

Cite this article

Scott B, Jaksa M and Mitchell P

Depth of influence of rolling dynamic compaction.

Proceedings of the Institution of Civil Engineers – Ground Improvement,<https://doi.org/10.1680/jgrim.18.00117>**Research Article**

Paper 1800117

Received 14/11/2018;

Accepted 07/04/2019

Keywords: design methods & aids/
field testing & monitoring/geotechnical
engineeringPublished with permission by the ICE under the CC-BY 4.0 license.
(<http://creativecommons.org/licenses/by/4.0/>)

Depth of influence of rolling dynamic compaction

1 Brendan Scott BEng

Lecturer, School of Civil, Environmental & Mining Engineering, The University of Adelaide, Adelaide, South Australia, Australia (corresponding author: brendan.scott@adelaide.edu.au) (Orcid:0000-0001-5409-7678)

2 Mark Jaksa BEng, PhD

Professor of Geotechnical Engineering, School of Civil, Environmental & Mining Engineering, The University of Adelaide, Adelaide, South Australia, Australia (Orcid:0000-0003-3756-2915)

3 Peter Mitchell BEng, PhD

Technical Director – Geotechnical Engineering, Aurecon, Adelaide, Australia; Adjunct Professor, School of Civil, Environmental & Mining Engineering, The University of Adelaide, Adelaide, South Australia, Australia (Orcid:0000-0002-6811-4122)



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
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)

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 Coetze (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

$$1. \quad D = \sqrt{mh}$$

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.

$$2. \quad D = n\sqrt{mh}$$

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 .

$$3. \quad D = \sqrt{\frac{n^2}{g}(mgh)}$$

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 ($h = 0.15$ 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 underestimating 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 measurable. 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

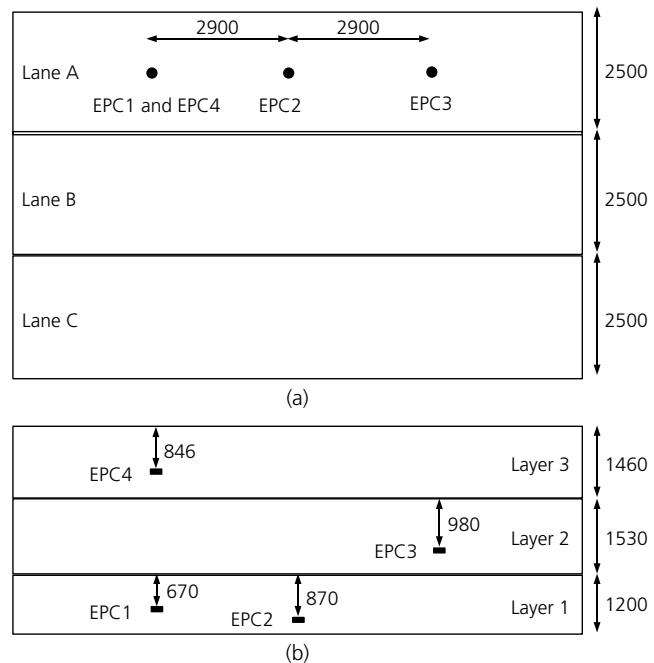


Figure 2. (a) Plan and (b) elevation views of test pad including EPC locations (all dimensions in mm)

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.

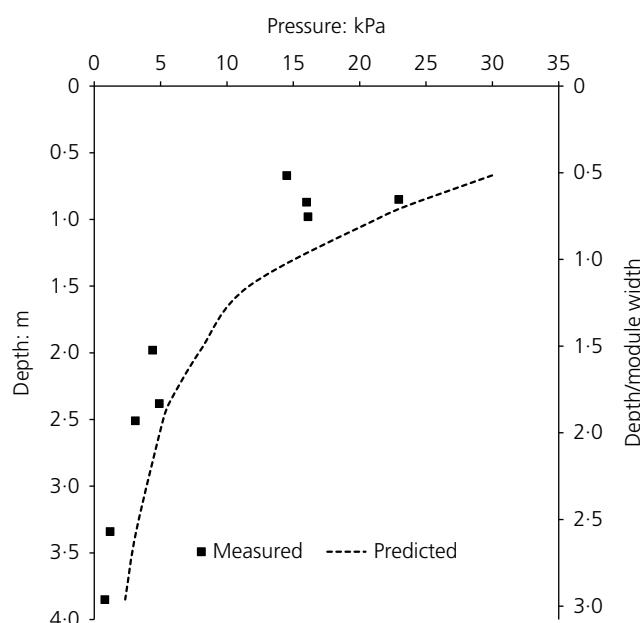


Figure 3. Measured and predicted pressures against depth for impact roller at rest

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

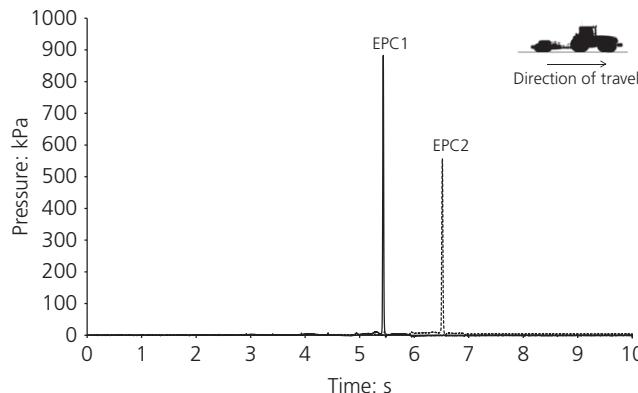


Figure 4. Example results of pressure against time for a single pass of the impact roller: lift 1 containing EPC1 and EPC2

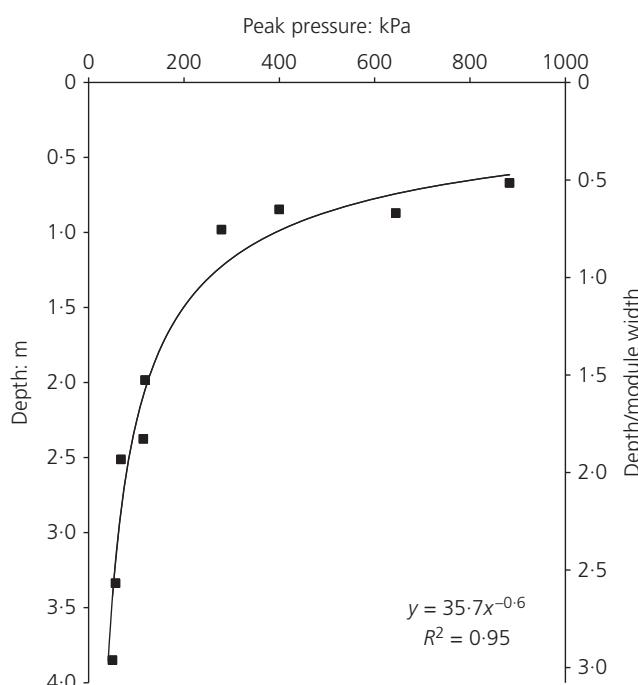


Figure 5. Measured peak pressure against depth with trend line fitted to data

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

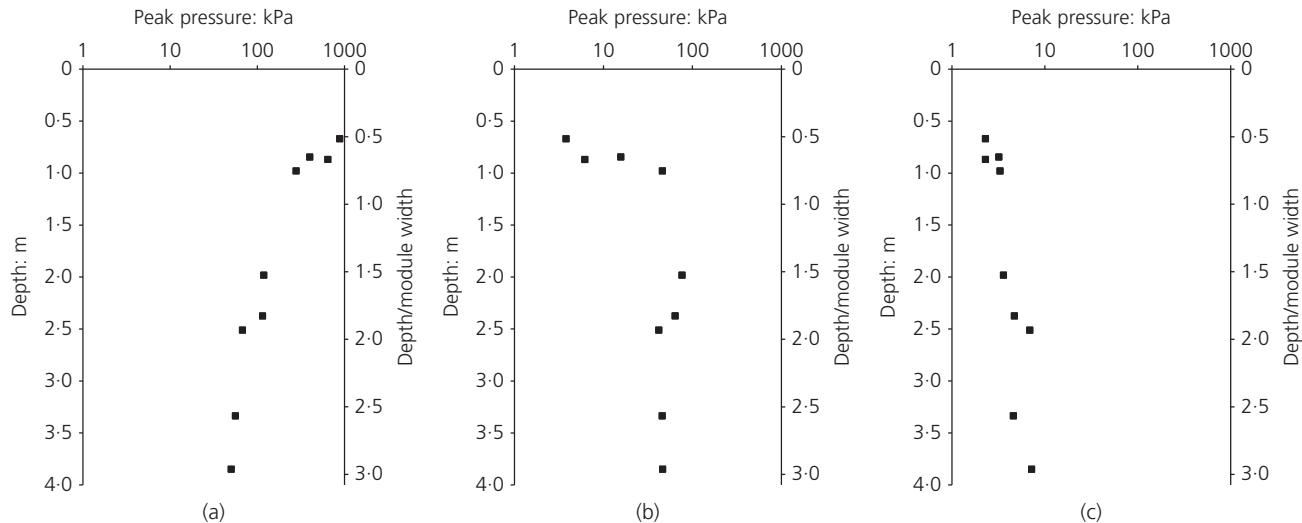


Figure 6. Measured peak pressure against depth for varying lateral distances from the centre of lane A: (a) 0 m; (b) 2.5 m; (c) 5.0 m

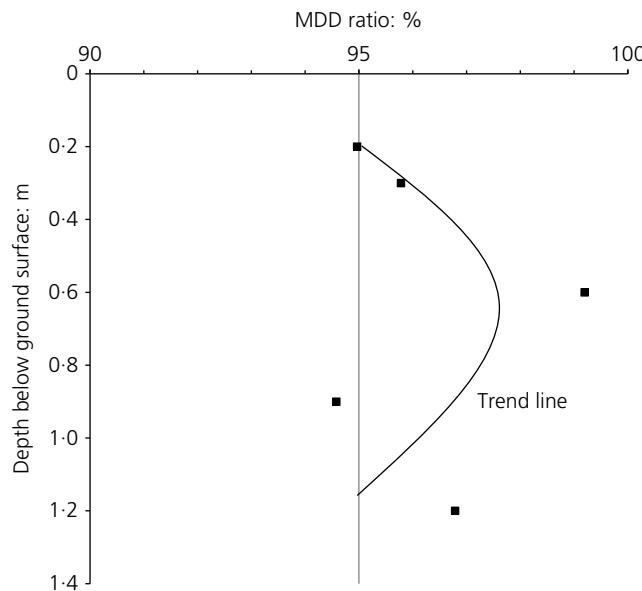


Figure 7. Modified maximum dry density ratio against depth after eight passes

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.

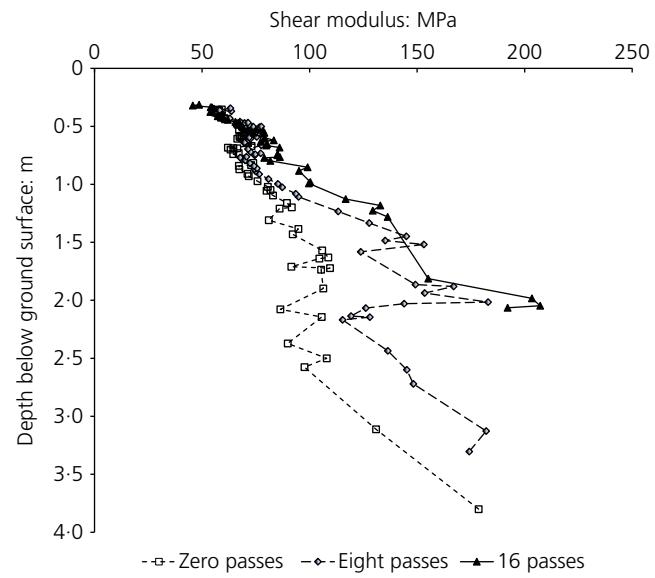


Figure 8. Geophysical (SASW) test results for zero, eight and 16 passes

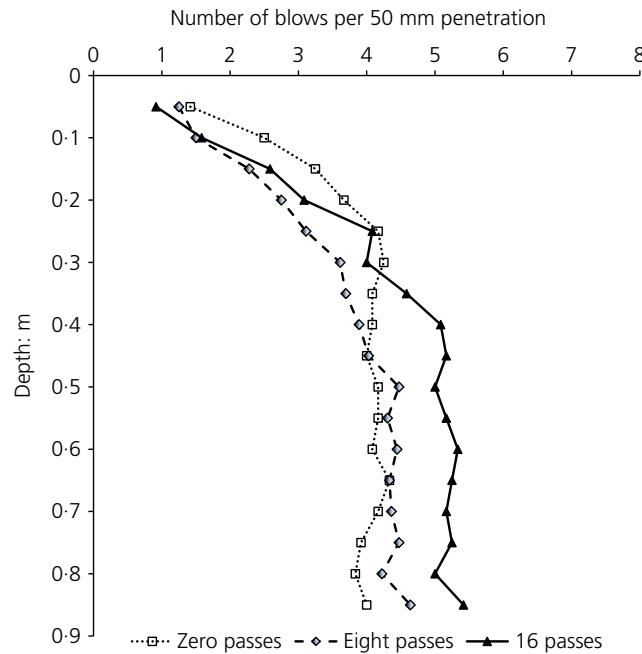


Figure 9. DCP test results for zero, eight and 16 passes

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	$\Delta PE_g:$ kJ	$\Delta KE:$ kJ
10.5	2.92	3.21	2.63	11.8	13.6

v , speed of towing unit; v_i , module velocity after impacting the ground; v_f , 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.

$$4. \quad EDI = k(n \sqrt{mh})$$

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

Table 5. Values of k for different towing speeds based on change in potential and kinetic energies

$v:$ km/h	$mgh:$ kJ	$\Delta KE:$ 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

and a variable k , which depends on the towing speed, as per Table 5.

$$5. \quad EDI = \sqrt{\frac{k^2 n^2}{g} (mgh)}$$

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.

$$6. \quad DMI = r(EDI)$$

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 ($n=0.3$) 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, 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.

Acknowledgements

The authors acknowledge the following final year civil engineering students from the University of Adelaide who contributed to the field work referred to in this paper: Nicole Mentha, Simon Pointon, Erfan Syamsuddin, Aidan Symons and Penelope Wrightson. The authors are grateful to the instrumentation and laboratory staff at the University of Adelaide who have provided invaluable support over the years and to Cathy Cates for her assistance with word processing. The authors are also grateful to Broons and HWE Mining personnel for access to equipment and the test site; without their help and support, the work undertaken in the field trial featured in this paper would not have been possible.

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.

How can you contribute?

To discuss this paper, please email up to 500 words to the editor at journals@ice.org.uk. Your contribution will be forwarded to the author(s) for a reply and, if considered appropriate by the editorial board, it will be published as discussion in a future issue of the journal.

Proceedings journals rely entirely on contributions from the civil engineering profession (and allied disciplines). Information about how to submit your paper online is available at www.icevirtuallibrary.com/page/authors, where you will also find detailed author guidelines.