Monitoring HEIC using Landpac CIR and CIS Technologies

Dermot Kelly, Landpac, United Kingdom, DKelly@landpac.co.uk
José Gil, Landpac, South Africa, jose@landpac.co.za

ABSTRACT

Poor or unstable ground conditions can make traditional and conventional forms of construction expensive and unviable. In such instances, it may be economically viable to improve the engineering properties of poor ground before continuing with any construction process. Ground improvement, unlike ground treatment, is the process of modifying the ground underlain by suspect or uncontrolled fills, as well as sites with soft or loose soils, through the use of mechanical means. The twin drum high energy impact compaction (HEIC) process of ground improvement is a well known technique used on highly voided mixed fills for Brownfield site development or on dredged marine sands for marine construction projects. It offers a unique, technically and economically viable solution for ground improvement and for general earthworks operations, supported by the control and certification thereof using the Continuous Impact Response (CIR) and Continuous Induced Settlement (CIS) monitoring systems that are fully integrated with GPS. These technologies and their applications are documented in this paper, with references made to projects using the technologies in conjunction with other deeper ground improvement processes on marine related projects.

1.0 INTRODUCTION

Quality control, in any industry, is a methodology employed that, if properly implemented, ensures that a performed service adheres to the requirements of the project design specification. Quality control is thus a process that is employed by a provider which includes actions deemed necessary to ensure that control and verification of certain characteristics are provided for, with the basic process goal being that the result meets specifications and/or expectations and that the quality of the works is assured.

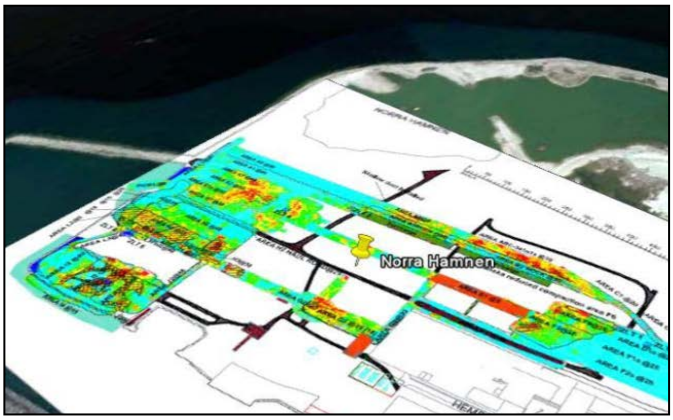


Figure 1a: Typical CIR overlay for 23 Hectare HEIC treatment area - Copenhagen Malmo Port (CMP) Container Terminal, Malmo, Sweden

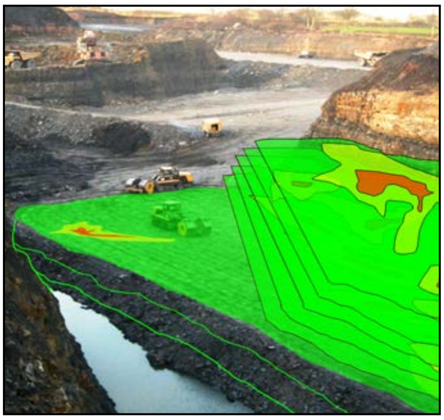


Figure 1b: Schematic of typical CIR overlay for HEIC 1m thick layerworks - Polkemmet Colliery Rehabilitation, Scotland

The well known twin drum HEIC application has proven viable in offering robust solutions to the ground and civil engineering industries, with unique ground improvement alternatives applicable to the global marine sector industry. The need for a reliable control and verification tool that supports the application of the technology led to the development of the Landpac Continuous Impact Response (CIR) and Continuous Induced Settlement (CIS) measurement systems which are fully integrated into the quality control process The process captures the specification requirements as established by the design/consulting engineers, develops correlations between measured data and the specific engineering properties being measured and requiring control, establishes control limits, captures data and plots the results for verification. Sections that fail to meet the specification requirements are clearly highlighted and emphasis can be placed on developing a corrective action process that remediates such sections.

The CIR is a specialised technique for monitoring the soil's response to the loads delivered by the twin drum HEIC process, with fully integrated GPS for accurate positioning, effectively producing an accurate indication of the soil's strength/stiffness across an entire site during the twin drum HEIC process. The CIS, employing a differential GPS, allows for levels to be accurately recorded during the same process. The CIR and CIS measurement systems thus offer the industry an opportunity to reliably and easily control the improvement and vastly improve the quality assurance of the engineered works.

2.0 THE TECHNOLOGY OF HIGH ENERGY IMPACT COMPACTION (HEIC)

Twin drum High Energy Impact Compaction (HEIC) involves the transfer of compaction energy into the soil by means of the lifting and falling motion of non-circular rotating masses. The rotation of such masses to their highest point results in an effective potential energy build-up. Further rotation of these masses results in the conversion of this potential energy into a falling kinetic energy, which is transferred to the soil upon the impact of the lowest point of the masses with the surface of the soil. The amount of energy transferred, in the form of compactive effort, is closely related to the amount of potential energy generated in the lifting process.

Figure 2a: 3-Sided 25kJ Landpac HEIC working on dredged marine sands in Morocco

The main features of this high energy impact compaction (HEIC) process include the following:

- Compaction Loads: the high energy and dynamic compaction action of the HEIC equipment leads to typical compaction loads of between 1200kN and 2500kN being generated depending upon the type and condition of the material being compacted.
- Material Moisture Condition: The high energy of the HEIC equipment leads to the ability to compact material to a higher maximum dry density than is achievable with conventional roller type of compaction equipment. This high energy also allows for the compaction of material over a wider range of moisture conditions particularly dry of optimum moisture content.
- Depth of Influence: The high compaction loads that are generated by the HEIC equipment lead to high surface contact pressure on the soil. This, coupled to the relatively large contact area over which the compaction energy transfer takes place, leads to a vastly increased depth of influence of the compaction. Ground improvement is typically measured to effective depths of 2m-3m with depths of up to 5m being recorded in some applications.
- Soil Compressibility: The shape of the non-circular masses allows for the high energy parcels to be transferred in the form of a “rolling impact”. This means that the load duration of the HEIC process is relatively long [typically 0.12s]. This extended load transfer duration in turn leads to a softer soil response to the load and hence enhanced soil compressibility is achievable.
- Compaction Productivity: The relatively high operating speed and depth of influence of the HEIC process leads to very high productivity of compaction. The HEIC process can typically cover 15,000m² per hour per surface coverage. The productivity of the HEIC process can be between 2 and 5 times higher than that of conventional shallow compaction equipment when performing fills work and many times more productive than that when it comes to the improvement of in-situ materials.

HEIC provides a process that allows for a wide range of applications from fill works compaction through to deep in-situ ground improvement. In all of the appropriate applications, it is possible to ensure project cost savings whilst at the same time enhancing the quality assurance of the works relative to the “in service” performance of the materials that have been treated.

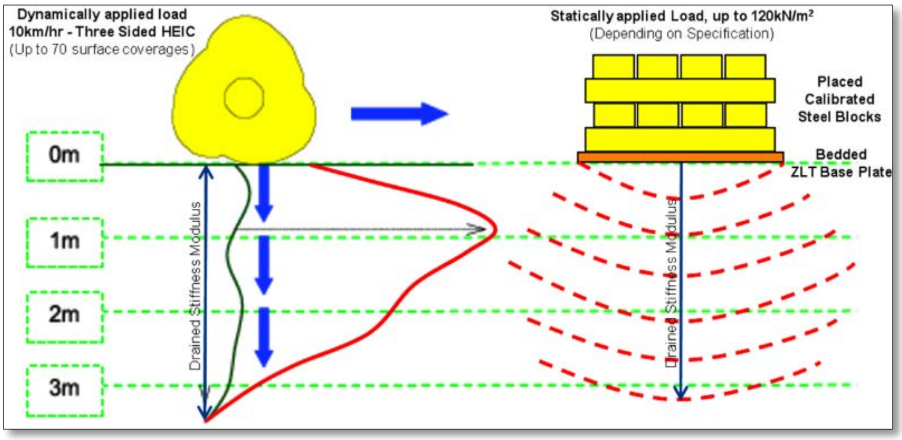


Figure 2b: Schematic of typical Drained Stiffness Modulus after HEIC for 30 surface coverages as demonstrated by 2m x 2m steel plate Zone Load Testing (ZLT) of 10 to 30MPa

The deep ground improvement capabilities of the equipment and technologies allow for innovative alternative solutions to be considered on many earthworks projects. Such innovation requires "out of the box thinking" although some of the more common alternative solutions include the following:

- Improvement of in-situ sub-grade materials providing benefits such as:
  - Improved sub-grade strength.
  - Potential elimination of some costly imported layer-works.
  - Reduced sub-grade settlement / differential settlement.
- Ironing of Vibro-compacted and dynamically compacted material.
- Fast and cost effective alternative to "remove and replace" improvement of in-situ materials.
- Thick Lift fills work.
- Reduced water requirements compaction works.
- Pavement rehabilitation from existing pavement surface eliminating large removal and rework costs.
- Proof rolling for settlement and differential settlement removal.
- Permeability reduction/Accelerated consolidation of saturated materials.

3.0 QUALITY CONTROL

3.1 Traditional Approaches to Compaction Control

The traditional approaches to compaction specification and control are limited in that there is typically an extremely small ratio between the volume of the material tested and that compacted (typically up to 1:100,000). Other limitations that traditional compaction testing and control approaches have include the following:

- The lack of correlation between laboratory and field compaction test results;
- The poor reproducibility of results;
- The long duration of certain testing methods; and
- The difficulty in testing heterogeneous materials.

3.2 Counteracting the Traditional Testing Approach Limitations

In view of the limitations associated with the use of traditional testing methods, new methods of compaction specification and control have been developed in order to exploit the capabilities of twin drum HEIC. The new approach for testing and certification of ground improvement using twin drum HEIC equipment revolves around the direct measurement of engineering properties of the material. In order to achieve this, the Continuous Impact Response (CIR) System, was developed by Landpac. This system is capable of measuring the soil response to every impact of the impact compactor, resulting in a direct measurement of the material stiffness.

The Continuous Impact Response measurement system employs the Landpac Impactometer to measure peak decelerations of the compaction masses with each impact. Each of these points is recorded relative to its position on site as determined by an integrated global positioning system. These accurately measured and recorded decelerations are then correlated back to a measurement of engineering properties using traditional testing method, such as density, Cone Penetration Testing (CPT), Dynamic Cone Penetration (DCP), Plate Load Testing (PLT), Zone Load Testing (ZLT), and California Bearing Ratio (CBR). The CIR system generates colour coded maps indicating the relative measure of the appropriate engineering property.

The maps generated by the CIR system can be used in conjunction with conventional testing techniques to provide a quality assurance system capable of certifying the entire site at a reduced cost and an increased level of certainty. The system is currently widely used and has proven to be a very useful tool in controlling the ground improvement process.

By using the CIR technology to identify the relative strength and stiffness of the material being treated, it is possible to focus the conventional tests in the relatively weaker areas. By ensuring that the relatively weaker areas conform to specification, it is then possible to use the CIR results to extrapolate the conventional test results over the entire site thereby increasing the certainty of the overall future performance of the compaction works. This process can actually allow for a reduced level of conventional testing thereby reducing the cost of testing whilst increasing the level of certainty of the test programme

The CIR provides a quality control system that quantifies the ground strength and stiffness during the compaction process whilst also monitoring the number of coverages and actual area compacted. These ground improvement maps can be used in the following ways:

- To indicate relative strength of the material during the varying stages of the ground improvement process and monitor improvement;
- To pin point focused areas for conventional testing;
- To identify weak areas requiring additional testing and remedial action; and
- To spread the conventional test results over the entire site thereby enhancing the quality assurance of the ground improvement.

In addition to Continuous Impact Response (CIR) measurement, it is also possible to simultaneously measure the relative settlement that is induced by the impact compaction ground improvement process.

The measurement of such settlement can be continuously monitored and colour coded maps of such Continuous Induced Settlement (CIS) can be generated. Such CIS maps can be used in the following ways:

- To indicate continuous settlement throughout the process;
- To indicate relative differential settlement,
- To monitor areas and volumes; and
- To monitor the absolute level of the ground improvement operation.

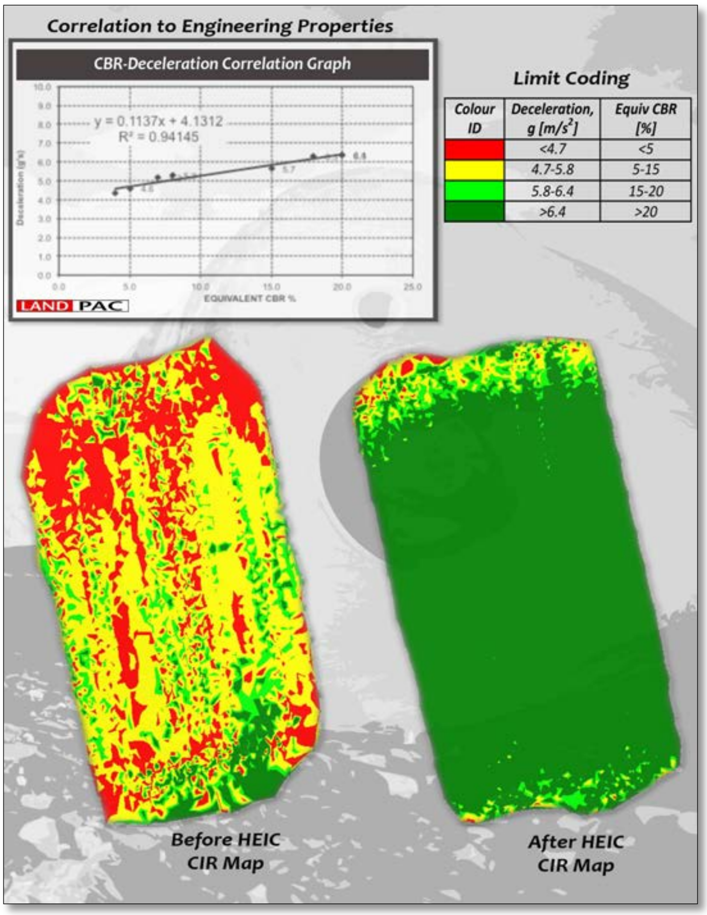
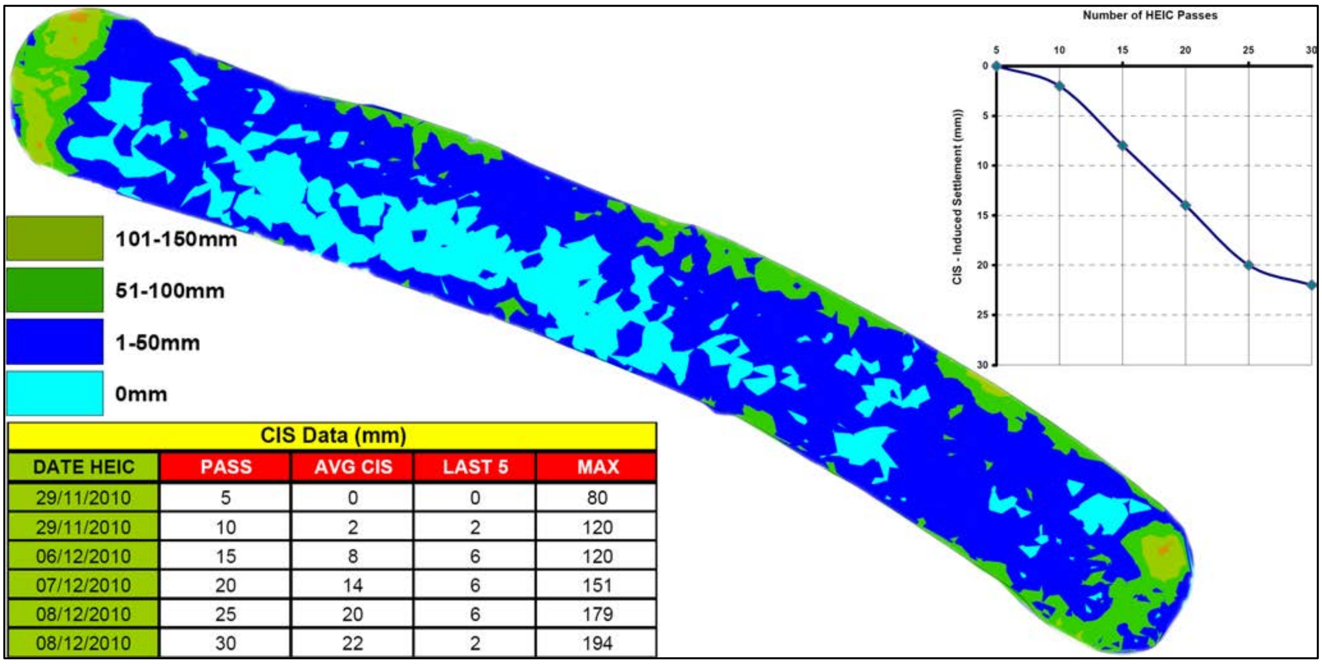


Figure 3a: Developing CIR Maps from Correlations between Decelerations and Engineering Properties



DATE HEIC	PASS	AVG CIS	LAST 5	MAX
29/11/2010	5	0	0	80
29/11/2010	10	2	2	120
06/12/2010	15	8	6	120
07/12/2010	20	14	6	151
08/12/2010	25	20	6	179
08/12/2010	30	22	2	194

Figure 3b: Typical CIS data for each batch of 5 HEIC surface coverages (to a max of 30) London Gateway Container Terminal, UK

The combination of CIR and CIS maps provide a detailed record of ground improvement works that can be used to greatly enhance the quality assurance of the works performed with high energy impact compaction.

4.0 PROJECT STUDIES

In order to demonstrate the capabilities of high energy impact compaction, not only as a standalone ground improvement alternative but also as a complimentary tool to other deeper ground improvement mechanisms, and the value of using CIR and CIS as a quality control and assurance tools, several project studies have been summarised below. These include:

- Jebel Ali Port, Dubai
  - HEIC after Vibro Compaction;
- Tanger Med II, Morocco
  - HEIC after Vibro Compaction;
- Copenhagen Malmo Port (CMP), Sweden
  - HEIC on mixed fills over reclaimed sea
- Port Botany, Sydney, Australia
  - HEIC after Dynamic Compaction

Figure 5: HEIC on dredged Sand materials at the London Gateway Container Terminal, UK

4.1 Project Study: Jebel Ali Port, Dubai

4.1.1 Project Statement

In July and August 2004, reclamation was done behind the new Quay 4 and Berth 21 of the Jebel Ali Port, Dubai (Middle East). Dredged marine sands were backfilled to a total depth of approximately 16m. Messrs. Belhasa Six Construct LLC was instructed by the client to commence with soil improvement works to induce settlement of the reclaimed marine sands. A specialised subcontractor was appointed to execute the improvement works that consisted of Vibro compaction and soil replacement, wherever Vibro compaction was not recommended (i.e. on silty soils). On completion of Vibro compaction works, the specified Cone Penetration Test (CPT) cone resistance of 6 MPa was not achieved in the top 2.0m. HEIC was contracted to improve the bearing characteristics of the dredged marine sands in the top 2.0m of the soil profile.

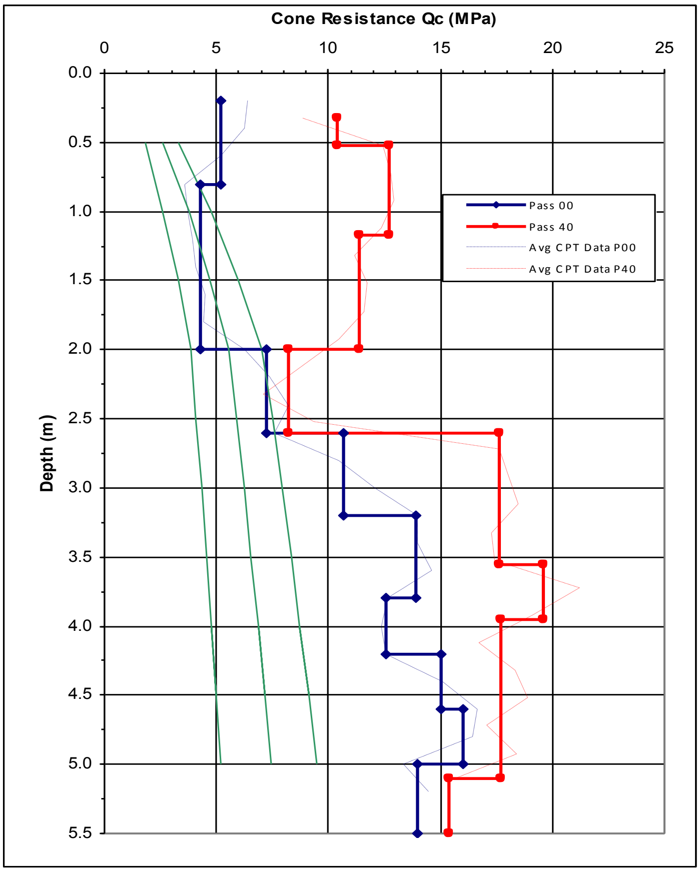


Figure 6a: CPT Results before and after HEIC

4.1.2 Material Classification

Laboratory testing indicated that the material could be classified as poorly graded sand with silt. The quality of material for subgrade is good and the material is of A-1-b (0) quality according to the AASHTO classification system.

4.1.3 Site Treatment and Results

The extended Berth 21 was created by deposition of dredged sand between a new quay wall and the existing container terminal platform. The material below sea level was initially improved by means of Vibro compaction. Cone penetration testing (CPT) results obtained after Vibro compaction, showed that compaction was generally poor down to approximately 2.0m depth (weighted average CPT cone resistance was 4.8MPa). Normally, excavation and re-compaction by means of conventional vibratory rollers is required in order to decrease the variability in the load bearing characteristics of the sand, to reduce differential settlement, to increase the bearing strength of the material by densification, and to increase aging, thereby reducing the rate of secondary creep settlement. The alternative method employed was the surface ironing using a 3 sided 25 kJ high energy impact compactor, resulting in significant increases in material consistency to depth, with improvement recorded up to 5.0m deep and that the largest improvement recorded between 0.5m and 2.0m. The weighted average cone resistance recorded in the top 2.0m improved from 4.7 MPa to 11.6 MPa after completion of 40 passes of the impact compactor (measured from compacted surface downwards), with the weighted average cone resistance over 4.8m depth improving from 8.9 MPa to 13.6 MPa after impact compactor.

Initial average decelerations were improved from 5.3g to up to a maximum of 11.4g after the completion of 40 passes of the impact compactor. A CPT-CIR relationship was derived by correlating the average CPT value in the top 2.0m of the soil profile to an average deceleration value obtained in the CPT test point area. With the correlations established, limits were set and a CIR map was plotted, as depicted in Figure 6b. Sections failing to meet specification were clearly identified, as highlighted by the colour red, and were remediated with additional impact compactor passes.

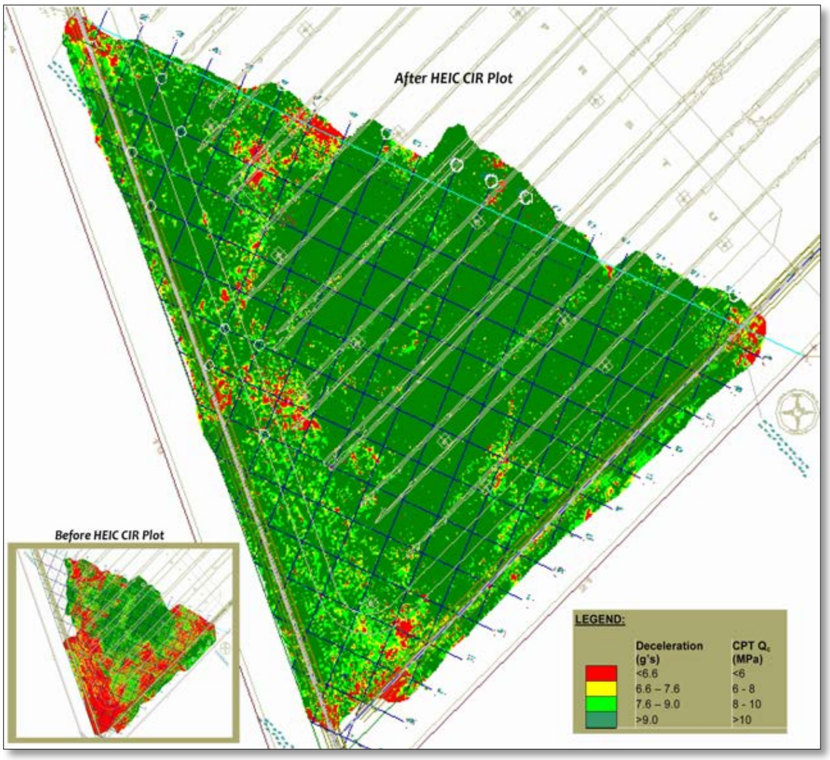


Figure 6b: CIR Map after HEIC

4.2 Project Study: Tanger Med II Container Terminal, Morocco

4.2.1 Project Statement

The Tanger MED II project is a continuation of the Tanger Med I project, which was completed several years ago, requiring up to a 140 hectare platform area to be constructed through a combination of a dredging/backfilling operation combined with deep and surface ground improvement, prior to pavement construction for a future container terminal. Up to five million cubic metres of material will be dredged, sourced offshore, and backfilled onto an area behind quay walls (currently being constructed). The backfilled dredged material will then be strengthened using deep Vibro compaction, with the final compaction planned for HEIC as a method of improving the top disturbed 2 to 3 meters created by the process of Vibro compaction.

4.2.2 Material Classification

Figure 7a shows typical particle size distribution of the dredged marine sands encountered at the site, basically a course grained marine sand.

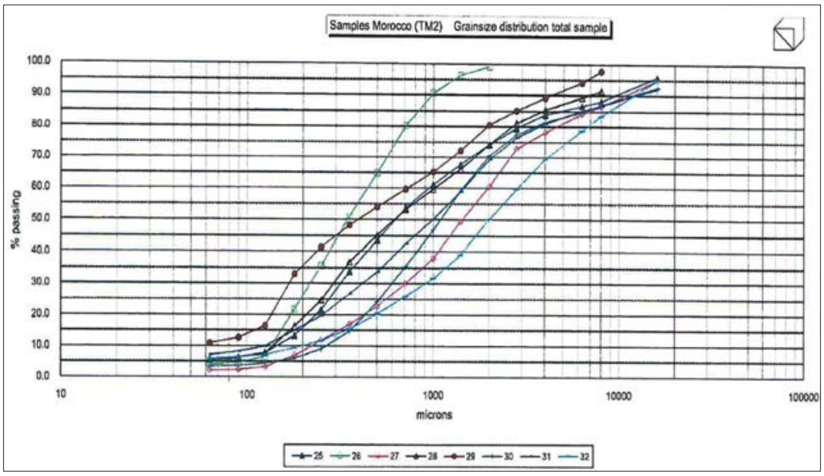


Figure 7a: Typical material grading analysis

4.2.3 Improvement Specification

Although of a poor quality, the material can be improved through the process of Vibro compaction and, although density and CBR requirements have been identified, the following controlling specification requirements have been set as the minimum:

- Cone Resistance (CPTU) $\geq$ 10MPa at surface through to -2m below the surface;
- Ev2 $\geq$ 100MPa at the surface; and
- k (Ev2/Ev1) $\leq$ 2 at the surface.

4.2.4 Site Treatment and Results

At the time of writing this paper, the final pavement design had yet to be finalised. There was, however, a 500mm layer of rock fill specified as part of the subgrade, which was to be introduced after improving the dredged material, prior to the 1m pavement structure. The section was treated with several methodologies in combination with HEIC and specification was achieved involving the following processes:

- Vibro compaction, to achieve CPTU $\geq$10MPa to -2m below ground level, followed by;
- Placement of a 250mm layer of Rockfill, then;
- Treated with a Landpac 3 sided 25kJ HEIC, to achieve CPTU $\geq$ 10MPa 0m to -2m below ground level, and finally;
- 8 passes of a smooth drum roller with moisture conditioning, to achieve Ev2 $\geq$ 100MPa & k $\leq$ 2.

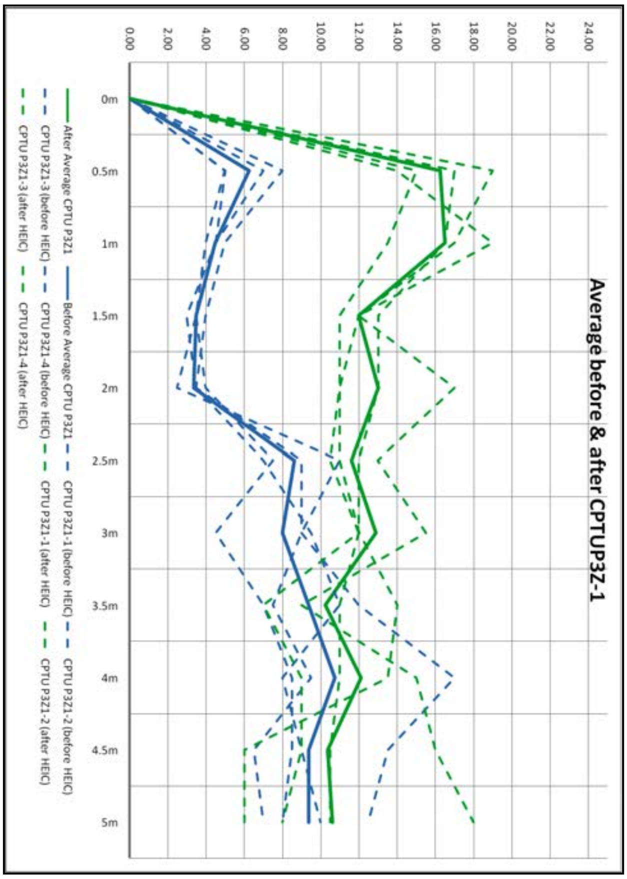


Figure 7b: CPT Results before and after 80 HEIC passes

The results are summarised as follows:

- CPTU results indicated Qc values $\geq$ 10MPa to the required depth of -2m below ground level, with similar improvement experienced between 3 and 5m in some sections.
- Plate load tests indicated Ev2 values ranging from 107 to 145 MPa, exceeding the specification requirements of 100 MPa at the surface.
- Ev2/Ev1 ratios (k) ranged between 1.72 and 2.0, also within the required specification.
- Average induced settlement (CIS) of 218mm was experienced, with a maximum settlement of 287mm recorded; confirming differential settlements have been reduced by the HEIC process.
- 80 Passes with recorded CIR decelerations ranging between 14 and 15 m/s^2 (18.16 m/s^2 max), resulting in a correlation with CPTU data that would require a g > 12 m/s^2 to achieve a Cone Resistance > 10 MPa, as specified.

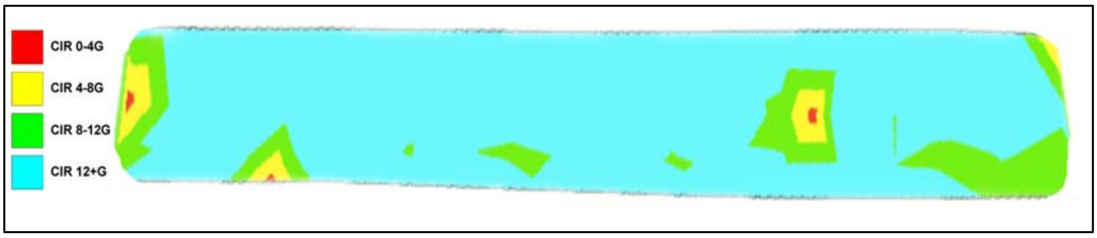


Figure 7c: Typical CIR plot after 60 HEIC passes on a test strip with specification adherence shown in blue, Qc>10MPa

4.3 Project Study: Copenhagen Malmo Port (CMP), Sweden

4.3.1 Project Statement

LANDPAC were appointed by Skanska, to undertake ground improvement HEIC works as part of the "site preparatory works" on behalf of the client – Copenhagen Malmo Port (CMP) and the client's consultant – Ramböll to characterise the site and permit the development to support proposed container terminal pavements, externals and rail corridor. City of Malmö signed an agreement with Skanska to build a major new port facility for CMP in Norra Hamnen on 23 Hectares within the overall 150 Hectare site. The development included three new terminals and associated pavement & rail-line construction. The joint project involved the City of Malmö, who owns the land in Norra Hamnen, and CMP, which operates the port. The area earmarked is the result of landfilling over sea, thus land reclamation, including earth from the then City Tunnel project in Malmö.

4.3.2 Material Classification

The site comprises reclaimed land with approximately 3m to 6m thickness of 'end-tipped' soil from the nearby Malmo City Rail tunnelling project and sea dredged materials from past harbour maintenance. No compaction had taken place prior to HEIC. Some locations, the existing materials contained soil to be a mixture of concrete and demolition debris from gravel to boulder size in a matrix of silty sand and sandy gravelly clay. Other locations, the existing materials varied from a mixture of granular / cohesive / Silt fills. Groundwater was at about 2m to 3m depth.

4.3.3 Improvement Specification

Although of a poor and varied quality, the majority of the mixed fill materials were to be improved through the process of HEIC, investigative CIR & CIS and soft spot identification / removal / replacement with the following controlling specification requirement having been set as the minimum:

- $Ev2 \geq 30MPa$; and
- k value $(Ev2/Ev1) \leq 2.5$

4.3.4 Site Treatment and Results

CIR stiffness profile monitoring was used during the HEIC application to characterise and verify Ev2 specification, after correlation with CIR, of the site existing fill material. The CIR data was to be correlated with numerous Dynamic Plate Test (DPT) results, which allowed a site wide characterisation and also determined the soil replacement areas for the client, which resulted in minimising costly excavations.

The site was treated with HEIC and specification was achieved involving the following methodology:

- Treat with a Landpac 5 sided 22kJ HEIC, to induce maximum settlement possible & $Ev2 \geq 30MPa$,
- Dynamic Plate Testing (DPT) at surface and at varying depths
- Correlate CIR and DPT data
- CIR characterisation of the treated area/s to identify soft spots needing removal & replacement.
- Soft sections, highlighted and precisely marked using the CIR, were removed, replaced and recompacted to specification

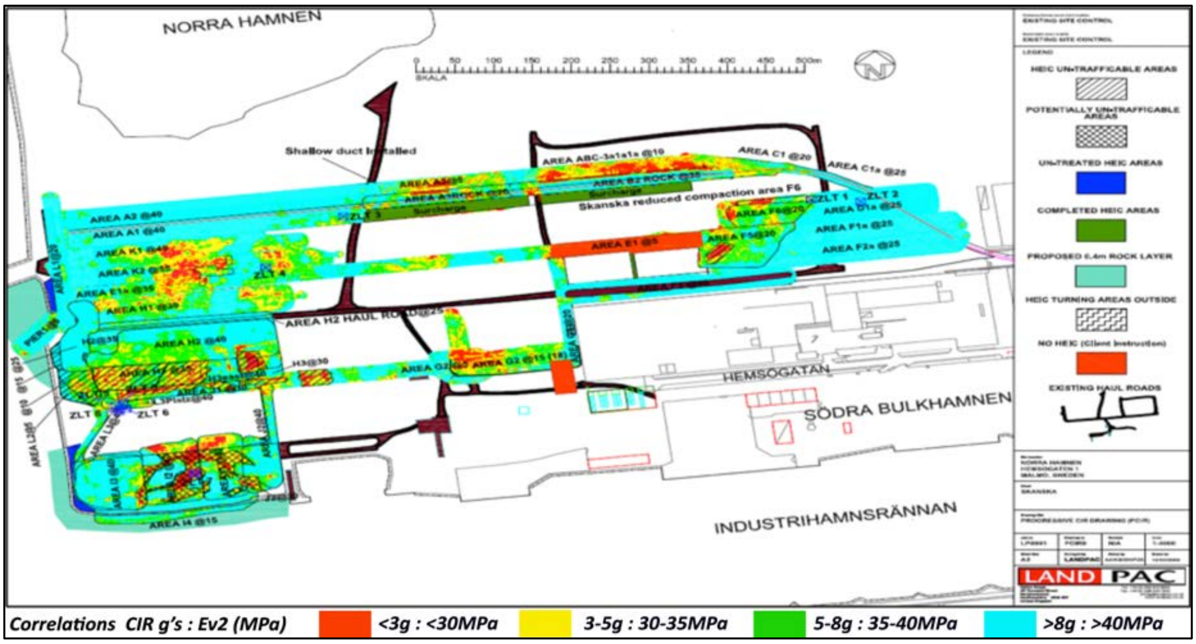


Figure 8: CIR correlated with Dynamic Plate Tests (Ev2) and site characterized for soft spots

4.4 Project Study: Port Botany, Sydney, Australia

4.4.1 Project Statement

The project involved the reclamation of 63Ha with 8 million m^3 of dredged sand, making it one of the largest port projects ever undertaken in Australia in the last 30 years. The project infrastructure included a new container terminal and almost 2km of extra berth length. The new berth structures required the construction of blockwork and counterfort walls up to 21m high. Also included in the project was the reclamation of a 2Ha area for a public boat ramp and a car parking area.

Figure 9a: HEIC process post Dynamic Compaction improvement at Port Botany.

4.4.2 Material Classification

The borrow area consists of fine to medium grained marine sands with lenses containing organic and clay. The specification for the dredged sand used for the reclamation requires less than 10% fines passing through the 75μm sieve.

4.4.3 Site Treatment and Results

The Impaction Compaction process in the early work areas were carried out on a nominal 300mm Sandstone constraining layer that was placed over the sand fill that had been subject to Dynamic Compaction. The 300mm layer formed part of a working layer for the construction access and hardstand areas. Cone Penetrometer testing was carried out on these areas to verify the compaction results. The average Cone Resistance (Qc) improved from an average of less than 8MPa post dynamic compaction to an average exceeding 15MPa post HEIC in the top 2m. Cone resistances exceeding 20MPa were recorded between 2 and 4m, post HEIC treatment.

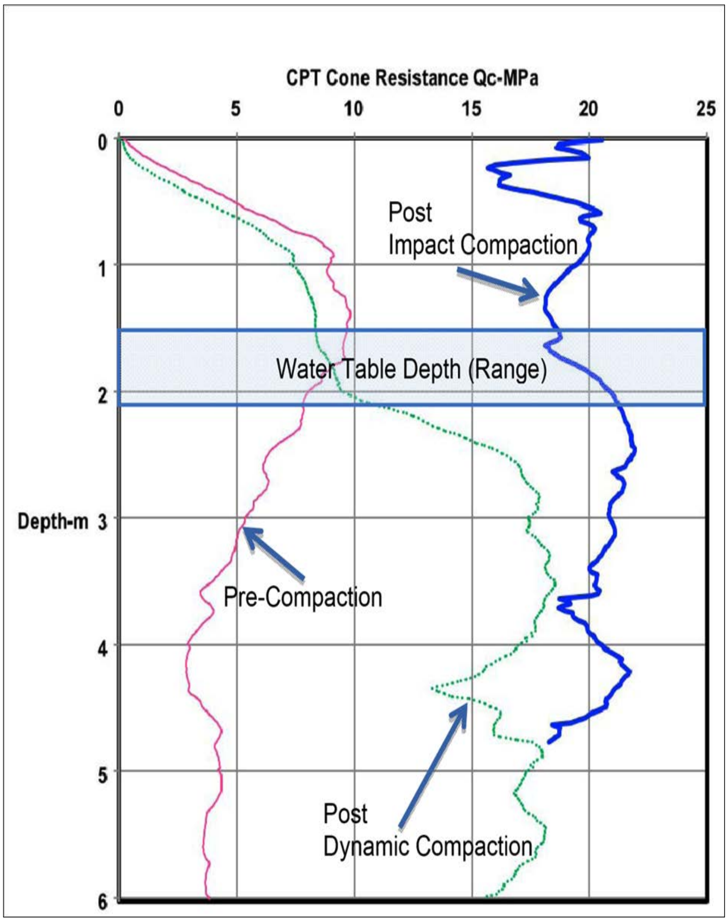


Figure 9b: CPT results showing the improvement of Cone Resistance post HEIC

The Impact Compaction in the New Terminal area was carried out on the sand fill surface that had been subject to either Vibro Compaction or dynamic compaction. Density tests were carried out in test pits to verify the compaction results. The average density recorded in the depth range from 100-1800mm below the compacted surface, at an average field moisture content of 6.9%, was 106.9%.

The final area treated was the Public Boat Ramp area and although pre-compaction CPTs were not done, post compaction results indicated an average Cone Resistance (Qc) of 15MPa in the top 1m, greater than 20MPa from 1-2m below the surface, tapering down to approximately 10MPa from 2 to 3m below the surface.

With the specification set to achieving a density index of 75% in the top 2m and a Cone Resistance (Qc) exceeding 5 MPa in the full depth of the reclamation area, HEIC was successfully used to improve the top 4m that would not have met specification post treatment by the deep ground improvement techniques that had been employed. Results beyond 4m were within the requirements of the specification. The combination of the two technologies certainly offered a cost effective solution to the project.

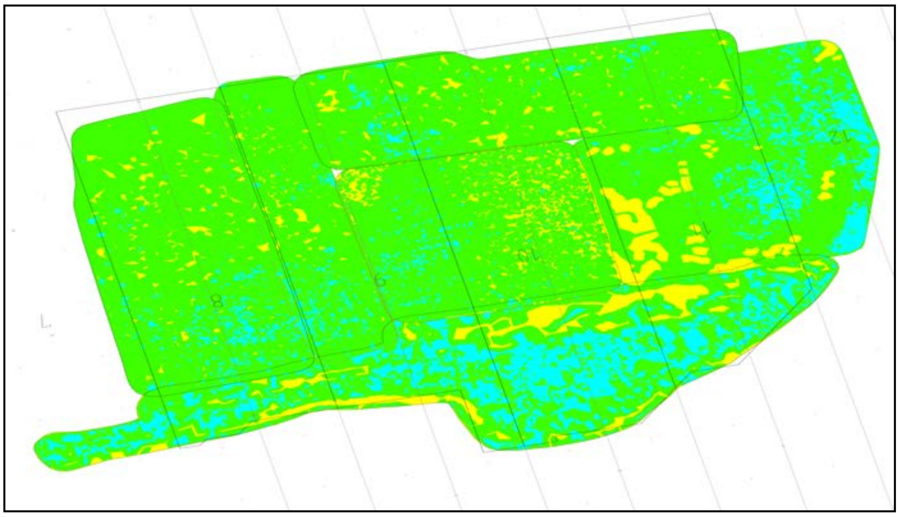


Figure 8c: Typical CIR plot post HEIC treatment where sections not meeting specification would have been highlighted in red.

5.0 CONCLUSION

Rapid industrial growth has increased demand for further land development through land reclamation and utilisation of unsuitable and environmentally affected materials. The conversion of such requirements into usable land has been made possible through the adoption of one or more ground improvement techniques, making this a rapidly expanding field of applications.

Ground improvement techniques are used extensively to solve a broad spectrum of geotechnical problems, with the techniques enabling innovative solutions to be considered and applied. The utilisation of the twin drum HEIC has proven to be innovative in not only solving some of the geotechnical concerns with ground improvement, but also offering it cost effectively with improved production possibilities. Although the technology has been very successful in offering stand alone solutions to some problems, it has been equally successful in offering solutions in conjunction with deeper ground improvement technologies, like vibro and dynamic compaction, in mixed and contaminated fills and, specifically, on dredged marine sands.

Problematic material improvement places an increased importance on quality control measures. The Landpac developed CIR and CIS technologies, with fully integrated GPS, used in conjunction with the twin drum HEIC, involves the direct measurement of engineering properties of the material with real time continuous measurement, offering high levels of quality control and improvement certification.

The increase in the scope and complexity of current global ground improvement projects places a great deal of emphasis on innovative solutions with improved quality control techniques. The advantages associated with HEIC and the CIR and CIS quality control systems have been documented in this paper, with references made to actual case projects.

6.0 REFERENCES

McCann K. & Schofield N., 2007, "Innovative Methods in the In-situ Determination of Design Parameters on Heterogeneous Sites Subject To Ground Treatment Using Deep Impact Compaction", ANZGEO2007 - 10th Australia New Zealand Conference on Geomechanics, Brisbane, Australia

Jumo I. and Geldenhuys J., 2004,"Impact Compaction of Subgrades – Experience on the trans-Kalahari highway including Continuous Impact response (CIR) as a method of Quality Control", Proceedings of the 8th Conference on Asphalt Pavements for Southern Africa (CAPSA 04).

Wilken P.J., 2001, "The development of the Continuous Impact Response (CIR) system", Seminar on Ground Improvement through the Geotechnical Division of the South African Institution of Civil Engineering, Pretoria, South Africa.

Kelly D., 2000, "Deep In-situ Ground Improvement using High Energy Impact Compaction (HEIC) Technology", GeoEng 2000 – International Conference on Geotechnical and Geological Engineering, Melbourne, Australia