Deep Dynamic Compaction and Rapid Impact Compaction Adopted to Treat Loose Soil Formations and Fill Compaction for Large Structures and Roads - Case Study

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Abstract

The current case study is concerning a facility located near Dammam, Saudi Arabia. The project consisted of three main categories of design criteria to be achieved. It included nine Bearing Capacity and Settlement criteria for infinite, combined and isolated foundations, Relative Density (Rd) criterion for Road/Open Areas and Liquefaction Risk Mitigation criterion for the entire site, which encompassed an area of approximately 180,000m². The allotted time for soil improvement works was limited to 6 months, due to the project being of fast-track category. The soil profile was composed largely of granular material and the depth of improvement went as deep as 10m. Both Dynamic Compaction and Rapid Impact Compaction are popular techniques in compacting granular material, due to their high efficiency in achieving the design criteria and fast rate of improvement. The techniques are also cost-effective and clean, in terms not requiring water nor electricity for operations compared to Vibro-Improvement counter techniques, proving to be value-engineered options. The improvement area was segregated into three regions based on existing loose soils and fill compaction requirements, wherein the techniques would be implemented independently or in combination with one another. The production works lasted around 4.5 months. Post-Improvement Quality Control tests indicated the achievement of Design Criteria by a substantial margin, exemplifying the efficiency of Deep Dynamic Compaction and Rapid Impact Compaction techniques in terms of achieving the design criteria and a fast rate of production in operations.

Introduction

The project location is situated in the northeast of Dammam, KSA. The project consisted of structures, parking areas and roads, for a total area of 180,000 m². The scope of work included existing soil improvement and fill compaction works. The soil composition was mainly granular with presence of stiff fine-grained layers. The project was fast track and required optimized improvement and compaction strategy to meet a 6-month deadline. With the same constrained requirement, roller compaction would prove difficult and an expensive option. The same constraint motivated the need for value-engineered alternatives.

The current paper consists of the following abbreviations as defined in Table 1.

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>KSA</td>
<td>Kingdom of Saudi Arabia</td>
</tr>
<tr>
<td>DC</td>
<td>Dynamic Compaction</td>
</tr>
<tr>
<td>DR</td>
<td>Dynamic Replacement</td>
</tr>
<tr>
<td>VC</td>
<td>Vibro Compaction</td>
</tr>
<tr>
<td>VR</td>
<td>Vibro Replacement</td>
</tr>
<tr>
<td>CPTu</td>
<td>Piezocone Penetration Test</td>
</tr>
<tr>
<td>R_d</td>
<td>Relative Density</td>
</tr>
<tr>
<td>q_c</td>
<td>Cone Tip Resistance</td>
</tr>
<tr>
<td>I_c</td>
<td>Soil Behavior Type Index</td>
</tr>
</tbody>
</table>

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Background

Two soil investigation campaigns were conducted prior to improvement-compaction works. The campaigns will hereafter be referred to as SI(A) and SI(B). Both investigations were carried out mostly at the structures locations. As per investigation works conducted by SI(A), the following profile displayed in Figure 1 can be used as a summary of geological conditions.

Figure 1: Soil Profile as per SI(A)

Two profiles assessed by SI(B) are presented in the Figure 2 (a & b).

Figure 2: Soil Profiles as determined by SI(B)

Although a variation was observed in the two campaigns, a basic knowledge of the profile was attained, that mainly the sub-surface profile consisted of granular material with lenses of fine soils, which required compaction. This granular layer had thickness varying from 4m until 7m. The sub-stratum was typically a stiffer material and ranged from granular to cohesive material with little or no soft cohesive materials predicted in the profile.

It is typical for investigations to produce slightly varying results. However, by instilling an adequate Front-End Engineering Design, unexpected conditions may be avoided and a preliminary understanding of the soil conditions in the project can attained prior (Spyropoulos & Khan, 2020).

Problem Statement

Taking into account the soil conditions, earthwork requirements and constrained schedule, optimized strategy for soil improvement and fill compaction requirement was identified. Removal and replacement, followed by conventional layer-by-layer roller compaction would prove expensive and prevent meeting the time schedule.

Observing the soil suitability recommendations by Braiek (2017) and Han (2015), two prominent techniques may be implemented as shown in Figures 5 & 6:

1. Rapid Impact Compaction
2. Dynamic Compaction

A brief description with the principle of both techniques is given as follows:

Rapid Impact Compaction: Rapid Impact Compaction is a cheaper and faster alternative to conventional roller compaction, typically implemented for shallow compaction of soil within a thickness of 5m. The technique is implemented on granular or coarse-grained soils, however it may be implemented for soil types with fine content up to 20%. The principle of Rapid Impact Compaction involves compaction of soil, as a result of energy transferred by the repeated free fall of a hammer, on a set grid spacing. The number of blows, height of fall and the set grid are optimized in real-time, as a function of the behaviour of the ground reaction and penetration, to deliver the most optimum results. A work sequence of the Rapid Impact Compaction technique is shown in Figure 3.

Figure 3: Rapid Impact Compaction Work Sequence

Dynamic Compaction: Dynamic Compaction is a cheaper and faster alternative to Vibro-Compaction (VC), typically implemented for treatment of soils within a thickness of 8-10m. The technique is implemented on granular or coarse grained soils, however it may be implemented for soil types with fine content up to 30%. The principle of Dynamic Compaction involves compaction of soil, as a result of energy transferred by the repeated free fall of a Heavy Pounder, on a set grid spacing. The number of blows, height of fall and the set grid are optimized in real-time, as a function of the behaviour of the ground reaction and penetration, to deliver
the most optimum results. A work sequence of the Dynamic Compaction method is shown in Figure 4.

**Figure 4:** Dynamic Compaction Work Sequence

An embedment of 1.3m was to be considered for the following foundation designs shown in Table 2.

**Table 2:** Foundations considered for Analysis

<table>
<thead>
<tr>
<th>Type of Footing</th>
<th>Footing Size</th>
<th>Allowable Bearing Capacity (kPa)</th>
<th>Allowable Settlement (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Isolated/Spread</td>
<td>1.0 x 1.0 m²</td>
<td>250</td>
<td>25</td>
</tr>
<tr>
<td></td>
<td>1.5 x 1.5 m²</td>
<td>180</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2.0 x 2.0 m²</td>
<td>145</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2.5 x 2.5 m²</td>
<td>125</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3.0 x 3.0 m²</td>
<td>110</td>
<td></td>
</tr>
<tr>
<td>Strip</td>
<td>Width 0.7m</td>
<td>240</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Width 1.0m</td>
<td>185</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Width 1.5m</td>
<td>143</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Width 2.0 m</td>
<td>125</td>
<td></td>
</tr>
</tbody>
</table>

**Liquefaction**

The following liquefaction criteria was to be achieved after soil improvement works.

- Minimum Factor of Safety against Liquefaction: 1.2
- Peak Ground Acceleration (PGA): 0.07g
- Magnitude (M): 4.0

The assessment of Liquefaction Risk Potential was to be carried out implementing Youd et al. (2001). Within the summary report by Youd et al. (2001), it is explained how the Cyclic Stress Ratio is determined (implementing average shear stress and stress reduction factor by Seed and Idriss (1971) and Blake (1996), both cited in Youd et al. (2001)). Following which Cyclic Resistance Ratio is calculated for a 7.5 magnitude earthquake (using Rauch (1998) as cited in Youd et al. (2001)). A Magnitude Scaling Factor (after Youd et al. (2001)) is applied to the applicable design and the Factor of Safety is assessed, where resistance is larger than the stress predicted.

**Fill Compaction – Performance Line**

The compacted fill was to meet required density based on project specifications. Minimum relative density of 85% after fill compaction works was required (fill thickness of 3m).

Relative density is estimated by reverse calculating the required degree of relative density (Rd) to cone tip resistance (qc) values based on a standard, thereby creating performance lines and comparing them to the post compaction cone resistance values. For the proposed improvement strategy explained herein, a performance
Hypothesis

In the current hypothesis section, the authors detail the preliminary scenario, predicted duration and closing to meet the 6-month time duration.

Reviewing data from previous studies, Table 3 summarizes general parameters for both techniques.

Table 3: Dynamic Compaction and Rapid Impact Compaction

<table>
<thead>
<tr>
<th>Technique</th>
<th>Parameter</th>
<th>Range</th>
<th>Citation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Diameter of Tamper</td>
<td>2.2-2.5m</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Tamper Weight</td>
<td>10-40 Tons</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Grid Spacing:</td>
<td>1.5 - 2.5m (Tamper Diameter)</td>
<td>Rouaighia and Al-Zahrani (2002)</td>
</tr>
<tr>
<td></td>
<td>Height of Drop:</td>
<td>10-25m</td>
<td>Lokas (1995)</td>
</tr>
<tr>
<td></td>
<td>Energy Estimation</td>
<td>( E = \frac{N \times W \times H \times P}{(grid\ spacing)^2} )</td>
<td>Lukas (1995)</td>
</tr>
<tr>
<td></td>
<td>Energy</td>
<td>150 kJ/m²</td>
<td>Han (2015)</td>
</tr>
<tr>
<td>Rapid Impact Compaction</td>
<td>Diameter of Hammer</td>
<td>1.5-2.0m</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Tamper Weight</td>
<td>9-16 Tons</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Grid Spacing:</td>
<td>Primary: 6 x 6m² (adjusted based on soil conditions, tamper weight and trial, preliminary grid size shall be assessed empirically)</td>
<td>Chu et al. (2009)</td>
</tr>
<tr>
<td></td>
<td>Tertiary: 3 x 3m²</td>
<td></td>
<td>Braiek (2017)</td>
</tr>
<tr>
<td></td>
<td>Height of Drop:</td>
<td>Up to 1.2m (depending on equipment)</td>
<td>Han (2015)</td>
</tr>
<tr>
<td></td>
<td>Energy Estimation</td>
<td>Please refer Eq. (1)</td>
<td>Lukas (1995)</td>
</tr>
</tbody>
</table>

Note:
- Energy = (drop height x weight x number of drops) / soil volume expecting compacted.
- Number of passes should be kept as less as possible.

The aim was to attain a minimum of 1,154 m² of working days (26 days per month) production, with the added time allotted for earthwork filling works.

Equipment were in vicinity of the site and the mobilization and set up task could be completed in one working week. As per Khan (2019), the rate of production for both techniques may be assumed as follows,
- Rapid Impact Compaction: 75,000 m² / month (per rig under one shift per day)
- Dynamic Compaction: 35,000 m² / month (per rig under one shift per day)

Duration was to be slightly adjusted further for site conditions, soil conditions and other supplementary factors.

In attempt to provide a value engineered design, supplementary pre-investigation works were required. The same would then be reviewed along with the earthwork design, to effectively segregate areas where either technique would be applicable. In addition to the same, where applicable, the techniques would be designed in combination with one another, to boost production and provide a value engineered design.

Method – Ground Improvement

The designed testing regime consisted of varying frequency of Piezocone Penetration tests (CPTu) with respect to the areas designated either for structures or for roads. To simplify the same, a frequency of 4,000m² can be considered for each Pre-CPTu as shown in Figure 9.
Figures 9 & 10 aid in understanding the segregation of areas based on expected soil improvement to be carried out.

**Figure 9:** Pre-Investigation CPTu Campaign and Segregated Area

**Figure 10:** Priority Zones and Other Areas of the Project
Based on the results of the pre-investigation campaign by the soil improvement contractor and the earthworks design, the entire project area was segregated into the following soil improvement scenarios as given in Figure 11.

**Stage 1:** Dynamic Compaction from Existing Ground Level

**Stage 2:** Rapid Impact Compaction after Fill Works

*Figure 11: Soil Improvement Scenarios Chart*

Note: The chart above represents cross-sections of improvement methodology deployed during actual works. The elevations mentioned, are related to the cross-sections with respect to the existing ground level considered 0.0 for the sake of easier understanding. The Final Ground Level on the project ranged from +7.0m to +10.5m.
The estimated quantities of the scenarios mentioned in Figures 10 & 11 were as follows:

- Dynamic Compaction after fill placement: 104,000m$^2$
- Rapid Impact Compaction after fill placement: 76,000m$^2$
- Dynamic Compaction and Rapid Impact Compaction in Combination

Stage 1: Dynamic Compaction to improve existing soil – 16,000m$^2$
Stage 2: Rapid Impact Compaction for fill compaction – 16,000m$^2$

A preliminary project duration analysis was conducted in-line with the production details previously mentioned, which were further adjusted to site conditions and supplementary factors. The project duration was limited to 6 months as required and a Gantt Chart for the same is presented in Figure 12.

![Figure 12: Preliminary production duration analysis GANNT Chart](https://journalofcivilengg.com)

Based on the results of the project duration analysis, it was determined, implementing both Rapid Impact Compaction and Dynamic Compaction, independently and in combination with one another, with just one rig for each technique, the project could successfully be complemented in a little under 5 months. Taking a safe estimation of two working weeks for Calibration Works, the preliminary project duration was assumed to be 5.2 months which was in-line with the fast-track 6-months project requirement.

The basis of designing operation parameters for Dynamic Compaction and Rapid Impact Compaction techniques are detailed in Table 3. Based on the same, the following were deduced (subject to adjustment and further calibration during Trial Works).

In the exercise, general parameters based on soil type, expected soil behavior and required depth of influence were assumed, while trying to meet energy requirement for both techniques based on minimum energy required, as mentioned in Table 3.

**Dynamic Compaction**

\[
260.89 = \frac{15 \times 20.87 \times 15 \times 2}{(6)^2}
\]  

**Rapid Impact Compaction**

\[
150 = \frac{60 \times 14.51 \times 1.1 \times 2}{(3.5)^2}
\]

Using a 23 Ton pounder, with 15m height of drop, over a 6 x 6 m$^2$ grid spacing, for a total of 15 blows and 2 passes (discounting the ironing pass), the required energy can be attained. Dynamic Compaction works were further calibrated during Trials with parameters in a similar range.

Using a 16 Ton Hammer, with 1.1m height of drop, over a 3.5 x 3.5 m$^2$ grid spacing, for a total of 60 blows and 2 passes (discounting the ironing pass), the required energy can be attained. Rapid Impact Compaction works were further calibrated during Trials with parameters in similar ranges.

**Results and Discussion**

Calibration works were carried out for both techniques considered in the study. Three grid spacing were considered for the trials of both techniques as follows,
Dynamic Compaction
- Grid A: 5.0 x 5.0 m²
- Grid B: 5.5 x 5.5 m²
- Grid C: 6.0 x 6.0 m²

Rapid Impact Compaction
- Grid A: 3.5 x 3.5 m²
- Grid B: 4.0 x 4.0 m²
- Grid C: 4.5 x 4.5 m²

Successful completion of calibration works identified optimum production parameters shown in Table 4, i.e. parameter with which the required soil improvement can be achieved while avoiding overdesign of operations.

<table>
<thead>
<tr>
<th>Technique</th>
<th>Production Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dynamic Compaction</td>
<td>Grid C: 6 x 6 m²</td>
</tr>
<tr>
<td></td>
<td>Weight of Pounder: 23 Ton</td>
</tr>
<tr>
<td></td>
<td>Height of Drops: 15m</td>
</tr>
<tr>
<td></td>
<td>Number of Blows: 15</td>
</tr>
<tr>
<td>Rapid Impact Compaction</td>
<td>Grid C: 4.5 x 4.5 m²</td>
</tr>
<tr>
<td></td>
<td>Weight of Hammer: 16 Ton</td>
</tr>
<tr>
<td></td>
<td>Height of Drops: 0.9m</td>
</tr>
<tr>
<td></td>
<td>Number of Blows: 60</td>
</tr>
</tbody>
</table>

**Note:** General production parameters may vary based on soil conditions and soil behavior during actual soil improvement works.

**Table 4:** Operation parameters adopted for general production works

**Figure 13:** Pre & Post CPTu at Trial Areas (a) Dynamic Compaction (b) Rapid Impact Compaction

Soil Improvement works lasted 4.5 month. Verification of design criteria (as mentioned in section 3) were performed following guideline references as mentioned below:

- Settlement Assessment: Schmertmann et al. (1978).
- Relative Density: As mentioned in section 3.

The achievement of design criteria is shown in Figures 14 to 16.

**Figure 14:** Strip foundation bearing capacity and settlement assessment
Figure 15: Isolated foundation bearing capacity and settlement assessment

Figure 16: Liquefaction Risk Assessment
Following soil improvement works, all design criteria requirements were met by all performed Post CPTu’s, proving the value engineered design of combination of Dynamic Compaction and Rapid Impact Compaction for the current project, a success in terms of both, the efficiency in improving the soil and a time efficient strategy.

**Future Research**

Similar to the chart attached in Figure 5 (Braiek, 2017), the authors devised a similar chart to determine value engineering soil improvement technique based on applicable soil conditions as shown in Figure 17.

![Figure 17: Selection of soil improvement technique based in value engineering](image)

Figure 17 includes the inclusion of High Energy Impact Compaction (HEIC) and Rapid Impact Compaction (RIC) to the pre-existing chart as cost-effective solutions to granular soils. In terms of future studies, the authors suggest research into a new technique, which may be called Rapid Impact Replacement (RIR). The aim of the RIR technique is to provide a cost-effective solution to the treatment of soft cohesive soils to shallower depths, compared to existing techniques in the industry today. The authors envision an evolution of the technique from Rapid Impact Compaction, similar to the evolution of Dynamic Compaction to Dynamic Replacement.

**Conclusion**

In the current paper, a case study was presented for a fast-track project, which required the application of soil improvement works and fill compaction works in combination. Although a number of techniques exist in the market, in an attempt to meet the strict time duration constraint, the authors devised a value engineered strategy, involving the combination of Dynamic Compaction and Rapid Impact Compaction techniques. A review of the strategy, the design and the project duration analysis was presented in the paper. Following the same, the results of the campaign were provided, verifying the design of the strategy wherein, the project duration requirement was met, and the required design criteria was achieved.

**References**


7. Jamiołkowski M, Lo Presti DCF, Manassero M. Evaluation of relative density and shear strength of sands from CPT and DMT. In Soil behavior and soft ground construction.2003;201-238.


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