

Evaluating rolling dynamic compaction of fill using CPT

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ABSTRACT: Rolling Dynamic Compaction (RDC) is a ground improvement technique that involves compacting soil using a non-circular roller. Whilst conventional circular rollers are able to compact layer thicknesses typically in the range of 200 mm to 500 mm, thicker layers are able to be compacted using RDC. However, the depth of influence of RDC can vary significantly depending on the soil type, moisture content, loose layer thickness and number of passes. This paper focuses on how cone penetration testing was used during a compaction trial as a key site investigation technique to determine the zone of influence of RDC at a site involving quartzose and carbonate sand fill. The results presented quantify the increase in cone tip resistance with depth and illustrates how a number cone penetration tests (CPTs) were used to evaluate changes in soil strength due to increased roller passes, changes in moisture content or placed loose layer thickness.

1 INTRODUCTION

Rolling dynamic compaction (RDC) is a generic term associated with densifying the ground using a heavy (6-12 tonne) non-circular roller module of 3, 4 or 5 sides, that rotates about its corners as it is towed, causing the module to fall to the ground and compact it dynamically. A square impact rolling module is shown in Figure 1. A key advantage of RDC is the ability to provide deep layer compaction when compared to circular static and vibrating drum rollers. 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. The ability to compact thick layers can make RDC a productive and cost-effective option for earthwork projects; however, as noted by Avalue (2007) there are challenges associated with its verification. This paper discusses how the cone penetration test (CPT) was used as a key site investigation technique to quantify the zone of influence of ground improvement using RDC. The CPT rig used in the project is shown in Figure 2.

2 VERIFICATION OF RDC AND THE USE OF THE CPT

Whilst RDC has been used successfully on many projects in Australia and overseas in applications such as roads, airports and construction and land reclamation projects, there have been varying results as to what the depth of influence of RDC is for different soil conditions. The CPT has been used successfully on a number of RDC projects

in Australia, including Avalor & Carter (2005), who reported on the verification of RDC in sandy soils using the CPT; with improvement evident in plots of cone tip resistance (q_c) between depths of approximately 0.5-3.0 m below the ground surface. In a paper by Kelly (2000) plots of q_c versus depth below the ground surface also were provided for reclaimed sand deposits; based on their results, improvement was most evident between depths of 0.5-2.6 m below the ground surface; with Kelly quoting influence to depths of 5 m below the surface. In the same paper, increases in q_c to depths of 4 m in in situ sandy soils were reported from CPTs undertaken pre- and post-RDC; improvement was most evident between depths of 0.6-1.5 m.

When compacting thick layers with RDC it is not uncommon for large sized particles (such as concrete and rock fragments) to be present within heterogeneous fill. As reported by Avalor & Grounds (2004) this can cause loss of continuous data and a need for relief drilling where refusal was met due to high cone tip resistance. They found that the usefulness of the CPT to verify ground improvement using RDC was limited within heterogeneous fill due to the presence of large hard particles; as such only intermittent plots of cone tip resistance could be obtained making it difficult to determine if there was an indication of strength gain with increasing roller passes. Their work suggests that budget constraints, availability of equipment and the presence of heterogeneous fill material often dictate whether the CPT can be used to verify impact rolling applications. However, to quote Lunne et al. (1997), “the CPT has been found to be one of the best methods to monitor and document the effect of deep compaction due to the continuous, reliable and repeatable nature of the data”. This paper focusses on a compaction trial where CPTs were successfully used to quantify the depth of improvement of RDC.



Figure 1. 4-sided impact rolling module



Figure 2. CPT rig undertaking post compaction testing

3 CASE STUDY

An earthworks trial was undertaken on a remote site in Australia comprising predominantly quartzose and carbonate sand fill. Key objectives of the earthworks trial were to optimise the number of roller passes, loose lift layer thickness and moisture content of the fill, to achieve a dry density ratio of at least 90% of maximum modified dry density.

Despite the site of the compaction trial being located a 2-day drive from the nearest capital city; a specialist CPT contractor was engaged to carry out CPTs using a 10 cm² electric cone penetrometer. As shown in Figure 2, the CPT rig used was a tracked vehicle, making it ideal for traversing the disturbed undulating surface that remains after RDC. Figure 2 clearly shows the undulating sandy surface created by the RDC process. Given that the earthworks trial was undertaken in very hot weather conditions approaching 40°C, moisture conditioning of the fill material was challenging. CPTs were undertaken through the full thickness of placed fill and to a minimum of 2 m into the underlying natural soil to help assess the variability of the placed fill material and quantify the improvement of soil strength with increased roller passes.

The fill material consisted of a mix of locally excavated sand (quartzose and carbonate with a varying proportion of carbonate cementation) that was blended with red-brown sandy clay, silty sand and clayey sand material that was also sourced from site. The fill material was fairly typical of 'Pindan' sands that are common in the Kimberley and Pilbara regions of Western Australia. Based on the dozens of laboratory particle size distribution tests that were undertaken on the blended fill material, sand-sized particles typically varied between 60-85% by mass; the remaining fraction (15-40% by mass) consisted of fine-grained material, implying that there were no gravel-sized particles (or larger). Figure 3 shows a typical particle size distribution curve for the placed fill material. Atterberg limits testing indicated that the fine-grained component contained either non-plastic fines, or fines of low plasticity (liquid limit ~20% and plasticity index ~15%). The natural field moisture content of the fill typically varied between 4-9%. However, as RDC is less effective if the soil is too dry of the optimum moisture content, moisture conditioning of the fill prior to placement was undertaken. The thickness of the compacted fill was 1 m. The natural soil underlying the placed fill consisted of stiff to hard silty clay. Groundwater was not encountered within a depth of 5 m below the placed fill.

Figure 4 shows a typical result comparing q_c before and after rolling. An increase in soil shear strength was quantified by increasing cone tip resistances in the sandy fill layer and to a depth of approximately 0.75 m into the underlying natural clay (total depth of 1.75 m). The fill and natural soil interface at a depth of 1 m below the ground surface was clearly identified in the CPTs. Figure 5 shows a number of CPT plots that were superimposed to help quantify soil variability. Figures 4 and 5 are examples of a robust site investigation using CPTs to quantify the effectiveness of RDC to address the key project aims of optimising the number of roller passes and determining an appropriate layer thickness by quantifying the vertical zone of influence of RDC. In many ways this work is no different to previous work undertaken by Avalle & Carter (2005) and Kelly (2000) and so is not a large focus of this technical paper.

Figure 6 shows a typical plot of cone tip resistance versus depth after the same number of passes. The key variable between the two locations (ignoring spatial variability which would be inherently present) was the moisture conditioning of the sandy fill before placement. As can be observed in Figure 6, the fill placed with no additional moisture yielded quite poor results below a depth of 0.7 m when compared to the soil with moisture conditioning. Nuclear density and sand replacement tests that were conducted on site also confirmed the presence of loose sandy fill below 0.7 m; however, the CPT was used as a preferred method of quantifying the lateral extent of the issue because of its efficiency and ability to obtain real-time continuous data with depth. This was a key early finding that helped to guide the remainder of the compaction trial.

In Figure 4, the shape of the profile of cone tip resistance versus depth is unusual for a surface compaction ground improvement technique such as RDC. Typically, the near surface soils (e.g. 0.3 m) are disturbed with little evidence of improvement, below this depth increases in cone tip resistance are expected, which would steadily decrease down to some depth of influence (assuming uniform soil conditions). In Figure 4, there is an increase in cone tip resistance below a depth 0.7 m that is unlikely to be attributed to RDC, given that the sandy fill layer is approximately 1 m thick. The fact that this phenomenon was observed in the CPT plots before and after compaction suggests that is likely to be either a function of the fill placement method (this fill may have received more traffic compaction from trucks or dozers during placement), or, it is a case of the cone tip sensing a soil interface (layer boundary). The latter is discussed by Ahmadi & Robertson (2005) where they found that a soil interface could be measured up to 15 cone diameters ahead of the depth of the cone, depending upon the strength of the soil. For the 10 cm² (35.7 mm diameter) cone used on this project, it is therefore possible for the interface between the sandy fill and stiff-to-hard clay to be sensed within a depth of 0.5 m from the layer boundary. It is interesting to note that this phenomenon was not observed to the same extent for the case of the soil with no moisture added in Figure 6. However, this is not inconsistent with the findings of Ahmadi & Robertson (2005) who also indicated that in soft (loose) soils the soil interface could be sensed as little as 1 cone diameter ahead of the depth of the cone.

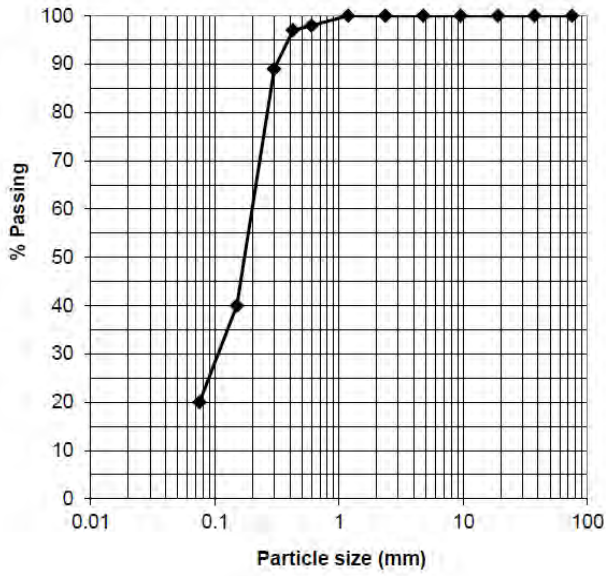


Figure 3. Typical particle size distribution curve for sandy fill material

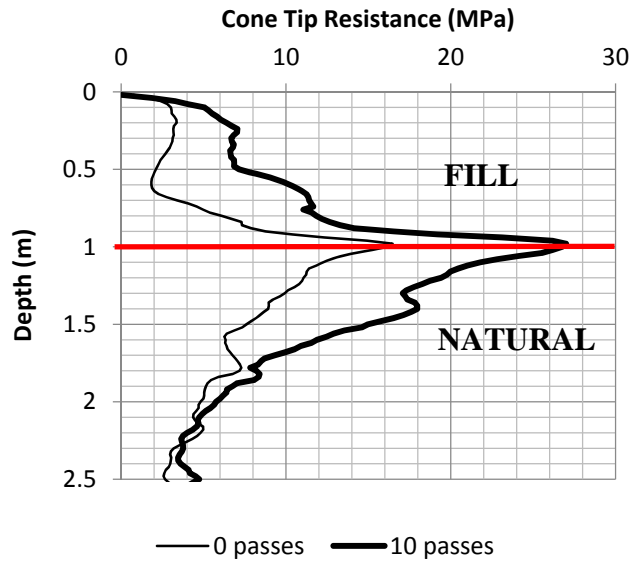


Figure 4. Typical plot of cone tip resistance (q_c) versus depth before and after compaction

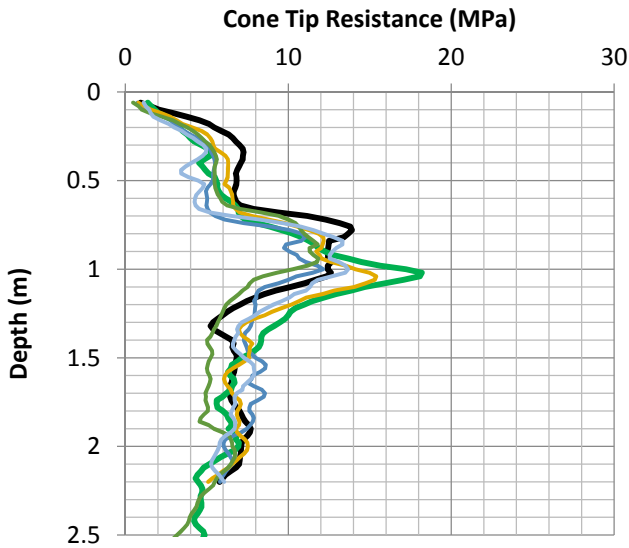


Figure 5. Comparing CPT results to determine compacted fill variability

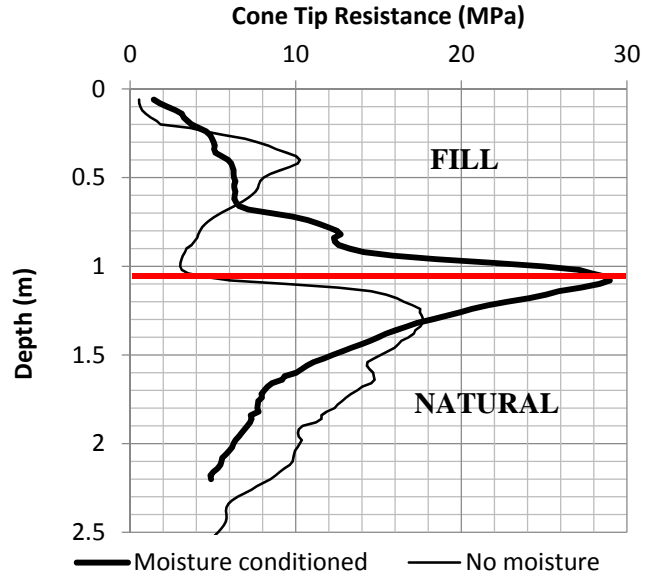


Figure 6. Comparing moisture conditioned and non-moisture conditioned soil after compaction

4 ZONE OF INFLUENCE OF RDC AND THE USE OF THE CPT

Rather than focussing on the results of the compaction trial, the remainder of this technical paper discusses how the CPT was used to determine not just the vertical extent of RDC, but also the lateral zone of influence. In order to quantify lateral effects, five closely spaced CPTs were undertaken, as illustrated in Figure 7 and summarised in Table 1.

The distance between impact rolling lanes is typically 2.3 m; CPTs 1-4 were equally spaced at a distance of 1.15 m apart. CPT 5 was located a distance of 3 m from CPT 4 in an area that was uncompacted but close enough to the other locations to be deemed typical of 0 passes, so that spatial variability was minimised. CPTs 1 and 3 were located at the centre of the impact rolling lane (centre of module imprint that remained on the ground surface after rolling). CPTs 2 and 4 were located on the wheel paths of the trailer that tows the module. In Figure 1 it can be observed that the module (width of 1.3 m) is narrower than the track distance between the trailer tyres. In RDC applications it is common for a 'wheel path to wheel path' rolling pattern to be adopted (rather than a module-to-module pattern) as it is thought that there is an overlap between locations of module impacts between adjacent impact rolling lanes; however, this has never been quantified (published). Therefore, a key aim was to quantify the difference in cone tip resistances between CPT locations to determine, not only the vertical depth of influence, but also any lateral effects due to RDC.



Figure 7. Location plan of CPTs

Table 1. Description of CPT locations

CPT Location	Comment
1	Centre of middle lane after 10 passes (both adjacent lanes also subjected to 10 passes)
2	Wheel path between middle lane (10 passes) and outside edge lane (10 passes)
3	Centre of edge lane after 10 passes (only one adjacent lane subjected to 10 passes)
4	Wheel path of outside edge lane
5	Uncompacted area 3 m beyond edge lane (0 passes).

The results from CPT locations 1, 3 and 5 are summarised in Figure 8, where it can be observed that the greatest improvement in cone tip resistance (and therefore soil shear strength) is in the middle lane (CPT 1), as expected. In the edge lane (CPT 3), which has also been subjected to 10 passes, there is quantifiable improvement in cone tip resistance to a depth of approximately 1.3 m when compared to zero passes, but less improvement than in the middle lane. The results from CPT locations 2, 4 and 5 are summarised in Figure 9, whereby it can be observed that there was greater improvement in cone tip resistance at the location in the wheel path between the middle and edge lanes (CPT 2) than at the location in the wheel path to the edge lane only (CPT 4).

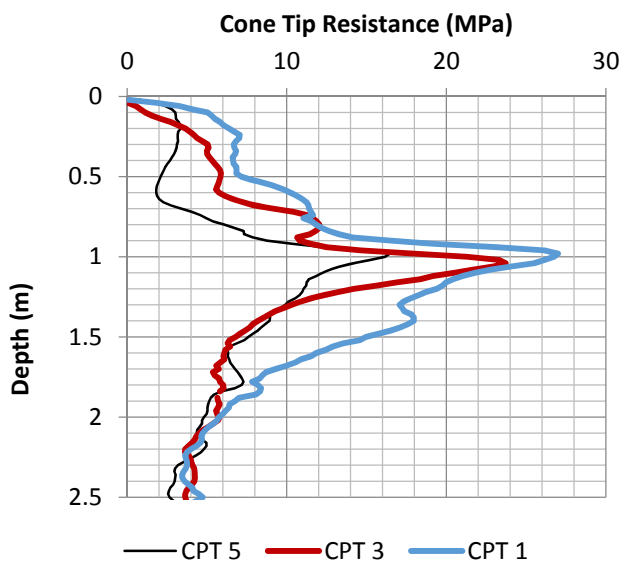


Figure 8. 0 passes versus 10 passes in edge lane versus 10 passes in middle lane

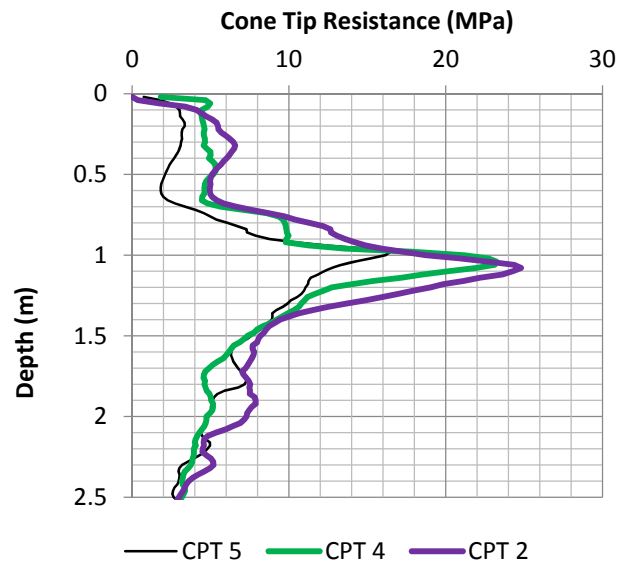


Figure 9. 0 passes versus wheel path to edge lane versus wheel path to edge / middle lane

To further quantify the improvement at each test location, the percentage change in cone tip resistance (from 0 passes) has been plotted with depth as shown in Figure 10. In this figure the values of cone tip resistance have been averaged and plotted over 100 mm depth intervals. This graph shows the evidence of a lateral zone of influence with wheel path locations (CPT 2 and CPT 4) yielding results not dissimilar to that of the edge lane (CPT 3) despite the module not impacting directly above these test locations. It is also clear from this analysis that the greatest increase in cone tip resistance and vertical depth of influence was for the middle lane (CPT 1), which benefited from both adjacent lanes being subjected to 10 passes, as well as 10 passes directly in that lane.

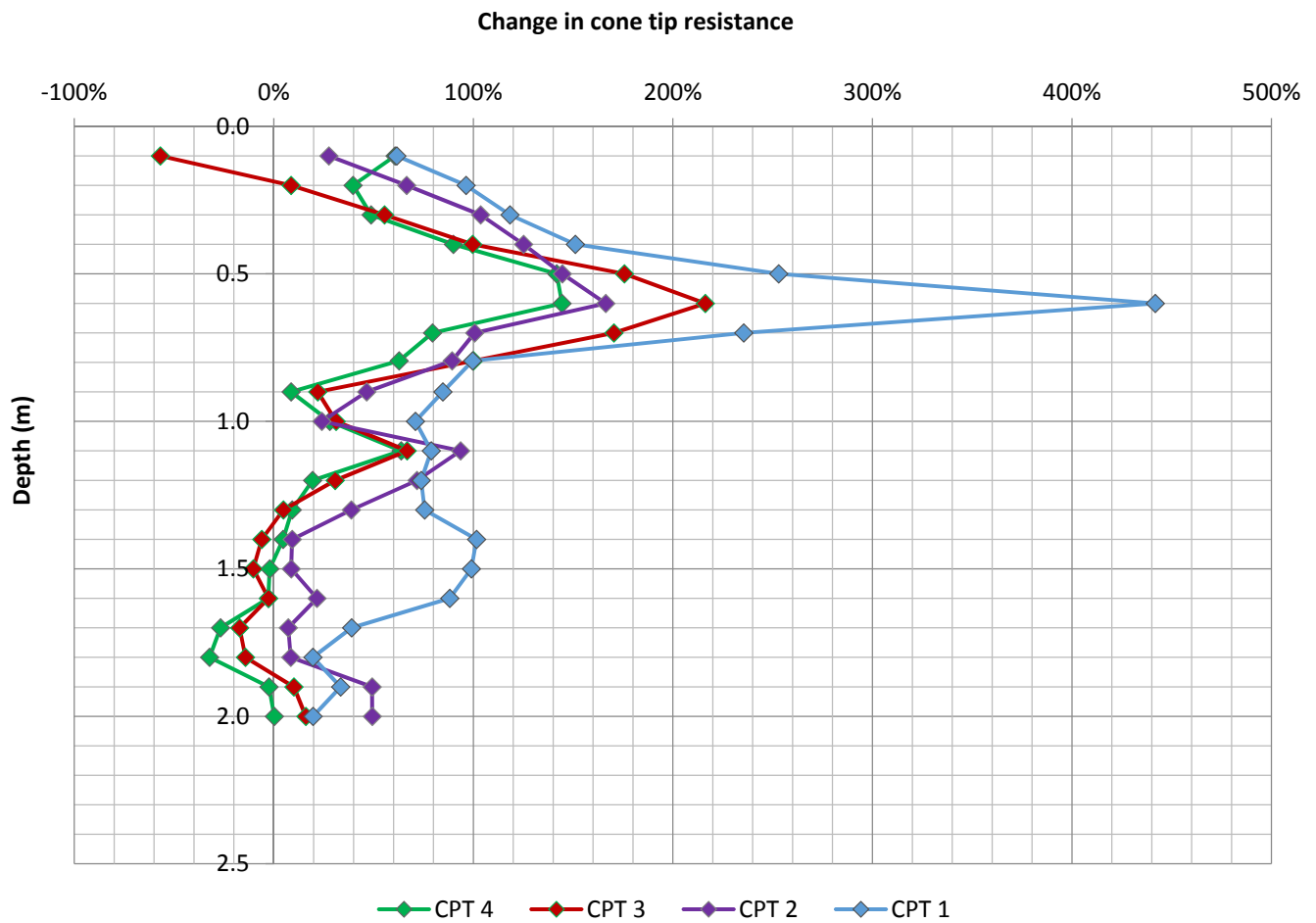


Figure 10. Percent changes in cone tip resistance versus depth below ground surface for CPTs 1-4

5 CONCLUSIONS

The case study presented in this paper demonstrates that the use of modern in situ testing methods such as the CPT help to quantify and validate the effects of RDC in a thick lift compaction application. The CPT was shown to be an efficient and preferred test method for quantifying the ground improvement by comparing values of cone tip resistance before and after rolling. Furthermore, the zone of influence of RDC was able to be quantified by analysing a series of closely-spaced CPTs which confirmed both vertical and lateral effects. Quantifying lateral effects of RDC using CPT is significant, as it confirms the appropriateness of a wheel path to wheel path rolling pattern which is commonly adopted in many earthworks applications.

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