A case study of soft ground improvement by dynamic consolidation approach

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Abstract: There are several ground improvement approaches which can be utilised to deliver results which are sought after in when constructing over poor ground conditions. Where soft grounds, such as soft saturated clays, are encountered, ground improvement utilising consolidation approaches such as, surcharge with PVD, are commonly adopted. It is known that surcharge fill is required to pressurise the porewater within the soft clay, hence creating an excess pore pressure within the pores of the clay matrix. This excess pore pressure drives the pore water towards the PVD and upwards towards the drainage blanket. An alternative method to pressurise the pore water is by applying impact energy such as HIEDYC dynamic compaction. This approach has proven to be capable of developing excess porewater pressures in soft saturated clays. The excess porewater pressure is ‘locked-in’ due to the low permeability of the clay. The magnitude of this excess pore pressure has been measured as up to 30kPa which is equivalent to the placement of 1.5m surcharge fill height. Hence, this method is coined ‘DYCON’ or Dynamic Consolidation. This method will require installation of PVD but with reduced surcharge requirements [1].

1. Introduction

It is quite common for designers of embankments on soft ground to specify surcharge preloading to compensate or eliminate post-construction settlements. Frequently this is accompanied by installation of vertical drainage elements such as PVD to assist in dissipating the excess pore pressures generated. This mechanism of placing surcharge fill is primarily to alter the pore water pressure to exceed the expected future stresses from future loads. This fill also imposes a compression load to collapse the soil matrix once the excess pore water pressures have been dissipated. This will manifest as ground settlements.

An alternative method to pressurise the pore water is by applying impact energy such as utilising dynamic compaction technologies available. This approach has proven to be capable of developing excess pore pressures in soft saturated clays. The excess pore pressure is ‘locked-in’ due to the low permeability of the clay. Hence, this method is coined ‘DYCON’ or Dynamic Consolidation. This method will require installation of PVD but with reduced surcharge requirements [1].
Dynamic consolidation adds another dimension to the pre-consolidation treatment of soft clays. This process merges dynamic compaction technologies to conventional consolidation processes. The application of dynamic stresses imposes instantaneous prestress in the pore water and creates instantaneous pore water pressures in the underlying soft clay. This effect is similar to that created by conventional surcharge preload. The provision of vertical drainage elements assists in accelerating the dissipation of the excess pore water pressures.

A case study of application of this approach in ground improvement in soft ground is described in this paper.

2. Conventional 1D Consolidation Model

In a conventional 1D consolidation model, surcharge fill is utilised to increase the stresses within the pore water system. This increase in pore water pressure is termed excess pore water pressure. As the permeability of soft clays is often low, thus the drainage of this excess pore pressure is also a slow process. The objective in soft ground treatment is to accelerate the dissipation of this excess pore water pressure by introducing vertical drains [2].

This process of consolidation is often explained with an idealized system composed of a spring, a container with a hole in its cover, and water as illustrated in Figure 1. In this system, the spring represents the compressibility or the structure of the soil itself, and the water which fills the container represents the pore water in the soil.

![Figure 1. Idealised Concept of 1-Dimensional Consolidation Process.](image)

1. The container is completely filled with water, and the hole is closed. (Fully saturated soil)
2. A load is applied onto the cover, while the hole is still unopened. At this stage, only the water resists the applied load. (Development of excess pore water pressure)
3. As soon as the hole is opened, water starts to drain out through the hole and the spring shortens. (Drainage of excess pore water pressure)
4. After some time, the drainage of water no longer occurs. Now, the spring alone resists the applied load. (Full dissipation of excess pore water pressure. End of consolidation)

The other function of the surcharge fill is to exert an overburden pressure to pre-collapse the soil matrix once the excess pore water pressure has been dissipated through the vertical drains. This process will result in consolidation settlement of the embankment.

This process results in ground settlement. The primary consolidation settlement in normally consolidated clay can be estimated as shown in Equation 1:

\[
\delta_c = \frac{c_c}{1+e_o} \cdot H_o \cdot log \left( \frac{o'_z f}{\sigma'_zf} \right)
\]  

(1)
Where
\[ \delta_c \] is the settlement due to primary consolidation.
\[ C_c \] is the compression index.
\[ e_0 \] is the initial void ratio.
\[ H_o \] is the thickness of the consolidating soil layer.
\[ \sigma'_zf \] is the final vertical stress.
\[ \sigma'_zo \] is the initial vertical stress.

This approach in treatment of soft ground requires adequate and ready supply of fill material to be used as surcharge material. In many instances, this resource is not readily available in adequate quantity. Hence, an alternative approach is proposed in applying this prestress load in place of high surcharge fill. Dynamic consolidation offers an opportunity to re-engineer the ground treatment process. Dynamic consolidation utilises dynamic compaction technology to apply a dynamic impact load to pressurise the pore water.

3. An Overview of Dynamic Compaction Technologies
Dynamic 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. However, recent developments have shown how dynamic compaction technologies can also be applied for treatment of soft clays, a process called ‘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 below [1, 7].

3.1 Deep Dynamic Compaction (DDC) with drop weights
The Deep Dynamic Compaction technique involves using a crane to drop weights of between 5 to 20 tons, from heights of up to 20m. The number of drops, weights used and the height of the drops depend on the required post-treatment bearing capacity, settlement performance and soil conditions [3]. DDC is commonly used in reclaimed areas, land fill rehabilitation to provide a strong ground with less susceptibility for settlement or differential settlement. The authors experience, however, has shown that DDC can be used in soft clays in combination with Vertical Drains that can withstand the impact of the drop weight.
3.2 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 is minimised. With the use of HIEDYC ground treatment process, the levels of vibration are relatively low and the use of HIEDYC ground treatment is suitable close to existing structures. 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 [1, 4, 5]. Figure 3 illustrates the various modules currently available.

HIEDYC treatment is possible for landfills, sands, silts and clays. It is the author’s experience that HIEDYC treatment will be effective when combined with prefabricated vertical drains. This scheme has been adopted in tailing ponds, airports and housing schemes by the authors’ company. Figure 4 shows a HIEDYC Tria (3 sided) working in a soft ground condition.

Figure 2. Example of Deep Dynamic Compaction (ref: Wikipedia).

Figure 3. Visuals of Tria (3-sided), Qadra (4-sided) and Penta (5-sided) HIEDYC modules (L to R) (courtesy of Infra Tech Group).
3.3 Rapid Impact Compactor (RIC) and Controlled Dynamic Compaction (CDYC)

The RIC unit is generally fitted to tracked base excavator of 35 tonne to 70 tonne weight which provides the dual benefit of allowing improved mobility and site accessibility. Having the RIC mounted on a tracked machine gives it the versatility to move about in narrow and limited height spaces, such as within existing warehouses and urban area lots. Also, being mounted on a tracked excavator, transport to site is easier. Figure 5 shows RIC in operation.

CDYC is similar to RIC and is the acronym for Controlled Dynamic Compaction technique. Figure 6 shows CDYC in operation. The authors’ experience have been that CDYC has been found to achieve deep compaction in sand and silts greater than 7m depth [4, 6]. Dynamic energy is imparted by a dropping a weight by hydraulics from a controlled height onto a foot plate of 1m² or 1.5m² 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. The drop height varies from 1m to 2m. Energy is transferred to the ground safely and efficiently as the RIC/CDYC's foot remains in contact with the ground. This is quicker than conventional DDC but the energy input is smaller per blow. Blows at each treatment position create imprints, which are subsequently filled with granular material.
The authors’ experience is that both DDC and HIEDYC in combination with PVD can be useful for deployment in soft clays.

4. An Overview of Dynamic Consolidation

Dynamic consolidation involves applying dynamic energy to pressurise the pore water [3] and to accelerate consolidation of the underlying soft ground using one of the dynamic compaction methods identified in Section 3 above and in combination of vertical drains. The authors have carried out a research with application of HIEDYC dynamic compaction on a soft clayey soil where 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 1.5m high surcharge fill. These results are indicated in Figure 7. 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 these resulted in a quick release of these excess pore water pressures [1].

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:

i. The reduced requirement for high surcharge fill will greatly reduce the overall project costs, in addition to mitigating need to source suitable fill material in areas where these materials are not readily available or costly [5].

Dynamic consolidation creates instantaneous development of excess pore water pressures, which can be quickly dissipated with the assistance of PVDs. This may result in much reduced requirement for lengthy consolidation or rest period thereby shortening project durations.
Figure 7. Development of excess pore water pressures with application of HIEDYC dynamic compaction.

5. Case Study
A case study of where the dynamic consolidation approach was utilised in accelerating the consolidation of soft marine clay. The project site is located in Batu Kawan, Penang where a Sales Gallery and show houses for a housing development are required to be constructed on a fast track basis. The geology map shows that the site is underlain by a quaternary deposit as shown in Figure 8.

Figure 8. Geology map of the site.

5.1 Subsoil Properties of Site
Typical SPT-value vs depth profile of the subsoil is illustrated in Figure 9.
Figures 10, 11 and 12 illustrate the distributions of compression ratio, coefficient of consolidation and over-consolidation ratio with depth below ground surface, respectively.

**Figure 9.** Typical distribution of SPT N-value.

**Figure 10.** Compression Ratio.

**Figure 11.** Coefficient of Consolidation.
Figure 12. Over-Consolidation Ratios (OCR).

As can be observed, the subsoil is comprised essentially of normally consolidated clay with compression index in the region of 0.2 and a coefficient of consolidation ranging between 1 and 4.

5.2 Earthwork and ground improvement processes
The existing ground surface was for the site was approximately at RL1m. The platform for the proposed Sales Gallery is to be raised to RL4.2m, whereas the platform for the Show Houses is to be raised by 3.0m. The ground improvement design comprised of installation of PVD at 1.0m centres and a surcharge fill of 1.0m. HIEDYC dynamic compaction was carried out at the base of fill as well as at the design platform level. The body of fill and surcharge fill were compacted by conventional vibratory rollers in accordance to the earthworks specification. Geosynthetic strip drains were used as drainage layer in place of a sand layer. The conventional design for the ground improvement was to install PVD at 1.0 centres with a surcharge fill of 2.0m.

Geotechnical instruments installed at the site include rod settlement gauge, piezometers and inclinometers. These were monitored regularly on a weekly schedule during the earthworks and surcharging durations.

5.3 Settlement monitoring results
The settlement monitoring of RSG1 at the Sales Gallery is shown in Figure 13.
The settlement monitoring of RSG2 at the Show Houses is shown in Figure 14.

As can be observed, settlement at both locations levelled off at about 126 days from the start of filling, i.e. approximately 60 days from the completion of fill placement. The bulk of the observed settlement occurred during placement of fill. The predicted total settlement at the Sales Gallery is 1.2m and 1.05m at the Show Unit using lower bound soil properties. The observed settlement appeared to match the predicted settlement fairly accurately.

5.4 Project deliverables and Pictorial illustration of project activities

The project deliverables are an allowable bearing capacity of 200kPa. This was validated via Plate Bearing Tests using 500mm diameter plates. Results show settlements at ultimate load of 200kPa (is less than 3mm and settlements at 400kPa (i.e. twice design load) remain less than 8mm. Typical results from plate bearing tests are shown in Figure 15. With these results the foundation of the Sales Gallery and Show Houses were constructed on Raft Slabs. Figure 16 to 19 illustrate the critical project activities and project deliverables.
6. Summary
This paper described an overview of conventional consolidation treatment of soft soils, an overview of dynamic compaction technologies currently available and the application of dynamic consolidation processes in soft ground improvement. It illustrated an opportunity to utilise this dynamic consolidation technique for soft ground treatment in situations where road embankments are to be constructed over soft ground.
A case study was described to illustrate the dynamic consolidation approach in treatment of deep soft soil exceeding 25m depth to enable construction of earth embankments and structures over soft ground. The approach illustrated the benefits that can be derived, namely reduction in requirement of surcharge fill, accelerated settlements and increased bearing capacity. The case study also illustrates an innovative use of geosynthetics as horizontal drainage element in place of conventional sand blanket. This geosynthetic strip drain possesses a consistent drainage capacity in comparison with the drainage capacity of sand blanket. It is commonly known that the drainage capacity of sand blanket is highly influenced by its clay or silt content, and it is difficult task to ensure the clay or silt content is kept to a consistent minimum value.

This case study thus illustrates an alternative approach in treatment of soft soil and is recommended for sites with similar soft soil condition. It is particularly suitable where supply of fill for surcharging is sparse or costly.

7. References
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