# Dynamic Consolidation of Soft Soils – Concept and Application

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ABSTRACT : The development of various Dynamic Compaction techniques such as HIEDYC, RIC, CDYC and DDC, together with the ability to predict the impact energy delivered as well as the depth of influence of the impact energy using Cumulative Momentum Theory, lead to the advancement and research in alternative forms of consolidation treatment of soft clayey soils.This paper discusses the various forms of Dynamic Compaction and how they can be combined with PVDs to accelerate consolidation in soft clays or silts; this has been termed as Dynamic Consolidation. A case study is discussed to illustrate the application of the dynamic consolidation methodology in improving the engineering properties and behaviour of soft clays or silts.

## 1 INTRODUCTION

Dynamic soil-compaction methods have historically involved the use of tall cranes and free-falling weights, imposing limitations on the types of sites that can be treated. These techniques are generally suitable for sands and not suitable for fine grained materials. Recent developments in various forms of dynamic compaction has driven the research into application of dynamic compaction for fine grained soils.This paper presents the various development in alternative forms of Dynamic Compaction, the development in the cumulative momentum theory and also how Dynamic Compaction can be applied for the consolidation treatment of soft clays (called Dynamic Consolidation).

## 2 ABRIEF OVERVIEW OF DYNAMIC COMPACTION METHODS

Dynamic compaction is a ground improvement technique for compacting fills as well as soft or loose natural soils. Dynamic compaction has proved to be an effective and economical alternative to deep vibratory compaction and the smooth wheel vibratory roller compactor.

Dynamic compaction requires a controlled application of dynamic stresses to the ground surface. The dynamic stresses are generated by the following methods:

- Deep dynamic compaction (DDC) with drop weights, which involves using a crane to drop weights of between 5 to 20 tons, from heights of up to 20m (see Fig. 1). The technique is best suited to large, open sites where few obstructions are present.The authors experience has shown that DDC can be used in clays in combination with Prefabricated Vertical Drains or Jute drains that can withstand the impact of the drop weight.

Fig. 1 A crane operated DDC unit

- Impact Rolling using High Impact Energy Dynamic Compaction (HIEDYC). HIEDYC ground treatment imparts vertical energy into the ground to depths ranging from 2m to 5m. In view of the near vertical energy input, the spread of energy along the ground surface as surface waves in minimised.

HIEDYC ground treatment relies upon a towed non-circular module of 3, 4 or 5 sides that compacts as it rotates around a ‘corner’ and ‘falls’ to impact onto the ground (see Fig. 2). HIEDYC ground treatment has found applications on loose granular soils, gravels and crushed rock, mine haul roads and waste materials. Significant density and strength is usually obtained to 2m to 5m (or more) in sands and waste materials. The authors’ research has shown the HIEDYC, when combined with PVDs, can also be applied to accelerate consolidation of soft cohesive soils.

Fig. 2 A 5-sided HIEDYC compaction unit

- Rapid Impact Compactor (RIC), also known as Controlled Dynamic Compaction (CDYC). The RIC/CDYC unit is generally fitted to tracked base excavator of 35tonne to 70 tonne weight which provides the dual benefit of allowing improved mobility and site accessibility (see Fig. 3).

Fig. 3 CDYC dynamic compaction in operation

The authors’ experience have been that CDYC has been found to achieve deep compaction in sand and silts greater than the target 7m depth when the soils were above water table. CDYC compaction has been deployed in compaction of loose sand. When combined with PVDs, CDYC can also be applied towards consolidation of soft soils.

Dynamic energy is imparted by a dropping a weight by hydraulics from a controlled height onto a foot plate of 1m$^2$ or 1.5m$^2$ or a circular plate. The RIC/CDYC impacts the soil at a rate of 10-60 blows per minute using a 5, 7, 9 or 12 Tonne drop weight.

## 3 ESTIMATING THE DEPTH OF TREATMENT USING THE CUMMULATIVE MOMENTUM THEORY

Equation 1 is commonly used to predict the depth of improvement for dynamiccompaction:

$$D = k\sqrt{M.H} \quad (1)$$

where D is the depth of improvement, the empirical correlation factor $k$ (usually varies from about 0.5 to 1.0), M= mass of pounder in tonnes, H is the drop height in meters (Menard &Broise (1975) & Lukas (1986).

A review of the methodology indicated that although energy per blow is an indicator of the depth of improvement achievable, the use of total cumulative energy and total cumulative momentum of the compactor are better indicators of the depth and degree of compaction achievable (Oshima and Takada (1997), Lee and Gu (2004)).To calculate momentum the following equations are used (Mayne, 1983):

$$v = \sqrt{2.gH} \quad (2)$$

$$\text{Momentum} = \text{M}.v = M.\sqrt{2.gH} \quad (3)$$

where$v$ is the velocity in m/sec, H is the drop height in meters, and g = 9.81 m/sec$^2$. Momentum is therefore directly proportional to the pounder mass. Therefore increasing the drop height is less efficient in increasing the momentum than increasing the pounder mass.

Table 1. Comparison of momentum of various compactors and momentum depth predictions (from Oshima& Takada, 1997)

| Type | M (t) | H (m) | $v$ (m/s) | N. M$v$ (t.m/s) | D (m) |
|---|---|---|---|---|---|
| RIC | 9 | 1 | 4.43 | 2400 | 5.67 |
| DDC | 12 | 19 | 19.31 | 2320 | 5.61 |
| HIEDYC TRIA | 16 | 0.232 | 2.13 | 680 | 3.66 |

## 4 CONVENTIONAL METHODS OF CONSOLIDATION TREATMENT OF SOFT SOILS

Conventional consolidation treatment approach of saturated soft soils involves the following mechanisms:

- A mechanism to increase the pore water pressure either by applying an external compressive load or an applied suction pressure, and
- A mechanism to dissipate these excess pore water pressures, such as with vertical sand drains or prefabricated vertical drains (PVD).

Conventional methods of consolidation ground improvement approach for soft clay include:

1. Surcharge preloading with vertical drainage (typically PVD or sand/stone columns).This method has been successful on improvement method of soft soils. It typically requires a rest period of between 4 months to a year, depending on the parameters $C_v$ and $C_h$, spacing of vertical drainage, and amount of surcharge preload.

2. Vacuum consolidation combined with PVD with/without surcharge preload.A maximum suction pressure of up to 100 kPa creates an increase in effective stress. Effectively this suction pressure has a limitation of a maximum depth of treatment of up to 10m. To overcome this limitation, this method is often aided with placement of surcharge preload.There is a requirement for good control of the sealing mechanism to prevent air leaks during process.

   However, the efficiency of the method depends on preventing the surface sand from being affected by the pressure from pervious layers of sand and discontinuities in the ground.

## 3 APPLICATION OF DYNAMIC CONSOLIDATION

Dynamic consolidation involves applying dynamic energy to pressurise the pore water and to accelerate consolidation of the underlying soft ground using one of the dynamic compaction methods identified in Sections 2 and 3 above.

The authors have carried out a research with application of HIEDYC dynamic compaction on soft clayey and silty soils. Piezometers were installed at depths of 3m, 6m and 12m and the research has shown that the dynamic energy impacted by HIEDYC dynamic compaction creates an instantaneous increase in pore water pressure to a depth exceeding the maximum instrumented depth of 12m. Excess pore water pressures in excess of 30kPa were observed; this is equivalent to the placement of about a 1.5m high surcharge fill. These results are indicated in Fig. 4.

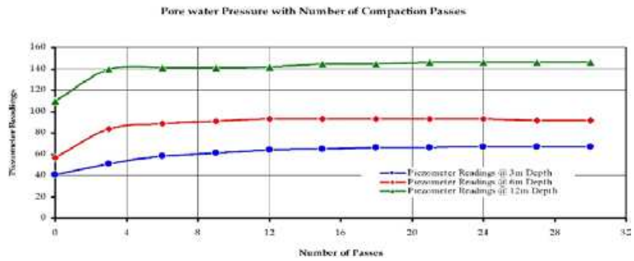


Fig. 4: Development of excess pore pressure with application of HIEDYC dynamic compaction

Pore water pressure measurements were again read a month later and the results show that the pore water pressures were locked in and remained the same. Following these measurements, prefabricated vertical drains (PVD) were installed and this resulted in a quick release of these excess pore water pressures.

The fundamental concept of dynamic consolidation utilises these results to demonstrate that dynamic consolidation can work, with installation of PVDs, to accelerate the consolidation of soft soils and to reduce the need for placement of high surcharge fills. The benefits that can be derived from dynamic consolidation are:

- The reduced requirement for high surcharge fill which will greatly reduce project costs,
- The instantaneous development excess pore water pressure can be quickly dissipated with the aid of PVDs. This significantly shortens the consolidation duration and subsequently project duration.

In other words, dynamic consolidation can further accelerate consolidation treatment of soft soils.

## 4 A CASE STUDY OF DYNAMIC CONSOLIDATION

This case study describes a ground improvement programme for the extension of the runway at Kota Kinabalu Airport in Sabah, Malaysia. A major part of the extension was on reclaimed land extending into the sea.

The seabed soils beneath the reclamation fill consist of compressible soft clayey silt occurring in varying thickness of 2 to 3m. Engineering properties of the soft clay are:

- $c_v$ of 2
- $c_c$ of 0.2 and
- $e_o$ of 0.9

The thickness of the hydraulic fill varies from 5m up to 8m. The initial design of the ground improvement works comprise of installation of prefabricated vertical drains spaced at 1m centres with a preload height of 3m placed. An analysis of this design yielded an estimated ultimate primary consolidation settlement in the region of 400mm and a waiting period of 9 months to achieve 90% degree of consolidation. An alternative approach using dynamic consolidation was adopted with PVDs at 1.2m centres, application of HIEDYC compaction and placement of 1.5m high surcharge fill.

Fig. 5 PVDs and HIEDYC compaction used for dynamic consolidation

Settlement monitoring was carried out. However, the placement of surcharge fill was staggered staggered over a period of nearly 1 year due to material shortage, as shown in Fig. 6.

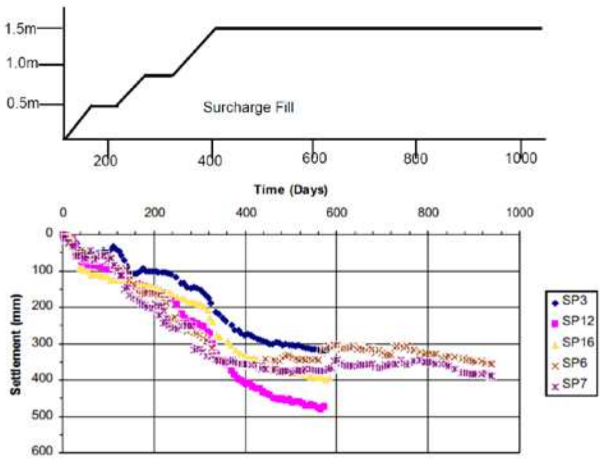


Fig. 6 Rate of placement of fill and settlement readings

The interpretation of the settlement monitoring data was carried out using the Asaoka Plot to assess the degree of consolidation achieved, Asaoka (1978). A summary of the results of the Asaoka Plots and the Settlement Data is presented in Table 2.

Table 2. Summary of consolidation settlement measurements

| *Instrument ID* | *Measured Settlement (mm)* | *Ultimate Settlement from Asaoka Plot (mm)* | *Degree of Consolidation* |
|---|---|---|---|
| SP6 | 347 | 375 | 92.53% |
| SP7 | 386 | 425 | 90.82% |
| SP3 | 340 | 350 | 97.14% |
| SP12 | 499 | 510 | 97.84% |
| SP16 | 410 | 425 | 96.47% |

## 5 SUMMARY

The application of High Impact Energy Dynamic Compaction technique in conjunction with prefabricated vertical drains and surcharge had been proven to be effective in obtaining a high degree of consolidation at a relatively short time in soft compressible soils. The HIEDYC dynamic compaction technique is able to impose deep compaction and at the same time induce development of instantaneous high pore water pressures within the soft soil deposit. The rapid dissipation of this excess pore water pressures is facilitated by the installation of prefabricated vertical drains.

An application of this technique for the ground treatment for the extension of the runway at the Kota Kinabalu International Airport has proven that degrees of consolidation in excess of 90% were consistently achieved even with reduced surcharge fill.

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