Case Report

High Energy Impact Compaction (HEIC) Utilization for Shallow Depths of Fill Densification

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Abstract

The HEIC is a densification method able to compact various soil formations at shallow depths typically in the range of 2m. The usage of the HEIC is mostly applicable for shallow earthwork filling applications. The traditional roller compaction includes soil lifts of 200mm which are developed, compacted, and tested prior of proceeding to the next lift. At projects with considerable fill thickness the HEIC can be a substitute of the roller densification method since thicker lifts can be compacted resulting in cost and time schedule savings. The HEIC technique densifies thicker soil deposits due to the energy which is transmitted to the soil through the lifting and falling motion of the non-circular rotating mass. The effectiveness of the HEIC to compact thick soil lifts and the benefits acquired compared to the roller compaction has been assessed through an experiment trial carried out in Saudi Arabia. Trial findings and interpretations are discussed within this paper. Influence depth and relative density differences by depth were estimated with reference to the different soil types utilized in the field Trial.

Keywords: High Energy Impact Compaction; Fill; Site Preparation; Relative Density; Influence Depth

I. Introduction

High Energy Impact Compaction (HEIC) is a soil compaction method that has become increasingly popular in the construction industry over the past few decades. This method employs a non-circular (3, 4 and 5-sided) heavy module (6 to 16 tones) which is drawn behind a tractor and, which distinguishes HEIC from other conventional compaction methods as shown in Figure 1.

At present, HEIC is commercially available in different compactor module designs, implemented worldwide, employing 3-, 4- and 5 -sided drum shapes that have been developed in order to achieve compaction of various soil formations at various depths. HEIC efforts are controlled by the energy input which varies from 10kJ/m to 30kJ/m. Drum weights range from 8 tons to 16 tons whereas height of drop is about 150mm. Modification of the drum masses and drop altitudes effect the energy effort which in sequence controls the depth as well as the grade of enhancement usage (Kelly, D., 2012). Figure 1 illustrates the different module shapes of the HEIC in current use.

The dynamic densification method is capable of mitigating bearing capacity and settlements issues across a widespread variety of earth formations for typically fills and virgin materials of sandy nature. HEIC is a relatively quick technique of dynamic compaction where earths of numerous arrangements can be enhanced at depths up to 2m.

Compaction through the dynamic effects is achieved through the procedures of lifting and dropping heavy weights from specified heights. HEIC follows these procedures via the raising/dropping of the impact drum as the compactor continuously operates from the top surface. Energy is generated due to the heavy weight drop which is transferred at deeper soil horizons resulting on re-arrangement

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of soil particles and compaction. This dynamic process leads to increase on the densification and bearing capacity of the soils allowing shallow foundations to be viable.

It is noticed that 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. Preceding to the implementation of the HEIC procedure a complete appraisal of accessible geotechnical information should be evaluated, to determine the appropriateness of the several unit arrangements for the specified earth category and site settings. A considerate of the earth response throughout the HEIC has amplified meaningfully over recent years (Kelly, D., 2012).

The association among the depths of effect and the enhancement of the in-situ earth density by means of HEIC have been found to differ meaningfully. The depth of effect of HEIC is frequently enumerated by associating in-situ test outcomes before and after densification. Nevertheless, at sites comprising of noteworthy earth changeability, the usage of pre- and post-compaction testing can be challenging (Brendan Scott, et. al 2019).

A number of investigators (Landpac Technologies Pty Ltd, 1998; Kim, K. 2010; Avalle& Carter, 2005) observed that the HEIC having a vigorous role to the following:

- Increase of the bearing capacity of the soils where foundations are anticipated.
- Reduce of the total and differential settlement to acceptable levels.
- Mitigation of the risks that can be caused by the dynamic loading.

Generally, the HEIC method can be utilized, as time and cost-effective substitute to the traditional roller compaction (soil layers of 200mm), within site preparation filling projects. HEIC includes soil lifts development reaching 1.5m to 2m and subsequent compaction from the top surface level.

This study is envisioned to fix all parameters controlling the impact energy input of HEIC technique used in ground improvement. The main objective of this study is directing to assess and quantify the efficiency of HEIC technique in ground improvement and estimate the depth of influence under three different soil materials.

II. Background

Prior to the major construction projects, early site preparation contracts are involved especially at cases where existing grades are far from the final. These site preparation activities involve cut and fill operations to achieve the final design levels. Filling procedures are usually undertaken by placing, compacting and testing soil layers with specified thickness of 200mm. The same process is constantly repeated up to the required grade elevations.

HEIC method solves all the disadvantages associated to the old-style 200mm layer style since can attain equivalent post compaction earth features for sole lifts of 1.5m to 2m thick resulting on cost and...
time schedule efficiency. In addition, this method eliminates the requirement of adding water to soils to achieve optimal moisture content and required compaction.

Worldwide knowledge in HEIC method (Avalle and Carter, 2005; Kim, K. 2010) shows that scheme areas associated to the filling groundworks are massive and the old-style method of placement and densification displays drawbacks related to the following:

- Time schedule necessary from the commencement to the completion of the filling activities including placement, compaction, and testing of each 200mm layer.
- Excessive areas to be treated since compaction areas are multiples of the top surface area.
- Cost considerations due to the extent of the areas require compaction.
- Typically requires water usage to achieve optimum moisture content.

HEIC method addresses all the disadvantages linked to the traditional 200mm layer style since can accomplish equivalent post compaction earth features for single lifts of 1.5m to 2m thick without water usage, ensuing on cost and time schedule efficacy.

Mayne et al. (1984) and Lukas (1995), specified that the difference in forecast depth of enhancement is not merely attributed to the mass weight and drop height, but is also predisposed by other features for example the weight surface area, entire energy utilized, interaction pressure of the weight mass, effectiveness of the falling mechanism, primary earth settings and groundwater stages.

Available studies relating to typical four-sided impact rollers that have enhanced the soil formations in-situ and have densified earth in thick deposits are provided summarized in Tables 1 and 2. These Tables presented evidently that the efficacy depth of enhancement by using the HEIC method ranges based on the soil nature. Summarizing the HEIC has a better depth of effect in sandy formations rather than in cohesive materials.

Nazhat (2013) examined the performance of granular based soils exposed to dynamic loading and recognized compaction effects by means of the high-speed photography and image correlation methods from laboratory-based testing.

Field pilots on dissimilar kinds of earths revealed that HEIC provides important growth in the in-situ strength to a substantial depth in sandy formations compared to clay type of materials. Berry (2001) and Asar S, et al, (2006) indicated that at areas with high groundwater presence it is likely for the high-amplitude and low-frequency vibrations related to HEIC to induce pore pressures to escalate to the surface.

Table 1: Improvement depths for compacting in-situ soil (cited in Brendan Scott, et. al 2019)

<table>
<thead>
<tr>
<th>Reference</th>
<th>Soil type</th>
<th>Improvement depth: m</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clifford (1978)</td>
<td>Sand</td>
<td>&gt;2.5</td>
</tr>
<tr>
<td>Clifford (1978)</td>
<td>Sand</td>
<td>&gt;2.0</td>
</tr>
<tr>
<td>Avalle and Young (2004)</td>
<td>Fill (clay)</td>
<td>1</td>
</tr>
<tr>
<td>Avalle (2004)</td>
<td>Fill (sand)</td>
<td>&gt;2.0</td>
</tr>
<tr>
<td>Avalle and Grounds (2004)</td>
<td>Fill (mixed)</td>
<td>1.5</td>
</tr>
<tr>
<td>Avalle and Mackenzie (2005)</td>
<td>Fill (clay)</td>
<td>2</td>
</tr>
<tr>
<td>Avalle and Carter (2005)</td>
<td>Fill (sand) over natural sand</td>
<td>3</td>
</tr>
<tr>
<td>Avalle (2007)</td>
<td>Fill (sand)</td>
<td>2.5</td>
</tr>
<tr>
<td>Scott and Suto (2007)</td>
<td>Fill (gravelly clay)</td>
<td>1.5</td>
</tr>
<tr>
<td>Whiteley and Caffi (2014)</td>
<td>Fill (mixed)</td>
<td>1.5</td>
</tr>
<tr>
<td>Scott and Jaksa (2014)</td>
<td>Fill (clayey sand) over natural clay</td>
<td>1.75</td>
</tr>
</tbody>
</table>

At few project cases (Brendan Scott, et al 2019; Suto, K., 2013) it was observed that. Numerous testing approaches were undertaken at pre- and post-densification stages to enumerate earth enhancement with growing densification effort. These testing procedures included Field Density Measurements, Standard Penetration Tests (SPT), Cone-Penetration Tests (CPT) and Geophysical Techniques.

Advantages that can be revealed by utilizing the HEIC technique (Kelly, D. 2012; Avalle and Carter, 2005) are below summarized:

1. This technique is uniformly applied over the whole vertical and horizontal extent of the fill.
2. Lift thickness of the soil is considerably increased to almost 2m compared to the 200mm when the traditional roller is used leading to time schedule enhancements.
Table 2: Thickness of compacted layers (cited in Brendan Scott, et. al 2019)

<table>
<thead>
<tr>
<th>Reference</th>
<th>Soil type</th>
<th>Layer thickness: m</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wolmarans and Clifford (1975)</td>
<td>Sand</td>
<td>1.5</td>
</tr>
<tr>
<td>Wolmarans and Clifford (1975)</td>
<td>Clay</td>
<td>0.6</td>
</tr>
<tr>
<td>Clifford (1980)</td>
<td>Clay</td>
<td>0.5</td>
</tr>
<tr>
<td>Clifford and Coetzee (1987)</td>
<td>Fill (coal discard material)</td>
<td>0.5</td>
</tr>
<tr>
<td>Avalle and Grounds (2004)</td>
<td>Fill (gravel)</td>
<td>1</td>
</tr>
<tr>
<td>Avalle (2007)</td>
<td>Sandy day/clayey sand</td>
<td>0.7</td>
</tr>
<tr>
<td>Scott and Jaksa (2012)</td>
<td>Fill (mixed)</td>
<td>1</td>
</tr>
<tr>
<td>Scott and Jaksa (2014)</td>
<td>Fill (clayey sand)</td>
<td>1</td>
</tr>
</tbody>
</table>

Figure 2: HEIC Trial Embankments Preparation

Figure 3: HEIC in operation within the Trials
**Figure 4:** Embankment with fine content of less than 30% (Trial 1)

**Figure 5:** Embankment with fine content less than 13% (Trial 2)

**Figure 6:** Embankment with fine content up to 2% (Trial 3)
3. Natural weak ground materials at depths not exceeding 2m can be improved to the required specifications without the need of excavation and replacement.

4. HEIC can mitigate moderately deep natural soil formations resulting on design optimizations in relation to either foundations (type and size of footings required) or road schemes (reduction of base course materials).

5. HEIC showed significant reduction in infiltration rate into the ground after a few rollers passes.

6. HEIC can provide significant cost savings in the civil construction sector.

7. Speed of the impact compactors can be five times the speed of the roller compactors.

8. Production rates are amplified by the utilization of the HEIC (varies between 6,000m$^2$ and 8,000m$^2$ per shift) due to the increased lift thickness and equipment's speed.

9. Ground attributes at real time is possible to be monitored through the continuous impact response as the HEIC is advanced. Stiffness of the ground is measured through sensors attached at the drum axle at each and every location.

III. Field Trials

Following is a summary of the HEIC ground improvement Trials conducted in the Eastern part of Saudi Arabia in 2019.

- Field Trials & Embankments Preparation

These objectives were addressed through piloting procedures undertaken in Saudi Arabia. The calibration was performed at three embankments having thickness of three meter composed of loose soil formations with various fine contents (2%, 13% and less than 30%). As a result, the impact of the HEIC at different soils settings was also investigated.

The imported fill was positioned at the top of natural ground level. Each type of fill related to different fine content occupies an area of 20m x 30m. The three embankments were placed next to each other resulting on continuous compaction procedures utilizing the same HEIC parameters. A typical arrangement of the embankment's preparation is shown in Figure 2. Acceptance criteria were set to 85% of Relative Density.

This trial study is focused on an impact compactor with a drum rolling mass of 16 Tons and an impact energy of 30KJ/m. Speed of operation for this type of compactor range from 10 km/hour to 15 km/hour. HEIC in operation within the trials are shown in Figure 3.

- Soil Characteristics

A special emphasis has been carried out to characterize the soil material used in land reclamation at the three embankments and subjected to HEIC process. Results of lab testing in relation to particle size distribution are shown in Figures 4, 5, and 6.

IV. HEIC Operation and Measurement Procedures

- HEIC Compactor

In this study an impact drum Model (HEIC-1) was utilized in the designated trials. Description of impact drum model, compaction details and drum dimensions are summarized in Table 3:

- HEIC Operation

The success of densification through the HEIC is associated to the applied impact energy which in turn is related to the roller weight, operation speed, and the drop height. A graphical representation of the HEIC is illustrated in Figure 7. The rolling procedures shall be undertaken over the whole area where improvement of soil properties is required.

Overlapping roller tracks at both the clockwise and counter-clockwise directions are needed for the scheme to be successful. A typical arrangement that applied over the pilot area is shown in Figure 8. The number of passes along each track based on the project specifications whereas the offset between each track is a function of the impact roller used. Improvement depths varying from 1.5m to 2m.

- In Situ Testing (HEIC Trial Activities)

The piloting procedures consists of the following activities:

- Embankments preparation based on guidelines described above in relation to dimensions and soil composition.
- Before commencing the HEIC works pre-treatment Cone Penetration Tests (CPT) were performed to confirm the loose state of soil compaction (2 Nos. for each embankment).
- Execution of the HEIC based on predefined parameters of mass, height, and speed.
- Several passes were undertaken depending on the achievement of the project specifications.
- Post-treatment CPT were carried out to confirm the depth effectiveness of the HEIC method over the various soil settings (1 No. for each embankment).
- The top 200mm were compacted by the usage of the traditional roller compaction due to the development of uneven surfaces through the HEIC utilization.
Table 3: Specifications of impact drum and compaction details used in this study

<table>
<thead>
<tr>
<th>Specifications and Dimension of Impact Drum</th>
<th>Compaction Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model</td>
<td>No. of Sides</td>
</tr>
<tr>
<td>HEIC-1</td>
<td>3</td>
</tr>
</tbody>
</table>

Figure 7: General shape of improvement below HEIC (after Land Pack, 1999)

Figure 8: HEIC - Overlapping roller passes at both the clockwise and counter-clockwise directions
V. Results and Discussion

Results and findings of CPT records and equivalents relative density by depth that can be utilized as indicator of performance and improvement of soil materials used in the three trials will be discussed in the following sections:

(A) Pre and Post Compaction CPT Analysis

Having completed the HEIC works (with eight passes) 1 No. of Post CPTs was carried out at each embankment. The increment of the improvement as well as the depth of efficacy is shown in Figures 9 to 11 where a comparison of pre- and post-compaction tests is illustrated.

Cone resistance records in the three trials throughout the course of the trials using the 3 sidedHEIC are demonstrated in Figures 9, 10 and 11. Based on the results of the cone tests pre and post compaction, it shows that a uniform increase in densification of the soil materials used in embankments at Trials 1, 2 and 3 was achieved to depths up to 3m with different rate of improvement.

Soil materials improvement that are used in the three trials using the same components of 3-sidedHEIC compactor, applying the same energy input and different soil materials can be summarized as follows:

- **Trial 1 with soil material having less than 30% fine fractions**: It was demonstrated at the site of Trial 1 that HEIC was successful in compacting soil type with less than 30% fines to depths of 3m below the surface and distributed by depth as a 10% increase in cone resistance recorded at depths of 0 to 1m, 133 % at depths of 1 to 2m and 42% at depths of 2 to 3m below the surface level. The strength improvement at this type of soil with 30% fine fractions reaches up to 3m from the existing ground surface and the average improvement reached up to 61% (Figure 9).

![Figure 9: Pre and post compaction CPTs - Embankment with fine content less than 30% (Trial 1)](https://journalofcivilengg.com)
• **Trial 2 with soil material having less than 13% fine fractions:** It was demonstrated at the site of Trial 2 that HEIC was successful in compacting soil type with less than 13% fines to depths of 3m below the surface and distributed by depth as a 150% increase in cone resistance recorded at depths of 0 to 1m, 333% at depths of 1 to 2m and 250% at depths of 2 to 3m below the surface level. The strength improvement at this type of soil with 13% fine fractions reaches up to 3m from existing ground surface and average improvement was reached up to 244% (Figure 10).

• **Trial 3 with soil material having less than 2% fine fractions:** It was demonstrated at the site of Trial 3 that HEIC was successful in compacting soil type with 2% fine to depths of 3m below the surface and distributed by depth as a 17% increase in cone resistance recorded at depths of 0 to 1m, about 200% at depths of 1 to 2m and 200% at depths of 2 to 3m below the surface level. As shown, the strength improvement at this type of soil with 2% fine fractions reaches up to 3m from the existing ground surface and the average improvement was reached up to 139% (Figure 11).

### (B) Pre and Post Compaction Relative Density Analysis

The Relative Density of soil material used in this study at Trials 1, 2 and 3 has been calculated and the increase in Relative Density between the pre- and post-compaction stages at the three different trials is displayed in Figures 12 to 13.

As shown in Figures 12 and 13, remarkable increase in relative density by applying the HEIC technique at depths between 1 and 2.5m from ground surface was achieved. Increase of relative density...
Figure 11: Pre and post compaction CPTs - Embankment with fine content less than 2% (Trial 3)

ranges from 40% to 80% in Trial 1, from 40% to 97% in Trial 2 and from 40% to 80% in Trial 3, whereas the upper part of the three trials showed that relative density pre- and post-compaction reaches up to 100%.

(C) Acceptance Criteria

The acceptance criteria appropriate to the HEIC scheme (within site preparation earthwork operations) based on the relative density concepts has been considered at this study and relative density was estimated using Baldi et al, 1986; Jamilowskiet al., 1985; Schmertmann (1978). Acceptance criteria for the trial were set to 85% of Relative Density.

The acceptance criteria are fulfilled by generating a respective performance line which is assessed through the estimation of the CPT tip resistance relating to the required specification project criteria of relative density. Several correlations containing the relative density and cone tip resistance have been utilized in order to obtain various performance lines. Examples of such correlations are provided in Table 4.

The final performance line was defined as the average of the various correlations utilized. A performance line applicable for relative density of 85% within dry fill formations up to 4m depth is illustrated in Figure 14.
Figure 12: Pre and post compaction Relative Density - Embankment with fine content less than 30% (Trial 1)

Figure 13: Pre and post compaction Relative Density - Embankments with fine content less than 13% and up to 2%, respectively (Trials 2 and 3)
Table 4: Calculation of Relative density with reference to CPT values

<table>
<thead>
<tr>
<th>Method</th>
<th>Formula</th>
</tr>
</thead>
</table>
| Baldi et. al. (1986) modified by Lune (2006) | \[ D_r = \frac{1}{C_2} \ln \left( \frac{q_c}{C_0 (\sigma'_{v0} + \sigma'_{0}) \epsilon_1} \right) \]  
  \[ C_0 = 157, C_1 = 0.55, C_2 = 2.41 \] |
| Jamiolkowski et. al. (1985)     | \[ D_r = -98 + \left( \frac{66 \times \log_{10} \left( \frac{q_c}{\sigma'_{v0}^{0.5}} \right)}{7} \right) \] |
| Schmertmann (1978)              |![](image.png) |

\( D_r \) = Relative Density  
\( q_c \) = Cone Penetration Test Tip Resistance  
\( \sigma'_{v0} \) = Effective Vertical Stress

Figure 14: HEIC Trial Average Performance Line  
applicable for 85% of Relative Density
(D) Pre and Post Compaction CPTs and Performance Line

The post compaction cone tip resistances are overlaid to the average performance line for determining compliance to the project specifications and illustrated in Figures 15, 16 and 17.

Results and findings of the post compaction CPT tests with reference to the performance line values revealed that the acceptance criteria have been fulfilled to the trial depth of approximately 1.2m in Trials 1 and 3 that are dominated with soil materials with less than 30% and less than 2% fines content, while accepted performance depth reaches up to 2m in Trial 2 that is comprised of soil material with less than 13% fines content as shown in Figures 15, 16 and 17.

Figure 15: Post compaction CPTs and Performance Line - Embankment with fine content less than 30% (Trial 1)
• Post Compaction Relative Density

Additionally, the post compaction Relative Density were calculated using Baldi et al, 1986; Jamiolkowski et. al, 1985 based on the actual Post CPTs values for all different soil material in the three trials and illustrated in Figures 18 to 19. The various equations utilized for obtaining the values of Relative Density are shown within Table 4.

Results and findings of post compaction relative density with reference to the performance line (Relative Density is 85%) revealed that an acceptable performance (Relative Density >85%) is noticed in the upper 1.2m of Trials 1 and 3 that are dominated with soil material with less than 30% and less than 2% fines content. While depth of acceptable performance (Relative density > 85%) is noticed about 2m from ground surface in Trial 2 that is hosting soil material with less than 13% fines content.
Figure 17: Post compaction CPTs and Performance Line - Embankment with fine content up to 2% (Trial 3)
Figure 18: Post compaction Relative Density based on various literature together with Performance Line - Embankment with fine content less than 30% (Trial 1)
Figure 19: Post compaction Relative Density based on various literature together with Performance Line - Embankments with fine content less than 13% and up to 2%, respectively (Trials 2 and 3)
Figure 20: Pre and post compaction average Relative Density together with Performance Line - Embankment with fine content less than 30% (Trial 1)

Figure 21: Pre and post compaction average Relative Density together with Performance Line - Embankments with fine content less than 13% and up to 2%, respectively (Trials 2 and 3)
• **Pre and Post Compaction Relative Density**

Furthermore, the average pre- and post-compaction Relative Density together with the required set of specifications is illustrated in Figures 20 and 21.

Results and findings of the pre- and post-compaction with average Relative Density together with Performance Line (85%) revealed that the acceptance criteria have been fulfilled to the depth of approximately 1.2m in Trial 1 that is hosting soil with less than 30% fines content, about 2m in Trial 2 that is dominated with soil material up to 13% fines content and about 1m in Trial 3 that is hosting soil material with 2% fines content. (Figures 20, 21).

**VI. Conclusions & Recommendations**

This paper demonstrated improving ground in-situ and compaction of soil in thick layers of three type of soils by using the HEIC technique. Results and findings have reached for the following conclusion and remarks:

• A trial of the HEIC densification method was carried in Saudi Arabia aiming to compact soil formations of various compositions at relatively shallow depths.

• Results of Cone Penetration Tests (CPT) indicated that the average improvement of soil densification using 3-sided HEIC technique reaches up to 61%, 244% and 139% in Trials 1, 2 and 3 that are built of soil material dominated with less than 30%, 13% and 2% fines content, respectively.

• Results revealed that the HEIC can be successfully utilized within earthwork filling applications. It is concluded that the HEIC technique densifies up to 2m thick soil deposits due to the energy which is transmitted to the soil through the lifting and falling motion of the non-circular rotating mass and is able to mitigate bearing capacity and settlements issues encountered at an extensive range of soil formations mostly fills and virgin grounds of sandy nature.

• The effectiveness of the HEIC to compact thick soil lifts and the benefits acquired compared to the roller compaction has been assessed and discussed within this paper.

• Results from cone penetration Tests (CPT) show significant depths of compaction influence using HEIC technique, which for the natural sand and variable fine contents fill material were recorded down to depths of 2 m.

• The effective depth of influence was estimated with reference to the Performance Line (Relative density is 85%) and CPT values to be about 1.5m for sand soil dominated with fines content (less than 30%) and about 2m for sandy soil with less than 13% fine fractions.

• In conclusion, the HEIC method, including development of 2m soil lifts, can be utilized as time and cost-effective substitute to the traditional roller compaction (soil layers of 200mm) within site preparation filling projects.

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**References**


