DETERMINING THE EFFECT OF GROUND IMPROVEMENT USING IMPACT ROLLING FOR VARYING SITE CONDITIONS

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ABSTRACT

Deep compaction techniques have been in use for a number of years. There are a number of deep compaction techniques that can be applied in ground improvement. These range from the traditional drop weight to eccentrically shaped (impact) rollers.

It is generally accepted that either of these techniques would affect some degree of ground improvement in non-cohesive soils. The depth of ground improvement would be dependent on a range of factors including mechanical characteristics of the soil i.e. PSD, Atterberg limits and the location of ground water table.

To date anyone undertaking deep ground improvement using impact rolling techniques does not have a way of predicatively determining the depth of ground improvement in different soil and ground water conditions.

It is the authors' intent to present a series of case studies where deep ground improvement using impact rolling techniques was successfully utilised across a variety of ground and phreatic conditions. The degree of improvement was evaluated in terms of CPT Tip Resistance (Qc), Young's modulus (E) and bearing capacity.

The intent of these case studies is to investigate relationships between the degree of improvement and potential contributing factors including the soil properties, the weight of the impact rolling module used, the number of roller passes and the location of the water table. These relationships are developed for a series of non-cohesive soil conditions specifically well graded sand, uniformly graded sand and crushed limestone, and are presented as nomographs. These nomographs can provide a guidance to predictively determine the number of passes required to effect ground improvement to a given depth for a particular soils type in various phreatic conditions.

1 INTRODUCTION

As construction activities increasingly take place in less than ideal ground conditions, ground improvement has become an important construction aspect. Ground improvement is often required in sites with incompetent soils which cannot achieve the required bearing capacity to sustain loads imparted by structures or construction loads.

Soils are complex materials and require detailed investigation to examine its material properties and analyse their behaviour when subjected to loading. With advances in computer modelling capabilities, the investigation of complex soil-structure interaction mechanisms has become more efficient, increasing the precision in which geotechnical engineers design ground improvement methods to treat such materials.

Ground improvement methods are contingent on project budgets, time and site specific conditions such as the presence of high plasticity swelling clays, uncontrolled fill or other such material which would be unsuitable without treatment. Methods such as preloading with or without Prefabricated Vertical Drains (PVD) are a commonly used method for improving soft clay deposits by consolidation. Other commonly used ground improvement methods include removing soft soils and replacing with imported material, Vibro-flotation, Soil Mixing, Piling and Impact Rolling.

Dynamic Compaction is often used to improve the mechanical properties of the soil by transmitting high energy treatment delivered by dropping a heavy weight or pounder from a significant height to compact loose soils that initially have low bearing capacity and high settlement potential such as loose sands. The depth of improvement using this method depends on the drop height, the weight of the pounder and the mechanical properties of the soil undergoing improvement. Menard and Broise (1976) developed an empirical equation in which the depth of influence was equal to the square root of the impact energy (Eqn. 1); i.e. the product of the pounder weight (in metric tons) by the drop height (in metres).

Since the development of the Menard and Broise empirical equation, further research has been carried out refining the relationship and investigating how other factors such as the shape of the pounder effect the depth of improvement.

A more suitable and accepted form of the equation was proposed by Lukas (1995) which introduced an empirical coefficient factor to the Menard and Broise equation to account for site specific considerations.

This paper investigates impact rolling, which is a soil improvement technique involving a heavy non circular module (impact roller) that is towed by a prime mover, causing it to rotate and fall to the ground, compacting the soil dynamically. Due to the cumulative dynamic effect of the process, a greater depth of influence is achieved than when using a conventional roller. Hitherto when undertaking deep ground improvement using impact rolling techniques there is no way of predicatively determine the depth of ground improvement in different soil and ground water conditions. The paper will present nomographs developed from field trials which can be used to predictively determine the number of passes required to effect ground improvement to a given depth for a particular soils type in various phreatic conditions.

1.1 DEFINITION OF PROBLEM

The prediction of the extent of ground improvement using impact rollers is currently not adequately understood, to date there are no constitutive models have been developed that can predict the depth or the degree of improvement as a result of impact rolling.

The closest algorithm that attempts to predict the depth of ground improvement as a result of dropping a weight from a certain height has been put forward by Lukas (1995) shown below.

$$d_{max} = n\sqrt{W.H} \tag{1}$$

where,

d_{max}= the depth of influence

n = a coefficient depending on the site properties with typical values ranging between 0.3 and 0.8. Values between 0.5 and 0.6 are generally used for granular soils.

W= Pounder mass (t)

H= Drop height (m)

The above empirical equation is not applicable to impact rolling as it does not take into account factors such as the different means by which the load is applied i.e. the compaction module is towed causing it to rotate and fall to the ground as opposed to being dropped from a height. Additionally, as the compaction module is towed, the velocity at which the compaction module impacts the ground and thus the energy imparted varies. Furthermore, the compaction of the ground using impact rollers is cumulative, i.e. the compaction results from multiple passes occurring at a single location as opposed to a single 'drop' of a weight as in Dynamic Compaction.

As far as the authors are aware, no research has been conducted to develop alternative empirical or analytical solutions for the above relationship. As a result, the application of impact rolling is typically carried out based on observational outcomes as opposed to a prescribed methodology or criteria so as to presage the number of passes necessary to deliver the intended level of ground improvement. This lack of a predictive model results in an inability to accurately calculate the time or effort required for ground improvement and hence associated costs.

The difficulty in predicting the effect of ground improvement using impact rolling stems from the variations in ground conditions encountered across different sites. The material properties of sandy sites for example vary in terms of material gradation, depth to water table and other relevant factors. The intent of this paper is to develop nomographs that predict the effectiveness of impact rolling for various depths. It is the authors intent that these nomographs can be used by practitioners in a predictive capacity when designing ground improvement based on impact rolling.

2 SELECTION OF TRIAL SITES FOR TESTING

The application of impact compaction across different sites will yield different results. This is due to the varying site conditions and materials encountered. For example, the effect of impact rolling on a site with cohesive soil will be different to a site consisting of granular materials.

This paper focuses only on impact rolling on sites with granular or cohesionless sand materials to develop nomographs to predict the depth of ground improvement, so that these nomographs can be used predictively on other sites with similar material conditions. Each of these sites are slightly different as they consist of different phreatic and material grading curves as discussed below.

In each of these sites, the effective compaction was checked using either Cone Penetration Tests (CPT) or Multichannel Analysis of Surface Waves (MASW) Seismic survey. The ground impact roller operations at each site was documented including the number of impact roller passes completed. In each of these cases the following criteria was fixed;

- Weight of the module which was 17 tonne
- Shape of the module which was triangular
- Prime mover velocity which was 12 km/h to 14 km/hr
- Improved ground is defined by a Young's modulus of 20 MPa

2.1 CASE STUDY 1

Site 1 was a relatively flat site covering an area of approximate 3ha and positioned close to a natural watercourse. The site had been surcharged by 1.5m with sand fill for a - period of 3 years resulting in an approximate total settlement of 3m. Subsequent to the surcharge period the embankment was trimmed to design elevation.

At design elevation, the ground conditions comprised of two metres of sand fill, underlain by natural ground. The water table was located approximately 0.5m below the existing ground level.

Impact rolling was employed in the aim of improving the material to meet minimum compaction requirements and to avoid removing the material then replacing and compacting in 300mm lifts using conventional static rollers. The trial works concluded that impact rolling was only effective at 1.5 to 2.0m due to the high water table. The depth of improvement was likely influenced by the water table.

The impact compaction was validated after the compaction of each lift using seismic shear wave to ensure the minimum criteria of 20 MPa was achieved.

Validation testing showed that the ground improvement implemented successfully improved material to a depth of 4m below ground surface which met the Clients requirements.

2.2 CASE STUDY 2

Site 2 was located south of Perth, had an area approximately of 5.6 ha and was comprised of sandy material. The site had previously contained industrial buildings which were demolished to allow for the new development. To install services, trenches were excavated throughout the site to depths of up to 4.0m. Subsequent to the installation of services these excavations were 'bulk filled' with the excavated material in single lifts without moisture conditioning or compaction; creating soft pockets of material across the site. Additionally, records of the locations of trenches were not maintained.

Material testing was not undertaken to characterise the sand, however from field observations it was noted that the sand was uniformly graded with rounded grains.

Due to the absence of construction records, impact rolling was employed across the entire site in the aim of compacting the loose pockets of material and negate the need to dig out and re-compact material. A 17 t triangular compaction module was used to undertake the work. Up to 60 passes were performed across the site and DCP testing was used throughout compaction works to monitor the degree of improvement as compaction progressed

At the completion of impact rolling, seismic shear wave testing was carried out at locations selected by the client to assess the compaction works.

The post-compaction testing revealed that approximately 85% of the site had been suitably compacted, however 15% of the site failed to meet the required compaction criteria. The 15% that did not meet the criteria was found in two isolated pockets in which the greatest depths of loose material were noted to be. In the areas which 'failed', impact rolling was noted to have adequately improved material up to 1.5m of ground surface, below this some improvement was noted, though the material failed to improve to the level required (20 MPa Young's modulus).

2.3 CASE STUDY 3

This site was situated north of Perth towards the base of a shallow valley with an area of 2.9 ha. A lake and swamp areas were located approximately 300m from the site.

The ground conditions encountered beneath the site comprised of loose to medium dense sandy soils to a depth 5.2m (the vertical extent of the investigation). Geotechnical testing undertaken at the site included CPT's, Test Pits, PSPs and a soil electrical resistivity test. Laboratory testing carried out on samples taken from test pits revealed that the material was poorly graded sand (SP) with a Maximum Dry Density of 1.78 t/m^3. The loose zones with potential high compressibility were encountered in pockets across the site at depths ranging between 1.6m and 3.85m. The groundwater table was present at approximately 3.6m below ground surface.

Impact rolling was implemented using a 17 t triangular compaction module in the aim of compacting the loose sand so as to achieve a Young's modulus of greater than 20 MPa.

A total of 20 passes was performed across the site and validation testing was carried out using MASW.

Subsequent to the application of impact rolling the soft pockets and zones of potentially high compressibility were noted to have improved and a solid consistent raft with a depth of up to 4m was created. A post ground improvement large strain modulus of greater than 20 MPa was achieved.

2.4 DISCUSSION OF CASE STUDY OUTCOMES

The above presented sites all comprised of cohesionless sand materials however; they consisted of different grading and phreatic conditions. These varying conditions variably impacted on the efficacy of the impact rolling. The following are noted to be the key distinguishing features observed at the respective sites.

- Site 1 – A high water table was present which adversely affected compaction due to the high pore-water pressure in the soil. Adequate compaction was achieved, however material had to be excavated and compaction carried out in multiple lifts.
- Site 2 – This site contained uniformly graded sands. Uniformly graded sands have a high void ratio which makes it difficult to achieve a high density.
- Site 3 – This site contained loose sandy material; the water table was located 3.6m ground surface.

It is noted that in case study 1 the presence of the high water table restricted the depth of ground improvement. In case study 2 the "pockets" that could not be treated were found to consist of uniformly graded sands and this also limited the depth of improvement to less than 1.5m where well graded sand was present depths of improvement up to 4 meters were observed.

The authors have developed predictive nomographs accounting for these differences in ground conditions as discussed further below.

3 DEVELOPMENT OF PREDICTIVE NOMOGRAPHS

3.1 DATA ANALYSIS

Seismic shear wave measurements using the continuous shear wave system was undertaken incrementally on each site every two passes. As mentioned previously in Section 2, a number of aspects have been fixed;

- Weight of the module which was 17 tonne
- Shape of the module which was triangular
- Prime mover velocity which was 12 km/h to 14 km/hr

It is therefore assumed that the only variables affecting the depth of ground improvement i.e. achievement of 20 MPa modulus are the phreatic conditions and the grading characteristics of the in-situ material.

Shown below is the plot of seismic shear wave results obtained for each of the test sites at intervals of two passes.

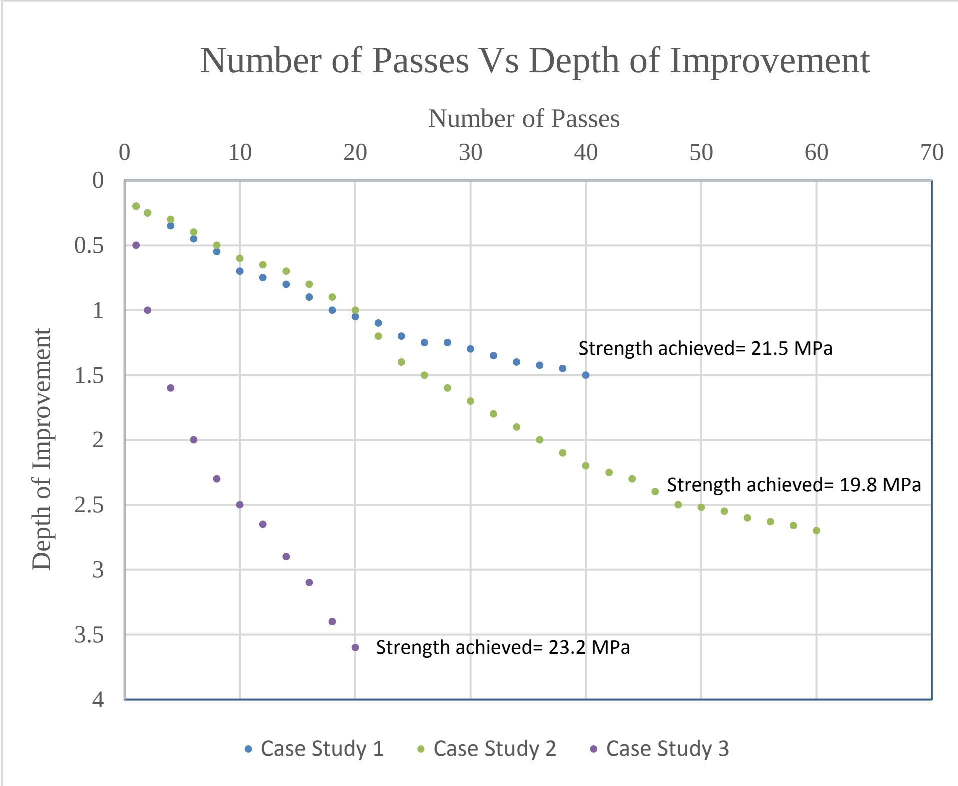

Figure 1: Case studies data

The following can be noted from Figure 1:

- Case Study 3 has the deepest depth of ground improvement and this site consists of well graded sands and no water table present within the depth of improved ground.
- Case Study 2 is also a “dry site” however the depth of ground improvement was truncated at approximately 2.5m in a few areas. These areas corresponded to localised pockets of uniformly graded sand.
- Case study 1 had the shallowest depth of ground improvement which was approximately 1.5m and this corresponded to the high water table present at 0.3m to 0.5m below ground surface.

Based on the above observations it would be reasonable to conclude that where well graded sands are present, depths of ground improvement of up to 3.5 to 4.0m can be achieved if targeting a Young’s modulus of approximately 20 MPa, which at a strain of approximately 1% corresponds to a bearing capacity of 200 kPa.

It is evident that the water table and lack of ideal grading limits the depth of effective ground improvement. This is evident from the results of case studies 2 and 3.

Taking the above into consideration the following nomograph correlating the depth of ground improvement to the number of passes can be developed as shown in Figure 2.

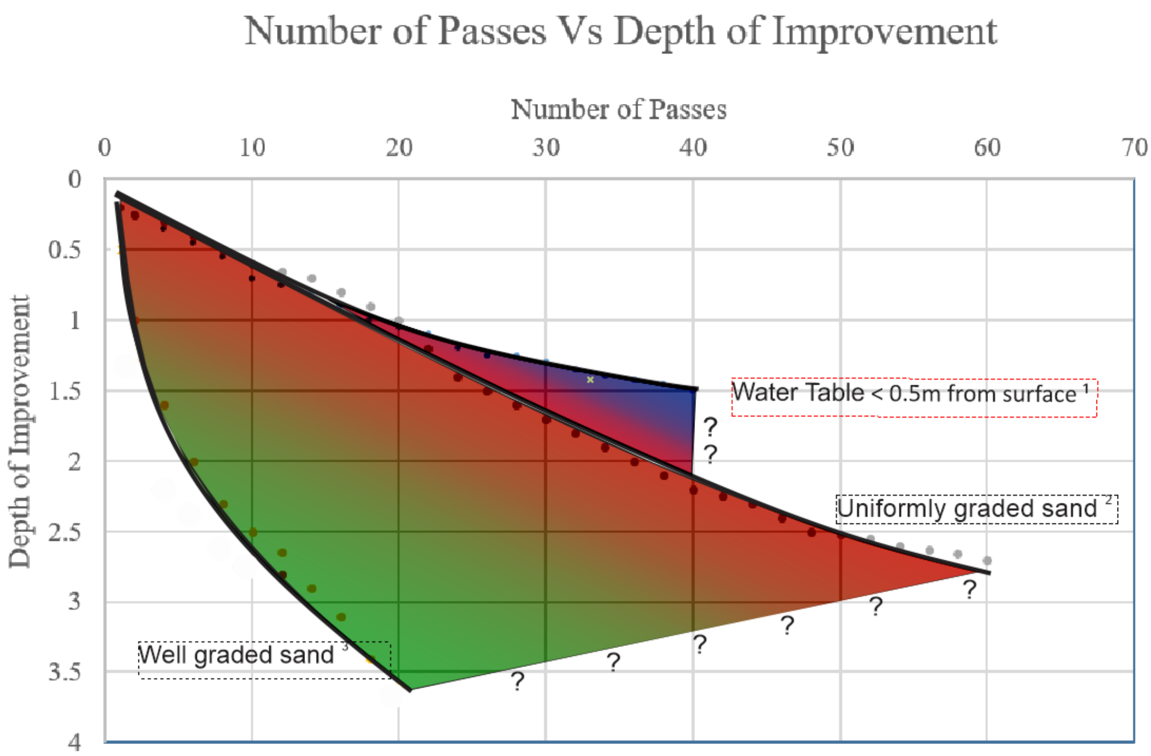

Figure 2: Predictive nomograph for determining the depth of ground improvement

3.3 LIMITATIONS AND FURTHER WORK

It is the authors' intent that the above graph can be used by other practitioners as a guidance to predict the depth of ground improvement when impact rolling is applied on sites consisting of sand. There are still some uncertainties surrounding the depth of ground improvement in varying levels of ground water conditions and material gradation characteristics. This is shown above whereby the transition for depth of ground improvement between uniformly and well graded sand still needs to be investigated further.

It is the authors intent to further refine the above relationships with the benefit of undertaking further testing and investigation at other sand sites. The authors also intend to develop similar monographs for other ground conditions such as cohesive materials, peat, etc.

4 CONCLUSIONS

With respect to the three case studies presented in this paper, it is evident that the water table and a lack of ideal grading limits the depth of effective ground improvement. On sites with well graded sands it can be considered reasonable to expect depths of ground improvement of up to 3.5 to 4.0m after 20 passes of impact rolling can be achieved if targeting a Young's modulus of approximately 20 MPa.

At sites with uniformly graded sands or sites with high water table a comparatively shallower depth of ground improvement can be expected and a greater number of impact roller passes should be anticipated to achieve similar performance criteria to that at well graded sand sites.

The authors hope that this paper will enable industry practitioners to have some degree of certainty when applying impact rolling techniques for the purposes of ground improvement in sand sites. The authors acknowledge that further work needs to be undertaken to further refine these relationships with the benefit of having tested sites with differing particle size gradation and phreatic conditions. It is the authors' ultimate intent to develop a mathematical formula to precinct the depth of ground improvement for a given series of in-situ ground and phreatic conditions.

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