Physical modeling of rolling dynamic compaction

Modélisation physique du compactage roulant dynamique

Oi Yin Chung, Brendan Scott, Mark Jaksa, Yien Lik Kuo
School of Civil, Environmental and Mining Engineering, University of Adelaide, Australia, oiyin.chung@adelaide.edu.au

David Airey
Department of Civil Engineering, University of Sydney, Australia

ABSTRACT: Rolling dynamic compaction (RDC) is the generic term used for soil densification involving traversing the ground with a 3-, 4- or 5-sided module. Originally developed in South Africa in the late 1940s, RDC is particularly attractive as it is able to compact the ground more effectively, i.e. 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 conventional circular drum rollers. Due to the combination of kinetic and potential energies, and the large mass of the module, RDC has demonstrated compacting effort to more than 3 m in some soils, which is far deeper than conventional static or vibratory rolling, which is generally limited to depths of less than 0.5 m. In order to understand better the efficacy of RDC in a range of soil types and ground and field conditions, a sophisticated 1:13 scale testing facility has been established. The paper presents an overview of RDC, its applications in civil and mining engineering, the testing facility and experimental program, and the research outcomes to date.

RÉSUMÉ: Compactage roulant dynamique (RDC) est le terme générique utilisé pour la densification du sol impliquant traversant le sol avec un module 3, 4 ou 5 faces. Développé initialement en Afrique du Sud à la fin des années 1940, RDC est particulièrement attrayante car elle est capable de compacter le sol plus efficacement, c'est à dire aux profondeurs plus grandes que ses homologues statiques et rouleaux vibrants, et plus efficacement en raison de sa plus grande vitesse - 12 kmh par rapport à 4 kmh en utilisant des rouleaux cylindriques circulaires conventionnels. En raison de la combinaison des énergies cinétiques et potentielles, et la grande masse du module, RDC a démontré l'effort de compactage à plus de 3 m dans certains sols, ce qui est beaucoup plus profonde que laminage statique ou vibratoire classique, qui est généralement limitée à des profondeurs moins de 0,5 m. Afin de mieux comprendre l'efficacité de la RDC dans une gamme de types de conditions du sol et du terrain, une installation sophistiquée de test à l'échelle 1:13 a été établie. Le document présente un aperçu du RDC, de ses applications en génie civil et de l'exploitation minière, l'installation d'essai et du programme expérimental et des résultats de la recherche à ce jour.

KEYWORDS: impact roller, dynamic compaction, ground improvement, 1-g physical model

1 INTRODUCTION

Dynamic compaction (DC) is widely adopted internationally and is a well-recognized and effective method of ground improvement. DC densifies the ground to significant depth by applying large impact energy at the ground surface, with the depth of improvement being a function of the imparted energy and the ground conditions. Originally known as heavy tamping, DC was introduced in the 1970s by Louis Menard and involves the dropping of tampers that weigh tens of tonnes from heights between 15 m and 40 m and enables ground improvement to depths of between 10 to 30 m below the ground surface (Menard and Broise 1975). Due to the very high energy at impact, DC results in a series of craters being produced and also creates significant vibrations, which are unacceptable in many developed areas. Rolling dynamic compaction (RDC) improves the ground to shallower depths also by impact energy. RDC consists of a heavy roller (6 to 12 tonnes), non-circular in cross-section, incorporating 3, 4 or 5 sides, and which is towed by a tractor during operation. The RDC module is shaped such that the center of gravity lifts when the module rotates about its corners. In the case of the 4-sided 'impact roller', the focus of this study, the rolling of the module is assisted by a dual spring linkage system, such that the springs store and release energy to facilitate rotation and increase the energy delivered to the ground. The practical speed of RDC operation is between 9 to 14 km/h, which is significantly higher than conventional circular drum rollers that travel at approximately 4 km/h. Applications of RDC in mining, roadworks and agriculture have demonstrated that RDC provides ground improvement from 1 to 3 m below the ground (Avalle and Carter 2005), and

the induced vibrations are not excessive (Bouazza and Avalle 2006).

Although the demand for RDC operations is increasing globally, no theoretical model is available to predict accurately the depth and extent of ground improvement. Limited research based on physical modeling has been undertaken to study the processes of DC and RDC. Small-scale model tests allow for parametric studies to be conducted in a controlled laboratory environment and are often more cost effective than field trials. Correct scaling is essential to ensure that the physical model tests accurately represent the behavior of the prototype.

In an effort to develop a reliable numerical model, this paper presents preliminary results of tests undertaken using a 1:13 scale model of the 4-sided, 8-tonne, Broons BH-1300 impact roller (Fig. 1) performed in a bespoke test facility.

2. TEST FACILITY

The 1-g physical model testing facility is located at Gillman, South Australia. It incorporates a test rig (Fig. 2), which consists of an elliptical track and two 1.2 m high × 0.75 m wide × 1.075 m long steel bins, containing the soil to be improved by the RDC model and incorporating embedded instrumentation. The RDC model is towed along the track via a chain-driven carriage, which is powered by a variable-speed, electric motor.

The RDC model (Fig. 3) is a faithful replica of the BH-1300 impact roller at a scale of 1:13. This ratio was selected as an appropriate compromise between the size and weight of the soil test bins, overall dimensions of the test rig, traditional soil particle size and test accuracy.

Figure 1. Broons 4-sided, 8-tonne, BH-1300 impact roller.

Figure 2. Test rig for scale model impact roller.

Figure 3. Model of Broons BH-1300, 4-sided impact roller. (The dual spring-linkages can be seen on the left- and right-hand sides of the module.)

3 EXPERIMENTAL PROGRAM

The overall experimental research program will incorporate and investigate each of the RDC modules in current and widespread operation worldwide, which include the 3-, 4- and 5-sided variations in various weights. A range of soil types will also be investigated to examine the efficacy of RDC. Initially, a readily available and homogeneous Sandy Gravel has been studied, as it has been examined in a number of field studies conducted at Monarto Quarries, South Australia (Scott et al. 2016). The other soils that will be considered in the future will include Sand (fine-grained and coarse-grained), Clayey Sand, Sandy Clay, and Clay (low and high plasticity), which represent soils typically encountered in civil construction projects globally.

3.1 Soil characteristics

Model compaction tests have been carried out using a well-graded Sandy Gravel soil obtained from Monarto Quarries in South Australia. A series of soil classification and consolidation tests have been performed to determine the basic soil characteristics and the critical state parameter, λ. The test results are summarized in Table 1.

Table 1. Soil characteristics for RDC model compaction testing.

USCS classification	Sandy gravel (GW)
Critical state parameter, λ	0.11
Specific gravity	2.62
Standard optimum moisture content	12%
Standard maximum dry density	19 kN/m^3
Maximum particle size	10 mm

Note: Soil particles greater than 10 mm in size have been sieved.

3.2 Scaling laws

In order to obtain meaningful results from 1-g physical modeling, it is essential that the initial state of a soil element at model scale is related to the correspondent element in the prototype (full scale) in a specific manner and the two soil elements are subjected to a similar stress path (Roscoe and Poorooshasb, 1963, Altaee and Fellenius 1994). The critical state has been selected as the reference state, which is defined as the stress reached in a soil when continuous shearing occurs at a constant shear stress to normal effective stress ratio and constant volume. Equation 1 (Roscoe and Poorooshasb 1963) correlates the imposed stress in the model and prototype as a function of the initial void ratio and critical state parameter λ.

$$\frac{\Delta\sigma_m}{\Delta\sigma_p} = \frac{\sigma'_{0m}}{\sigma'_{0p}} = exp\left(\frac{e_{0p} - e_{0m}}{\lambda}\right) \qquad (1)$$

where $\Delta\sigma$ is the stress imposed, σ'_0 is the initial stress, e_0 is the initial void ratio, λ is the slope of the critical state line for e vs. log σ, and the subscripts m and p denote the model and prototype, respectively.

3.3 Boundary effects

The geometry of the soil bins was designed with the aid of numerical modeling, such that edge effects are effectively eliminated and data are not affected by reflections from compression waves at the sides of the bins. In order to validate this design, sensors were placed at the bottom and at the edge of one of the soil bins, at various depths between 50 and 400 mm. The results showed that the increase in soil pressure and accelerations were negligible when the model compactor traversed along the track compacting the soil inside the bins at a speed equivalent to 12 km/h of a prototype.

3.4 Soil preparation, instrumentation and measurement of soil density

As the first step in the model testing, the soil was weighed and then thoroughly moisture conditioned prior to placement in the soil bins to achieve a consistent moisture content of 12%. The soil was weighed and placed into the bins in layers of approximately 100 mm in thickness in order to achieve a uniform initial density. During the process of placing the soil in layers, Keller Series 9 PD earth pressure cells (EPCs), 19 mm diameter piezo resistive pressure transducers, were embedded in

the soil at depths of 55, 85, 200 and 300 mm beneath the centerline of RDC module as it traversed across the soil bins. Accelerometers were attached to each EPC to measure ground acceleration in the X- and Y-planes to measure tilt, and in the Z-plane to measure vertical acceleration. The EPCs and accelerometers were connected to a custom-built data acquisition system and Labview software program. A sampling frequency of 2 kHz was selected for this trial to capture the true peak pressure and ground accelerations. Due to space constraints in this paper, acceleration results are not presented but will be included in a future paper.

A total of 80 passes of soil compaction were carried out using the scaled model of an 8-tonne 4-sided module, at a speed equivalent to 11 km/h of a prototype. In addition to measuring real-time dynamic pressures using EPCs, soil density was measured using a nuclear density gauge, prior to, and after 80 passes of model compaction. The use of a nuclear density gauge is not common in a laboratory environment, but has been used by Cassaro et al. (2000) who successfully used it to detect compacted soil layers that were placed at known depths within a container of soil.

3.5 *Results from scale model testing*

The peak pressures recorded for all 80 passes of model compaction are summarized in Figure 4 for test depths of 55 and 85 mm. Figure 4 indicates that there is no clear trend between peak pressure and number of passes. The maximum measured soil pressure from 80 passes of model compaction is 29 kPa, at 55 mm depth (mean, μ, of 13 kPa, standard deviation, σ, of 4 kPa). At a depth of 85 mm, the maximum recorded pressure is 12 kPa (μ = 6 kPa; σ = 2 kPa). Test depths of 200 and 300 mm are not shown for clarity in Figure 4, but the maximum peak pressures that were measured for all depths are included in Figure 5. As expected, the magnitude of measured pressures reduced with increasing depth, with relatively low readings recorded below 200 mm depth.

Soil densities were measured using a nuclear density gauge pre- and post-compaction at incremental depths of 25 mm to a maximum depth of 300 mm. The results are plotted in Figure 6, where a convergence between the pre- and post-test void ratios occurs at a depth of 250 mm, suggesting an increase in soil density due to model compaction above this depth.

4 COMPARISON WITH FULL SIZE IMPACT ROLLER

A field trial conducted by Scott et al. (2016) at Monarto Quarries used a full-size 4-sided, 8-tonne BH-1300 module on a trial pad consisting of 1.5 m deep Sandy Gravel soil (as used for the tests described in this paper). The measured peak pressure recorded for each pass of the full size impact roller, 80 no. in total, is displayed in Figure 7. Again, there is no clear relationship between number of passes and measured peak pressure. In Figure 7, the maximum measured soil pressure after 80 passes is 1,206 kPa at 0.7 m depth, and 716 kPa at 1.1 m depth. As explained by Scott et al. (2016) it is not possible to capture the maximum ground response from each and every impact by burying sensors into the soil at discrete locations, as the variation in measured pressures can be largely attributed to the impact location of the module relative to the underlying EPCs.

A nuclear density gauge was used to measure field density pre- and post-compaction. The variation of void ratio with depth is summarized in Figure 8, whereby it can be observed that the greatest reductions in void ratio occur above a depth of 1.4 m. Below 1.4 m, the test results are not conclusive as only 1.5 m of Sandy Gravel soil was placed.
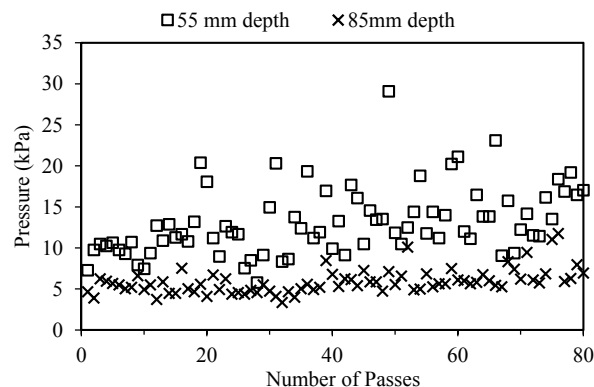

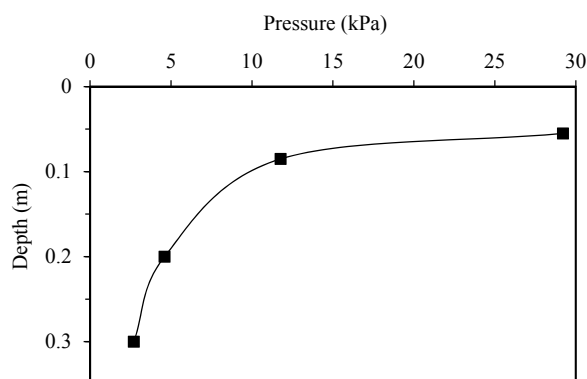Figure 4. Measured peak pressures for each pass of model compaction.

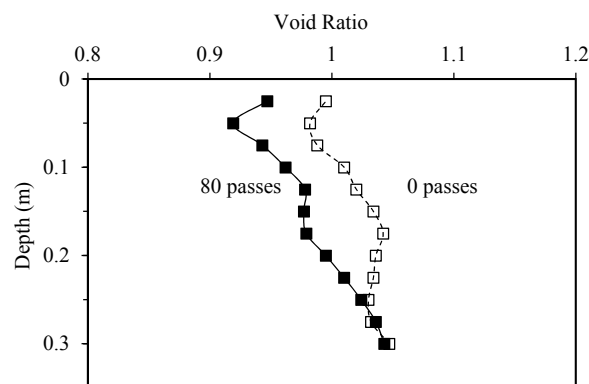Figure 5. Peak pressure versus depth for model compaction.

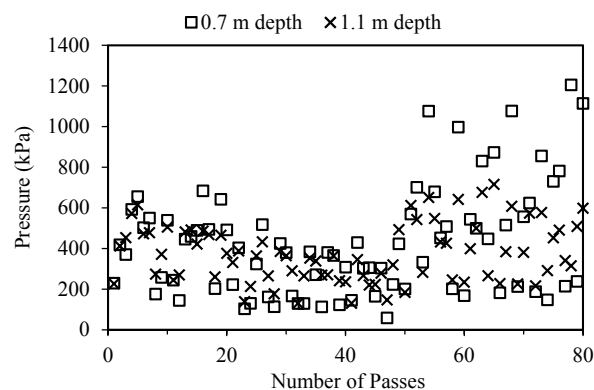Figure 6. Void ratio versus depth for RDC model testing.

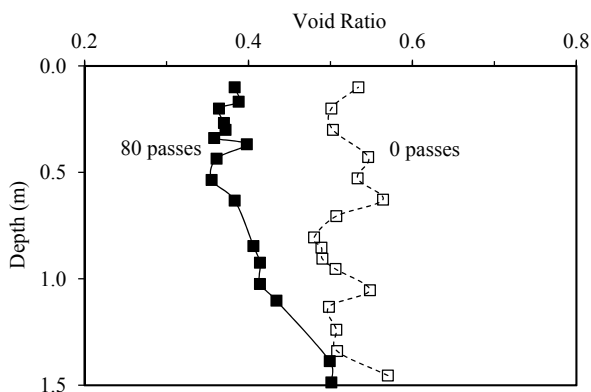Figure 7. Measured peak pressure for each pass of the BH-1300 impact roller during field testing.

Figure 8. Void ratio versus depth from field density testing

4.1 *Scaling of model pressures and comparing to full size measured data*

The scaling ratio for soil stress, $\sigma'_{0m}/\sigma'_{0p}$, is calculated using λ from Table 1 as per Equation 1. Given that e_{0m} and e_{0p} values vary with depth, as shown in Figures 6 and 8, respectively, the scaling ratio (from model to prototype) also varies with depth. Using the scaling ratio, it is possible to predict the maximum soil pressures due to the full size impact roller. Figure 9 shows the comparison between measured peak pressures from Scott et al. (2016) and predicted pressures from model compaction testing. It can be observed from Figure 9, that the model compaction results generally agree with the measured values from full size field testing, albeit slightly higher than expected. At depths of 0.7 m and 1.1 m, the predicted pressures are 1,450 kPa and 840 kPa, respectively, larger than the measured values of 1,206 kPa and 716 kPa.

The plot of predicted pressure versus depth in Figure 9 indicates that the largest pressures are expected to occur above a depth of 2 m, which is in broad agreement with the conclusions of Scott et al. (2016) based on field testing. Whilst these early results are encouraging, it does suggest that some refinement of scale model testing is still required. Rajarathnam et al. (2016) undertook 1-g model testing on a 3-sided RDC module and suggested that refinement of the speed of travel of the scale model may be required. It also recognized by the authors, that a Sandy Gravel soil type has not been the easiest soil type to work with for the initial scale model testing; it was chosen because of the availability of measured field data.
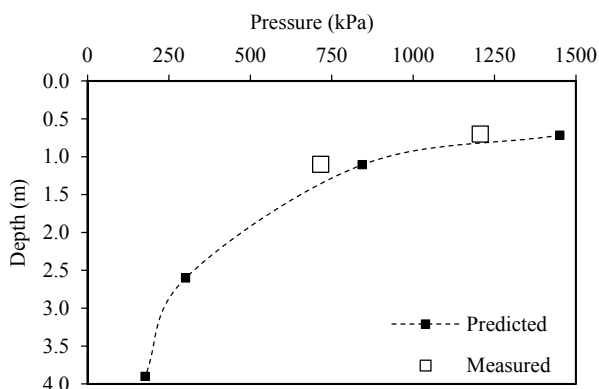

Figure 9. Predicted pressures from model compaction versus measured pressures from full size impact roller.

5 CONCLUSIONS

This paper presents the results of 1-g physical model testing of RDC using a 1:13 scale model of a 4-sided, 8-tonne impact roller. The testing facility, located in South Australia, includes a test rig that incorporates an elliptical track and two rectangular steel bins which house the soil to be improved by the RDC model. Earth pressure cells and density testing are used quantify the soil improvement due to 80 passes of model compaction. The depth of improvement due to model compaction inferred from density testing is in broad agreement with depths at which relatively low peak pressures were measured.

Correct scaling is crucial for appropriate interpretation of the results from 1-g physical modeling. The critical state has been selected as the reference state in this study and a suite of soil properties and consolidation tests have been performed on the soil in order to determine the critical state parameter λ. Measurements of void ratio, and soil pressures from model compaction, enable predictions of pressures imparted by the full size impact roller in field conditions. Comparing the predicted pressures based on model compaction testing and measured pressures from full size testing yields encouraging results. The predicted depth of improvement is approximately 2 m for the Sandy Gravel tested, which is in general agreement with the findings of Scott et al. (2016) who tested the same soil in field trials using the full size BH-1300 impact roller.

7 REFERENCES

Altaee A. and Fellenius B.H. (1994). Physical modeling in sand. Canadian Geotechnical Journal, 31: 420–431.

Avalle D.L. and Carter J.P 2005. Evaluating the improvement from impact rolling on sand. *Proc. 6th Int Conf. on Ground Improvement Techniques, Coimbra, Portugal,* 153-160.

Bouazza A. and Avalle, D.L. (2006). Effectiveness of Rolling Dynamic Compaction on an Old Waste Tip, *ISSMGE 5th Int. Congress on Environmental Geotechnics*, Cardiff.

Cassaro F.A.M., Tominaga, T.T., Bacchi, O.O.S., Reichardt, K., Martins de Oliveira, J.C. and Timm, L.C. (2000). The use of a Surface Gamma-Neutron Gauge to explore compacted soil layers. *Soil Science*, 165(8): 665–676.

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

Rajarathnam P., Masoudian M.S., Airey D.W. and Jaksa M.B. (2016). Model tests of rolling dynamic compaction. Proc. *19th Southeast Asian Geotechnical Conf. and 2nd AGSSEA Conf.*, Kuala Lumpur, Malaysia, 505–510.

Roscoe K.H. and Poorooshasb H. (1963). A fundamental principle of similarity in model test for earth pressure problems. *Proc. of 2nd Asian Regional Conf. on Soil Mechanics and Foundation Engrg.*, Tokyo, Japan, Vol. 1, 134–140.

Scott B.T., Jaksa M.B. and Syamsuddin E. (2016). Verification of an impact rolling compaction trial using various in situ testing methods. *Proc. of 5th Int. Conf. on Geotechnical and Geophysical Site Characterisation,* Gold Coast, Australia.