Quantifying the influence of rolling dynamic compaction

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ABSTRACT

Rolling dynamic compaction (RDC) is a commonly used ground improvement technique. A key feature of RDC is the ability to provide deep layer compaction when compared to conventional rollers. This greater zone of influence makes it a productive and cost-effective option in earthworks applications. Whilst RDC has been used successfully on many projects in Australia and overseas in applications such as roads, airports, construction and land reclamation projects, there are cases where the expected ground improvement has not occurred. There is a lack of information indicating what the zone of influence of the roller is, and how much input energy is required for different soil conditions. The methods of testing the effectiveness of RDC need improvement. Relationships are needed that relate the input energy and the ground improvement that can be expected for different soil types.

1 INTRODUCTION

Rolling dynamic compaction (RDC) consists of a non-circular module of 3, 4 or 5 sides, that rotates about its corners as it is towed, causing it to fall to the ground and compact it dynamically. A square impact rolling module is shown in Figure 1. A cross section of this 4-sided module, which is concrete filled and encased with steel, is shown in Figure 2. The module is towed at a speed typically in the range of 10-12 km/h (Pinard 1999).

Figure 1: 4-sided impact roller

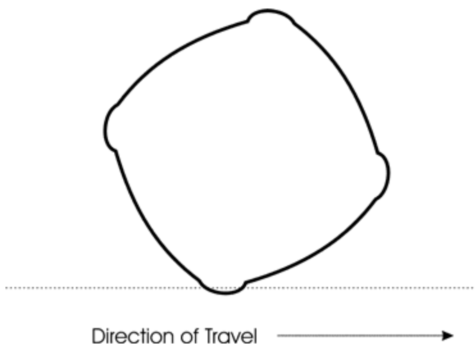

Figure 2: Cross-section of 4-sided module

2 NEED FOR GROUND IMPROVEMENT

One of the major functions of geotechnical engineering is to design, implement and evaluate ground improvement schemes for civil engineering infrastructure projects. Since the 1970s 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 & Juran (2000), Munfakh & Wyllie (2000) and Munfakh (2003). The general consensus from the aforementioned authors is that ground improvement using surface dynamic compaction techniques such as RDC can be successfully undertaken to improve a soil's shear strength and stiffness, or reduce its permeability.

RDC has been used successfully in many earthworks applications in Australia and overseas including the improvement of poor quality ground insitu, the compaction of thick layers for in-filling deep excavations, the proof rolling of road and subgrade materials and the compaction of reclaimed land. In recent years, RDC has been used to construct haul roads in the mining industry, as well as in agriculture, where it is used to compact soil in irrigated areas to reduce soil permeability and conserve water.

3 WHAT IS THE DEPTH OF INFLUENCE OF RDC?

RDC has demonstrated improvements in soil density to depths of more than one metre below the ground surface for clay soils and 2-3 m or more in sands (Avalle, 2004, Avalle & Carter, 2005). This zone of influence is far deeper than conventional static or vibratory rolling techniques (Clegg & Berrangé 1971, Clifford 1976, 1978), which are generally limited to depths of less than 0.5 m. This ability to provide deep layer compaction, as well as its relatively fast operating speed (when compared to conventional rollers) makes RDC a productive and cost-effective option in earthworks 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.

Whilst RDC has the proven ability to improve a variety of soil types, for example sand (Figure 3) and clay (Figure 4), not all site conditions lend themselves to using RDC. Small or restricted sites are not suitable, as the roller is not able to maintain an operating speed in the vicinity of 10-12 km/h. Clifford & Bowes (1995) predicted the impact energy of the square roller and concluded that the speed of the module striking the ground was the most significant parameter contributing to the energy imparted by the impact roller. In the author's experience, careful assessment (e.g. the use of an impact rolling trial) is highly recommended in soil conditions where non-engineered fill material is present, particularly if the site contains large oversized material; depending upon the nature and depth of the material it may be able to be broken down and compacted, however, there is also the potential for it to bridge underlying soil that would otherwise be improved (Scott & Suto 2007). Cases have also been observed where the high energy impacts of RDC have caused existing inter-particle bonds to break within the soil; hence careful assessment of the suitability of RDC is needed in such soil conditions.

The depth of influence of RDC varies, depending upon factors such as the soil material type, moisture, groundwater conditions and the input energy (Avalle 2004). There is currently little 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 project application. This prediction as to whether to adopt RDC for ground improvement at a site, may or may not prove to be cost-effective, as RDC has the potential to save significant time and construction costs (or otherwise). In applications where deep layers of imported fill material are being compacted it is common for cost benefits to still be obtained whilst 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 insitu material, as a back-up plan may need to be implemented if ground improvement is not achieved to the required (or expected) depths. The variable depth of treatment using 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. Broons (2008) recommends that at least 1.5 metres of soil cover is required to prevent such damage, however, further research is warranted to verify or refine this requirement.

4 HOW IS GROUND IMPROVEMENT USING RDC VERIFIED?

There are currently no guidance documents to provide the engineering profession with recommended testing methods to use for various soil conditions so that appropriate decisions and assessments can be made on the ground improvement undertaken by RDC. Whilst the latest edition of the Australian Earthworks Code, AS 3798 (Standards Australia 2007) now recognises deep compaction by impact rolling as an alternative procedure for earthworks, it offers little guidance as to how to determine if ground improvement has been achieved, only stating that "trial programs may be required to develop the most appropriate testing regime for any particular project or site". As explained by Avalle (2004) there is no simple rule that outlines what the scope and nature of trial programs should be, as this depends on factors such as budget, efficiency, risk and site conditions.

Field density testing (in order to comply with AS 3798) is commonly undertaken to verify thick-lift filling or ground improvement using RDC. The determination of field density testing using a nuclear surface moisture-density gauge (Standards Australia 1995), is the current industry standard, and involves determining the in situ density at discrete locations within 300 mm below the tested surface, making it an ideal testing method where conventional surface compaction techniques and relatively thin layers (lifts) are used. However, RDC applications involving thicker lifts or where surface improvement of in situ ground is undertaken, verification using field density testing requires excavation through compacted material to the desired test levels. Scott & Suto (2007) used this method to help quantify ground improvement using RDC, and cited limitations such as lengthy test durations and the difficulty with the testing process for mixed soils, particularly where oversized particles are present.

The cone penetration test (CPT) involves statically pushing a cone penetrometer and associated drilling rods into the ground and continuously recording the resistance to penetration mobilised in the soil (Lunne et al. 1997). The CPT has been shown to be one of the most accurate in situ test methods available in routine geotechnical engineering practice (Jaksa et al. 1997), and has been successfully used in RDC applications to verify the ground conditions prior to, and after impact rolling. Avalle & Carter (2005) reported the verification of RDC in sandy soils; with improvement evident to at least 3 metres below the ground surface (refer Figure 3). Budget constraints, availability of equipment and the presence of heterogeneous fill material often dictate as to whether the CPT can be used to verify impact rolling applications.

For sites containing significant quantities of mixed soils or oversized particles that are not conducive to traditional (intrusive) geotechnical investigation methods, the use of seismic methods is becoming increasingly common. The use of seismic methods such as MASW (Multi-Channel Analysis of Surface Waves) and CSWS (Continuous Surface Wave System) as reported by Scott & Suto (2007) and Avalle & Mackenzie (2005), respectively, enable correlations of Young's modulus to be made from measuring seismic velocity. Avalle & Mackenzie (2005) reported the verification of RDC in a clay landfill capping overlying refuse using CSWS; with improvement evident to approximately 2 metres below the ground surface (refer Figure 4). Budget constraints and the use of highly specialised equipment are factors that may limit the use of seismic methods to verify RDC.

The use of on-board sensing equipment to measure density, stiffness, subgrade strength or modulus based on the response of the roller as it travels across the ground surface is becoming increasingly common. This technology (known as Intelligent Compaction or Continuous Compaction Control) was first used on vibrating drum rollers the mid 1990s to help identify soft spots and to create more uniform pavement and subgrade layers (Petersen & Peterson 2006). Similar technology, known as the Continuous Impact Response (CIR) system, has recently been introduced into RDC applications and is discussed in detail by McCann & Dix (2007) and Landpac (2008). The CIR system involves measuring ground decelerations from accelerometers that are placed on the impact rolling module. With increasing passes, ground decelerations increase as the soil density and stiffness increase. A GPS system is employed to spatially monitor the movements of the impact roller, thereby enabling soft spots to be identified from both ground decelerations and spatial data. Due to the inherent heterogeneity of soils in terms of their material properties and moisture contents, technology such as Intelligent Compaction and CIR will become more prevalent in the future, and are good examples of how advances in technology are helping to improve confidence in achieving uniform compaction.

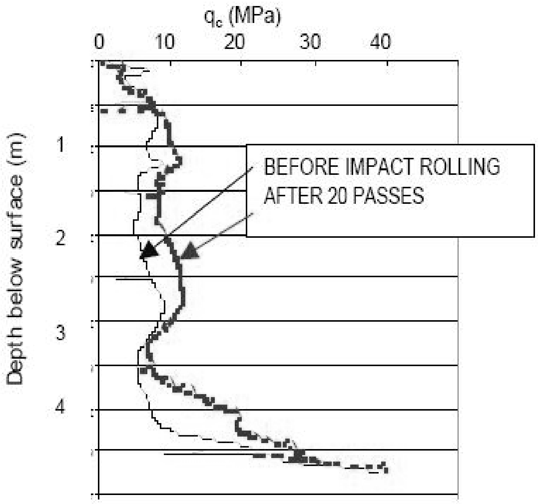

Figure 3: Verification using CPT (Avalle & Carter 2005)

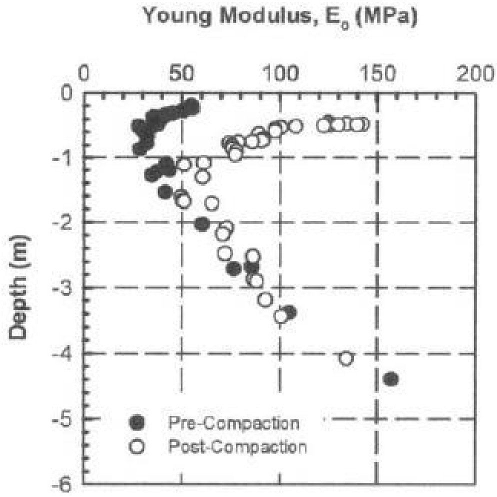

Figure 4: Verification using seismic methods (Avalle & Mackenzie 2005)

Measuring surface settlements is commonly adopted; this can be undertaken in a number of ways, ranging from the use of accurate robotic total station equipment to the use of simple string lines and tape measures (Avalle 2004). Whilst settlement monitoring output can generally be obtained in an efficient and cost-effective manner, care needs to be taken to account for the effect of surface undulations caused by the periodic impacts of the module on the ground (as observed in Figure 1). Such surface undulations can typically have up to 200-300 mm height difference between the high and low points, meaning that if accurate surface settlements are to be obtained, a grader and smooth-drum roller are often required to produce a finished level surface. Alternatively, embedded steel plates can be placed beneath the surface to help overcome the effect of surface undulations. This method has been adopted in recent trials undertaken by the authors, whereby central vertical tell-tale rods of variable lengths can be bolted to the steel plates prior to embedment to measure settlement at various depths below the ground surface. The use of magnetic extensometers installed within boreholes has also been trialled for this purpose, and is the more promising method for determining settlement in targeted soil layers, especially as installing and removing embedded steel plates can become quite cumbersome when placed greater than 300 mm below the ground surface.

Further to the methods discussed previously, Avalle (2004) offers a comprehensive list of testing methods that have been adopted prior to, and after impact rolling to quantify ground improvement. As stated by Avalle (2004) the different test methods chosen often depend on factors such as the geotechnical engineer's preference of field testing methods and experience with impact rolling, available testing equipment, budget constraints, site location and ground conditions. It is the author's opinion that site specific field trials are the most appropriate and efficient way of assessing factors and considerations such as: will RDC be suitable for the site conditions? How many passes are required? What testing methods are appropriate to quantify and validate the performance of RDC? With a large variation in current approaches, there is a need for some direction and guidance.

5 NEED FOR FURTHER RESEARCH INTO RDC

Currently, a key limitation that restricts the use of RDC is the reluctance by the engineering profession to specify the use of impact rolling. This is largely due to the theory behind RDC generally not being well understood, particularly as the use of RDC is often guided by intuition, or based on experience in similar soils and applications. Whilst RDC is a commonly used technique to improve poor or marginal ground, there is little published information on what the zone of influence is for different soil types, or to indicate what testing methods should be adopted to quantify its effectiveness.

In order to develop, calibrate and validate a suitable model for RDC applications, field and laboratory measurements are needed in a variety of site conditions. A database containing testing data from previous RDC projects is being used to assist with this research; however, further field testing and measurements are required to complement existing data. This will involve conducting field testing both prior to, and after impact rolling to compare and evaluate a number of different testing methods. Commonly specified testing methods on impact rolling projects (such as those discussed in Section 4), as well as insitu permeability and porewater pressure testing will be trialled in a variety of soil conditions. Laboratory tests to classify soil types and to determine shear strength and compressibility parameters will also be undertaken so that accurate and efficient testing and verification techniques and protocols can be recommended to quantify the improvement of RDC in the field.

To determine the zone of influence of RDC on different soil conditions, commonly used testing methods will be combined with instrumentation that is embedded into the ground to quantify the zone of influence of RDC. The transfer of energy of the impact rolling module to the underlying ground will be measured at various depths, using load cells and accelerometers that will be embedded into the ground. The impact roller will pass over the embedded instrumentation whereby the force measured in the load cell, and the ground deceleration measured using accelerometers can be used to determine the energy recorded. By measuring the energy at various depths below ground level, and for differing soil types, it will enable the zone of influence of the roller to be quantified.

6 CONCLUSIONS

Although RDC has been used on many projects in Australia and overseas, there is little published information quantifying what the zone of influence is, or how much energy is required in order to improve soils of different types. There is also little guidance on how RDC should be verified to quantify its effectiveness.

It is anticipated that the outcomes of this work will enable RDC to be applied and validated more appropriately for a range of soil conditions. More accurate assessments of RDC, as well as improved testing regimes, are expected to reduce design conservatism and construction costs. In addition, perhaps most significantly, quantifying the effectiveness of RDC in terms of the energy imparted into the ground and the zone of influence for various soils will lead to a greater understanding of its theory, which will enable RDC to be used more effectively and with greater confidence in a range of engineering applications.

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