Geotechnical and Geophysical Site Characterisation 5 – Lehane, Acosta-Martínez & Kelly (Eds)

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.

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.

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.

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.

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.

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.

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).

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.

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.

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.

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

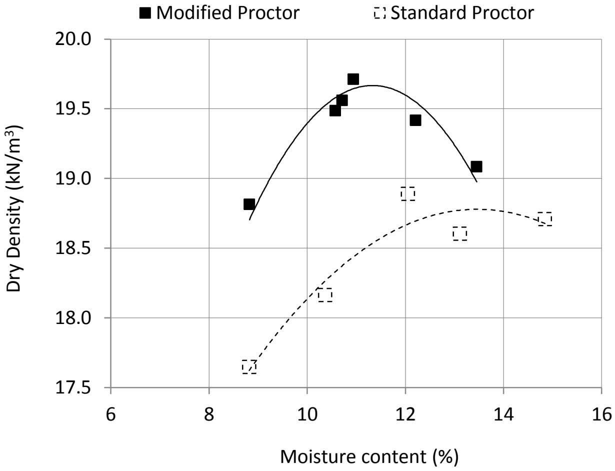

Figure 2. Modified and Standard Proctor compaction curves for 20 mm quarry material.

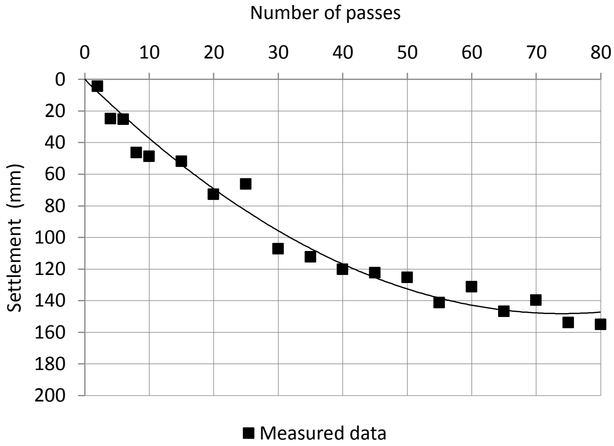

Figure 3. Summary of surface settlement with trend line through the measured data points.

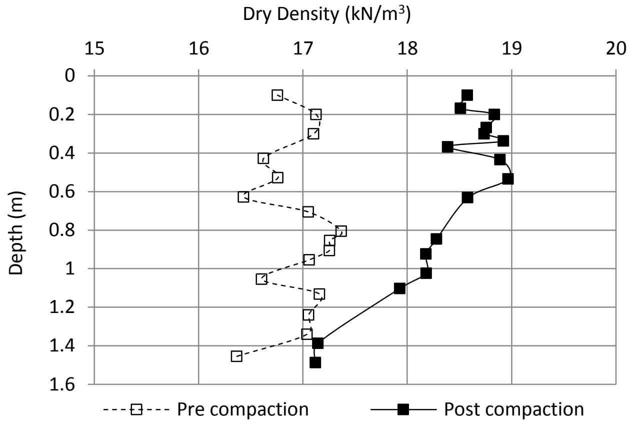

Figure 4. Dry density versus depth from field density testing.

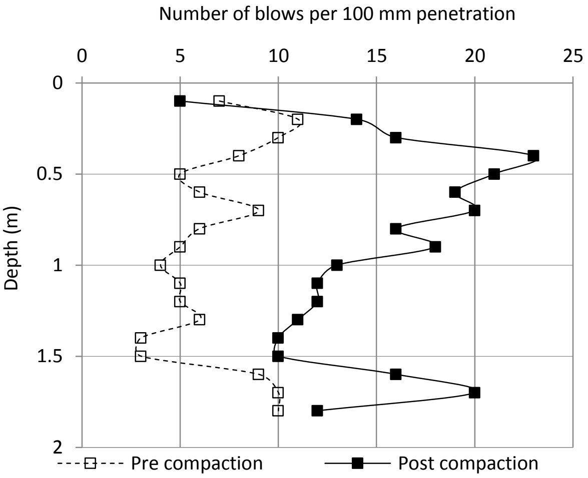

Figure 5. DCP pre and post compaction results.

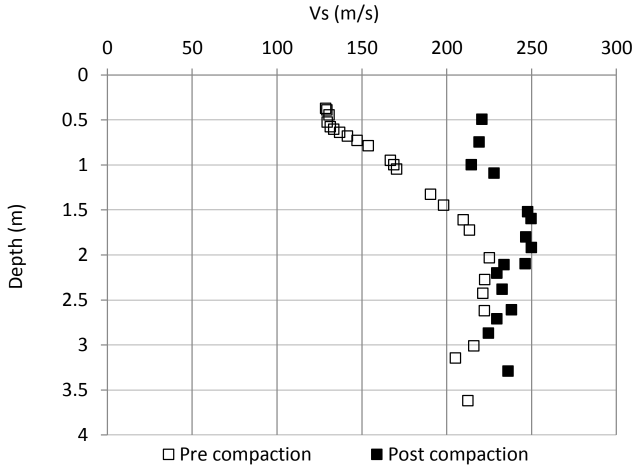

Figure 6. Shear wave velocity versus depth from SASW testing.

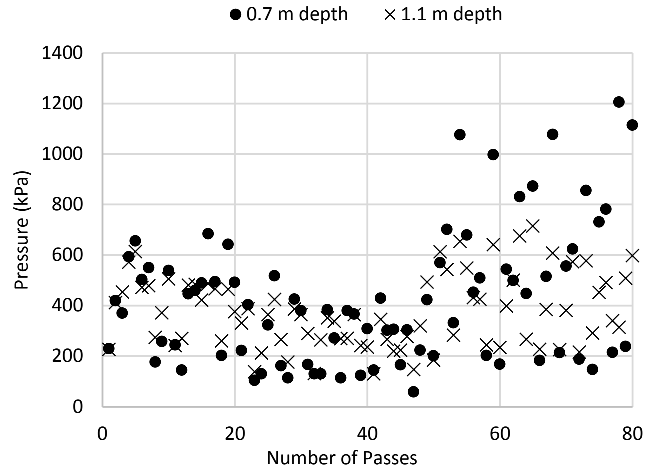

Figure 7. Measured peak pressure for each pass of the impact roller.

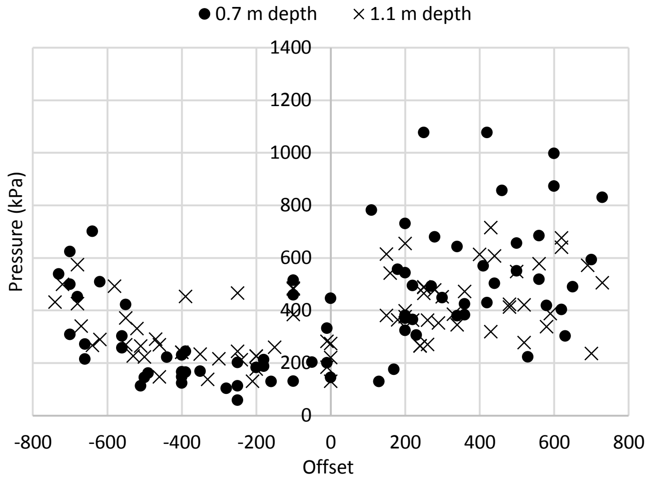

Figure 10. Distribution of peak pressure with offset distance.

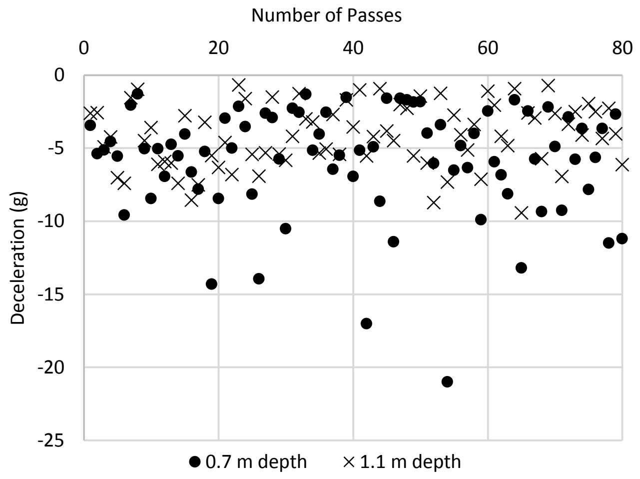

Figure 8. Measured peak deceleration for each pass of the impact roller.

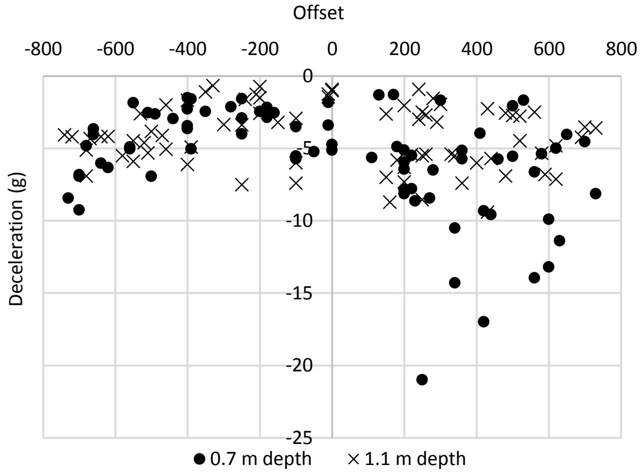

Figure 11. Distribution of peak deceleration with offset distance.

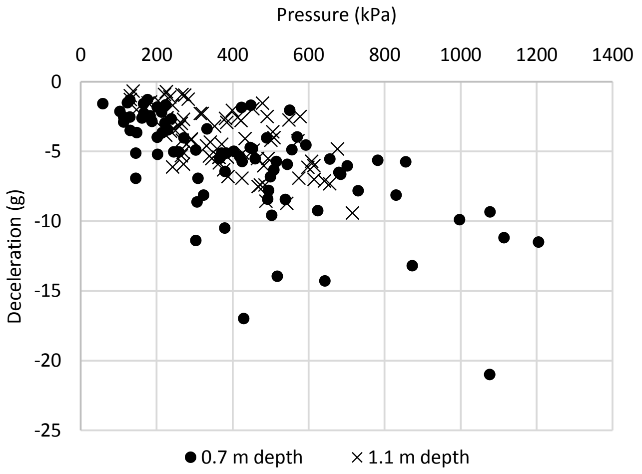

Figure 9. Correlation between measured peak pressure and deceleration.

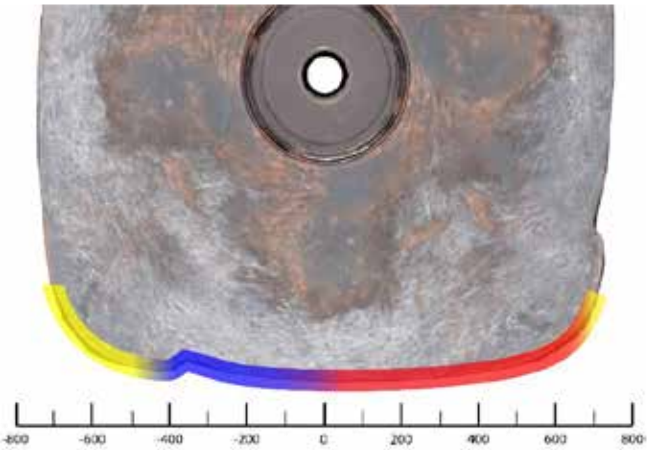

Figure 12. Heat map for 4-sided impact roller indicating the most influential parts of the contact surface that produced maximum peak pressure and peak ground deceleration.

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.

5 ACKNOWLEDGEMENTS

The authors sincerely thank instrumentation staff at The University of Adelaide for their technical support with the accelerometers and earth pressure cells; the staff at Broons for their assistance with the compaction trial and supplying the 4-sided impact roller; and Monarto Quarries for making their site available and for providing quarry material and earthmoving equipment. The authors would also like to thank the following Honours Research students who have contributed to the test results referred to within this paper: Gianfranco Canala, Chris Gauro, Jackson March, Richard Strapps, Stefan Chenoweth, Jordan Colbert, Julianne Saw and Ross Vince. Without their support the work contained in this paper would not have been possible.

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