The 4-sided impact roller – guidance for practitioners

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ABSTRACT: Rolling Dynamic Compaction (RDC) imparts energy to the ground via the use of a heavy non-circular module that rotates as it is towed, causing it to fall to the ground and compact it dynamically. This paper summarises the predictions of energy imparted to the ground from a single impact for both the standard (8-tonne), and heavy duty (12-tonne) 4-sided impact rollers. Several published case studies are summarised for the applications of: (1) improving ground in situ; and (2) compacting soil in thick layers. This paper addresses the need for these two distinctly different applications of RDC to be treated separately. Finally, this paper augments deep dynamic compaction theory and provides relationships for estimating the depths of soil that can be improved in situ, and layer thicknesses capable of being compacted by RDC.

KEYWORDS: Rolling, dynamic, compaction, depth, energy.

1 INTRODUCTION

Rolling Dynamic Compaction (RDC) imparts energy to the ground via the use of a heavy non-circular module of 3, 4 or 5 sides that rotates as it is towed, causing it to fall to the ground and compact it dynamically. This ground improvement technique is typically used to improve a soil's shear strength and stiffness, or reduce its permeability.

The 4-sided (square) impact roller was originally developed in South Africa with the intention of improving the properties of granular soils, in particular collapsing sands within 3 m of the surface in southern Africa (Clifford, 1978). Since that time, RDC has been used in many varied applications, including the improvement of poor quality ground, compaction of thick layers for in-filling deep excavations, proof rolling of road and subgrade materials, construction of haul roads and rubbilising rocks in the mining industry, compaction of soil in irrigated areas to reduce soil permeability and conserve water and compaction of reclaimed land on large scale earthworks projects where it has been used to complement deeper ground improvement techniques.

The underlying objective of this paper is to communicate recent research findings that provide guidance on predicting the depths of improvement for both the standard (8-tonne) and heavy duty (12-tonne) 4-sided square impact rollers using an energy-based approach for two of the most common applications: (1) improving ground in situ, and (2) compacting soil that is placed in thick layers.

2 EFFECT OF TOWING SPEED

Scott et al. (2020) undertook two full-scale field trials using the 8-tonne impact roller (shown in Figure 1) to capture the changes in stress imparted to the ground with increasing towing speed. Homogeneous soils were used in both field trials so that key variables were controlled, allowing the effects of towing speed to be isolated. The field trials by Scott et al. (2020) determined that towing speed influences the stress that is imparted into the ground. At towing speeds less than 9 km/h, the dynamic effects of the module are not maximised, compared with towing speeds of 10-12 km/h that were found to be optimal. At towing speeds above 12 km/h, higher stresses could occasionally be imparted into the ground, but the kinematics of the module impacting the ground changed if it was towed too quickly, causing it to skip and jump from corner to corner, instead of the sides of the module falling to impact the ground in a predictable and reproducible manner. These research findings confirm the need for impact rolling specifications to detail a target towing speed range.

Based on the authors' experiences, the optimum speed will vary depending on site conditions. To optimise the use of the 4-sided impact roller, a towing speed range of 10-12 km/h is recommended, which is consistent with the findings of the field trials reported in Scott et al. (2020).

Figure 1. 4-sided impact roller.

3 ENERGY IMPARTED TO THE GROUND

The effect of towing speed on the energy imparted to the ground from the 4-sided impact roller was also examined by Scott et al. (2020). They combined theory from Halliday et al. (1993), observations from two full-scale field trials undertaken by the authors, high-speed photography by Clifford & Bowes (1995), as well as quantifying the spring energy generated from the double-spring-linkage system. Additionally, estimates of energy imparted to the ground for the 3-sided roller by Heyns (1998), and the 8-tonne 4-sided impact roller by Bradley et al. (2019) were analysed. Bradley et al. (2019) quantified the imparted energy from a single module impact of the standard 4-sided impact roller to be 23 kJ (±4 kJ) for a towing speed of 10 km/h, using high-speed photography, consistent with the findings of Scott et al. (2020).

Scott et al. (2020) concluded that the energy delivered by a single impact is dependent upon towing speed and that energy imparted to the ground is a function of the net work done. The net work done is equal to the sum of the change in gravitational potential and kinetic energies. Work is being done against gravity, as well as inertia and frictional resistive forces, and is considered a more appropriate means to describe the energy delivered by RDC, rather than describing it solely using gravitational potential or total kinetic energy.

Scott et al. (2020) refined the maximum estimated energy that is imparted to the ground by the 8-tonne 4-sided module to be between 22 kJ to 30 kJ for typical towing speeds of 9 to 12 km/h, as shown in Table 1. This is in contrast to previous estimates for the 8-tonne 4-sided impact roller that predicted values of 12 kJ based on potential energy, and between 30 kJ to 54 kJ for the same towing speed range based on kinetic energy. In this paper, the work of Scott et al. (2020) has been extended to the heavy duty (12-tonne) 4-sided impact roller. As shown in Table 2, the maximum estimated energy that is imparted to the ground by the 12-tonne 4-sided module is between 33 kJ to 44 kJ for typical towing speeds of 9 to 12 km/h. In Tables 1 and 2, v is the speed of the towing unit; ΔPE is the change in potential energy and ΔKE is the change in kinetic energy.

Table 1. Energy imparted by the 8-tonne 4-sided module.

v (km/h)	ΔPE (kJ)	ΔKE (kJ)	ΔPE + ΔKE (kJ)
9	11.8	10.0	21.8
10.5	11.8	13.6	25.4
12	11.8	17.8	29.5

Table 2. Energy imparted by the 12-tonne 4-sided module.

v (km/h)	ΔPE (kJ)	ΔKE (kJ)	ΔPE + ΔKE (kJ)
9	17.7	15.0	32.7
10.5	17.7	20.4	38.1
12	17.7	26.7	44.3

The use of high-speed photography adopted by both Clifford & Bowes (1995) and Bradley et al. (2019) enabled the module motion to be captured and analysed. Consequently, this technique captured factors that cause the module to change velocity, such as the frictional resistance between the module and the ground surface, and the effects of the double-spring-linkage system. As explained by Clifford & Bowes (1995), the double-spring-linkage system slows the module during the lifting phase as the springs are compressed and releases the stored spring energy during the impact phase, causing the module velocity to increase. Scott et al. (2020) quantified the effects of the double-spring-linkage system but didn't quantify the frictional resistance at the module-soil interface, as it is difficult to evaluate theoretically. Instead, Scott et al. (2020) used the work of Bradley et al. (2019) to support the assumptions made by Clifford & Bowes (1995) regarding the relationship between towing speed and module velocity that were used to estimate the change in kinetic energy.

Current practice of using either total kinetic energy or gravitational potential energy should be avoided as neither can accurately quantify RDC when towing speed is varied. The use of total kinetic energy overestimates the energy imparted to the ground. Describing the energy via the use of gravitational potential energy should also be avoided, as it is counter-productive for the impact rolling industry to develop specifications stipulating target towing speeds when impact rollers are described solely in terms of their gravitational potential energy.

4 DEPTH OF INFLUENCE

Published case studies involving the 8-tonne 4-sided impact roller that have improved the ground in situ, or and have compacted soil in thick layers, are summarised in Tables 3 and 4, respectively. It is evident from Tables 3 and 4 that the depth of improvement of RDC varies significantly depending upon the soil material type. It is reasonable to conclude that RDC has a greater depth of influence in granular soils compared to clays. It is also evident that the thickness of compacted layers is less than the depth of improvement in the same soil type, as the compacted layer thickness is typically tailored to meet a target specification.

It is often up to the project engineer to predict if the use of RDC will improve the ground sufficiently for a desired project outcome. However, unless site conditions match well with a previously published case study, there is little published information quantifying depths to which ground can be improved, and how that may vary depending upon the soil type. Additionally, there is confusion between two common applications of RDC: (1) improving soil in situ; and (2) compacting soil in thick lifts. These are two distinctly different applications of RDC that must be treated separately.

Table 3. Improvement depths for compacting in situ (8-tonne module).

Reference	Soil type	Improvement Depth (m)
Clifford (1978)	Sand	>2.5
Clifford (1978)	Sand	>2.0
Avalle & Young (2004)	Fill (clay)	1.0
Avalle (2004)	Fill (sand)	>2.0
Avalle & Grounds (2004)	Fill (mixed)	1.5
Avalle & McKenzie (2005)	Fill (clay)	2.0
Avalle & Carter (2005)	Fill (sand) over natural sand	3.0
Avalle (2007)	Fill (sand)	2.5
Scott & Suto (2007)	Fill (gravelly clay)	1.5
Whiteley & Caffi (2014)	Fill (mixed)	1.5
Scott & Jaksa (2014)	Fill (clayey sand) over natural clay	1.75

Table 4. Thickness of compacted layers (8-tonne module).

Reference	Soil type	Layer Thickness (m)
Wolmarans & Clifford (1975)	Sand	1.5
Wolmarans & Clifford (1975)	Clay	0.6
Clifford (1980)	Clay	0.5
Clifford & Coetzee (1987)	Fill (coal discard material)	0.5
Avalle & Grounds (2004)	Fill (gravel)	1.0
Avalle (2007)	Sandy clay / clayey sand	0.7
Scott & Jaksa (2012)	Fill (mixed)	1.0
Scott & Jaksa (2014)	Fill (clayey sand)	1.0

Whilst not summarised in Tables 3 and 4, other variables such as moisture content, ground water conditions and the number of passes applied also affect the depth to which ground can be improved. Additionally, the target specification, testing methods used to quantify improvement, and the interpretation of how the depth of improvement is both defined and quantified, varies between the listed references, making it difficult to draw definitive conclusions as to the maximum improvement depth or layer thickness that may be achieved.

The term "influence depth" can be interpreted differently and is not used consistently across the industry. The are many in situ techniques that are used to quantify the depth of influence of RDC; however, 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 the context of predicting depths to which RDC may be effective. Firstly, 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. Scott et al. (2021) made no attempt to quantify the depth at which RDC has a small positive influence. Instead, an energy-based approach was used to estimate the depths beneath the surface that RDC can improve for different soil conditions and applications. Two other basic definitions introduced by Scott et al. (2021) are: the effective depth of improvement (*EDI*), and the depth of maximum improvement (*DMI*).

The use of *EDI* is appropriate for determining the depths to which ground can be improved in situ, as per the case studies referenced in Table 3. *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. *EDI* is calculated as the product of Eq. 1 (which is based on module mass, m, lift height, h, and an empirical factor n from dynamic compaction theory), multiplied by a new term k, defined as the ratio of the energy imparted to the ground divided by the change in gravitational potential energy, as shown in Eq. 2.

$$D = n\sqrt{mh} \tag{1}$$

$$EDI = k(n\sqrt{mh}) \tag{2}$$

Alternatively, Eq. 2 can be re-written as shown in Eq. 3. In this form, *EDI* is written in terms of the material characteristics, n, gravitational potential energy, mgh and the energy ratio k, which depends upon the towing speed.

$$EDI = \sqrt{\frac{k^2n^2}{g}(mgh)} \tag{3}$$

For determining the maximum layer thickness that can be compacted using RDC in thick lifts, the use of *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. *DMI* is consistent in the approach adopted by Slocombe (2004) to determine the zone of major improvement from the effective depth of improvement, whereby a reduction factor, r, is used. *DMI* is equal to r (a constant that varies between 0.5–0.67) multiplied by *EDI* as defined in Eq. 4.

$$DMI = r(EDI) \tag{4}$$

Values for *EDI* and *DMI* are summarised in Tables 5 and 6, for the 8-tonne and 12-tonne modules, respectively. In Tables 5 and 6, v is the speed of the towing unit; n, is the empirical factor that accounts for soil type (the values are consistent with the range proposed by Mayne et al. (1984), where lower values are applicable for clay soils and higher values are valid for granular soils, and mixed soils require intermediate values of n to be adopted); D is the depth of soil compacted due to gravitational potential energy (only); and k, is defined as the ratio of the energy imparted to the ground divided by the change in gravitational potential energy. The calculated values in Table 5 are in broad agreement with the case studies summarised in Tables 3 and 4.

Table 5. Predicted effective and maximum depths of improvement for the 8-tonne module.

v (km/h)	*n*	*D* (m)	k	*EDI* (m)	*DMI* (m)
9	0.3	0.33	1.8	0.59	0.30-0.40
9	0.5	0.55	1.8	0.99	0.49-0.66
9	0.8	0.88	1.8	1.58	0.79-1.06
10.5	0.3	0.33	2.2	0.72	0.36-0.48
10.5	0.5	0.55	2.2	1.20	0.60-0.81
10.5	0.8	0.88	2.2	1.93	0.96-1.29
12	0.3	0.33	2.5	0.82	0.41-0.55
12	0.5	0.55	2.5	1.37	0.68-0.92
12	0.8	0.88	2.5	2.19	1.10-1.47

Table 6. Predicted effective and maximum depths of improvement for the 12-tonne module.

v (km/h)	*n*	*D* (m)	k	*EDI* (m)	*DMI* (m)
9	0.3	0.40	1.8	0.72	0.36-0.49
9	0.5	0.67	1.8	1.21	0.60-0.81
9	0.8	1.07	1.8	1.93	0.97-1.29
10.5	0.3	0.40	2.2	0.89	0.44-0.59
10.5	0.5	0.67	2.2	1.48	0.74-0.99
10.5	0.8	1.07	2.2	2.36	1.18-1.58
12	0.3	0.40	2.5	1.01	0.50-0.67
12	0.5	0.67	2.5	1.68	0.84-1.12
12	0.8	1.07	2.5	2.68	1.34-1.80

Whilst both module mass and towing speed influence the improvement depths that are achievable, it is evident from Tables 5 and 6 that soil type is the single most important variable in quantifying the depth to which RDC can improve soil. The depth to which RDC can improve and compact granular soils is influenced more by towing speed than for clay soils. However, not all ground surface conditions can sustain a towing speed of 12 km/h; therefore, in the absence of site-specific information, or if unsure, the author would recommend adopting a median towing speed of 10.5 km/h when using Tables 1, 2, 5 or 6 in this paper.

Test results from the full-scale field trial in homogenous soils conducted by Scott et al. (2021) confirmed that the formula for deep dynamic compaction (Eq. 1) first proposed by Menard & Broise (1975) could not be used directly for RDC without modification. Eqs. 2–4 presented in this paper augment the relationship (Eq. 1) for dynamic compaction first proposed by Menard & Broise (1975). In addition to soil type, module mass and drop height, the equations presented also incorporate the effect of towing speed. The energy-based approach yields estimations for depths capable of being significantly improved in situ, and layer thicknesses capable of being compacted by RDC, that are in broad agreement with the findings of the field trial presented, and the results of published case studies involving the 8-tonne 4-sided impact roller over the past four decades.

It is acknowledged that the equations developed to estimate the depth of improvement are simplistic and have limitations. The equations rely solely on module mass, drop height, and the n (soil type) and k (taking into account that the energy imparted into the ground is not solely gravitational potential energy) values. They do not include variables such as moisture content, number of passes and contact area of module with the ground.

There is also scope to examine if there are advantages in refining and improving Eq. 3 to include the change in kinetic energy term, ΔKE. Eq. 2 retains the form of the original Menard & Broise (1975) equation (Eq. 1), along with an empirical factor n that takes into account soil type (as per dynamic compaction theory). This equation was augmented for RDC by multiplying by an energy ratio parameter, k, which varies with towing speed and is based on an estimation of ΔKE. Augmenting the original Menard & Broise (1975) equation was deliberate to allow practitioners to infer a depth of influence based on physical parameters associated with the module that can be quantified easily.

5 CONCLUSIONS

For the 4-sided impact roller, a towing speed range of 9-12 km/h is recommended, with 10-12 km/h optimal. The maximum estimated energy that is imparted to the ground varies with towing speed. For the 8-tonne module, the maximum energy imparted to the ground per impact varies between 22 kJ to 30 kJ for towing speeds of 9 to 12 km/h, respectively. For the 12-tonne module, the maximum energy impacted is 33 kJ to 44 kJ, for towing speeds of 9 to 12 km/h, respectively.

Improving ground in situ and compacting soil in thick layers are two distinctly different applications of RDC that must be treated separately but are often confused. The relationships that are proposed are in broad agreement with the results of published case studies involving the 8-tonne 4-sided impact roller over the past four decades.

It is anticipated that quantifying the effects of towing speed, energy imparted to the ground and estimated depths of improvement will help guide practitioners to understand both the capabilities and limitations of RDC with greater confidence.

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