DEEP IN-SITU GROUND IMPROVEMENT USING HIGH ENERGY IMPACT COMPACTION (HEIC) TECHNOLOGY

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ABSTRACT

The research presented in this paper highlights the recent developments that have taken place in deep in-situ ground improvement using the high-energy impact compaction (HEIC) technology. The results of three HEIC ground improvement trials and projects are presented. The test sites were subsequently certified by recognized geotechnical consultancies and used to support economical industrial pavements, slab on ground and high-level foundations on the HEIC improved soils. The paper briefly highlights the characteristics of the three materials in each of the case studies, which are regularly encountered on construction projects for industrial, commercial and residential developments. The results provide a clear indication of the depth of influence of the high-energy impact compaction process and the significant increases in soil strength for a natural "marine" sand, a reclaimed sand deposit and for a variable clay fill. Results from cone penetrometer tests (CPT - AS 1289 F.15. - 1977) show significant depths of influence, which for the natural "marine" sand and variable clay fill were recorded down to depths of 4 m and for the reclaimed sand deposit were recorded down to depths of 5 m below the surface.

INTRODUCTION TO HIGH ENERGY IMPACT COMPACTION (HEIC)

The effective depths of influence for the current generation of HEICs has shifted the principle of impact compaction from being simply a compaction "tool", for relatively shallow in-situ fill, to a deep in-situ ground improvement "Geotechnical Solution". HEIC is essentially a form of dynamic compaction, which is a process of raising and lowering a large weight from a height to achieve deep in-situ densification. Impact compactors similarly raise and drop the impact drum/s from a height as the module travels at speed along the site surface. The compaction work executed at depth is related to the momentum of the falling mass and the impulse generated on impact. With both dynamic compaction and HEIC the capacity to apply compaction effort is normally measured in terms of potential energy (mgh) input.

One benefit of the HEIC process is the uniform application over the whole site surface area. Various 5 and 3 sided HEIC dual drum configurations have been developed to optimise the effectiveness of HEIC for varying soil types and site conditions. HEIC specific energy inputs range from 10 to 28 kJ/m_, with the weight and drop height of the drum modules ranging from 8 to 12 tonne and 150 to 230 mm, respectively. Varying the size, shape and drop height of the HEIC drums varies the Specific Energy Input and thus the depth of influence and the magnitude of increase of the in-situ soil strength. Prior to the application of the HEIC process a full review of available geotechnical data should be assessed, to ascertain the suitability of the various module configurations for the given soil type and site conditions. An understanding of the soil response during HEIC has increased significantly over recent years. The relationship between the depth of influence and the improvement in in-situ soil strength has become more predictable.

Modern in-situ testing regimes have made the integrity validation of deep in-situ soil after HEIC, more efficient. Processes developed by experienced Geotechnical and Civil Engineers, controlled by strict quality assurance systems and the application of deep in-situ integrity validation testing has increased the confidence and therefore the success of the HEIC process, in recent years, as an effective deep in-situ ground improvement technique. The advancements in the application of the HEIC process are illustrated in the following case studies.

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HEIC ON NON-COHESIVE SOILS

Case Study One

The following is a summary of the HEIC ground improvement process (conducted by Landpac Technologies Pty Ltd) recently completed in November 1999 on a 4-hectare site for an industrial development in Banksmeadow, Sydney, Australia. A trial with a 3-sided HEIC was initially conducted during the Geotechnical Investigation performed by Douglas & Partners Pty Ltd[2]. The HEIC trial was performed to ensure that satisfactory compaction was attainable within very loose to loose Botany sands to depths of 4 m below the surface. If proven successful the HEIC ground improvement process would enable proposed industrial loadings to be supported by slab on ground and high level foundations. The water table was at a depth of 2.5 to 3.0 m below the ground surface.

Cone penetration tests were conducted prior to, during and subsequent to the HEIC process, with periodic settlement monitoring conducted after [*]Total Energy Inputs of 90, 150 and 240 kJ/m_. The fieldwork confirmed the site was underlain by a uniform bed of Botany sand, comprising essentially light grey to brown quartz sand of fine to medium grain size. Figure 1 shows a typical grading curve for Botany Sands within the Sydney region.

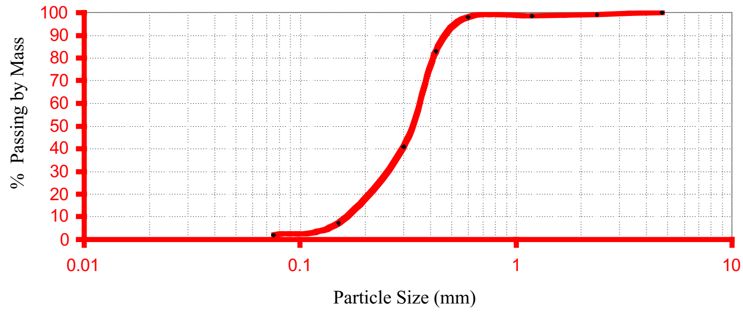

Figure 1 : Typical Grading Curve for Botany Sands (AS 1289.3.6.1, 1995)

During the Geotechnical Investigation significant variation was recorded in the cone resistance as the cone penetrated the sands. At most locations, the sands were mainly medium dense at first, becoming very dense below depths of 3 to 6 m. During the initial series of cone tests a number of zones of very loose sand were identified within the upper 4 to 6 m of the sand bed. The loose zones appeared to have a more or less random distribution throughout the site. Local variation was evident in the thickness of the loose zones, which ranged from 0.5 m to a maximum of some 6 m.

A noticeable improvement in the cone resistance was recorded in the very loose sand progressively throughout the course of the trial using the 3 sided HEIC. Based on the results of the cone tests it was evident that uniform increase in densification of the weak very loose sands was achieved to depths of some 4 m, as illustrated in Figure 2. A 60 % increase in cone resistance was recorded after a *Total Energy Input of 90 kJ/m_, 90 % increase after 150 kJ/m_ and some 110 % increase after 240 kJ/m_ at depths of 2 to 4 m below the surface level. Average induced settlement of 140 mm was recorded after a *Total Energy Input of 90 kJ/m_ increasing to 170 mm after 150 kJ/m_ and 210 mm after 240 kJ/m_.

It was demonstrated at the site that HEIC was successful in compacting weak very loose sands to depths of some 4 m below the surface. A Total Energy Input of 240 kJ/m_ with the 3 sided HEIC uniformly densified the weak sands from very loose to a medium dense condition. This significantly reduced the risk of "shake down" settlement. In view of the success of the trial, it was considered prudent to apply the 3 sided HEIC ground improvement process on all areas within the building envelope. The HEIC process was applied on the remainder of the site, which was monitored with level differences recorded on a 20 m rectangular grid after a minimum *Total Energy Input of 90, 150, 240 kJ/m_.

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[2] refer Douglas Partners Pty Ltd Report No 28006 to Charter Hall Holdings & Egis Consulting Australia, June 1999

[*] Total Energy Input based on Potential Energy – mgh – applied per unit area of the whole surface area of the site.

The natural sands at the site, after uniform densification by HEIC, provided suitable subgrades for the warehouse floor slabs to be cast at grade and high-level foundation systems to be constructed within the HEIC improved sands. The floor slab design was based on the following parameters after the HEIC process was complete: Point or wheel loading - 40 kPa per mm and Distributed loading - 5 kPa per mm.

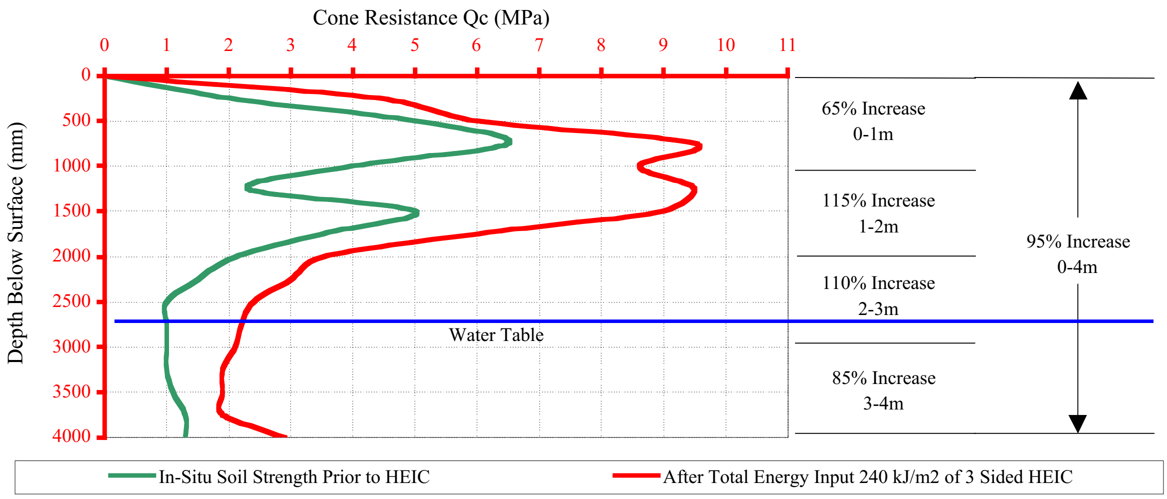

Figure 2 : Cone Penetration Test Results on HEIC Improved Botany Sands

Pad footings were proportioned in HEIC improved sands for an allowable bearing pressure of 250 kPa at a minimum depth of 800mm. Similarly, strip footings were designed for an allowable bearing pressure of 175 kPa at a minimum depth of 600mm. It was anticipated that when designed in accordance with the guidelines given above, settlement would not exceed approximately 1% of the footing width.

Without the application of the HEIC ground improvement technique, that uniformly densified the sands, it would have been necessary to utilize a deep foundation system for the support of the proposed industrial structural loadings. Displacement piles would have extended into the very dense sands, at a depth greater than 6m over the site.

Case Study Two

The following is a summary of a HEIC Ground Improvement process (conducted by Landpac Technologies Pty Ltd) recently completed in November 1999 on a 4-hectare site in Port Botany, Sydney, Australia. Prior to, during and after the HEIC process Black Geotechnical Pty Ltd[3] performed cone penetration tests and certification. The site consisted of 4-5 m of very loose reclaimed Botany sand deposit of a similar grading to that shown in Figure 1, with shell content. The water table was at a depth of 2.5 m below the ground surface. The HEIC process was performed across the whole site area with a combination of the 5 and 3 sided HEICs for a [*]Total Energy Input of 240 and 120 kJ/m_, respectively. Cone penetration tests indicated that the combination of the 5 and 3 sided HEICs significantly optimized the cone resistance at depths of 4 to 5 m, as shown in Figure 3. Level surveys performed during the HEIC process indicated that the average induced settlement ranged from 150 mm to 200 mm.

The proposed structure consisted of a single level steel frame precast clad building with high level foundations and a concrete slab-on-ground at the site. The proposed container terminal pavement subgrade was the reclaimed sand surface. The pavement subgrade and proposed pavement make-up was to support 90 tonne forklift traffic.

Cone tests conducted clearly demonstrate the marked effect of the HEIC process on improving the sub-surface to a significant depth with the average results indicating a 300 %, or so, increase in core resistance over the upper 3 m and 100 % increase down to a depth of 4 to 5 m as illustrated in Figure 3. These

[3] refer Black Geotechnical Pty Ltd Report No M269R to Rickard & Partners, October 1999

[*] Total Energy Input based on Potential Energy – mgh – applied per unit area of the whole surface area of the site

differences prior to and after HEIC are considerable. The combined use of the 5 and 3 sided HEICs improved the sub-surface, down to 5.0 m, by an additional 40 % greater than compared to a 5 sided HEIC process only with a *Total Energy Input of 240 kJ/m_.

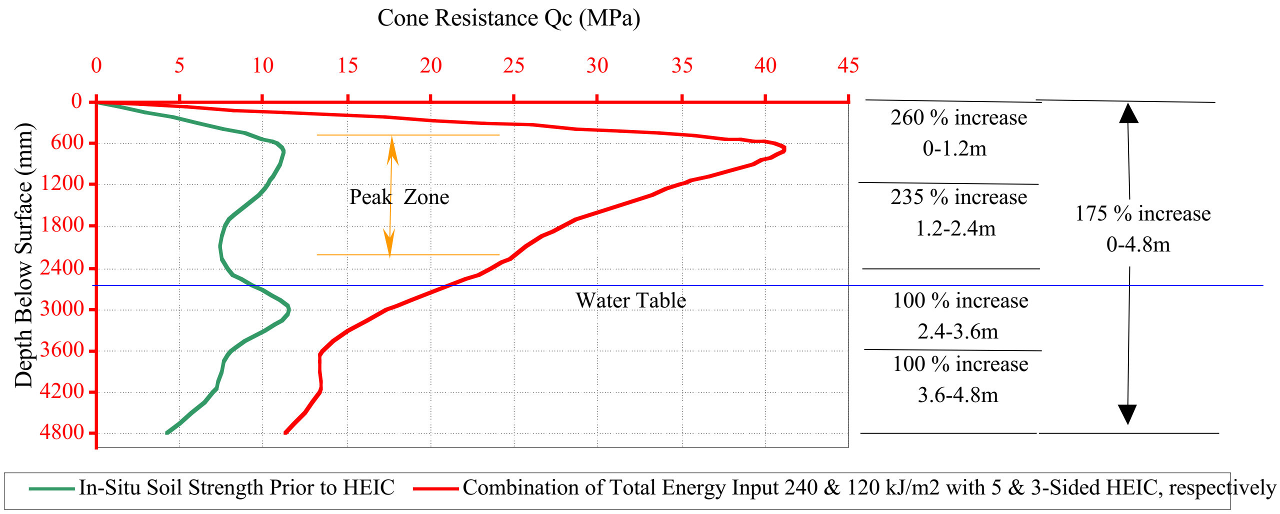

Figure 3 : Cone Penetration Test Results of HEIC Improved Botany Dredged Placed Sands

A significant benefit of the HEIC ground improvement process is that it reduces near surface differential settlement due to variable loading within proposed industrial floor slabs. The HEIC process produces a higher strength and less compressible stratum in which to support high-level foundation systems. Modern steel frame panel clad industrial buildings are relatively flexible. Unless there are unusually high loads or tight deflection tolerances, HEIC will generally allow a high-level foundation system to be adopted in soil conditions that would otherwise be considered unsuitable. High bearing pressures with small footings founded as close as possible to the surface should be adopted to keep the stress applied by the footing as much as possible within the HEIC peak zone – see Figure 3 (approximate HEIC peak zone).

HEIC ON COHESIVE SOILS

Case Study Three

The following is a summary of the HEIC ground improvement process (conducted by Landpac Technologies Pty Ltd) completed in May 1999 on a 2-hectare industrial development project in Huntingwood, Sydney, Australia. The site consisted of 3 to 6 m of un-compacted/un-controlled variable clay fill. Prior to, during and after the HEIC process Douglas Partners Pty Ltd[4] performed cone penetration tests. Cone penetration tests were performed to determine the degree of sub-surface improvement and the depth of improvement within the un-engineered clay fill platform after the application of the HEIC process was complete.

The existing deep fill comprised predominantly medium to high plasticity clay (PI's ranging from 20-40) and decomposed or weathered rock material, but was shown to have a wide range of strength properties, indicating un-compacted and un-controlled placement. Strength values within the in-situ deep fill were indicated to vary from soft to very stiff. The deeper in-situ fill, below depths of 3 to 4 m, generally indicated to be firm to stiff down to depths of 3 to 6 m. An area at the northern end of the site, 60 % of the proposed building floor slab, was underlain by significantly poorer material having strength and compaction well deficient of that considered necessary for slab and pavement support. Natural clays underlying the in-situ fill, below 3 to 6 m, were found to be generally firm, becoming very stiff to hard with increasing depth, merging into very low strength Siltstone.

[4] refer Douglas Partners Pty Ltd Reports No 27267B to Prime Constructions Pty Ltd, April & May 1999

The proposed development at the site comprised industrial floor loadings of 20 kPa. The decision as to whether to support ground slabs at grade, or to suspend the slabs, was governed by the surface treatment provided by HEIC during the earthworks phase of construction and the time frame in which building construction took place. HEIC was undertaken with surface levels monitored after a total *Total Energy Input of 60, 120, 150 and 360 kJ/m_. Cone penetration tests were conducted prior to the HEIC process and following a Total Energy Input of 150 and 340 kJ/m_.

For the southern 40% of the site, at most locations, induced settlements recorded after *Total Energy Input of 150 kJ/m_ ranged from 30 mm to 175 mm with an average induced settlement of some 106 mm. The results of the HEIC process demonstrated that the 3 sided HEIC was effective in further compacting the existing material, which had already been partially compacted conventionally at the southern end of the site. The fill platform finally gained sufficient strength properties after the HEIC process to adequately support the floor slabs and external pavements.

The HEIC process was continued to a *Total Energy Input of 360 kJ/m_ on the northern end of the site. Additional cone penetration tests after HEIC was complete revealed a marked improvement in the strength of the upper filling soils over the poorer ground at the northern end of the site. Compared with earlier cone test results, strength values were increased by some 60-120 % in the filling to depths of some 4 m, with much of the improvement recorded in the upper 3 m, as illustrated in Figure 4, signifying an improvement in shear strength of the material within this depth.

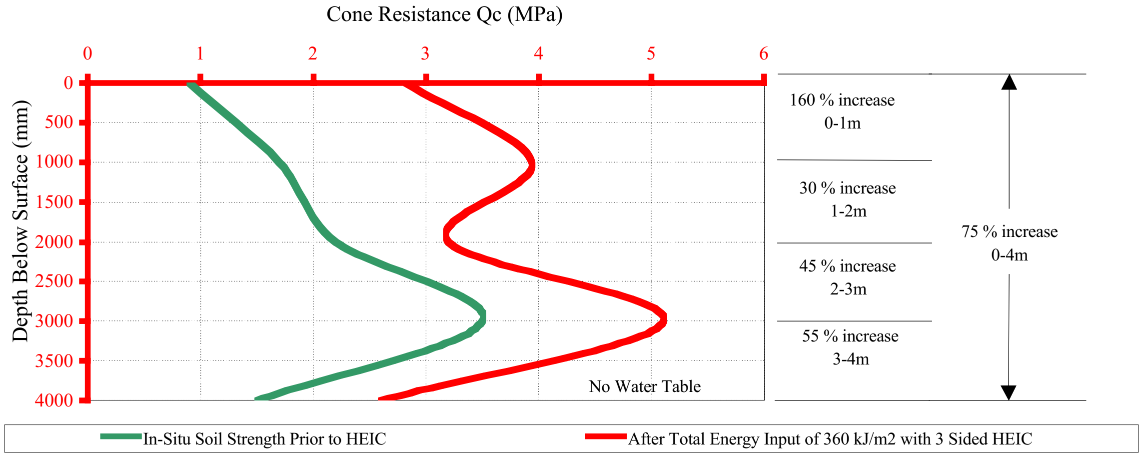

Figure 4 : Cone Penetration Test Results of HEIC Improved Medium to High Plasticity Clay Fill

A level survey indicated average induced settlement of some 136mm over the northern sector of the site (60% of site area). After a *Total Energy Input of 150 kJ/m_ total induced settlement recorded ranged from 25 mm to 260 mm with an average induced settlement of some 136 mm. This range of induced settlement was considered significant in respect of the intention to support ground slab at grade. Average induced settlement increased by some 60% between a *Total Energy Input of 150 to 360 kJ/m_, justifying the decision to have the HEIC operations extended until near zero induced settlement. The proposed building platform was supported on slabs on-ground in accordance with the design intent of the project after the HEIC ground improvement process was complete.

CONCLUSIONS

The paper clearly indicates that the HEIC ground improvement process improves weak soils to depths of 4-5m below the compacting surface, across a spectrum of weak natural sands, weak reclaimed sand deposits and un-compacted/un-controlled variable clay fills. The reaction of soils during HEIC treatment varies with soil type, in-situ moisture content and Specific Energy Input. The Specific Energy Input required is optimized by selecting the appropriate impact drum weight, drum shape, drum compaction coverage and

* Total Energy Input based on Potential Energy – mgh – applied per unit area of the whole surface area of the site

drop height to suit the given in-situ material types and site conditions. The application of the HEIC process on deep variable in-situ fills or natural weak materials is a geotechnical process and should only be judiciously controlled by engineers with experience of the unique HEIC techniques.

Cone penetration tests and average induced settlements recorded for each of the three case studies signify that a uniform engineered platform can be created from the surface to depths of 4 to 5 m deep without the need for costly and time consuming displacement foundation systems, pre-loading or excavations. Based on the induced settlements data and cone penetration test results, the HEIC process has allowed such constructions as industrial slabs-on-ground, high level footings for industrial column loadings and the validation of subgrades for the support of up to 90 tonne forklift traffic. Establishing the depth of influence of the HEIC process to depths of 4 to 5 m and substantiating the significant increase in the in-situ strength of materials being treated to considerable depth, has allowed the HEIC process to compete successfully in the 0 to 4 m deep in-situ ground improvement market within the Geotechnical/Civil/Construction industries.

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