening of near-surface soils (<0·3 m) as a consequence of RDC is consistent with the findings of Clifford (1975) and Ellis (1979), who both suggested that RDC is unsuitable as a finishing roller.

5.3 Surface settlement monitoring

The average surface settlement across the test pad against number of passes was also measured. It was found that the majority of settlement occurred within the first eight passes; the average surface settlement measured was 106 and 128 mm, after eight and 16 passes, respectively.

6. Discussion

In current practice, the influence depth of RDC can be interpreted differently as there are many in situ techniques that can be, and are, used to measure it. In essence, these estimates are only as good as the quality of the pre- and post-compaction testing undertaken. It is suggested that three basic definitions are relevant in this context. First, the depth of influence, in simple terms, is the depth to which some improvement in density or reduction in void ratio is evident, regardless of magnitude. To determine this, predictive models such as that



(a)

(b)

(c)

Figure 6. Measured peak pressure against depth for varying lateral distances from the centre of lane A: (a) 0 m; (b) 2·5 m; (c) 5·0 m

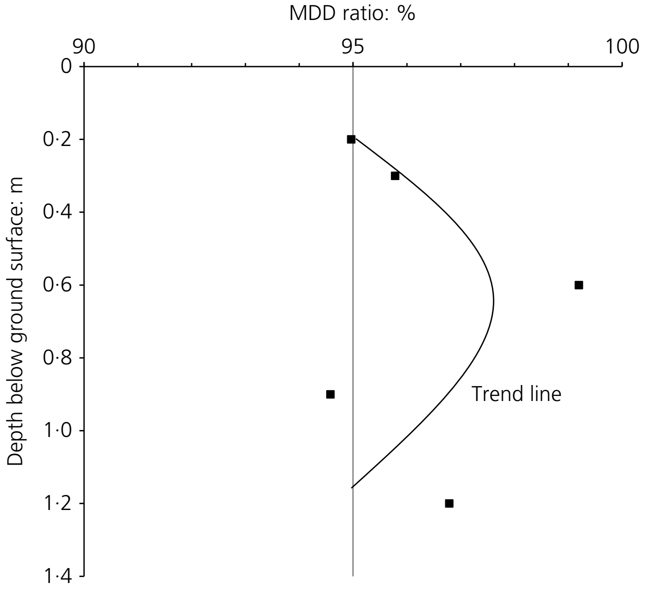


Figure 7. Modified maximum dry density ratio against depth after eight passes

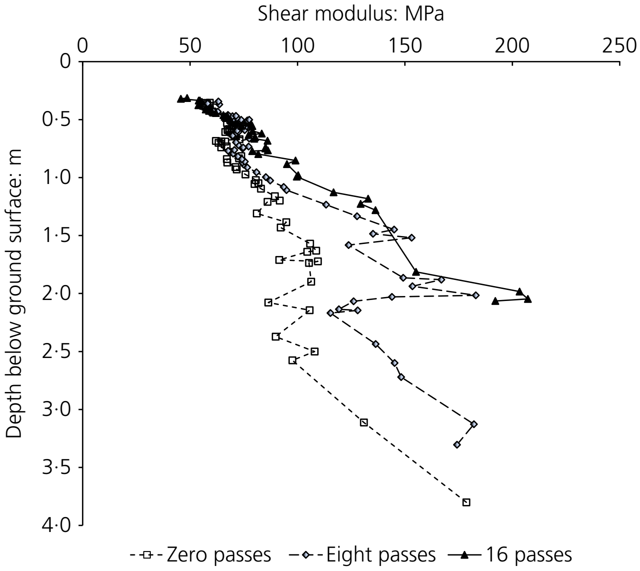


Figure 8. Geophysical (SASW) test results for zero, eight and 16 passes

proposed by Berry (2001) could be adopted; applying this theory to the four-sided roller yielded an influence depth of 3·9 m. Alternatively, sensitive measuring equipment, such as EPCs, or intrusive site-investigation techniques, such as the cone-penetration test and dilatometer test, could be used.

Here, no attempt is made to quantify the depth to which RDC has a small positive influence. Instead, an energy-based approach is proposed to provide estimations of the depths capable of being significantly improved in situ and the layer thicknesses capable of being compacted by RDC. Gravitational potential energy forms part of the total energy imparted to the ground. Other factors include the potential energy due to the double-spring–linkage system and the kinetic energy due to friction between the soil and module interface. The effects of the double-spring–linkage system can be quantified by way of a change in module velocity, and hence considered part of the kinetic energy component delivered by the impact roller. For the towing speed adopted in the field trial reported in this paper, the changes in potential and kinetic energies are listed in Table 4.

The second definition is applicable when improving ground in situ; in such cases, depths shallower than the maximum capable by RDC are typically targeted for improvement.

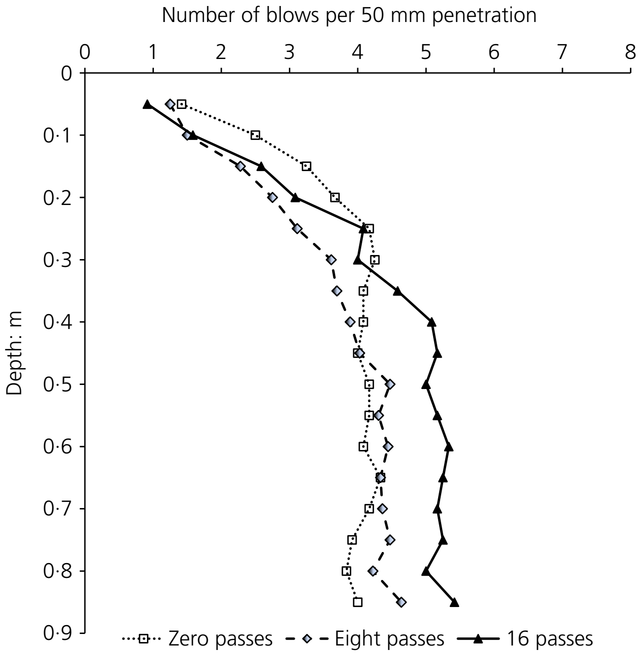


Figure 9. DCP test results for zero, eight and 16 passes

Table 4. Predicted changes in potential and kinetic energies for a towing speed of 10·5 km/h

v: km/h	v: m/s	v_i: m/s	v_f: m/s	ΔPE_g: kJ	ΔKE: kJ
10·5	2·92	3·21	2·63	11·8	13·6

v, speed of towing unit; v_f, module velocity after impacting the ground; v_i, module velocity prior to impacting the ground

Working within the limitations of RDC ensures that quantifiable improvement occurs and the properties of the ground are improved such that a specified target criterion is met. The concept of an effective depth of improvement (EDI) is most relevant for applications involving improving ground in situ (as per the case studies referenced in Table 1). The EDI can be considered as the equivalent of the term described by Slocombe (2004) for dynamic compaction, being the maximum depth to which significant improvement occurs. As shown in Equation 4, the new parameter EDI is calculated as the product of Equation 2 (based on module mass, m, lift height, h, and empirical factor n from dynamic compaction theory) and a new term k, defined as the ratio of the energy imparted to the ground divided by the gravitational potential energy, as listed in Table 5.

$$4. \quad \mathrm{EDI} = k(n\sqrt{mh})$$

Alternatively, Equation 4 can be re-written as shown in Equation 5. In this form, the EDI is written in terms of the material characteristics, n, gravitational potential energy, mgh and a variable k, which depends on the towing speed, as per Table 5.

Table 5. Values of k for different towing speeds based on change in potential and kinetic energies

v: km/h	mgh: kJ	ΔKE: kJ	$mgh + \Delta KE$: kJ	k
9	11·8	10·0	21·8	1·8
10·5	11·8	13·6	25·4	2·2
12	11·8	17·8	29·6	2·5

v, speed of towing unit; k, ratio of the energy imparted to the ground divided by gravitational potential energy

$$5. \quad \mathrm{EDI} = \sqrt{\frac{k^2 n^2}{g}(mgh)}$$

Third, for determining the maximum layer thickness that can be compacted in thick lifts, the concept of the depth of major improvement (DMI) is appropriate. This applies to situations where a target criterion that is comparable to what can be achieved by conventional compaction equipment in thin lifts is required. Consistent with the description adopted by Slocombe (2004) to determine the zone of major improvement from the EDI, a reduction factor, r, is used. DMI is equal to r (a constant that varies between 0·5 and 0·67) multiplied by the EDI, as defined in Equation 6.

$$6. \quad \mathrm{DMI} = r(\mathrm{EDI})$$

Values for EDI and DMI are summarised in Table 6 for different values of k, as calculated in Table 5, and n, consistent with the range of values proposed by Mayne *et al.* (1984). Lower values of n are applicable for clay soils; higher values of n are valid for granular soils; mixed soils require intermediate values of n to be adopted. The calculated values in Table 6 are in broad agreement with the case studies summarised in Tables 1 and 2.

For the field trial described in this paper, RDC was measured to have an influence at a depth of 3·85 m; however, the majority of improvement occurred within the top 2·0 m from the surface, consistent with the definition of the EDI. While RDC improved the soil beneath this so-called effective depth, for a uniform soil profile, the magnitude of improvement beyond this depth was less significant. A maximum dry density ratio of 95% with respect to modified compaction was obtained for a layer thickness of 1·2 m (DMI). The values for EDI and DMI obtained are consistent with Table 6 for an n value of 0·8, reasonable for granular soils, and a k value of 2·2, consistent for the 10·5 km/h towing speed adopted in the trial. Table 6 suggests that the depths to which RDC can improve and compact granular soils is influenced more by

Table 6. Predicted effective and maximum depths of improvement for RDC

v: km/h	n	m: t	h: m	D: m	k	EDI: m	r	DMI: m
9	0·3	8	0·15	0·33	1·8	0·59	0·5–0·67	0·30–0·40
9	0·5	8	0·15	0·55	1·8	0·99	0·5–0·67	0·49–0·66
9	0·8	8	0·15	0·88	1·8	1·58	0·5–0·67	0·79–1·06
10·5	0·3	8	0·15	0·33	2·2	0·73	0·5–0·67	0·37–0·49
10·5	0·5	8	0·15	0·55	2·2	1·21	0·5–0·67	0·61–0·81
10·5	0·8	8	0·15	0·88	2·2	1·94	0·5–0·67	0·97–1·30
12	0·3	8	0·15	0·33	2·5	0·83	0·5–0·67	0·42–0·56
12	0·5	8	0·15	0·55	2·5	1·38	0·5–0·67	0·69–0·92
12	0·8	8	0·15	0·88	2·5	2·20	0·5–0·67	1·10–1·47

v, speed of towing unit; *n*, empirical factor in depth of improvement equation (lower values of *n* for clay, higher values of *n* for granular soils, intermediate values of *n* for mixed soils); *m*, module mass; *h*, maximum module drop height; *D*, depth of soil compacted due to gravitational potential energy; *k*, ratio of the energy imparted to the ground divided by gravitational potential energy; *r*, reduction factor for determining DMI

towing speed than for clay soils. However, not all ground conditions can sustain a towing speed of 12 km/h for the 8 t four-sided impact roller; therefore, in the absence of site-specific information, a median towing speed of 10·5 km/h is recommended for use in Table 6.

7. Conclusions

This paper examined improving ground in situ and compaction of soil in thick layers as they are two distinctly different applications for RDC that, in the authors' opinion, need to be treated independently. For a towing speed of 10·5 km/h for the 8 t four-sided impact roller, the EDI was estimated to be 0·73 m for clay soils ($n = 0{\cdot}3$) and 1·94 m for granular soils ($n = 0{\cdot}8$). This highlights that soil type is the single most important variable in quantifying the depth to which RDC can improve soil. A relationship to evaluate EDI is presented as a function of the energy imparted to the ground by RDC, which is appropriate for determining the depths to which ground can be improved in situ. For the field trial presented in this paper, an EDI of 2·0 m was measured using buried EPCs and complementary in situ testing.

A second relationship to determine DMI, is also introduced, which is appropriate for determining the thickness of layers that can be compacted using RDC, typically half to two thirds of the EDI. For the field trial presented in this paper, a DMI of 1·2 m was measured using in situ testing. The equations presented in this paper augment the relationship for dynamic compaction first proposed by Menard and Broise (1975). In addition to soil type, module mass and drop height, the equations presented also incorporate the effect of towing speed. While the equations presented in this paper are relatively simple in nature, the proposed energy-based approach yields estimations of the depths capable of being significantly improved in situ and the layer thicknesses capable of being compacted by RDC, which are in broad agreement with the findings of the field trial presented and the results of published case studies involving the 8 t four-sided impact roller over the past four decades.

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REFERENCES

ASTM (2007) D 698: Standard test methods for laboratory compaction characteristics of soil using standard effort. ASTM International, West Conshohocken, PA, USA.

ASTM (2008) D 5195: Standard test methods for density of soil and rock in-place at depths below surface by nuclear methods. ASTM International, West Conshohocken, PA, USA.

ASTM (2009a) D 6913: Standard test methods for particle-size distribution (gradation) of soils using sieve analysis. ASTM International, West Conshohocken, PA, USA.

ASTM (2009b) D 1557: Standard test methods for laboratory compaction characteristics of soil using modified effort. ASTM International, West Conshohocken, PA, USA.

ASTM (2010a) D 2216: Standard test methods for laboratory determination of water (moisture) content of soil and rock by mass. ASTM International, West Conshohocken, PA, USA.

ASTM (2010b) D 4318: Standard test methods for liquid limit, plastic limit, and plasticity index of soils. ASTM International, West Conshohocken, PA, USA.

Avalle DL (2004) Ground improvement using the 'square' impact roller – case studies. In *Proceedings of the 5th International Conference on Ground Improvement Techniques, Kuala Lumpur, Malaysia* (Faisal A (ed.)). CI-Premier, Singapore, pp. 101–108.

Avalle DL (2007) Trials and validation of deep compaction using the 'square' impact roller. In *Symposium Advances in Earthworks.* Australian Geomechanics Society, Sydney, Australia, pp. 63–69.

Avalle DL and Carter JP (2005) Evaluating the improvement from impact rolling on sand. In *Proceedings of the 6th International Conference on Ground Improvement Techniques, Coimbra, Portugal*

(Isabel M, Pinto M and Jefferson I (eds)). CI-Premier, Singapore, pp. 153–160.

Avalle D and Grounds R (2004) Improving pavement subgrade with the 'square' impact roller. In *Proceedings of the 23rd Annual Southern African Transport Conference, Pretoria, South Africa*, pp. 44–54.

Avalle DL and Mackenzie RW (2005) Ground improvement of landfill site using the 'square' impact roller. *Australian Geomechanics* **40(4)**: 15–21.

Avalle D and Young G (2004) Trial programme and recent use of the impact roller in Sydney. In *Earthworks Seminar*, Australian Geomechanics Society, Adelaide, Australia, pp. 1–5.

Avsar S, Bakker M, Bartholomeeusen G and Vanmechelen J (2006) Six sigma quality improvement of compaction at the New Doha International Airport Project. *Terra et aqua* **103**: 14–22.

Berry AD (2001) *Development of a Volumetric Strain Influence Ground Improvement Prediction Model with Special Reference to Impact Compaction*. MEng dissertation, University of Pretoria, Pretoria, South Africa.

Charles JA, Burford D and Watts KS (1981) Field studies of the effectiveness of dynamic consolidation. In *Proceedings of the 10th International Conference on Soil Mechanics and Foundation Engineering, Stockholm, Sweden*. Balkema, Rotterdam, the Netherlands, vol. 3, pp. 617–622.

Clifford JM (1975) *An Introduction to Impact Rollers*. National Institute for Road Research, South Africa, Internal report RP/2/75.

Clifford JM (1978) *Evaluation of Compaction Plant and Methods for the Construction of Earthworks in Southern Africa*. MSc dissertation, University of Natal, Durban, South Africa.

Clifford JM (1980) *The Development and Use of Impact Rollers in the Construction of Earthworks in SOUTHERN Africa*. National Institute for Transport and Road Research, Pretoria, South Africa, Bulletin 16, CSIR Report 373.

Clifford JM and Coetzee SD (1987) Coal and discard stockpiling with an impact roller. In *Proceedings of International Conference on Mining and Industrial Waste Management, Johannesburg, South Africa* (Wates JA and Brink D (eds)). South African Institution of Civil Engineers, Johannesburg, South Africa, pp. 75–79.

Ellis CI (1979) *Pavement Engineering in Developing Countries*. Transport and Road Research Laboratory, Crowthorne, UK, TRRL Supplementary Report 537.

Fadum RE (1948) Influence values for estimating stresses in elastic foundations. In *Proceedings of the 2nd International ISSMFE Conference, Rotterdam, the Netherlands*, vol. 3, 77–84.

Geokon (2007) *Instruction Manual Model 3500, 3510, 3515, 3600 Earth Pressure Cells*. Geokon Incorporated, Lebanon, NH, USA.

Hamidi B, Nikraz H and Varaksin S (2009) A review of impact oriented ground improvement techniques. *Australian Geomechanics* **44(2)**: 17–24.

Kim K (2010) *Numerical Simulation of Impact Rollers for Estimating the Influence Depth of Soil Compaction*. MSc dissertation, Texas A&M University, College Station, TX, USA.

Leonards GA, Holtz RD and Cutter WA (1980) Dynamic compaction of granular soils. *Journal of Geotechnical Engineering Division ASCE* **106(1)**: 35–44.

Lukas RG (1980) Densification of loose deposits by pounding. *Journal of Geotechnical Engineering Division ASCE* **106(4)**: 435–446.

Lukas RG (1995) *Dynamic Compaction*. Federal Highway Administration, Washington, DC, USA, Geotechnical Engineering Circular No. 1, U.S. DOT, Publication No. FHWA-SA-95-037.

Mayne PW, Jones JS and Dumas JC (1984) Ground response to dynamic compaction. *Journal of Geotechnical Engineering ASCE* **110(6)**: 757–774.

Menard L and Broise Y (1975) Theoretical and practical aspects of dynamic consolidation. *Géotechnique* **25(1)**: 3–18, https://doi.org/10.1680/geot.1975.25.1.3.

National Instruments (2019) http://www.ni.com/en-us/shop/labview.html (accessed 03/05/2019).

Nazhat Y (2013) *Behaviour of Sandy Soil Subjected to Dynamic Loading*. PhD thesis, University of Sydney, Sydney, Australia.

SA (Standards Australia) (1997) AS 1289.6.3.3: Methods of testing soils for engineering purposes – Soil strength and consolidation tests – Determination of the penetration resistance of a soil – Perth sand penetrometer test. SA, Sydney, Australia.

Salgado R and Yoon S (2003) *Dynamic Cone Penetration test (DCPT) for Subgrade Assessment*. Joint Transportation Research Program, West Lafayette, IN, USA, Report FHWA/IN/JTRP-2002/30.

Scott BT and Jaksa MB (2008) Quantifying the influence of rolling dynamic compaction. In *Proceedings of the 8th Australia New Zealand Young Geotechnical Professionals Conference*, New Zealand Geotechnical Society, Wellington, New Zealand, pp. 199–204.

Scott BT and Jaksa MB (2012) Mining applications and case studies of rolling dynamic compaction. In *Proceedings of the 11th Australia New Zealand Conference on Geomechanics* (Narsilio G, Arulrajah A and Kodikara J (eds)). Australian Geomechanics Society, Melbourne, Australia, pp. 961–966.

Scott BT and Jaksa MB (2014) Evaluating rolling dynamic compaction of fill using CPT. *Proceedings of the 3rd International Symposium on Cone Penetration Testing, Las Vegas, NV, USA* (Robertson PK and Cabal K (eds)). Omnipress, Madison, WI, USA, pp. 941–948.

Scott BT and Suto K (2007) Case study of ground improvement at an industrial estate containing uncontrolled fill. In *Proceedings of the 10th Australia New Zealand Conference on Geomechanics* (Ameratunga J, Taylor B and Patten M (eds)). Australian Geomechanics Society, Brisbane, Australia, vol. 2, pp. 150–155.

Slocombe BC (2004) Dynamic compaction. In *Ground Improvement*, 2nd edn (Moseley MP and Kirsch K (eds)). Spon Press, New York, NY, USA, pp. 93–118.

Whiteley RJ and Caffi P (2014) Evaluating the effectiveness of rolling impact compaction at a brownfield site with high and low frequency seismic surface waves and geotechnical testing. *Near Surface Geophysics* **12(3)**: 405–414.

Wolmarans CH and Clifford JM (1975) An evaluation of the CSIR impact roller. *Proceedings of the 6th Regional Conference for Africa on Soil Mechanics and Foundation Engineering, Durban, South Africa* (Pells PJN, Mac A and Robertson G (eds)). AA Balkema, Cape Town, South Africa, pp. 33–39.

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Ground response to rolling dynamic compaction

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Rolling dynamic compaction (RDC) is typically used for improving ground in situ or compacting fill in thick lifts. In many project applications, the effects of RDC are verified by way of testing that is undertaken pre- and/or post-compaction. This study presents results from a full-scale field trial that involved placing an earth pressure cell (EPC) and accelerometers at a depth of 0·7 m within a 1·5 m thick layer of homogeneous sandy gravel to measure the response to RDC in real-time. Double integration of acceleration–time data enabled settlement to be inferred, while the EPC measured the change in stress due to impact. The maximum change in vertical stress recorded over the 80 passes undertaken was approximately 1100 kPa. During a typical module impact, the loading and unloading response occurred over a duration of approximately 0·05 s. The acceleration response of RDC was measured in three orthogonal directions, with the vertical accelerations dominant.

KEYWORDS: compaction; field instrumentation; ground improvement

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NOTATION

d_{50}	particle size at per cent finer of 50%
g	free-fall acceleration (9·81 m/s^2)
W_{elastic}	elastic work done (energy imparted to ground that is recovered elastically)
W_{plastic}	plastic work done (energy imparted in ground that causes permanent settlement)
W_{total}	total work done (area under the load–displacement curve) = $W_{\text{elastic}} + W_{\text{plastic}}$
Δt	duration of applied load
δ_{elastic}	elastic (rebound) settlement
δ_{plastic}	plastic (permanent) settlement

INTRODUCTION

Rolling dynamic compaction (RDC) imparts energy to the ground through the use of a heavy, non-circular module that falls to impact the ground. A limitation of many past field investigations to verify the effects of RDC is that testing is typically performed pre- and/or post-compaction. Such investigations often serve their intended purpose for determining if a project specification has been met (or otherwise) but they do not capture the dynamic effects of a heavy module impacting the ground in real-time. This study has used a buried earth pressure cell (EPC) and accelerometers to better understand the ground response beneath the surface during the passage of an impact roller.

BACKGROUND

Impact rollers with different module masses, shapes and drop heights, have been compared to predict the energy imparted into the ground (McCann, 2015). A limitation with such a prediction is that a RDC module that is towed across the surface impacts the ground in a different manner to a dynamic compaction pounder that is a function of mass, drop height and vertical acceleration due to gravity. An RDC module, shown in Fig. 1, impacts the ground in a similar way to a falling hinged trap door; the geometry and surface area of the module that is in contact with the ground is non-uniform; as is the impact velocity of the module when it contacts the ground.

In RDC applications, accelerometers have been placed on an impact roller to measure the ground surface response. Heyns (1998) and McCann & Schofield (2007) both noted that an increase in the magnitude of decelerations is commonly measured with increasing passes, as the surface soil stiffness increases. This finding is consistent with the work of Clifford (1978), who observed that the module drop height increases as the ground surface becomes harder; the cross-sectional area of the module that is in contact with the ground changes with drop height due to the geometry of the rounded corners and how far they embed in the ground. The energy imparted by the roller is spread over a smaller area as the stiffness of the surficial soil increases; this results in greater contact pressures being imparted to the soil with increasing passes. The use of module-mounted accelerometers has proven useful in identifying less stiff near-surface soils that typically exhibit lower decelerations (McCann & Schofield, 2007); however, there is no guarantee that measuring the response of an impact roller as it passes over the ground surface gives a true indication of the soil response below the surface. Inferring improvement due to RDC from surface measurements can be challenging given RDC typically disturbs the near-surface soils, which can be further complicated by sites containing inherent soil variability. Mooney & Rinehart (2007) carried out a field investigation using a smooth drum vibrating roller. They performed multiple passes across test areas comprising both heterogeneous and homogeneous soils. They found that soil heterogeneity presented significant challenges for

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interpreting instrumented roller data. This study overcomes previous limitations by attaching accelerometers to an EPC and burying them in homogeneous fill material to quantify the loading induced stress and ground deceleration beneath the ground surface, yet within the expected zone of influence of RDC.

Comparisons with dynamic compaction

Measuring the ground response of deep dynamic compaction has been studied by Mayne & Jones (1983), who attached an accelerometer to a 20·9 t pounder to monitor the deceleration on impact with the ground surface after falling a distance of 18·3 m; the deceleration–time response of the impact blow occurred over a duration of only 0·05 s. Also of significance is the magnitude of decelerations recorded was in the order of 70–85$\boldsymbol{g}$, and a trend of increasing magnitude with number of drops was observed. Clegg (1980) attached an accelerometer to a falling weight and found that the peak deceleration of the weight on impact with the soil was directly related to the soil resistance, described as a combination of both soil stiffness and shearing resistance. Chow *et al.* (1990) developed a theoretical framework that was based on matching deceleration measurements of a dynamic compaction pounder impacting the ground using an accelerometer that was attached to the pounder near the centre of gravity. The one-dimensional model that was developed was similar to pile driving analyses where the impact velocity was obtained by integrating measured decelerations. Yu (2004) double integrated the acceleration–time response of a vertically falling plate to generate the load–displacement relationship, which was integrated to quantify the work done. Analysis of a load–displacement response due to impact was also undertaken by Jha *et al.* (2012), who investigated energy dissipation to quantify the elastic energy that was recovered during unloading of multi-phase cementitious materials. They plotted the load–displacement response for cementitious materials subjected to nano-indentation and determined the area under the loading and unloading curves and quantified the work done. The key aims of this study are to measure the loading-induced stresses and displacements that soil particles beneath the ground surface experience, and to quantify the work done from measured force–displacement data.

Fig. 1. Eight tonne four-sided impact roller

RESEARCH TEST SITE

Figure 1 shows a four-sided 8 t impact roller (1450 mm square and 1300 mm wide module) that was used at a dedicated research site located at Monarto Quarries, approximately 60 km south-east of Adelaide, Australia. While conducting a full-scale trial that is not associated with a client-funded project is expensive, a research focused trial provided an ability to control a number of variables that can often conceal the true effects of RDC. Significantly, natural soil was excavated to a depth of 1·5 m and replaced with homogeneous fill; a crushed rock with a maximum particle size of 20 mm that was readily available and locally produced at the quarry. Six equal lifts of 250 mm thickness were adopted; the material was placed using a Volvo L150E loader, and was lightly compacted using a 60 kg vibrating plate and wheel rolling from the loader. The fill material was classified as a well-graded sandy gravel (GW) in accordance with the Unified Soil Classification System. The fill was tested for homogeneity through the use of particle-size distribution and Proctor compaction testing; the results are given in Table 1.

EPCs and accelerometers

Field trials undertaken by Avalle *et al.* (2009) and Scott *et al.* (2016) using the four-sided impact roller have shown that a module impacting the ground directly above embedded instrumentation results in significantly higher ground decelerations being recorded, compared with when the module strikes the ground off-set from embedded instrumentation. A limitation of burying equipment at discrete locations is that it is not possible to capture the maximum ground response from every impact. However, a key advantage of this technique is that it does provide real-time data on dynamic pressures and accelerations that are imparted into the ground that other testing methods are unable to do.

A custom-built accelerometer cluster consisting of ±5$\boldsymbol{g}$ and ±16$\boldsymbol{g}$ accelerometers in the Z-plane to measure vertical acceleration, and ±5$\boldsymbol{g}$ accelerometers in the X- and Y-planes, to measure tilt perpendicular to, and in the direction of travel, respectively. A total of 80 passes were undertaken. The accelerometer cluster was attached to an EPC (230 mm diameter and 6 mm thick) that was buried at a depth of 0·7 m below the ground surface, and connected to a bespoke data-acquisition system and Labview software program (refer Labview (2018)). The ability to capture an accurate ground response using EPCs and accelerometers relies heavily on adopting a sufficiently high sampling frequency. Given that displacement is to be quantified from the double integration of acceleration–time data, a sampling frequency of 4 kHz (twice that adopted by Avalle *et al.*, 2009) was selected for this trial to ensure that the true peak pressure and ground deceleration could be accurately captured. As

Table 1. Particle-size distribution, compaction and field moisture test results of fill material

Material	d_{50}: mm	Gravel size: %	Sand size: %	Fines: %	Standard OMC: %	Standard MDD: kN/m^3	FMC: %	Modified OMC: %	Modified MDD: kN/m^3
20 mm crushed rock	4·0	57	40	3	7·9	17·9	8·6	7·2	18·9

d_{50}, particle size at per cent finer of 50%; OMC, optimum moisture content; MDD, maximum dry density; FMC, field moisture content.

discussed by Thong *et al.* (2002), faster sampling rates can improve the accuracy of integration, but errors can increase with the duration of the time interval over which integration is undertaken.

RESULTS AND DISCUSSION

A single pass (54 summarised in Table 2) was selected out of the 80 passes undertaken for analysis as it featured a high peak pressure and the largest vertical deceleration recorded. In Fig. 2 the module impact resulted in a measured peak pressure of 1077 kPa at a depth of 0·7 m. It can be observed that the impulse pressure imparted to the ground was loaded and unloaded over a duration of approximately 0·05 s. Figure 3 illustrates the vertical (Z-) acceleration–time response for the same pass shown in Fig. 2, whereby a downward (negative) acceleration first occurs as the soil is loaded. In response to loading, the soil resistance is mobilised, which results in an upward acceleration before the acceleration trace dampens and returned to zero less than 0·1 s after loading. Significantly, a peak deceleration (negative acceleration) of 21***g*** was measured before the soil resistance was mobilised. Table 3 includes a summary of passes 1–10, as well as every fifth pass thereafter. As observed in Table 3, the magnitude of the peak downward acceleration was typically greater than the peak upward acceleration, this trend was more defined for impacts that generated large accelerations. Consequently, a

Table 2. Summary of pass 54 for test depth of 0·7 m

Pass	δ_{elastic}: mm	δ_{plastic}: mm	W_{total}: J	W_{elastic}: J	W_{plastic}: J	Peak pressure: kPa	Δt: s	Peak deceleration: ***g***	Peak acceleration: ***g***
54	4	5	254	36	218	1077	0·05	−21·0	6·3

δ_{elastic}, rebound settlement; δ_{plastic}, permanent settlement; W_{total}, total area under load–displacement curve; W_{elastic}, elastic work done; W_{plastic}=plastic work done; Δt, duration of applied load; peak dec., peak deceleration; peak acc., peak acceleration.

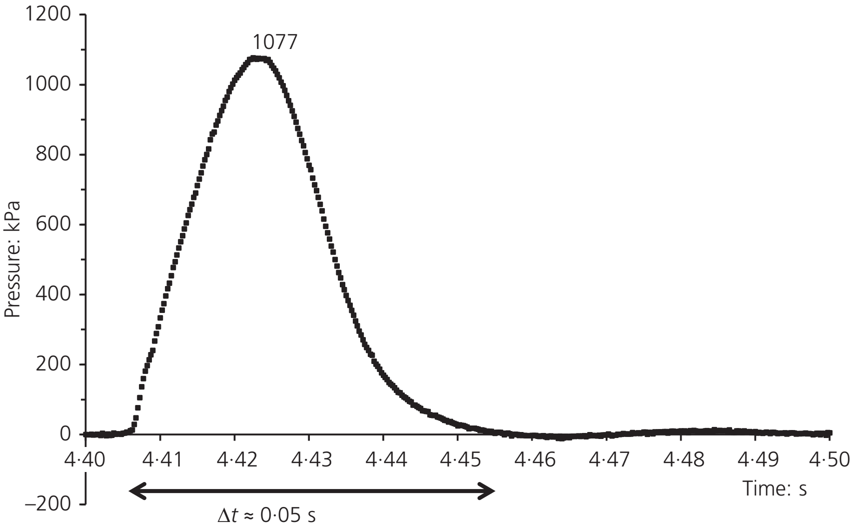

Fig. 2. Pressure distribution at time of module impact

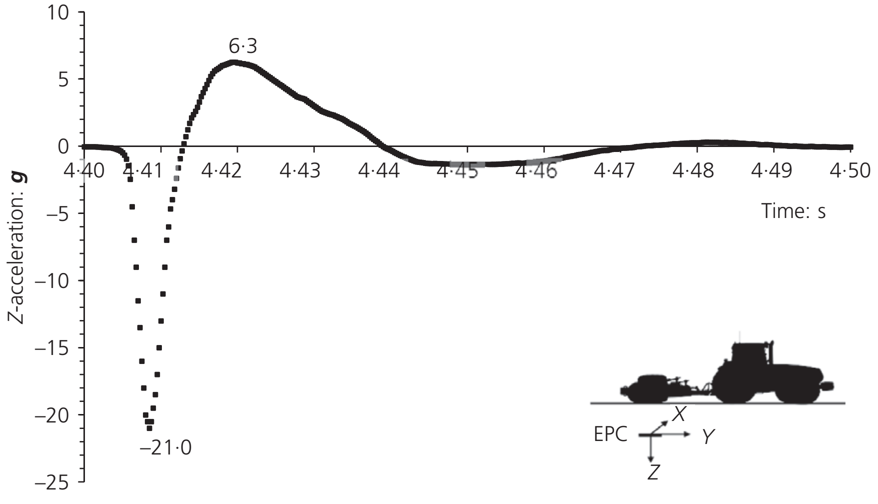

Fig. 3. *Z*-acceleration response at time of module impact

shift in the baseline (zero) reading was undertaken that enabled readings of −21***g*** and +6·3***g*** to be measured using a ±16***g*** accelerometer (range of 32***g***). Consistent with the findings of Mayne & Jones (1983), an increased number of passes generally resulted in larger accelerations (and peak pressures) being recorded. However, the variable location of the module landing on the ground surface relative to buried instrumentation, analysed and discussed by Scott *et al.* (2016), was also a contributing factor that would explain why some passes (e.g. pass 54) yielded much larger peak pressures and vertical accelerations than others.

Figure 4 shows a plot of *Y*-acceleration (in the direction of travel of the roller) against time. Of significance in this plot is the larger magnitude of the positive (compared with negative) *Y*-acceleration. It can be inferred that the direction of travel of the module influences the ground response, an expected result given the module drop is not solely in a vertical direction. Figure 5 shows a plot of *X*-acceleration (perpendicular to the direction of travel) with time. Both positive and negative accelerations are approximately equal suggesting that the module landing directly over the centre of the cell produces a relatively symmetrical response in the direction across the test lane, this is not unexpected given the

Table 3. Summary of passes for test depth of 0·7 m

Pass	$\delta_{elastic}$: mm	$\delta_{plastic}$: mm	W_{total}: J	$W_{elastic}$: J	$W_{plastic}$: J	Peak pressure: kPa	Impulse Δt: s	Peak dec.: ***g***	Peak acc.: ***g***
1	2·0	0·5	13	9	4	230	0·07	−3·5	3·0
2	3	1	44	13	31	419	0·07	−5·5	3·8
3	3·5	0·5	35	25	10	371	0·08	−5·3	4·4
4	3	2	76	20	56	594	0·08	−4·6	2·5
5	6·5	0	108	53	55	656	0·07	−5·6	7·7
6	3	2	71	13	58	503	0·06	−11·6	5·2
7	3	2	64	20	44	550	0·08	−2·1	3·4
8	1	1	73	45	28	177	0·08	−1·3	0·6
9	2	1	22	6	16	258	0·05	−4·9	2·8
10	3	2	71	14	57	539	0·06	−8·5	3·9
15	3	2	56	15	41	490	0·08	−4·0	1·7
20	3	2	62	18	44	492	0·05	−9·6	4·8
25	2·5	1·5	35	14	21	324	0·06	−8·0	4·7
30	6	0·5	58	29	29	380	0·06	−10·5	**9·6**
35	2·5	1	22	7	15	272	0·05	−4·0	2·9
40	2	3	41	5	36	309	0·04	−6·6	4·4
45	2·5	0·5	12	4	8	166	0·05	−1·6	2·6
50	2	1	11	7	4	202	0·06	−1·8	1·7
55	3·5	2·5	98	24	74	680	0·05	−7·2	5·6
60	2·5	0·5	11	7	4	169	0·07	−2·4	2·5
65	3·5	**3·5**	177	14	163	873	0·05	**−13·2**	5·4
70	4	1·5	60	34	26	557	0·07	−4·9	3·8
75	1·5	6	136	18	118	731	0·07	−9·2	4·5
80	**7·5**	0·5	**249**	**59**	**190**	**1115**	0·05	−11·2	8·0

$\delta_{elastic}$, rebound settlement; $\delta_{plastic}$, permanent settlement; W_{total}, total area under load–displacement curve; $W_{elastic}$, elastic work done; $W_{plastic}$, plastic work done; Δt, duration of applied load; Peak dec., peak deceleration; Peak acc., peak acceleration, peak values in bold.

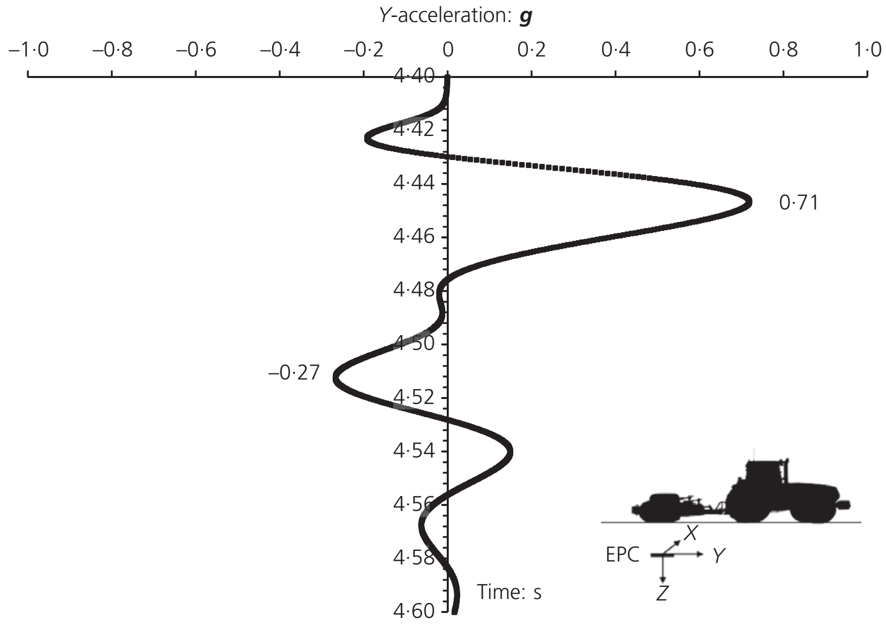

Fig. 4. *Y*-acceleration response at time of module impact

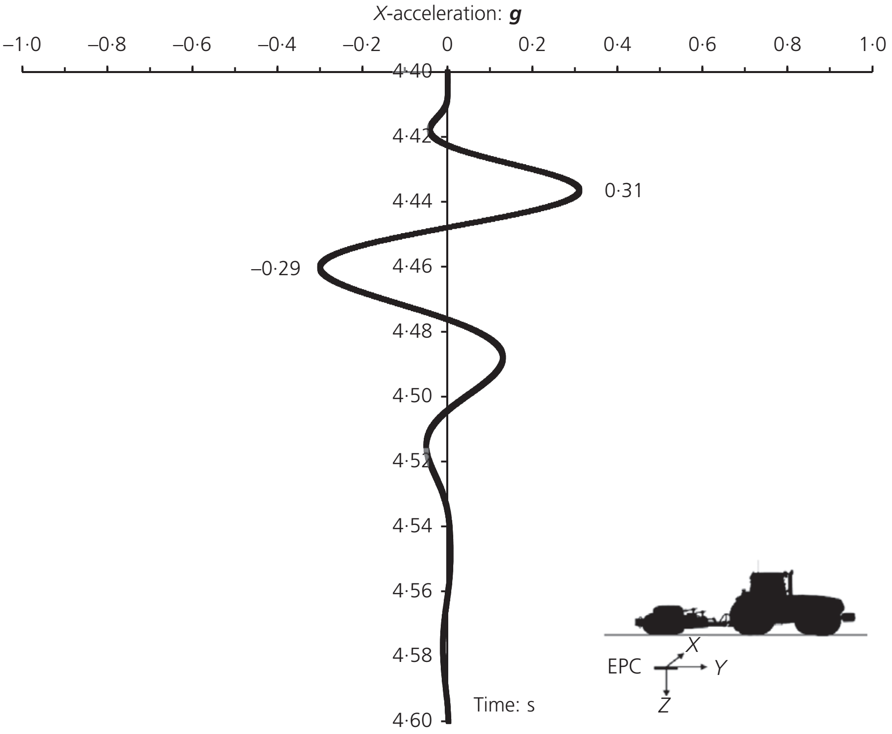

Fig. 5. *X*-acceleration response at time of module impact

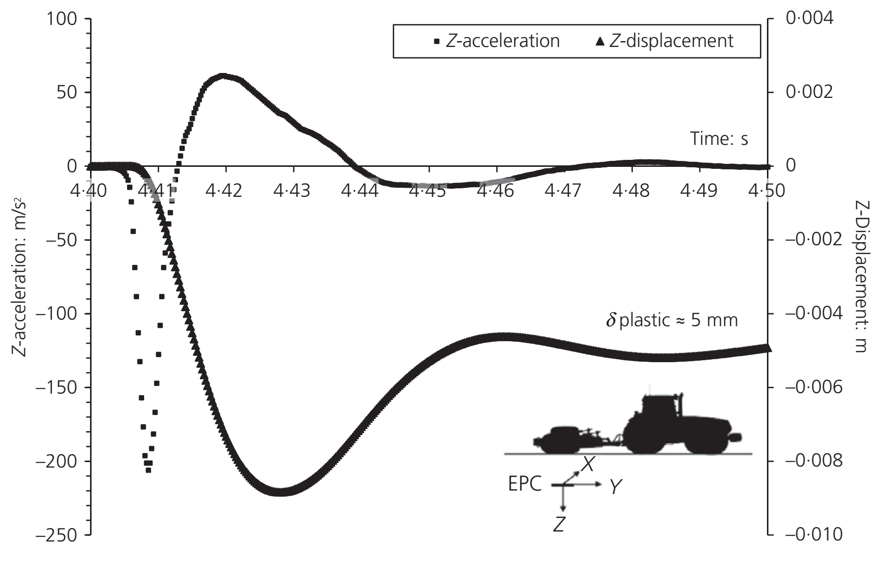

Fig. 6. *Z*-acceleration and *Z*-displacement against time

module only has a limited ability to move laterally within the trailer frame.

Figure 6 shows the variation of *Z*-acceleration and *Z*-displacement of the soil with time in response to a single module impact, whereby displacement was calculated from double integration of the acceleration–time response. From Fig. 6, it is evident that approximately 9 mm total displacement occurred due to loading; however, on unloading, the permanent displacement due to the single impact was 5 mm. The same impact blow is illustrated in Fig. 7, which shows the loading and unloading response of the soil due to a single pass of the impact roller at a measured depth of 0·7 m beneath the ground surface. Force is determined by adopting the peak pressure at the time of impact and multiplying it by the plan area of the EPC. Displacement is evaluated from double integration of the acceleration–time response. In Fig. 7 the portion of the curve between points A and B represents the loading of the soil. The unloading portion of the curve is shown between points B and C. The distance between points A and C provides a measure of the permanent deformation of the soil. For a perfectly elastic soil response with no hysteresis, AB and BC would be coincidental. Area ABC yields the plastic work done and the area CBD represents the elastic work that has been recovered during unloading. The total work done comprises both recoverable (elastic) and permanent (plastic) components.

Figure 8 shows the force–displacement response for consecutive module impacts (passes 1–10 inclusive, summarised in Table 3). As can be observed, there is a large variation in the shape and magnitudes of the force–displacement curves

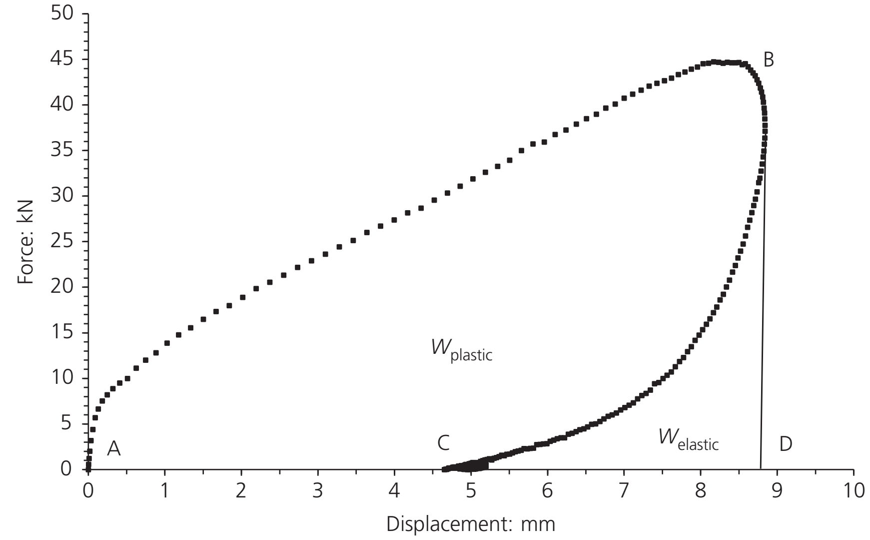

Fig. 7. Force–displacement curve for a single pass

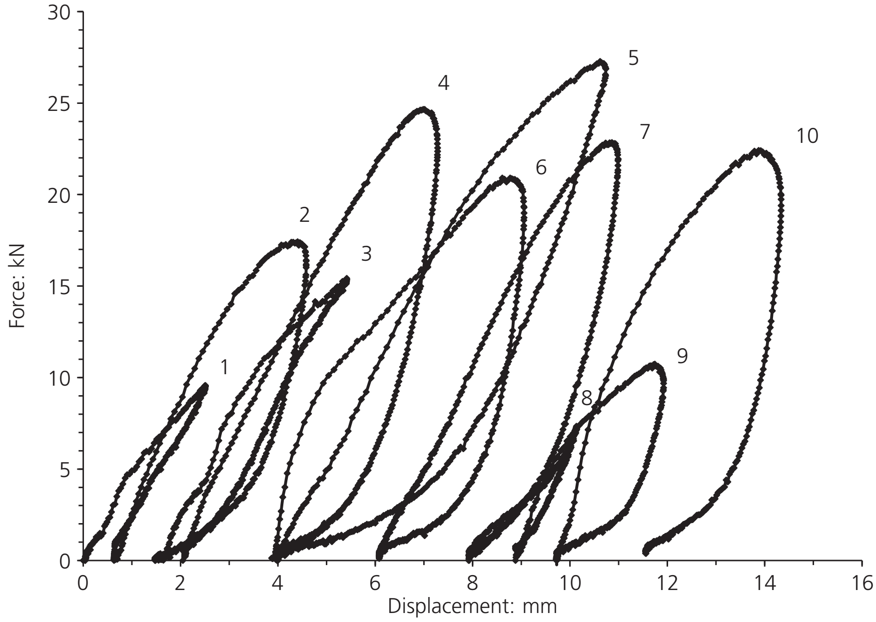

Fig. 8. Force–displacement curves for consecutive passes (1–10)

for individual passes. Pass 1 is close to an elastic impact where minimal work is done on the soil. The opposite is true for pass 10, which features a much larger area under the force–displacement curve.

CONCLUSIONS

To minimise soil variability, this study has captured the change in vertical stress due to RDC at a depth of 0·7 m beneath the surface using an EPC buried in a 1·5 m thick layer of homogeneous sandy gravel. The maximum change in vertical stress recorded over the 80 passes undertaken was approximately 1100 kPa. During a typical module impact, the loading and unloading of the soil occurred over a duration of roughly 0·05 s. The acceleration response of a single module impact was also measured in three orthogonal directions at 0·7 m depth, with the vertical accelerations dominant. In project applications, there is typically a trade-off between layer thickness and the number of passes required to significantly improve ground to meet a certain specified criterion. While the number of passes (80) undertaken in this study was greater than what would economically be undertaken in practice, the results from buried instrumentation indicate that 0·7 m is well within the depth range that can be significantly improved by RDC. Quantifying the dynamic behaviour of the soil beneath the ground surface in real-time emphasises that the uneven module geometry results in some passes imparting much greater pressure to the ground than others, this being a key reason why many passes are needed to ensure adequate coverage of a site.

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REFERENCES

Avalle, D. L., Scott, B. T. & Jaksa, M. B. (2009). Ground energy and impact of rolling dynamic compaction – results from research test site. In *Proceedings of the 17th international conference on soil mechanics and geotechnical engineering*, Alexandria, Egypt (eds M. Hamza, M. Shahien and Y. El-Mossallamy), vol. 3, pp. 2228–2231. Amsterdam, the Netherlands: IOS Press BV.

Chow, Y. K., Yong, D. M., Yong, K. Y. & Lee, S. L. (1990). Monitoring of dynamic compaction by deceleration measurements. *Comput. Geotech.* **10**, No. 3, 189–209.

Clegg, B. (1980). An impact soil test as alternative to California bearing ratio. In *Proceedings 3rd Australia–New Zealand conference on geomechanics*, pp. 225–230. Wellington, New Zealand: New Zealand Institution of Engineers.

Clifford, J. M. (1978). *Evaluation of compaction plant and methods for the construction of earthworks in Southern Africa*. Dissertation in partial fulfilment of the requirements for the degree of Master of Science in Engineering, University of Natal, Durban, South Africa.

Heyns, S. (1998). *Response analysis of an impact compactor*, Report LGI98/013, Project 020-DP. Pretoria, South Africa: Laboratory for Advanced Engineering Pty Ltd., University of Pretoria.

Jha, K. K., Suksawang, N., Lahiri, D. & Agarwal, A. (2012). Energy-based analysis of nanoindentation curves for cementitious materials. *ACI Mater. J.* **109**, No. 1, 81–90.

Labview (2018). http://www.ni.com/en-us/shop/labview.html (accessed 26/10/2018).

Mayne, P. W. & Jones, J. S. (1983). Impact stresses during dynamic compaction. *J. Geotech. Engng, ASCE* **109**, No. 10, 1342–1346.

McCann, K. (2015). The use of impact compaction for the near surface compaction on dredged sand land reclamation projects. In *Proceedings of the 12th Australia–New Zealand conference on geomechanics* (ed. G. Ramsay), pp. 1193–1200. Wellington, New Zealand: New Zealand Geotechnical Society.

McCann, K. & Schofield, N. (2007). Innovative methods in the in-situ determination of design parameters on heterogeneous sites subject to ground treatment using deep impact compaction. In *Proceedings of the 10th Australia–New Zealand conference on geomechanics* (eds J. Ameratunga, B. Taylor and M. Patten), vol. 2, pp. 126–131. Brisbane, Australia: Australian Geomechanics Society.

Mooney, M. A. & Rinehart, R. V. (2007). Field monitoring of roller vibration during compaction of subgrade soil. *J. Geotech. Geoenviron. Engng, ASCE* **133**, No. 3, 257–265.

Scott, B. T., Jaksa, M. B. & Syamsuddin, E. (2016). Verification of an impact rolling compaction trial using various in situ testing methods. In *Proceedings of the 5th international conference on geotechnical and geophysical site characterisation* (eds B. M. Lehane, H. E. Acosta-Martínez and R. Kelly), pp. 735–740. Sydney, Australia: Australian Geomechanics Society.

Thong, Y. K., Woolfson, M. S., Crowe, J. A., Hayes-Gill, B. R. & Challis, R. E. (2002). Dependence of inertial measurements of distance on accelerometer noise. *Meas. Sci. Technol.* **13**, No. 8, 1163–1172.

Yu, X. (2004). Field evaluation of ground stiffness by static and dynamic tests. *Electron. J. Geotech. Engng* **9**, No. D. See http://www.ejge.com/2004/Ppr0442/Abs0442.htm (accessed 22/03/2019).

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