Assessing the Effectiveness of Rolling Dynamic Compaction

Évaluation de l'efficacité du compactage dynamique roulant

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ABSTRACT: Rolling Dynamic Compaction (RDC) is a soil improvement technique, which involves a heavy (6– to 12–tonne) 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. This paper focuses on the 4-sided module and aims to quantify the effectiveness of RDC by means of a combination of field studies and numerical modeling. The field studies involved embedding earth pressure cells beneath the ground at varying depths 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 indicated that the depth of improvement exceeded 2 meters below the ground surface. Numerical modeling was undertaken using the dynamic finite element analysis software, LS-DYNA; the results align well with those obtained from the field studies. Parametric studies were also undertaken to determine the influence of varying soil parameters on the effectiveness of RDC.

RÉSUMÉ: Rolling compactage dynamique (RDC) est une technique d'amélioration du sol, ce qui implique une lourde (6– à 12–tonne) non circulaire du module (rouleau de percussion) qui tourne autour d'un coin comme il est tiré, ce qui provoque le module de tomber à l'sol et compact, il dynamiquement. Cet article se concentre sur le module 4-faces et vise à quantifier l'efficacité de la RDC par le biais d'une combinaison d'études sur le terrain et la modélisation numérique. Les études de terrain impliqué enrobage des cellules de pression des terres au-dessous du sol à des profondeurs différentes et à mesurer la contrainte in situ sur une plage de passes de modules. En outre, une grande variété de tests in situ ont été réalisées notamment pénétromètre, la densité de champ et de test pour mesurer l'amélioration géophysique densité, de nouveau en fonction du nombre de passes de modules. Les mesures sur le terrain ont indiqué que la profondeur de l'amélioration dépassé les 2 mètres sous la surface du sol. La modélisation numérique a été réalisée en utilisant le logiciel dynamique analyse par éléments finis, LS-DYNA, les résultats concordent bien avec ceux obtenus dans les études sur le terrain. Des études paramétriques ont également été entreprises pour déterminer l'influence de divers paramètres du sol sur l'efficacité de la RDC.

KEYWORDS: Rolling dynamic compaction, impact roller, LS-DYNA

1 INTRODUCTION

Rolling dynamic compaction (RDC) is a generic term used to describe the densification of the ground using a heavy non-circular module (of three, four or five sides), that rotates about a corner as it is towed, causing the module to fall to the ground and compact it dynamically. An example of RDC is illustrated in Figure 1. RDC is able to compact the ground more efficiently because of its greater operating speed – 12 km/h compared with 4 km/h of conventional rollers. Due to the combination of kinetic and potential energies, RDC has demonstrated improvement to more than one meter below the ground surface (and greater than three meters in some soils); far deeper than conventional static or vibratory rolling, which is generally limited to depths of less than 0.5 m. As a result, RDC has been used on applications such as land reclamation projects, compaction of sites with non-engineered fill, in the agricultural sector to reduce water loss, and in the mining sector to improve haul roads and construct tailings dams.

Quantifying the effectiveness of RDC via field based trials has been the focus of different researchers over the years, including Avalle and Carter (2005), Avalle (2007), Avalle et al. (2009) and Jaksa et al. (2012). Mentha et al. (2011) conducted a trial that involved three main focus areas: (a) the use of earth pressure cells (EPCs) for direct measurements of stress change to determine the extent of depth of influence and the stress distribution induced by the RDC; (b) undertaking field tests, including dynamic cone penetration tests (DCPs) and field

density measurements and the spectral analysis of surface waves (SASW) geophysical technique to measure and infer changes in density as a function of the number of module passes; and (c) conducting a series of laboratory tests (e.g. particle size distribution, hydrometer test, Atterberg's limits, standard and modified Proctor tests) on the samples collected from the site to characterize the soil. Field-based research typically involves a team of professional operators and technicians spending days diligently preparing a test pad, placing and burying EPCs at the required depth(s) and spacing, undertaking field tests before and after a number of rolling passes, collecting data from EPCs, and collecting soil samples for further laboratory testing.

Figure 1. An example of RDC – Broons BH-1300 4-sided impact roller.

Results from field-based research are typically site specific; supporting the notion that the effectiveness of RDC is highly dependent on the soil type and site conditions. 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 how the magnitude of improvement is both defined and quantified. For example, Avalle and Carter (2005) reported a depth of improvement to approximately 1.4 m in botany sands, whereas Avalle (2007) reported a depth of 7 m in calcareous sands. Additionally, time and cost constraints typically limit the number of field tests that can be undertaken. In the case of Mentha et al. (2011), there were requirements on the minimum depth from the surface that cells could be placed to avoid damage to the EPCs, as well as the minimum spacing between adjacent EPCs to reduce stress shadowing effects. Such arrangements provide physical limitations on the spatial resolution of data that can be collected. As a result, contour plots of vertical and lateral stress produced lack of resolution.

There is currently no employable theoretical model or robust predictive model to accurately predict the depth of influence of RDC, the energy imparted per blow or the effectiveness of RDC on different soil types and site conditions. Moreover, there is also limited published information from case studies to indicate the optimal number of passes needed to attain the targeted soil density for a given site or ground condition. A consequence is that costly and time consuming field trials are inevitably required before using RDC. Due to cost and time constraints this can limit the usage of RDC in some projects.

2 NUMERICAL MODELLING

This research aims to fill the knowledge gap discussed previously by evaluating the effectiveness of RDC using the dynamic finite element modeling (FEM) software LS-DYNA (Hallquist 2006). A 3D numerical model was developed that allowed the rolling dynamics of the 4-sided impact roller to be simulated. The model was then validated against field data collected by Mentha et al. (2011). The adopted final FEM model is illustrated in Figure 2.
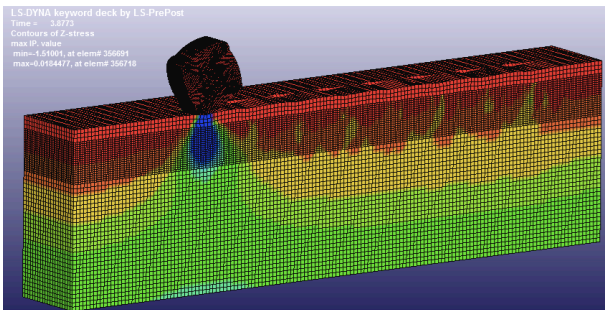

Figure 2. FEM model.

The FEM model consisted of two major parts: the 4-sided impact roller itself, which is a simplified model of the *Broons BH-1300 roller* (Figure 1), and the soil mass. The module is a steel encased concrete block. As it rolls, any deformation caused by the impact on the roller is very small and negligible. Therefore, it is reasonable to assume that the roller acts as a rigid body. The model utilized shell elements on the roller, whilst 8-node quadrilateral solid elements were used on the soil mass. To simulate the confinement and far field conditions, LS-DYNA boundary conditions *BOUNDARY_SPC_BIRTH _DEATH and *BOUNDARY_NON_REFLECTING were prescribed to the sides and base of the soil mass. Two of LS-DYNA's soil constitutive models were examined, namely the MAT_005_Soil_and_Foam and the MAT_193_Drucker_and_ Prager models. It was found that the MAT_005 underestimated the soil settlement caused by the roller and was therefore excluded from further modeling. During the initialization stage of the modeling, the effects of gravity loading were added using *LOAD_BODY_Z and *LOAD_RIGID_BODY. The contact definitions between the roller and the soil mass is described in LS-DYNA's *CONTACT_AUTOMATIC_ SURFACE_TO_

SURFACE_ID. Finally, the *BOUNDARY_PRESCRIBED_ MOTION_RIGID option was used to define the rolling motion (both horizontal and rotational speeds) of the roller. A detailed description of the FEM is given by Bradley et al. (2012).

3 FIELD WORK AND LABORATORY TESTING

The field work undertaken by Mentha et al. (2011) took place at the Project Magnet Tailings Storage Facility at the Iron Duke Mine, South Australia. The fill material typically consisted of coarse iron magnetite tailings that are a by-product of a consistent treatment process. The results from sieve analyses and plasticity tests indicated that the soil is a well graded sand (SW) with small quantities of gravel-sized material (14%) and clay fines (6%) of low plasticity (LL = ~22%, PL = ~11%). The average field moisture content was ~5% and the water table was located well below the influence depth of RDC.

The test pad consisted of three lanes; three lift heights of 1200 mm were achieved. The EPCs were strategically placed at various vertical and lateral levels. The EPCs were connected to a data acquisition system and a laptop to continuously record the pressures induced by the 8-tonne BH-1300 impact roller. EPC data for the roller at rest (static case) and in motion (dynamic case) were analyzed and reported.

Triaxial and direct shear testing was carried out by the authors to complement the results from Mentha et al. (2011) to characterize further the engineering properties of the tailings material. The results for key soil parameters, which are essential for MAT_193, are summarized in Table 1. The Poisson's ratio was assumed to be 0.3. These values were used in the subsequent numerical modeling.

Table 1. Summary of laboratory test results for key soil parameters.

Soil parameters	Results
Cohesion (kPa)	7
Angle of internal friction (°)	37
Elastic shear modulus (MPa)	5.7
Mass density (t/m^3)	2.55

4 VALIDATION OF FEM

Validation of the FEM focused on both static and dynamic (single pass at 10.5 km/hr rolling speed) cases. In the static case, the variations of influence stress with respect to depth from the FEM model were compared with solutions derived from classic Boussinesq theory and Fadum's chart. Comparisons are summarized in Figure 3. Note that, the influence stress plotted is due to the impact roller only; excluding the overburden pressure due to the soil's self weight. Moreover, the FEM predicted an immediate settlement of 4.4 mm, which is very close to the solution given by theoretical elastic theory of 5.1 mm.

In the dynamic case, the FEM was validated against field data collected by Mentha et al. (2011), and the results are shown in Figure 4. The comparison showed that the FEM accurately predicted the influence stress at various depths and exhibited a smooth trend. The FEM also predicted an immediate settlement of 17.8 mm after a single pass. Mentha et al. (2011) reported settlement data after the 8th and 16th passes only. In order to directly compare the results, approximations using linear and quadratic trend fitting to the field data yielded 17.0 and 18.5 mm respectively for a single pass. The settlement predictions from the FEM lay between these two values. In summary, the results showed that the FEM is able to predict accurately the influence stress and soil settlement in the static and dynamic cases.
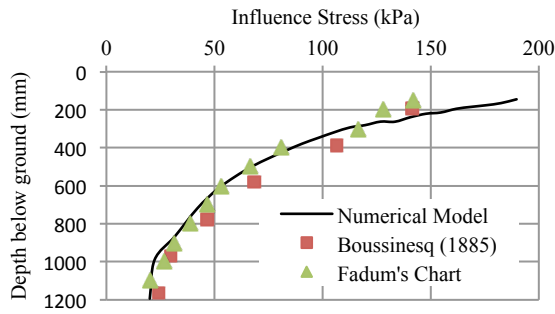
Figure 3. Validation of FEM model – static case.

5 RESULTS OF NUMERICAL MODELING

Some of the key results of a single pass are summarized in Table 2. In order to quantify the effectiveness of the impact roller on certain soils and specific site conditions, there is a need to distinguish between the *depth of influence zone* (or *influence depth* in short) and *improvement depth*. The traditional definition of *depth of influence zone* refers to the depth of soil affected by the load imposed at the ground surface; generally using 10% of the peak stress as a limit. On the other hand, the *improvement depth* is the depth over which the soil undergoes significant improvement in density and shear strength due to RDC, as illustrated in Figure 5. Improvement depth is, in the authors' opinion, a more appropriate measure of the effectiveness of the impact roller, as it is a function of soil type, site characteristics and the weight and operating speed of the RDC module. The results indicate that the influence depth is not equal to the improvement depth, as the low influence stress at greater depths may only cause soil to deform elastically, resulting in no change (or improvement) in soil density upon load removal.

Table 2. Summary of a single pass of the impact roller.

Parameters	Single pass
Peak stress (kPa)	720
Settlement (mm)	18
Influence depth (mm)	2,640
Maximum density change (%)	0.2
Improvement depth (mm)	2,350

Figure 5 shows the change in soil density varying with depth for both single and multiple passes of the impact roller. The positive change implies that density of the soil increased and the volume decreased. On the other hand, a negative change indicates decreased density and a volume increase. A few curious trends are observed in Figure 5. Firstly, the density of the soil is found to decrease within 200 to 250 mm of the ground surface. Kim (2011) found similar results, where the near surface soils actually become looser due to RDC. This is further confirmed by visual inspection of the surficial soil which is disturbed and loosened as a result of RDC where the soil is displaced laterally by the module rather than compacted. Additionally, the depth where the maximum density change is observed (~900 to 1,150 mm) does not correspond to the depth where peak influence stress occurs (~200 mm), as shown in Figure 5. This indicates that the compaction for the top layer of soil is inefficient; a higher influence stress does not necessarily result in an increased density. Furthermore, the depths and the magnitude of the peaks increase with the number of passes.
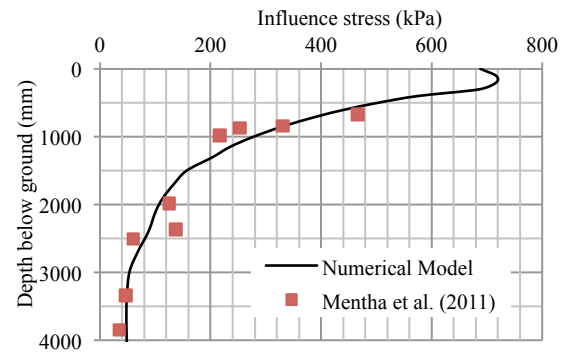

Figure 4. Validation of FEM model – dynamic case.

Figure 6 shows the relationship between influence stress and depth with the number of RDC passes, and Figure 7 shows the in situ stress measured in the field using the EPCs. It is evident from these figures that there is an upward trend of peak influence stress as the number of passes increases. This upward trend is expected, as the force imparted by the roller causes the void ratio of the soil to decrease, resulting in increased soil density and surface settlement. With increased density, the pressure wave can more readily propagate to deeper layers, resulting in increased pressures.
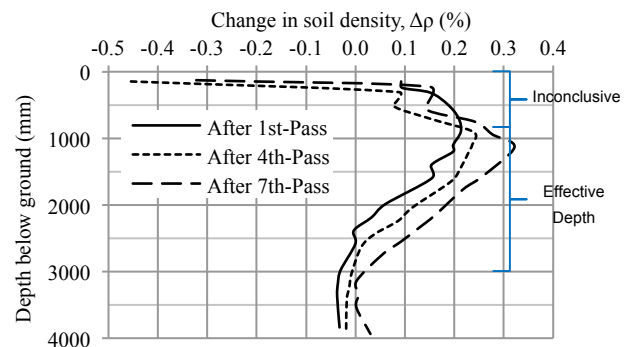

Figure 5. FEM predicted change in soil density versus depth after single and multiple passes.
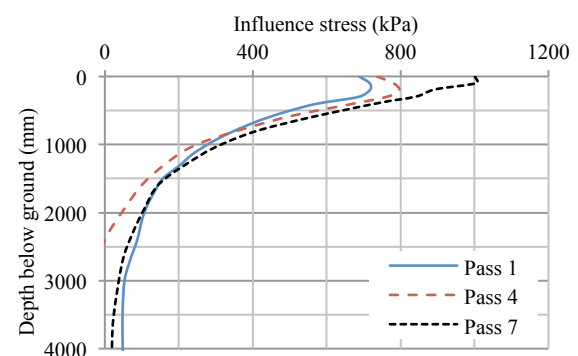

Figure 6. Influence stress versus depth for single and multiple passes.

Mentha et al. (2011) used SASW, in conjunction with dynamic cone penetration tests, to assess the same location at intervals of eight passes of the impact roller. Typical SASW results are shown in Figure 8, where it can be observed that increased number of passes results in a noticeable increase in shear modulus between depths of 0.5 to 2.1 m. This is an indication of increased soil density. Similar behavior is observed in the FEM model (Figure 5) between depths of 0.8 to 3.0 m. In Figure 8, above a depth of 0.8 m (same 0.8 m in Figure 5) the results were inconclusive, which is consistent with conclusions drawn from penetrometer and FEM results. Below

a depth of 2.5 m (3.0 m in Figure 5), the varying numbers of passes begin to converge, suggesting that this is the depth of influence of the roller for which there is quantifiable improvement. Below a depth of 2.5 m, results from field study were inconclusive due to insufficient data points.
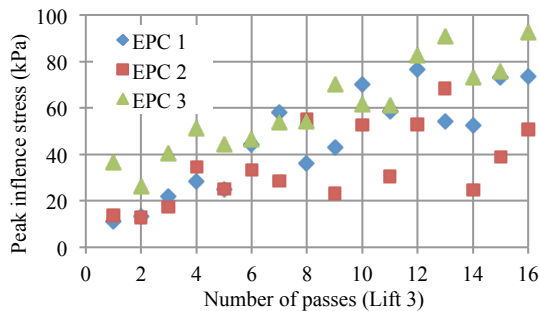

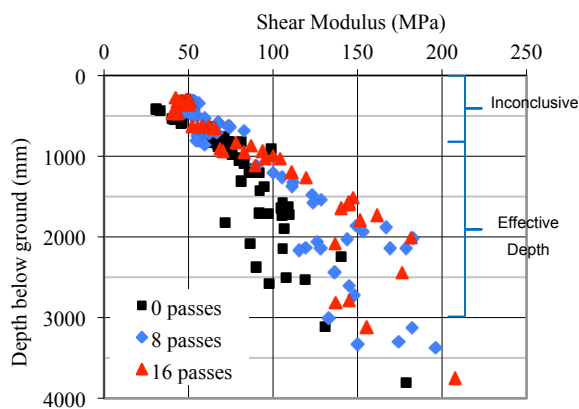Figure 7. Peak influence stress recorded by EPCs (Mentha et al. 2011).

Figure 8. SASW test results for varying passes (Mentha et al. 2011).

6 RESULTS OF PARAMETRIC STUDIES

A limited series of parametric studies was undertaken. The parameter that were examined were cohesion, shear modulus, soil's density, internal angle of friction, Poisson's ratio, mass and width of the roller and its application speed. It was found that the soil parameters that were the most significant in terms of the effectiveness of RDC were shear modulus, Poisson's ratio and cohesion (to a lesser extent). The variation of the module mass and roller width were also found to significantly affect the magnitude and depth of influence. Some of the results are presented in Figure 9.

7 CONCLUSION

This paper discussed and compared results obtained from a field study by Jaksa et al. (2012) with those obtained from finite element analysis modeling (FEM), to assess the effectiveness of rolling dynamic compaction (RDC). The FEM was validated against both theoretical solutions and field data obtained by Mentha et al. (2011). The numerical model was found to predict the soil settlement and soil stresses reasonably accurate for both the static and dynamic cases. It was observed that large surface deformations were noticeable within the first 0.8 m below the ground, with RDC proving to be most effective between depths of 0.8 m to 3.0 m. The soil within this effective depth range demonstrated an increase in soil density with increasing number of passes. A *preliminary* parametric study found that the most significant factors were soil cohesion, Poisson's ratio and shear modulus, as well as the width and mass of the RDC module.
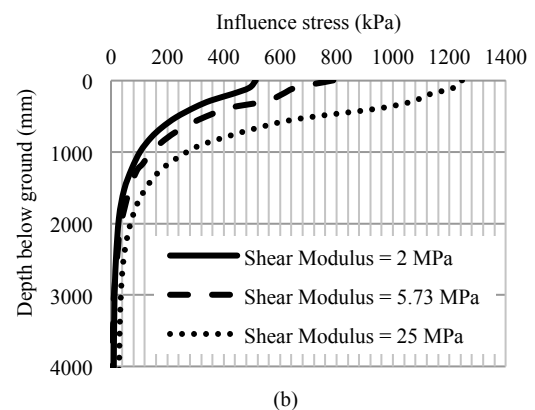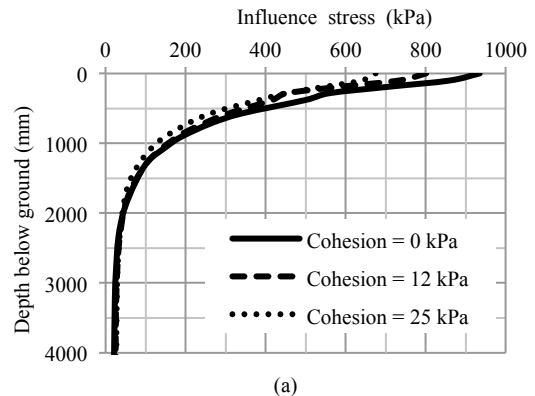
8 ACKNOWLEDGEMENTS

(a)

(b)

Figure 9. Results of parametric studies, varying: (a) cohesion; (b) shear modulus.

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