Ground energy and impact of rolling dynamic compaction – results from research test site

Energie du sol et impact de la dynamique de compaction par roulage– résultats de la recherche sur un site de tests

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ABSTRACT
As a major component of research activities at Sydney and Adelaide Universities into various aspects of rolling dynamic compaction as performed with the "square" impact roller, an experimental test site has been established. The test site is approximately 100m by 50m, and is part of a larger industrial property in Wingfield, South Australia. Geologically, the site comprises approximately 1-2m of non-engineered fill, overlying Estuarine deposits. The primary objectives of the work at the test site relate to quantifying the effects of the impact roller in terms of energy delivered to the ground and the ground response. Impact rollers with solid 4-sided modules of mass 8t and 12t are utilised. A monitoring and testing regime has been developed that includes physical measurements of energy on and below the impact module, surface settlement and sub-surface layer compression measurements. Early results from the testing programme provide a basis for understanding and developing the relationship of delivered to transmitted energy for the particular impact modules used at this site, the dissipation of energy through the ground and the effects on the various strata at depth due to module mass and number of passes (or energy input). The output from this study will form the basis for modelling ground conditions at this site and the effects of the impact rolling. The data thus generated will support further studies into numerical modelling of rolling dynamic compaction and the on-going programme of testing at other sites with different geological characteristics.

RÉSUMÉ
En tant que composante majeure des activités de recherche des Universités de Sydney et d'Adélaïde dans les divers domaines tels que la dynamique de compaction par roulage réalisés avec le rouleau d'impact « carré », une expérience sur site a été établie. Le site de tests mesure environ 100m sur 50m, et il fait partie d'une grande propriété industrielle à Wingfield, South Australia. Géologiquement, le site comprend environ 1.5 2m de remblai non exécuté sur plans d'ingénieurs, sus-jacents à des dépôts d'estuaire. Les premiers objectifs des travaux sur le site sont de quantifier les effets du rouleau amortisseur en termes d'énergie transmise dans le sol, et de la réponse de ce sol. Quatre solides modules latéraux de 8 à 12 tonnes de masse sont utilisés. Un régime de contrôles et de tests ont été développés, ce qui inclue des mesures physiques de l'énergie au dessus et en dessous du module d'impact, de l'affaissement de la surface, et des mesures des la compression de la couche de subsurface. Les premiers résultats de ce programme de tests fournit une base pour la compréhension des relations entre l'énergie délivrée par le rouleau l'energie transmise au sol dans le cas particulier des impacts des modules sur ce site, de la dissipation de l'énergie à travers le sol et les effets sur les différentes couches du fond due à la masse du module et du nombre de coups (ou puissance absorbée). Les conclusions de cette étude formeront une base pour la modélisation des conditions du sol de ce site, et les effets du rouleau amortisseur. Les données générées seront donc de grande utilité pour de futures études sur la modélisation numérique de la dynamique de compaction par roulage, et le programme de tests en cours le sera aussi pour des tests sur d'autres sites de différentes caractéristiques géologiques.

Keywords : rolling dynamic compaction, impact, energy

1 INTRODUCTION

The use of dynamic force for ground improvement is ages old. Practitioners and researchers have long sought after a formula to predict and verify its effects; however, such a solution remains elusive. With the inherent heterogeneity of ground conditions and varying methods for the application of dynamic compaction, the solution remains empirical. The use of impact rolling is often guided by intuition, or based on experience in similar soils and applications. Although there is little published information on what the zone of influence is, or how many passes are required for different soil types, it is known that certain combinations of ground conditions and dynamic compaction combine to good effect, resulting in improved foundation solutions.

Research initiatives at both Sydney and Adelaide Universities are focussing specifically on impact rollers and their characteristics in relation to their energy input and the corresponding ground response. Commencing in 2007, work has been continuing at a test site in Adelaide, South Australia.

2 THE "SQUARE" IMPACT ROLLER

"Square" impact rollers have been in use for several decades, primarily for the purposes of ground improvement. Also known as "rolling dynamic compaction", the technique involves a non circular impact module (as shown in Figure 1) that is towed at speeds typically in the range of 9-12 km/h, which results in the impact rolling module striking the ground approximately twice per second. The impact roller is usually towed using a four-wheel drive tractor, as shown in Figure 2. Trials that have been undertaken by the authors have shown that towing speeds slower than 9 km/h can result in insufficient momentum to keep the module turning over without sliding, whilst towing speeds faster than 12 km/h often result in an uncomfortable ride for the operator and may cause the module to bounce about within the trailer support frame, resulting in increased wear and tear on mechanical components.

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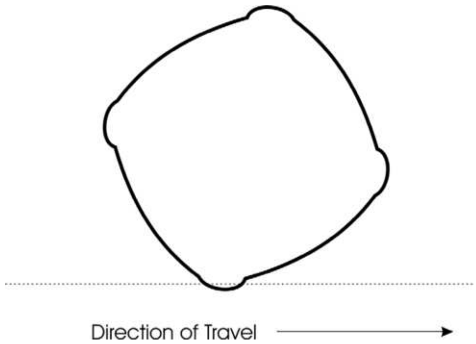

Figure 1. Cross-section of the "square" impact module.

Figure 2. Impact rolling in progress.

The module is connected to the frame by a system of linkage arms that allow the module freedom of movement within its frame and linkages. Once the tow unit commences forward movement, the module is dragged forward and begins to rotate due to friction and soon reaches its operating speed. The energy delivered to the ground results in ground modification. Dependent on the prevailing ground conditions and the characteristics of the impact roller, the effects are measurable by means such as surface settlement, or a relative gain in compaction or soil strength.

A description of rolling dynamic compaction is given by Scott and Jaksa (2008), and they provide several references as background to the subject.

3 TEST SITE CONDITIONS

The test site is part of an industrial property in Wingfield, to the north of the city of Adelaide. The site is approximately 100m long (north-south) and 50m wide, and is bounded by a main road to the south, an industrial site to the east, a railway line to the north and open ground to the west. The site lies in an area that is typically characterised by estuarine deposits, comprising sands, silts and clays. The land levels at the test site have been raised by man-made fill to facilitate future industrial development.

Eight boreholes were drilled across the site to depths of between 4 m and 6 m. Fill was encountered in each of the boreholes to depths ranging between 1.6-2.2 m. The fill generally consisted of very stiff to hard sandy clay with some gravel. Underlying the fill, natural soils consisting of grey and brown silty clay were encountered in each of the boreholes. The natural clay layers were generally of a firm to stiff consistency; however, some softer zones were encountered below the water table, which was located at approximately 3 m below the ground surface.

4 INSTRUMENTATION, TESTING AND SELECTED RESULTS

The objectives of the testing programme include the measurement of impact energy on the impact rolling module (input energy), and the measurement of energy that is imparted by the module into the ground (output energy). Also of interest are the dissipation of output energy as a function with depth, and the settlement of soil layers below the surface, as these factors help to identify the zone of influence of the roller.

The testing programme undertaken to date has included the installation of instrumentation on the impact module to measure input energy, the placement of instrumentation in the ground at or below the ground surface to measure output energy, and the measurement of settlements before and after rolling both at the surface and at depth, as described in further detail below.

4.1 *Instrumentation of the impact module*

The impact module is constructed of thick steel plate and completely filled with concrete, to form a solid block. The instrumentation of the impact rolling module will consist of accelerometers mounted within the steel plate forming the module "skin". At this stage, one accelerometer has been mounted on the side of the module and a wireless transmitter and receiver are being used to collect the output during operation, as shown in Figure 3. Two trials of the system have been undertaken to date, which have demonstrated the satisfactory operation of the data transmission. Further work is planned to embed multiple accelerometers within the module, and these results will be reported in due course.

Figure 3. Transmitter and accelerometer device mounted directly onto impact module.

4.2 *Energy delivered to the ground*

The output energy that is imparted to the ground is measured using a 1,000 kN load cell with 250 mm square x 20 mm thick top and bottom steel plates. Two accelerometers capable of withstanding accelerations up to 50 g were fixed to the underside of the top plate. The load cell was embedded in the ground in the centreline of the impact module path, with the top plate of the load cell flush with the ground surface, and the bottom plate of the load cell placed on bricks to provide a firm base reaction. The load cell system is illustrated in Figure 4.

A sampling frequency of 2,000 samples per second was adopted to capture the load and accelerometer data. Sampling frequencies in the range of 200 to 10,000 samples per second were trialled; however, the adopted sampling frequency was found to adequately capture the peak load and acceleration readings without acquiring unnecessarily large quantities of data. The data acquisition system used was linked to a laptop computer.

Load and acceleration data were recorded over a 10 second period, which captured the roller approaching, passing over and moving away from the load cell that was embedded in the test lane. Figure 5 shows the variation in the load as the impact roller passes over the embedded load cell. In Figure 5, the load that is imparted from the module to the ground occurs over a time of approximately 0.1 seconds. The magnitude of the peak load is approximately 137 kN, corresponding to an imposed bearing pressure of approximately 2,200 kPa over the contact area of the load cell. After impact, the load cell reading does not return exactly to 0 kN, suggesting that plastic deformation has occurred. Settlement of the load cell (and supporting bricks and soil beneath) was verified by survey measurements taken on the top plate of the load cell both before and after impact.

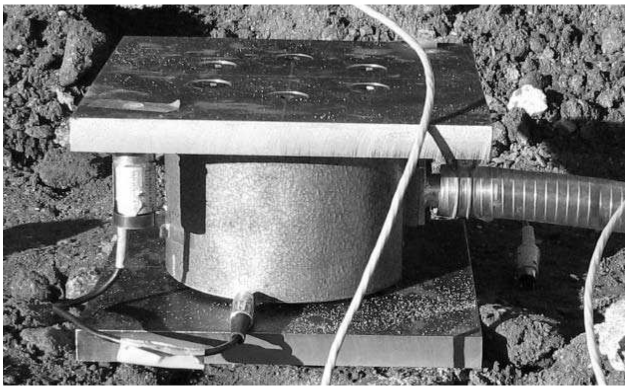

Figure 4. Load cell with accelerometers prior to embedment in the ground.

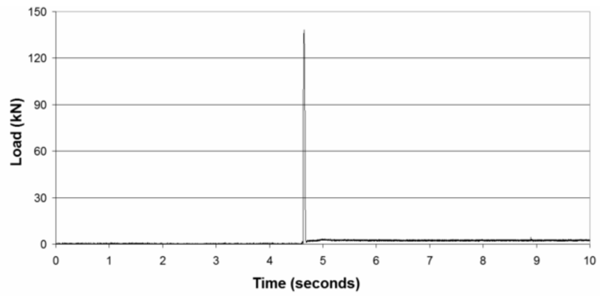

Figure 5. Measured load as the impact roller passes over embedded instrumentation.

Figure 6 shows the variation in measured acceleration as the roller approaches, impacts and then moves away from the embedded load cell. In Figure 6, as the impact roller passes over the load cell there is a large acceleration (downwards movement of the load cell), followed by a large deceleration (upwards) as the soil provides a reaction against the initial downward movement of the load cell. The field trials conducted at the test site to date indicate that a more rigid soil response is recorded with an increasing number of passes; this supports the findings of Landpac (2008) that the ground deceleration increased as the soil stiffness and density increased. In Figure 6, small accelerations are evident at approximately half-second intervals either side of the peak reading, indicating that ground accelerations have been recorded as the rolling module impacts the ground as it approaches and then moves away from the embedded load cell. These findings generally support the findings of Avalle (2007) who analysed the magnitude of ground vibrations as a function of the distance from impact rolling.

Field trials undertaken to date have proven that a module impacting the ground directly above embedded instrumentation results in significantly higher ground decelerations being recorded, compared to when the module strikes the ground off-set from the embedded instrumentation. Testing to date indicates that even small off-set distances can produce large discrepancies in the magnitude of decelerations measured by embedded instrumentation. Trials were undertaken to determine if the reproducibility of impacts could be controlled. Despite attempts at controlling the operating speed and using the same at-rest starting location, field testing verified that getting the module to land in precisely the same location is not possible, as it is dependent on a number of variables such as the ground conditions (moisture, compaction), how quickly the tractor operator changes through the gears and accelerates, as well as the operating speed of the towing unit.

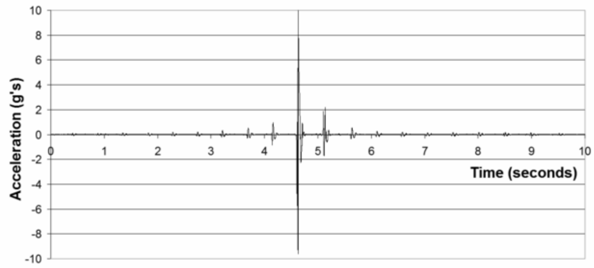

Figure 6. Measured acceleration as the roller passes over embedded instrumentation.

As the reproducibility of impacts could not be controlled, it was decided to measure the off-set distance from the centre of the module to the centre of the load cell to determine if there was a relationship with the peak load recorded (refer Figure 7). Similarly, the peak deceleration was measured and plotted against the off-set distance (Figure 8). The results of both Figures 7 and 8 indicate that there is a large discrepancy in the values of both peak load and deceleration, depending upon where the impact rolling module hits the ground relative to the embedded instrumentation. The highest values were recorded when the module struck the ground at a distance within 400 mm of the centre of the module's impact surface. This appears to be a function of the geometry of the impact rolling face, with the zone of maximum impact noted in Figure 9. These results indicate that the pressure distribution underneath the module impact is non-uniform.

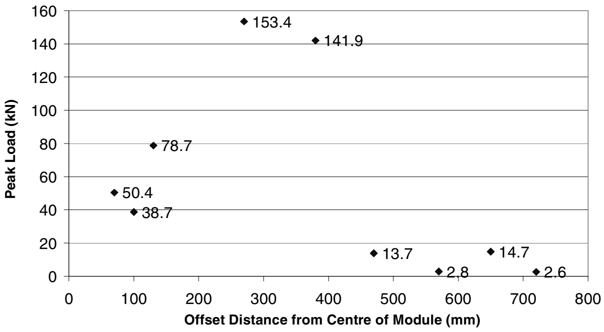

Figure 7. Peak load versus off-set distance from centre of module.

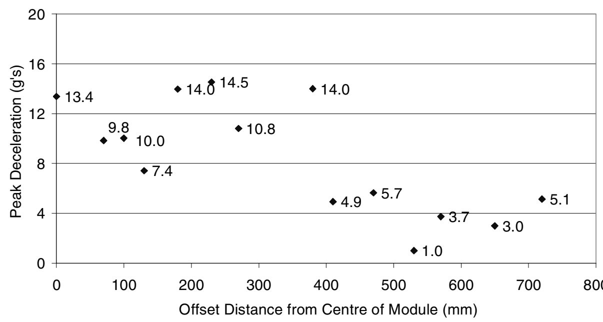

Figure 8. Peak deceleration versus off-set distance from the centre of the module.

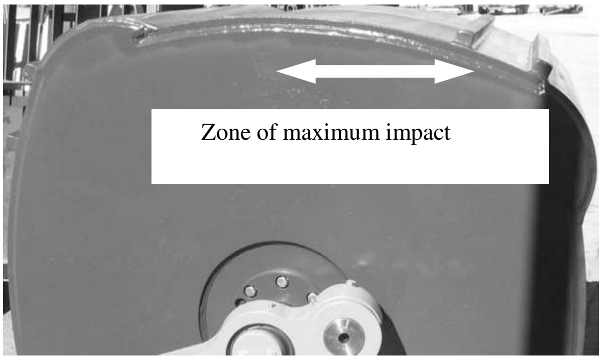

Figure 9. Geometry of impact rolling module face.

Trials have also been undertaken to determine typical distances that are required in order to get the impact roller up to its operating speed from a standing start. Trials undertaken to date indicate that a distance of approximately 20 m may be required. This generally supports the findings of Scott and Suto (2007), who reported that ground near the perimeter of a fenced site could not be improved as successfully as the rest of site due to access-related issues that reduced the towing speed of the module. This in turn, supports the theory proposed by Clifford and Bowes (1995), who suggested that the higher the velocity of the module upon impacting the ground, the greater the energy that is imparted, hence the more ground improvement that can be expected.

4.3 *Measurement of surface and subsurface deformation*

Measuring surface settlement is a commonly adopted technique for verifying ground improvement with an impact roller, as data can generally be obtained in an efficient and cost-effective manner. However, care needs to be taken to account for the effect of surface undulations caused by the periodic impacts of the module on the ground. Depending upon the soil conditions, surface undulations can typically have up to a 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 for surveying.

In order to measure settlement of soil layers below the ground surface embedded steel plates with central vertical tell-tale rods were buried beneath the surface. This method proved successful for measuring settlements within near surface layers, and proved to be a useful way to overcome the effect of surface undulations; however, installing and removing embedded steel plates became quite cumbersome when placed greater than 300 mm below the ground surface.

To measure settlements within layers at greater depths, magnet extensometers comprising three ring magnets were installed in each of four boreholes across the site. Within each borehole, the first magnetic extensometer (Magnet 1) was installed the fill layer, the second (Magnet 2) near the fill/natural soil interface and the third (Magnet 3) in the natural soil layer below the water table. The results of settlement data after 18 passes of the impact roller at one of the borehole locations is given in Table 1.

Table 1. Measured settlements at various depths below ground surface

Measuring Technique	Depth below ground surface (m)	Settlement relative to site datum (mm)
Steel Plate	0.1	20
Magnet 1	0.8	10
Magnet 2	1.9	5
Magnet 3	3.1	5

Whilst the magnitude of settlements recorded in the soil layers at depth were small (presumably due to the thick layer of very stiff to hard clay fill at the site), this method appears promising for determining settlement in targeted soil layers at depth.

5 FUTURE WORK

To determine the zone of influence of rolling dynamic compaction in different soil conditions, commonly used testing methods will be combined with instrumentation that is embedded deeper into the ground, in addition to the on-going development of the input energy system mounted on the impact module. The transfer of energy of the impact rolling module to the underlying ground will be measured at various depths, using earth pressure cells and accelerometers that will be embedded into the ground. The impact roller will pass over the embedded instrumentation whereby the pressure and ground deceleration measured using accelerometers can be used to determine the energy recorded. Measurement of the energy at various depths below ground level for differing soil types will enable the zone of influence of the impact roller to be quantified.

6 CONCLUSIONS

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 using dynamic means. It is anticipated that the outcomes of the current research programmes will enable rolling dynamic compaction to be applied and validated more appropriately for a range of soil conditions. In addition, quantifying the effectiveness of rolling dynamic compaction 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 impact rollers to be used more effectively and with greater confidence in a range of engineering applications.

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