CHAPTER 14

A Field-Based Study of the Effectiveness of Rolling Dynamic Compaction

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14.1 INTRODUCTION

Ground improvement is a fundamental and essential part of civil construction; an increasing number of new technologies and ground improvement methods have been developed and implemented to assist the geotechnical engineer in providing cost-effective solutions for construction on marginal or difficult sites.

The available methods and techniques to improve the geotechnical characteristics of soils are described in detail by Terashi and Juran (2000), Munfakh and Wyllie (2000), and Phear and Harris (2008). The general consensus from the aforementioned authors is that ground improvement using surface dynamic compaction techniques such as rolling dynamic compaction (RDC) can be successfully undertaken to improve a soil's shear strength and stiffness, or reduce its permeability. Of the available methods, compaction is arguably the simplest and most prevalent ground improvement technique, and involves increasing the density of the ground by means of mechanically applied energy such as static compaction, which employs drum, padfoot, sheepsfoot, and tire rollers, or dynamic compaction, which makes use of vibratory rollers and plates, rammers, heavy tamping, vibroflotation, and rolling dynamic compaction (Hausmann, 1990).

The advantage of dynamic compaction is that it enables ground to be improved to a much greater depth (>10 m as compared to 0.3 m for static compaction), with the depth of improvement dependent on the energy applied (Mayne et al., 1984). Lukas (1995) suggests that when compared to other ground improvement techniques, dynamic compaction is one of the most cost effective, but its use is limited by the large ground vibrations it induces, so is not suitable on small sites or adjacent to buildings and other infrastructure.

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RDC was originally developed by Aubrey Berrangé in South Africa in the late 1940s, but its value was not fully appreciated until the mid-1980s. Since then, RDC has been successfully implemented worldwide with different module designs having 3, 4, and 5 sides, as shown in Figs. 14.1, 14.2, and 14.3, respectively. RDC involves towing heavy (6–12 tons) noncircular modules that rotate about a corner and fall to impact the ground. RDC can compact thicker layers due to a greater depth of influence beneath the ground surface, which 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. In addition, RDC is unique in that it is able to compact large areas of open ground at depth, both effectively and efficiently because of its faster operating speed and thicker lifts compared to conventional circular drum rollers. Due to the combination of kinetic and potential energies, RDC has demonstrated improvement to more than 1 m below the

Figure 14.1 3-sided RDC module (Landpac).

Figure 14.2 4-sided RDC module (Broons).

Figure 14.3 5-sided RDC module (Infratech).

ground surface and greater than 3 m in some soils (Avalle and Carter, 2005)—far deeper than conventional static or vibratory rolling (Clegg and Berrangé, 1971; Clifford, 1976, 1978a,b), which is generally limited to depths of less than 0.5 m.

The ability to compact thick layers can make RDC a productive and cost-effective option for many different earthwork projects and applications. This view is supported by Pinard (1999), who stated that in most open-field situations, RDC is able to compact soil, crushed rock, and landfill waste cost-efficiently and to greater depths when compared to other available compaction methods. As a result, RDC has been used in land reclamation applications, projects that either require the compaction of nonengineered fill in situ, or, alternatively, compaction of thickly placed loose layers of fill in bulk earthworks. RDC has also been used in the agricultural sector to reduce water loss, and in mining applications to improve haul roads and construct tailings dams. Additional details on applications of RDC are presented in Section 14.3 of this chapter.

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 (2007a), Avalle et al. (2009), and Jaksa et al. (2012). Field-based research typically involves a team of professional operators and technicians spending days diligently preparing a test pad and undertaking testing before and after rolling to seek to quantify the effect; however, as noted by Avalle (2007a), there are challenges associated with verification due to the ability of RDC to compact thick layers that often include large (oversized) particles. Further details on verification techniques used to quantify the effectiveness of RDC are presented in Section 14.4, and in the case study in Section 14.5.

14.2 ROLLING DYNAMIC COMPACTION AND COMPACTION THEORY

The underlying theory of compaction applies to RDC. In simple terms, an impact roller applies mechanical energy used to reduce air voids and rearrange soil particles to increase density, which results in a reduction in the void ratio within a soil. As is the case for compaction with conventional circular drum rollers, to achieve the maximum dry density, an optimum amount of moisture is required; if too little or too much moisture is present, a reduction in dry density will result. A unique relationship between moisture content and dry density is generated for a given soil type and compactive effort. A key difference between RDC and conventional circular drum rollers is in the compactive effort applied, akin to the modified and standard Proctor compaction tests, respectively. To highlight the difference in compactive effort, both modified and standard Proctor compaction curves, performed on the same soil, are presented in Fig. 14.4.

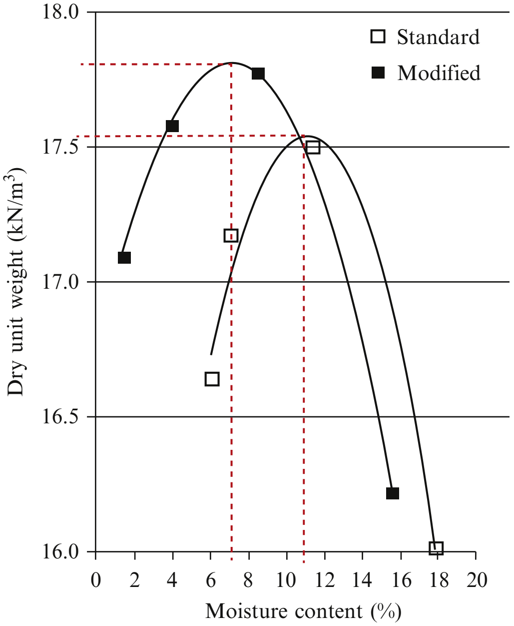

Figure 14.4 Standard and modified Proctor test results on the same soil.

It can be observed that the *maximum dry unit weight* for the modified test is higher than that resulting from the standard test, and corresponds to a lower optimum moisture content. A summary of the test results is included in Table 14.1. Figure 14.5 shows the particle-size distribution for the soil sample that was subjected to both laboratory test methods. The sample tested consisted of fine- to medium-grained sand (containing 3% clay-sized, 96% sand-sized, and 1% gravel-sized particles).

As Coduto et al. (2011) explain, the term *maximum dry unit weight* is somewhat misleading, because the standard and modified tests have two different maxima. However, as they describe, this term can best be thought of as "the greatest dry unit weight that can be achieved for that particular compactive effort." Changes in field compactive effort can significantly affect the relationship between moisture content and dry unit weight. For this reason, as observed by Scott et al. (2012), the use of RDC typically results in a target moisture

Table 14.1 Comparison of standard and modified Proctor test results

Laboratory test	Standard	Modified
Maximum dry unit weight kN/m^3	17.55	17.8
Optimum moisture content	~11%	~7%

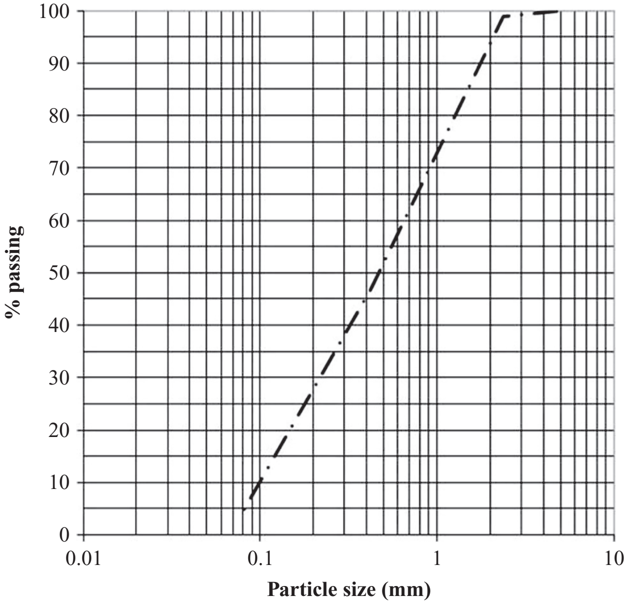

Figure 14.5 Particle-size distribution of tested soil.

content lower than the optimum moisture content (determined from the standard Proctor test), to achieve the corresponding maximum dry unit weight.

The ability of RDC to compact material in thicker lifts and at lower moisture contents (when compared to the optimum) has the potential for significant time and cost advantages. However, it is important to understand which baseline laboratory test is more representative to the field compactive effort that is proposed; a decision is often based on the loads to be supported, which in turn affects the compaction equipment to be used to ensure an appropriate dry unit weight will be achieved. The soil type, moisture content, and compacted layer thickness are all factors that affect density results and are often varied depending on the target specification required (typically a percentage of the maximum dry density) relative to either the standard or modified Proctor test. It should be noted that there is no "magic formula" that converts standard and modified compaction results, as the relationship between the two is unique for each soil type.

The authors' experience has demonstrated that, for cases where the standard Proctor test is used, impact rollers are likely to achieve the desired dry unit weight criterion (depending on the soil type and moisture content) in loosely placed layer thicknesses up to 1500 mm. If an additional moisture range is also included as part of a project specification (e.g., in the case of deep fills where hydrocompression is of concern), consideration needs to be given as to how representative the baseline laboratory test chosen will be for RDC. An earthworks contractor will inevitably aim to optimize site compaction by selecting an optimal combination of both compactive effort and moisture content range, bearing in mind that the contractor will also be optimizing against a third criterion (i.e., cost), thereby avoiding increased compactive effort and the need for additional moisture, wherever possible.

14.3 APPLICATIONS OF ROLLING DYNAMIC COMPACTION

RDC has been used successfully in many earthwork applications, including general civil construction works (Avalle, 2004a), roads (Jumo and Geldenhuys, 2004), airports, and land reclamation projects, as well as in agriculture, where it has been used to compact soil in irrigated areas to reduce soil permeability (Avalle, 2004b). Others include the compaction of sites with nonengineered fill, such as industrial land (Scott and Suto, 2007) or brownfield sites (Avalle and Mackenzie, 2005). Typical applications may involve the improvement of poor-quality ground in situ or the compaction of thickly placed layers for embankments or for infilling deep excavations.

The ability of RDC to identify weak (low density) areas or soft spots (zones of high moisture content in clayey soils) that can then be replaced or reworked, reduces the potential for differential settlements resulting from subgrade soils that have inadequate stiffness. The ability of RDC to improve the uniformity and density of subgrade soils makes RDC highly suitable as a proof roller, a view supported by Avalle (2006), who showed that improved haul roads can reduce the likelihood of rock spillage from haul trucks, thereby reducing the potential for damage to other haul road vehicles. The authors have witnessed the ability of RDC to detect soft spots in mining haul roads.

The use of RDC is becoming more prevalent in the mining sector, where large earthmoving equipment capable of hauling and placing high material volumes quickly complements the ability of RDC to compact large volumes efficiently. The authors have observed the effective use of RDC for the compaction of bulk earthworks of mine spoil materials, as described by Scott and Jaksa (2012). The use of thick layers that enabled large particle sizes to be used, facilitates greater recycling of mine spoil materials with a reduced need to screen large quantities of oversized particles. As well as haul roads, the authors have observed RDC used on pit floors and tip heads to aid in the breakdown and rubblization of large surface rocks that are potentially hazardous to haul truck tires and therefore costly for mine operators in terms of replacement cost and potential loss of production if spare tires are not readily available.

14.3.1 Thick lift compaction

Deep fills have been traditionally constructed by compacting soil in thin layers using relatively small particle sizes placed in a highly controlled manner. Field density tests are typically undertaken in each layer to confirm performance specifications of placed fill. The determination of field density testing using a nuclear density gauge is the current industry standard, and involves determining in situ density at discrete locations within a depth of 300 mm below the tested surface. This method is ideally suited for the verification of fill that has been placed in relatively thin layers using conventional static or vibrating drum rollers, as the maximum test depth of the nuclear density gauge is comparable to the influence depth of the aforementioned rollers.

The ability of RDC to compact material in larger quantities is an obvious advantage over compacting fill in thin layers; however, as noted by Avalle (2007a), there are challenges associated with verification. The authors have participated in several field trials across Australia where it was found that RDC could achieve compaction of layers between 500 and 1500 mm thick, depending on the soil type, moisture content, number of applied passes, and specified target dry density ratio. Verification of RDC using field density testing typically requires excavation through compacted material down to targeted bench levels to measure fill density and confirm the depth and extent of ground improvement.

Scott and Suto (2007) used this method to help quantify ground improvement using RDC and correlated other in situ test methods with density testing. They cited limitations such as lengthy test durations and the difficulty with the testing process for mixed soils, particularly where oversized particles are present. Pinard (1999) discussed similar issues and also identified the large ratio between the volume of material tested to that compacted and the poor correlation between laboratory and field results (in heterogeneous soils). The presence of oversized particles has the ability to constrain testing methods (and project specifications), making this a key area to be addressed in an impact rolling trial.

14.3.2 Limitations of rolling dynamic compaction

While RDC has the ability to improve a variety of soil types in a range of applications, not all site conditions lend themselves to using RDC. Small or restricted sites are unsuitable, where the roller is not able to maintain an operating speed within the range of 9–12 km/h. Clifford and Bowes (1995) predicted the impact energy of the square impact roller and concluded that the speed of the module striking the ground was the most significant parameter contributing to the energy imparted by the module.

As a result of dynamic effects, ground vibrations induced by RDC can be problematic if working close to adjacent infrastructure and can restrict its use. The authors recently observed an impact rolling trial (the results from which are yet to be published) that involved the use of RDC adjacent to historic infrastructure and therefore highly sensitive to vibrations and ground settlement. Vibration monitoring was undertaken to ensure that allowable peak particle velocities commensurate with cosmetic (if any) damage to historic buildings were not exceeded (typically 2–3 mm/s).

The aim of the trial was to determine how close the module could traverse so that the structural integrity of the nearby building was not compromised. The measurements of the vibration monitoring at a site consisting of fill that is not engineered resulted in a buffer distance being recommended by the authors. In this particular case, a safe (buffer) distance of 50 m was employed, but this distance is site specific and depends on the condition and construction type of adjacent infrastructure, as well as the rate of vibration decay, which depends on a number of factors, such as the ground characteristics and conditions and the mass and operating speed of the impact roller.

Vibration monitoring undertaken by Avalle (2007b) yielded similar findings and proposed a simple expression for obtaining an initial estimate of the potential magnitude of peak particle velocity (measured in mm/s), equal to $100/D$, where D was the distance in meters from an 8-t, 4-sided impact roller used in this body of work. The aforementioned vibration trial undertaken by the authors confirmed the expression proposed by Avalle (2007b) as being reasonable, but recommends caution for widespread use, given the number of variables involved. A site-specific trial is the most appropriate and safest way to determine how problematic vibrations induced by RDC might be to adjacent infrastructure.

Careful assessment of the suitability of RDC is needed, particularly for marginal or difficult sites. Although capable of compacting soils at moisture contents that are less than optimum, just as with other compaction techniques, RDC relies on sufficient moisture within the soil mass to attain a density in reasonable proximity to the maximum dry density. As observed earlier in Fig. 14.4, the attainable dry density can reduce significantly if too much or, as more commonly observed by the authors, too little moisture is present. There is a misconception among practitioners that RDC can successfully compact soils to achieve a high density at low moisture contents that are significantly dry of the optimum moisture content. As discussed in Section 14.2, compaction theory is valid, and target moisture ranges are still required to be met, albeit the moisture contents may be slightly lower due to the greater compactive effort imparted by RDC.

In applications where deep layers of imported fill material are being compacted, cost benefits can still be obtained while limiting the layer thicknesses to well within the capability of the machine, however, the variable depth to which ground improvement can be achieved is one of the biggest limitations on the use of RDC when improving in situ material, as a backup plan may need to be implemented if ground improvement is not achieved to the required (or expected) depths. The variable depth of treatment of RDC also has the potential to cause damage to existing services, culverts, or bridges (via load transfer) if an insufficient thickness of soil is not placed over such structures. It is recommended by the authors that at least 1.5 m of soil cover is required to prevent damage in most applications.

In the authors' experience, careful assessment (e.g., the use of an RDC trial) is highly recommended in soil conditions where nonengineered fill material is present, particularly if the site contains large oversized material. Depending on the nature and depth of the material, it may be able to be rubblized and compacted, however, there is also the potential for it to bridge underlying soil that would otherwise be improved, as found by Scott and Suto (2007).

When working at sites with a shallow water table, there is the potential for the repeated dynamic loading of soil to induce increased pore water pressures, which can bring water to the surface if too many passes are applied within a short period of time. The authors have observed RDC successfully used at sites with a shallow water table (i.e., within a depth of 1–2 m from the ground surface). The best results are obtained when the site is not "overrolled" and time is provided for pore water pressures to dissipate between sets of passes. The authors found that by using sets of no more than six passes and then rolling other parts of the site for a period of 1 hour (or utilizing lunch breaks) obtained successful results.

Cases have also been observed by the authors where the high energy impacts of RDC have caused existing interparticle bonds to break within weakly cemented sands at low in situ moisture contents, which actually resulted in negative improvement in soil density.

14.4 VERIFICATION OF ROLLING DYNAMIC COMPACTION

The depth of influence of RDC varies, depending on factors such as the soil material type, moisture, groundwater conditions, and the applied input energy (number of passes). 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 interpretation on 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 (2007a) reported a depth of 7 m in calcareous sands. Both used the cone penetration test (CPT) to quantify the depth of improvement as a result of RDC.

Scott and Jaksa (2014) also used the CPT as a key site investigation technique to quantify the zone of influence of ground improvement using RDC. There have been varying results as to what the depth of influence of RDC is for different soil conditions. There is currently little published information on predicted depths of treatment for varying soil conditions, and it is often up to the project engineer to predict if the use of RDC will improve the ground sufficiently for the desired project application. To determine whether ground improvement using RDC will be a cost-effective option, it is commonplace to undertake a trial.

14.4.1 Testing methods for verifying rolling dynamic compaction

Due to the ability of RDC to compact thick layers, alternative testing strategies may be appropriate depending on site conditions. As discussed in this section, one of the key aims of a field trial should be to determine the most appropriate testing regime for any particular project or site. Avalle (2004a) and Scott and Jaksa (2008) discuss a number of testing methods used prior to and after RDC to quantify ground improvement. As explained by Avalle, there is no simple rule that outlines which testing methods should be adopted or what the scope and nature of a field trial should be, as this depends on several factors such as site conditions, budget, efficiency, risk mitigation, and available equipment.

Common testing methods associated with the use of RDC applications include intrusive techniques such as dynamic cone penetration (DCP) testing, cone penetration testing, Marchetti flat plate dilatometer (DMT), field density testing (either via the use of a nuclear density gauge or, less commonly used, the sand replacement method). Nonintrusive (surface methods) are also widely used in RDC applications to measure ground response, including the use of plate load tests, accelerometers, the Clegg hammer, and lightweight falling deflectometer. Seismic (geophysical) techniques are also becoming more widely used in RDC applications, such as the multichannel analysis of surface waves (MASW) technique, as used by Scott and Suto (2007) and Whiteley and Caffi (2014), the spectral analysis of surface waves (SASW) method, as used by Jaksa et al. (2012), and the continuous surface wave system (CSWS) method used by Bouazza and Avalle (2006).

Observational techniques (visual and audible) are common, particularly in proof rolling applications. The measurement of ground deformation via surface settlement monitoring is a commonly used technique. Depending on the application, permeability, infiltration testing, or vibration monitoring (when working adjacent to existing infrastructure) are also appropriate. In situ stress measurement via the use of earth pressure cells has also been used by the authors as described in the case study presented in Section 14.5. Soil sampling for laboratory tests such as particle-size distribution, Atterberg limits, moisture content and standard or modified Proctor compaction testing is common practice.

14.4.2 Field trials

This section presents a field trial where the use of RDC for thick lift compaction was assessed. A test pad was constructed to assist in the determination of the optimal number of passes, moisture content, and range of loose layer thicknesses that could be compacted using RDC, as well as to determine verification techniques that were appropriate, given the site conditions.

RDC was used to proof roll the subgrade prior to placement of any fill material to ensure there were no observable soft spots that required remediation prior to commencement of placed fill. The test pad was constructed such that nine impact rolling lanes could be rolled. This enabled three separate zones of 10, 20, and 30 passes to be constructed that would allow testing after rolling to be undertaken simultaneously in the center of each zone. Given that one of the key objectives of this trial was to determine the thickness of fill that could be compacted under various compactive efforts, the height of the placed fill varied in thickness from 0.5–1.5 m. While the construction of the test pad took time and effort, from both surveying and dozer operation, it enabled all postcompaction testing to be conducted in an efficient and effective manner. Figure 14.6 shows a diagram of the test pad, both in plan and elevation.

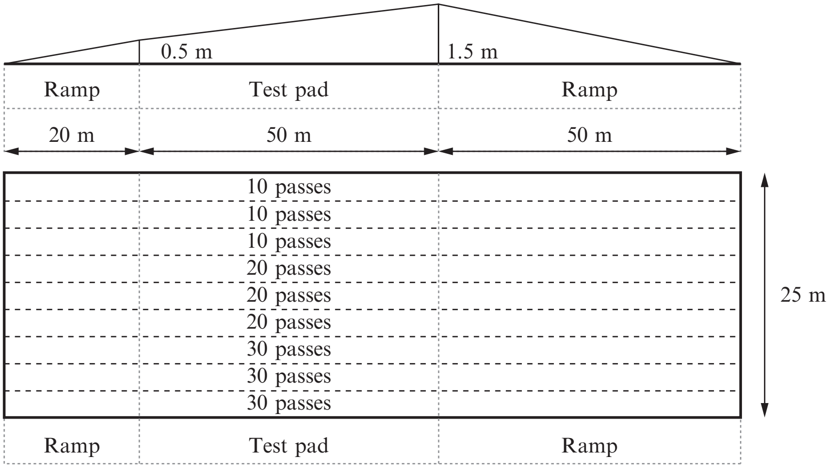

Figure 14.6 Test pad layout in plan and elevation.

The total length of the test pad, including ramps, was approximately 120 m; the actual area over which the testing was undertaken was 25 m × 50 m. Allowing 25 m at each end of the test pad for the impact roller to turn around and reach normal operating speed by the time it reached the ramp areas, a nominal area of 170 m long by 25 m wide was cordoned off and used for the trial. It was estimated that approximately 2500 m^3 of material was used for the compaction trial; sufficiently large to be representative of an embankment that was proposed. The construction of the test pad and the results that ensued enabled more than one unique solution to be developed for the site, giving the contractor the ability to determine an optimum compacted layer thickness based on the material, compactive effort, and scheduling of plant and equipment, so as to maximize efficiency of site operations.

14.5 CASE STUDY

The case study presented summarizes an RDC trial whereby the underlying objective was to determine an efficient relationship between the number of passes, placed loose layer thickness, moisture content, and corresponding dry density ratio that could be achieved. RDC was achieved using an 8-t, 4-sided impact roller, and the water table was located at a significant depth below the excavated bench level.

A test pad approximately 4 m high was constructed in three lifts. The trial was conducted as a staged process with one lift placed, rolled, and tested each day. The ability of the site to work 24 hours per day and use large loaders, excavators, and haul trucks made the staged trial possible in a short time frame, as the time to place significant earthwork volumes (even for a trial) should not be underestimated. Allowing for windrows on the sides and ramps at either end the test pad, it was estimated that at least 5000 m^3 of material was used in the trial.

While adopting multiple layers for the trial added extra time, it did mean that the compaction trial could address one of the key concerns for the large-scale operation: to determine whether a target density of 95% of maximum modified dry density could be achieved, not only for a single layer but also in the second and third layers placed above. Undertaking the trial in this manner was then representative of the construction of the tailings dam that was proposed, while it also enabled the depth of influence of the impact roller to be investigated.

The site contractors had the advantage of having previously worked with RDC for the construction of haul roads (albeit using different material), so had a preference for adopting a layer thickness that would complement the operational efficiency of other equipment onsite, even if it meant that the placed layer thickness was less than what the roller was capable of compacting to achieve the specified performance criteria. Given that the contractors had a preference for fewer passes and less thick layers, this enabled a trial pad to be constructed that featured layer thicknesses no greater than 1500 mm and a maximum of 16 passes applied, with intermediate testing undertaken to provide representative results for varying numbers of passes over a range of depths.

To measure the zone of influence and effectiveness of the impact roller, a test pad was constructed in three separate lifts of 1200, 1530, and 1460 mm, as illustrated in Fig. 14.7, which also shows the locations of embedded earth pressure cells (discussed later). The test pad was constructed by haul trucks end-tipping loose material adjacent to the pad, whereby a loader and excavator subsequently spread the material over the pad. The placement process caused the soil to be partly compacted by the self-weight of the plant; however, this method was deemed representative of the proposed construction method, therefore was consistent with the general aim of the trial to be as representative as possible given the site conditions.

Verification of RDC was undertaken using a combination of surveying of surface settlements, soil sampling, and conducting a series of laboratory tests (e.g., particle-size distribution, hydrometer test, Atterberg limits, standard and modified Proctor tests) to characterize the soil. In situ tests were

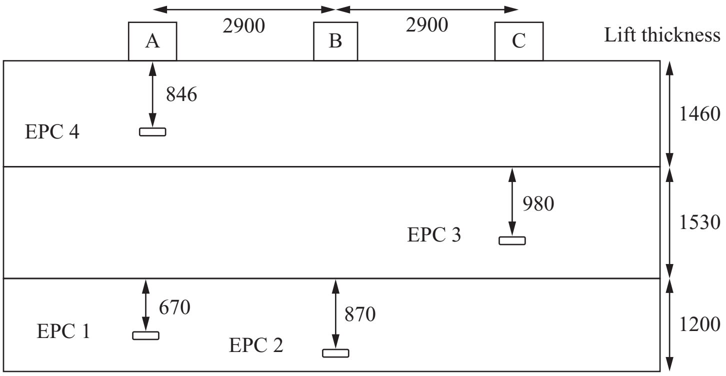

Figure 14.7 Cross-sectional view of test pad including EPC locations (all dimensions shown in mm).

performed at intervals of eight passes to quantify soil conditions with changes in compactive effort. The in situ tests undertaken included field density measurements, the SASW geophysical technique, and DCPs to measure and infer changes in density as a function of the number of module passes. Surface settlement monitoring was undertaken to quantify the change in surface level with number of passes. Earth pressure cells (EPCs) were installed at different depths to measure dynamic pressures to assist in quantifying the depth of influence and stress distribution induced by RDC.

Figure 14.8 shows the average grading curve obtained from nine particle-size distribution tests. The test pad was constructed using coarse, iron magnetite tailings that are a by-product of a consistent rock-crushing process. The grading curve produced is fairly typical of well-graded sand with some gravel: 6% clay-sized, 80% sand-sized, and 14% gravel-sized fractions. The Atterberg limits tests (liquid limit ~22%; plastic limit ~11%) and the particle-size distributions suggest that the material is consistent with well-graded sand (SW) with some clay fines of low plasticity. The average field moisture content was ~5%. Triaxial and direct shear testing was carried out to further characterize engineering properties of the tailings material. The results are summarized in Table 14.2. The high density is consistent with crushed magnetite.

Figure 14.9 shows a plot of the average modified dry density ratio versus depth below ground surface after eight passes and was used to determine the

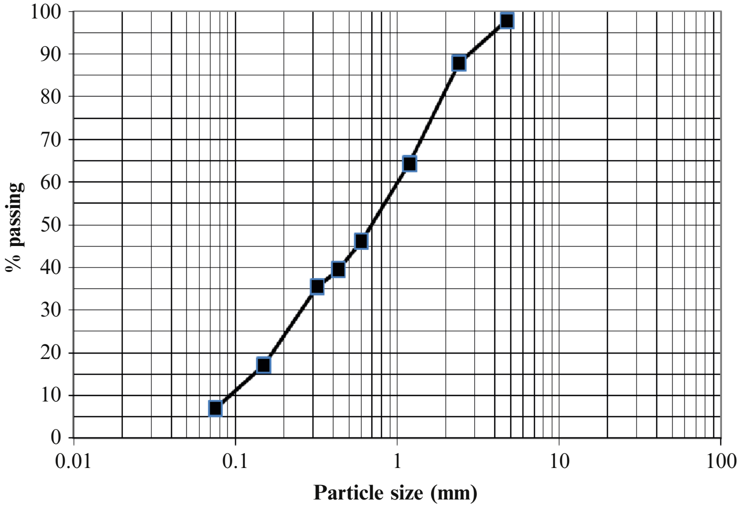

Figure 14.8 Average particle-size distribution of test pad material.

Table 14.2 Summary of laboratory test results for key soil parameters

Cohesion (kPa)	7
Internal angle of friction (°)	37
Elastic shear modulus (MPa)	6

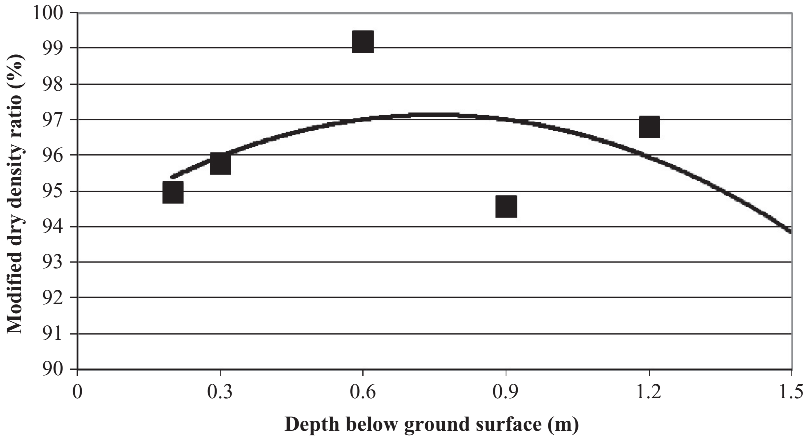

Figure 14.9 Modified dry density ratio vs. test depth after eight passes.

depth at which the target dry density ratio (95% with respect to modified compaction) was expected to be achieved. From this figure, it can be estimated that the effective depth for eight passes is a little more than 1.2 m (i.e., 8 passes of the impact roller will achieve a dry density ratio of 95%, provided that the placed layer thickness does not exceed about 1.3 m).

The SASW technique was used in conjunction with DCPs to assess the improvement with depth at the same location using two different methods at intervals of eight passes. Typical results are shown in Fig. 14.10, where it can be observed that an increased number of passes results in an increase in shear modulus between depths of 0.5–2.1 m. This is an indication of increased soil density. Below a depth of 2.1 m, results were inconclusive due to insufficient data.

Figure 14.11 summarizes the number of DCP blows per 50 mm penetration versus test depth below the ground surface. It can be observed that the test results confirm a noticeable increase in the number of blows with a greater number of passes. As each test was terminated at a depth of 850 mm due to the physical limit of the equipment, it was not possible to determine the depth of influence solely using this test; however, Fig. 14.11 suggests that

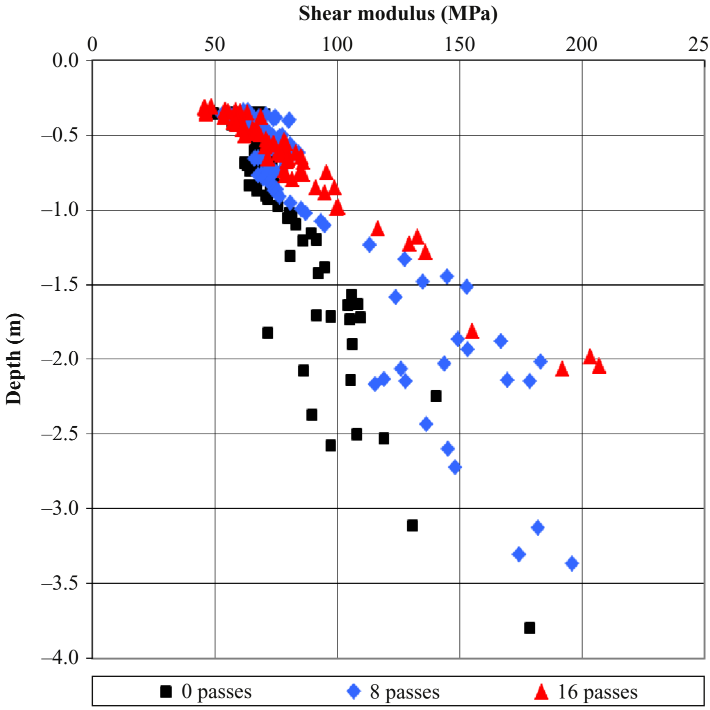

Figure 14.10 SASW test results for varying numbers of passes.

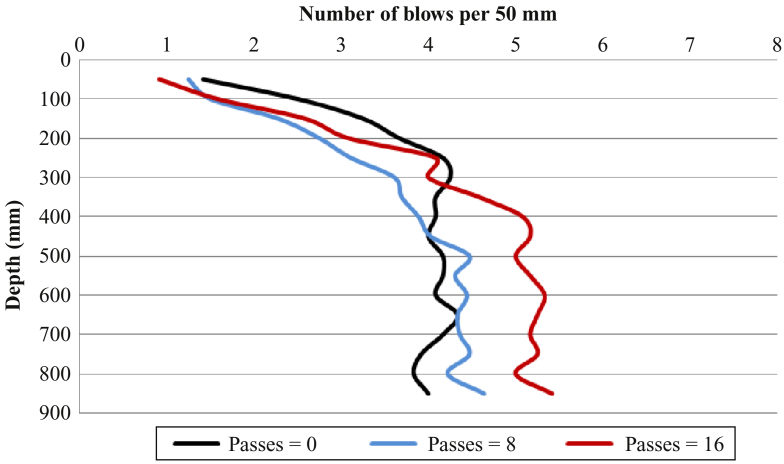

Figure 14.11 Results of dynamic cone penetrometer tests.

RDC is effective in improving the in situ density of the tailings material from a depth of 0.3 m to beyond the penetrometer depth of 0.85 m.

It is evident from Figs. 14.10 and 14.11 that there is little, if any, improvement of the near-surface soils with increasing passes. This can be attributed to the module causing the near-surface soils to displace laterally and heave rather than being compacted; this occurs in cases where the near-surface soils have insufficient bearing capacity to withstand the stresses imparted by the module. As it typically loosens and disturbs near-surface soils, RDC is unsuitable as a finishing roller.

Settlement of the ground surface as a result of varying numbers of impact roller passes was determined from survey measurements of the ground surface at 0, 8, and 16 passes. Due to the undulating nature of the ground surface after rolling, a consistent approach of determining settlement was adopted by always measuring the surface at the lowest point left by the impact rolling module. The average settlement presented in Fig. 14.12 was determined by averaging surface measurements across all three lifts. The figure shows that the majority of settlement occurred within the first 8 passes; with a comparatively small magnitude of the total settlement (17%) occurring in the second set of 8 passes.

Four Geokon 3500 earth pressure cells (EPCs) were buried at different depths and used to measure the dynamic pressures imparted by RDC. The locations of the EPCs (in cross section) were shown previously in Fig. 14.7. EPCs 1, 2, and 3 were separated by a half-turn of the roller (2.9 m) in the forward direction of travel and were installed at various vertical depths below locations A, B, and C, respectively. EPC 4 was located directly above EPC 1 at location A, but was separated vertically to prevent stress-shadowing effects as discussed by Rinehart and Mooney (2009), who used EPCs to measure stresses imparted

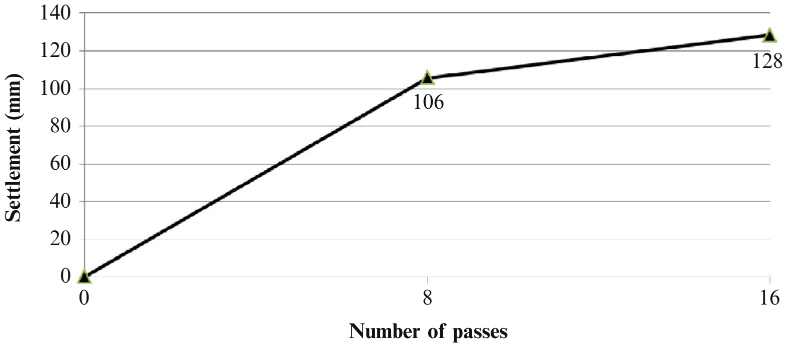

Figure 14.12 Average settlement vs. number of passes.

into the ground due to circular, static, and vibratory rollers. The EPCs were installed at each depth using an excavator to create a trench.

After installation, the soil was then replaced in the trench by the excavator and was compacted lightly by means of its bucket. This process attempted to replicate the virgin construction of each lift. The EPCs were connected to a data acquisition system and a laptop to continuously record the pressures induced by the impact roller. Measurements from the EPCs were acquired at a sampling frequency of 2 kHz (i.e., one sample every 0.0005 sec). That sampling frequency proved appropriate to balance conflicting requirements; on the one hand to detect the sudden increase in pressure caused by the roller striking the ground and, on the other, without generating overly excessive quantities of data.

An indication of the depth of influence can be obtained by analyzing the variation in peak pressure (resulting from a strike of the roller) with depth. To develop that relationship, data from all three lifts were used. As shown earlier in Fig. 14.7, two EPCs were installed when compacting Lift 1, three for Lift 2, and four for Lift 3, together providing pressure readings at nine different depths below the rolled surface, as the test pad was progressively constructed.

An example of data obtained from an EPC is shown in Fig. 14.13, where a direct impact is measured by the impact roller striking the ground

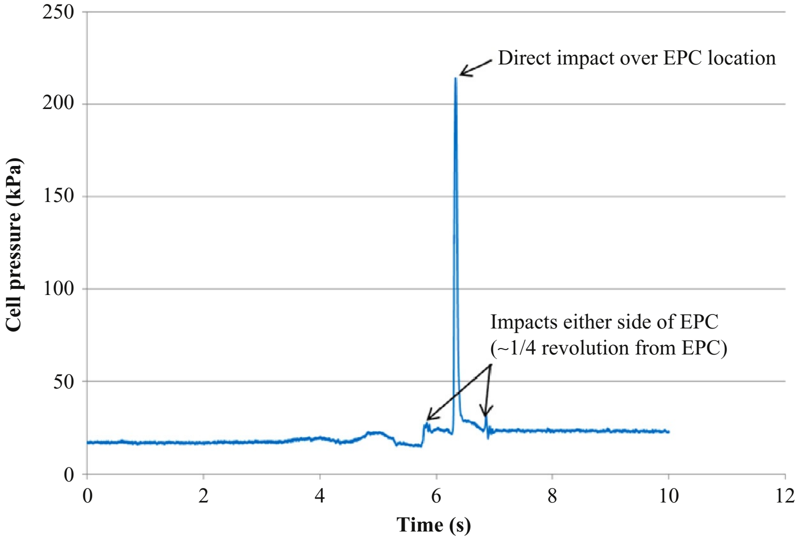

Figure 14.13 Example results obtained from direct impact over an EPC.

immediately above the buried EPC; a single large peak of more than 200 kPa is recorded. Two smaller peaks are also measured either side of the main peak, at intervals of approximately 0.5 s, which corresponds to the module striking the ground each quarter revolution before and after the location of the EPC. In this particular pass, the two adjacent peaks were readily visible; however all other peaks were barely detectable as the pressure dissipates rapidly through the soil as the impacts occur farther away.

Figure 14.14 shows the measured peak pressures averaged over all of the EPCs plotted against depth below ground. Only peak pressures corresponding to module impacts striking the ground directly over an EPC were used to develop this and the remaining figures. The plot shows that the highest pressure reading obtained in the field trial was 600 kPa at 0.7 m depth. The pressure then quickly dissipated, decreasing by more than 50% to around 260 kPa at 1 m depth. By 2 m depth the pressure had again more than halved to 120 kPa. The deepest EPC, located 3.85 m below ground, measured a pressure due to the roller of 38 kPa. That value was nearly equivalent to the static pressure of the impact roller at the surface, suggesting that, even at that depth, the roller was having some measurable influence.

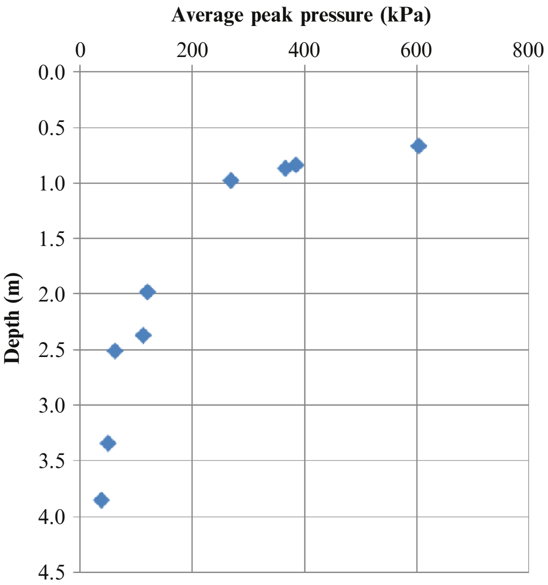

Figure 14.14 Average peak pressure vs. depth below ground.

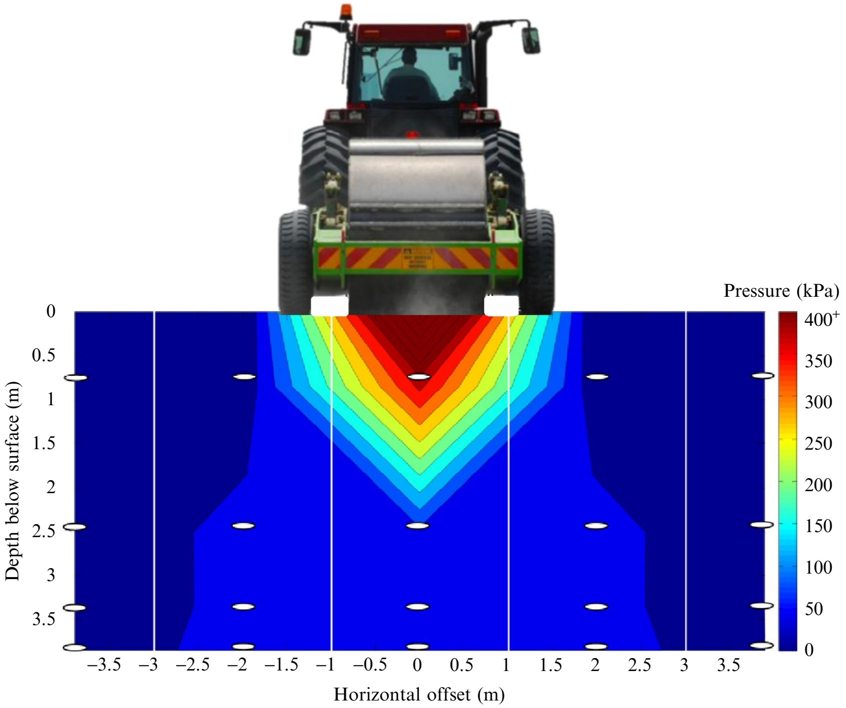

Figure 14.15 Pressure contours with depth after 16 passes perpendicular to direction of travel.

The pressure measurements from all lifts and EPCs were combined to produce a cross section showing the zone of influence in the plane perpendicular to the direction of travel. Figure 14.15 shows a summary contour plot of peak pressure imparted by the impact roller with depth after 16 passes of the impact roller. It can be observed that the highest pressure readings recorded (>150 kPa) were located within the upper 1.5 m from the surface, supporting other test data from this trial that suggested most of the quantifiable ground improvement occurs within this zone. Even the deepest pressure cell (buried at a depth of 3.85 m below the ground surface) registered positive pressure readings due to the impact roller, suggesting that the zone of influence extended beyond this depth.

The results of the compaction trial indicated that the target dry density ratio (95% of maximum modified dry density) can be expected to be achieved after a minimum of eight passes on a loose lift thickness of tailings material of 1200 mm.

14.6 CONCLUSION

While RDC is a simple and effective ground improvement technique, there is a need to understand the basic principles that govern its compaction of soil. As RDC can be used in a wide range of applications, it is important to understand that there is not a "one size fits all" approach, and each site needs to be treated individually. The involvement of an experienced geotechnical engineer will be of great benefit, as he or she will be able to realize the advantages of RDC, while also recognize its limitations, which is particularly important at marginal or difficult sites.

While the ability to compact material in large volumes effectively and efficiently is a significant advantage of RDC, there are challenges associated with verification. A field trial can be a useful way to determine the appropriateness of RDC at a particular site. One of the key aims of a field trial should be to determine the most appropriate testing regime for any particular project or site, which depends on factors such as the target specification, site conditions, budget, efficiency, risk mitigation, and available equipment. Other aims of a field trial should include determining the number of passes required, the range of moisture contents that are appropriate, and the depth of influence or range of loose layer thicknesses that can be compacted using RDC.

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