Innovative soft clay improvement technique using vacuum and dynamic compaction (HVDM)

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ABSTRACT
Recent advances in soft clay improvement that involves the use of vacuum dewatering and deep dynamic compaction are described in this paper. The working principles of the series of invention termed "High Vacuum Densification Method" are described, followed by a discussion of advantages in terms of cost and time saving. Two case studies are presented to elucidate the practical HVDM process. Detailed observations from instrumentation at the Ningbo Port Project provided in-depth knowledge of the soil improvement mechanisms associated with HVDM.

RÉSUMÉ
Este artículopresentaavancesrecientes en el mejoramiento de arcillassuavesinvolucrando el usode ladeshidrataciónbajovacío yla compactacióndinámicaprofunda. Los principios de operación de la técnicadenominada"Método de Densificación de Alto Vacío-MDAV" son descritos y lasventajasasociadasaésta en términos de disminución de tiempo y costosson discutidas. Con el fin de elucidar el procesopráctico de operacióndel MDAV, dos casos de estudioson presentados. Elartículoincluyeobservacionesdetalladasde la instrumentaciónutilizada en el proyectodel Puerto de Ningbo, lascualessuministraronelementospara el entendimiento a profundidad de los mecanismos de mejoramiento delsueloasociados con el MDAV.

1 INTRODUCTION

In-situ improvement of soft cohesive soils is one of the main challenges facing geotechnical engineers and contractors alike. In countries such as China, India, and other emerging countries in Asia where population is large and infrastructure development is in heightened pace, the need for fast, economic in-situ improvement of soft cohesive soils in a large-scale is clearly evident. The traditional methods of soft cohesive soil treatments include the use of the following techniques: (a) prefabricated vertical drains (PVDs) and fill preloading, (b) vacuum consolidation together with PVDs, (c) stone columns, (d) thermal treatment, (e) chemical mixing, (f) electro-osmosis, and (f) deep dynamic compaction. Despite the availability of various methods of in-situ improvements listed in the above, the method incorporating PVDs with fill preloading appears to be the most widely used technique throughout the world, even though recently the vacuum consolidation method seems to gain some interests. In applications, such as land reclamation of the dredged materials, port facility constructions, economic zone development along the coastal areas, petro-chemical plants near shorelines, steel mills and power plants, airport runways and highways, the areas to be treated could be excessively large and the availability of usable earth for fill preloading could be scare. Therefore, there is a great interest in developing a more effective way of treating soft cohesive soils in a large area where preloading fill could not be economically found (Indraratna etc. 2010, Kjellman 1952).

Due to rapid infrastructure development in China, an innovative soft cohesive soil treatment technique was developed in 2000 and had since been rapidly applied in China and other countries in Asia. The core of this innovative, in-situ, cohesive soil treatment method was termed as "High Vacuum Densification Method (HVDM)", and was granted a series of international patents and registered in more than 25 countries. The success of HVDM was quite remarkable in a sense that the technique blends two well known soil improvement methods, vacuum consolidation and deep dynamic compaction, into an intelligent yet efficient soft soil treatment method that can treat a large area within a relatively short time period (Liang and Xu 2010, Mostafa 2010).

The purpose of this paper is to present the working principles of HVDM. In addition, the two variations of HVDM that can work together with other soft soil treatment techniques will be described. The two variations are vacuum preloading plus HVDM, and HVDM plus stone columns. The main applications of these two variations are to treat deep soft soil deposit and to achieve higher bearing capacity, respectively. Case studies will also be presented in this paper.

2 METHOD I: HVDM (HIGH VACUUM DENSIFICATION METHOD)

HVDM is a patented, fast soft soil treatment method. It combines efforts of vacuum drainage and deep dynamic compaction in designated cycles, so that soils at the project site can be improved through the effects of lowered water content and increased density. As a result, soil strength and stiffness are improved. Furthermore, total and differential settlements after HVDM treatment are minimized.

2.1 HVDM - Its Root

The development of HVDM can be traced back to early 2000, when the inventor (the patent holder), Mr. Shi-Long Xu of Shanghai Geoharbour Group, started experimenting the concept of high vacuum densification method and applying it in large-scale to many well known projects around Shanghai, such as Shanghai Pudong Airport Runway No. 2, Shanghai Formula F1 Race Track, Shanghai port expansion. Mr. Xu later filed patent application and received PCT (Patent Cooperation Treaty) approval for several separate but related soft ground improvement technologies. Among the three main patents are the following: (a) patent no. ZL01127046.2, involving the use of multiple cycles of high vacuum process and varied dynamic compaction efforts (or mechanical compaction) to reduce water content in soft soils, (2) patent no. ZL 200410014257.9, involving the combined use of surcharge preloading or vacuum consolidation, followed by HVDM, and (3) patent no. ZL 200510134966.5, involving the use of HVDM followed by construction of stone columns or other types of composite foundations. After initial successful applications in Shanghai area, HVDM was expanded into other areas in China and other countries in Asia, such as Vietnam, Malaysia, and Indonesia. Currently, HVDM has become a major method used in land reclamation projects along the coastal areas in China, with over 9 million meter square of land treated in the last 7 to 8 years.

2.2 HVDM - working Principles

HVDM can be described as a fast ground improvement technology utilizing drainage, consolidation, and densification principles. HVDM is generally executed in a controlled manner based on feedback of on-site monitoring data for both QA/QC purpose. Figure 1 provides a schematic drawing of HVDM using vacuum consolidation and deep dynamic compaction. The HVDM consists of the following steps:

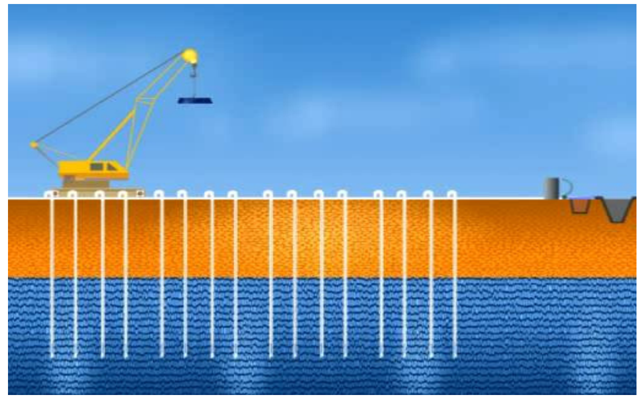

Figure 1. Schematics of HVDM method.

Step 1: Conduct detailed geotechnical investigation at the project site. Evaluate and determine soil profile at the site with detailed knowledge of the depth and thickness and distribution pattern of soft soils requiring treatment. Obtain important basic soil properties, including gradation curves, Atterberg Limits, water content, hydraulic conductivity, compressibility, and coefficient of consolidation. Conduct in-situ tests, such as CPT or STP to establish baseline values prior to commencing HVDM in the field. Understand and establish performance criteria of ground treatment. Perform preliminary design to provide plans for optimum spacing and depth of vacuum pipes, energy level of deep dynamic compaction and number of drops and grid spacing of tamper, time needed for vacuum consolidation between cycles of dynamic compaction, etc. However, it should be emphasized that the initial plans will generally need to be modified based on on-site monitoring data and the expected final performance criteria.

Step 2: Install vertical vacuum pipes and horizontal drainage pipes. The vertical vacuum pipes can be installed using several different methods, such as a vibratory hammer and a mandrel, or a hydraulic system to directly push vacuum pipes into ground. It is noted that vacuum pipes are steel pipes, typically 1 to 1.25 inch in outside diameter, and 1/8 inch in thickness. The vacuum pipes contain perforated holes and are wrapped around on the outside by a geotextile fabric for filtration purpose. The horizontal drainage pipes are typically PVCs, which are connected to steel vacuum pipes through an elbow connector. Figure 2 shows an array of horizontal drainage pipes connected to vertical vacuum pipes at a project site.

Figure 2. Array of vacuum pips and horizontal drainage pips.

Step 3: Apply first cycle of vacuum to reduce water content in the influence zone. This is a phase in which vacuum induced dewatering of cohesive soils takes place. Generally, the net effect of this phase of vacuum dewatering is an increase of effective stress up to about 50- 80 kPa, depending upon the efficiency of vacuum consolidation. It is noted that the highest vacuum pressure that can exert on the pore water in the soil is 1 atmosphere pressure, 100 kPa. The undrained strength gain of normally consolidated soft clays corresponding to 50 to 80 kPa effective stress increase is roughly 15 to25 kPa. Therefore, this phase of vacuum dewatering is primarily for making the site accessible for equipment to carry out the next phase of work, i.e., deep dynamic compaction. The time for completing this cycle of vacuum consolidation is dictated by spacing of vertical vacuum pipes and horizontal hydraulic conductivity of the soils. Smearing effects due to installation of vertical vacuum pipes need to be taken into account. Nevertheless, this phase of work is usually completed within 7 days before proceeding to the next phase of work.

Step 4: Apply deep dynamic compaction to create crater and to generate positive pore water pressure. The direct impact by the heavy tamping creates crater, resulting in displacement of soils and the corresponding reduction in void ratio (direct densification), while producing positive pore pressure in the influence zone. Previous studies indicated that deep dynamic compaction in cohesive soils can cause rapid increase of both pore water pressure and gas pressure, whether the soil is fully saturated or not, due to the presence of micro air bubbles. The important controlling parameters of dynamic compaction are the weight, dimension, drop height, grid spacing, and number of tamper drops per spots. The decision of these parameters needs to be made from site monitoring results to ensure that the soils underneath the bottom of the crater do not suffer undrained shear failure or the so called “rubber soil” phenomenon. Typical dimension of the tamper is about 1 to 1.5 meter in diameter, and the weight can vary from 20 to 70 tons. The tamper drop height varies from 10 meter to about 20 meter. A study by Mostafa (2010) provides useful correlations between crater depth, soil properties, influence zones, and tamper energy. The charts presented in Mostafa’s dissertation could be used in the preliminary selection of the controlling parameters. The duration of this phase of work can be accomplished within 7 days for a typical 10,000 meter square coverage area.

Step 5: Apply the second cycle of vacuum to facilitate rapid dissipation of pore pressure and to further reduce water content and void ratio of the soils in the influence zone. The combined efforts of vacuum generated negative pore water pressure and the deep dynamic compaction generated positive pore water pressure create very high pore pressure gradient, which in turn help facilitate accelerated dissipation of pore water pressure, resulting in reduced water content. The duration of this phase is generally 7 days or less.

Step 6: Evaluate the soil properties after completing Step 5. In particular, the water content, pore pressures, ground water elevation, ground subsidence, and in-situ test results such as cone resistance of CPT or N values of STP, need to be determined to assess the results of the first cycle (Steps 4 and 5) of HVDM process. Evaluation of the outcome of ground improvement at this stage would allow for adjusting the operation parameters (spacing and depth of vacuum pipes, dynamic compaction energy level and grid spacing of tamping points, etc.) in the next cycle of HVDM process.

Step 7: Repeat Steps 4 to 6 until the performance criteria are satisfied. It should be pointed that in general two cycles of HVDM process are generally sufficient to achieve the required performance criteria, such as strength as determined by CPT or STP and the post-treatment settlement.

2.3 Distinguishing Features of HVDM

Through the use of high vacuum system and adjustment of compaction parameters, the water content in the soil can be reduced. This creative use of high vacuum effectively overcomes the conventional reluctance in using dynamic compaction in saturated soft soils. Furthermore, with the sequenced and repeated cycles of vacuum dewatering and deep dynamic compaction, HVDM can successfully treat soils with low permeability within a significantly shortened duration. HVDM produces a hard shell of up to 5 to 8 meter in thickness on the surface of the treated ground, which serves as an excellent load bearing layer and an impervious seepage barrier. The hardened and impervious shell effectively diffuses the surface loads and impedes drainage of water from soils underneath the hardened surface layer, thus effectively reducing post-treatment consolidation rate (if any) with the beneficial results of minimized post-treatment total and differential settlement.

2.4 Advantages and Limitations of HVDM

Technical breakthrough of HVDM includes: (a) extending the vacuum well drainage to fairly impermeable cohesive soils, (b) overcoming the common notion that dynamic compaction could not be applied to saturated cohesive soils, and (c) expediting pore pressure dissipation due to creation of high pore pressure gradient. The results of HVDM include the following particular end products: (a) creation of a highly over-consolidated clay layer on the upper portion of the ground with thickness in the range of 5 to 8 meters depending upon the deep dynamic compaction efforts and the influence zone, (b) eliminating the post-treatment drainage path due to withdrawal of vacuum pipes from the ground after completion and creation of a fairly impervious soil layer on the ground surface, which is contrast to the conventional PVDs that would have to be left in the ground. The limitation of HVDM include that the treatment depth cannot exceed 10 meter due to the limit of influence zone of deep dynamic compaction and loss of efficiency for vacuum dewatering exceeding that depth. In addition, cohesive soils contain large portion of organic materials may not be suitable for HVDM. The range of cohesive soils for HVDM is fine grained soils with hydraulic conductivity not less than 5 × 10-7 cm/sec.

2.5 QA/QC Process

The success of HVDM depends upon intelligent utilization of field monitoring of relevant information to allow for optimization of HVDM operation parameters, including heavy tamping energy (mass of tamper, height of drop, spacing and number of drops per spot) and vacuum consolidation parameters, such as vacuum pipes spacing and depth, among others. Field monitoring typically includes measurement of pore water pressure, ground water level, crater depth, ground subsidence, water content, and CPT (or SPT).

3 METHOD II: VACUUM CONSOLIDATION / SURCHARGE PRELOADING FOLLOWED BY HVDM

Vacuum consolidation was first introduced by Kjellman (1952). Since then, there have been many successful applications of vacuum consolidation for soft soil improvement. Recent research efforts by Professor Indraratna (2010) have significantly advanced state of art in vacuum consolidations. The advantages and practical guidelines are well documented in a series of publications by Professor Indraratna. However, vacuum consolidation by itself cannot accomplish the necessary strength gains to meet project requirements due to the fact that only about 15 kPa to 25 kPa of undrained shear strength improvement can be achieved. Therefore, vacuum consolidation is often combined with surcharge using fills, in conjunction with PVDs for accelerated consolidation. The treatment depth of vacuum consolidation/ preloading using fill can be greater than 8 to 10 meters, which in fact is the limit of HVDM. Nevertheless, if HVDM is applied after vacuum consolidation/fill preloading, then it is likely that the amount of preloading load could be reduced. Therefore, it is worthwhile to evaluate the pros and cons between using vacuum consolidation/surcharge preloading followed by HVDM and surcharge preloading only. Of course, the outcome could be dependent upon the performance criteria of the project.

3.1 HVDM plus Composite Foundation

For the projects that may need to install deep foundation or other vertical columns (e.g., stone columns, jet grouting columns, deep soil mixing columns, etc.) in soft clay to support heavy loads, such as oil storage tanks, HVDM could used first to improve the ground. As demonstrated in Figure 3, ground improvement by HVDM plus composite foundation provides the following distinctive advantages: (a) Optimized shaft/soil load, decreased negative friction on shaft, increased side shaft friction, and reduced number of shafts, (b)Reduced total and differential settlements, and (c) reduced cost and construction schedule compared to piling foundation.

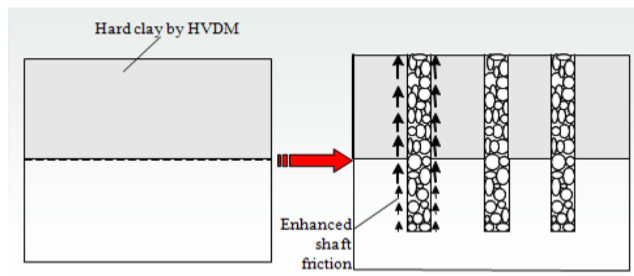

Figure 3. HVDM plus stone columns as composite foundation.

3.2 Selection of Suitable HVDM Series of Methods

As discussed in the previous sections, three variations of HVDM techniques are available for different site conditions and performance criteria. HVDM is most suitable for treating clay deposits to the depth of no more than 8 to 10 meters. Vacuum consolidation/preloading, supplemented with HVDM, could be most suitable for treating soils to the depth greater than 10 m. HVDM plus composite foundation could be most suitable for providing high load carrying capacity to support heavy loads. Based on vast experiences in the past 5 to 6 years in China, HVDM series of methods, when used appropriately, could provide cost savings up to 50 % compared to the use of PVDs and fill preloading. Also, HVDM series of methods generally can expedite ground improvement by cutting project duration close to 50 % compared to the conventional surcharge preloading method. The necessary QA/QC procedure during the entire HVDM process ensures that the end product will meet the performance criteria. HVDM is a green technology as it does not involve the use of any chemical additive.

4 CASE STUDIES

4.1 Case I: Shanghai Pudong Runway No. 2

The area to be treated for construction of Pudong Airport Runway No.2 was about 110 hectares. The soil conditions prior to treatment are depicted in Figure 4. As can be seen, the soils are essentially very soft bay mud with thickness in the range of 20 m to 30 m. The ground improvement criteria consist of limiting post treatment settlement and differential settlement not to exceed 10 cm and 1/1000, respectively. Ground subsidence during HVDM was observed to be 55.7 cm. After the runway has been in service for nearly 6 years, the monitored settlement was in the range of 10 cm. The ground improvement job at Runway No. 2 was completed in 4 months. The use of HVDM was able to save the Pudong Airport Authority roughly 100 million RMB, compared to the use of the traditional ground improvement method involving the PVDs and fill surcharge.

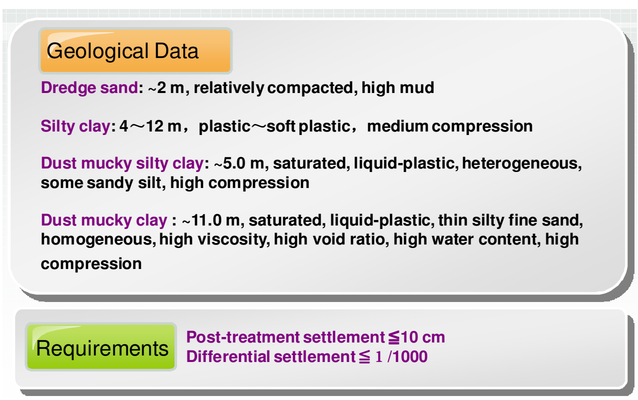

Figure 4. Soil profile at Shanghai Pudong Airport Runway No. 2 Project.

4.2 Case II: Ningbo Port

This is a land reclamation project with an objective to provide a site for coke storage with the intended storage up to 5 million ton per acre of area. The soil profile at the site consists of a 2 m of fill of sand, underlain by a 1.7 m of hydraulically filled fly ash, and underlain by a 2.3 m of mud clay layer, and then underlain by a 1.2 m of silty sand. The first phase of treatment area is about 300,000 square meters with the requirement that the improved site can provide bearing pressure up to 30 to 40 kPa. Pictures of site condition prior and after HVDM are shown in Figure 5. Typical comparisons of CPT cone resistance results before and after HVDM are shown in Figure 6.

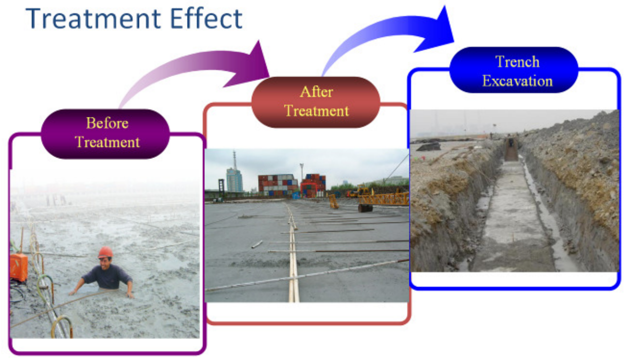

Figure 5. Photos of site condition prior and after HVDM.

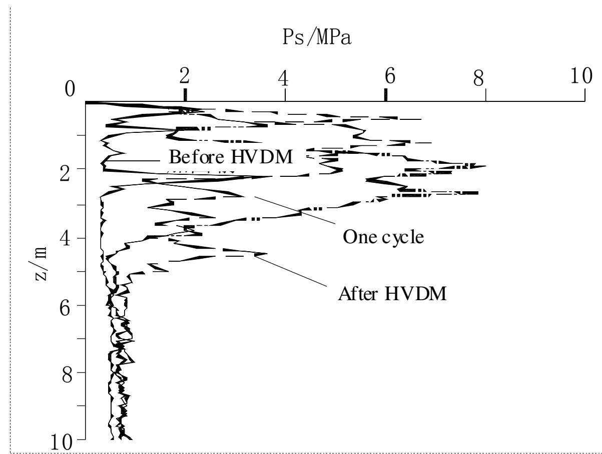

Figure 6. Comparison of CPT cone resistance between before and after HVDM.

As part of this project, a test program was conducted in four subdivisions shown in Figure 7. The vacuum pipes and PVDs arrangements in each zone are summarized in Table 1. The deep dynamic compaction controlling parameters for each subdivision are presented in Table 2.

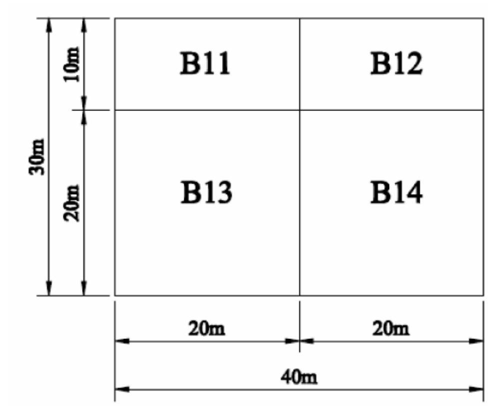

Figure 7. Subdivisions at the test site at Ningbo Port Project.

Table 1. Arrangement of vacuum pipes and PVDs.

Areas	Wick Drains Spacing (m)	Wellpoint (6 m deep) Spacing (m)	Wellpoint (3 m deep) Spacing (m)
B11	1.1×1.1	3.5×5.0	3.5×2.25
B12	1.1×1.1	3.5×5.5	3.5×2.75
B13	1.1×1.1	3.5×5.0	3.5×2.25
B14	1.1×1.1	3.5×5.5	3.5×2.75

During the experimental program, several items of the site response were monitored. The surface elevation was measured with a 5 m by 5 m grid. Pore pressure sensors were installed at the depths of 3.5 m and 6 meter. A groundwater observation well down at 4 m elevation was installed and monitored twice a day. Water content in the soil was measured prior to and after each cycle of dynamic compaction. Monitoring of vacuum pressure was also performed at the test site. As part of evaluation of the soil properties, static cone Penetration, vane test, plate load test, and STP were conducted.

Table 2. Dynamic compaction controlling parameters.

Areas	Spacing (m)	1st Stage of DC		2st Stage of DC	
		Effort (kN.m)	Drops	Effort (kN.m)	Drops
B11	4.0×4.0	800	3	1200	2
B12	4.0×4.0	1200	2	1600	2
B13	4.0×4.0	800	3	1200	2
B14	4.0×4.0	1200	2	1600	2

4.3 Analysis of Monitoring Results at Test Sites

4.3.1 Surface settlement

At the end of each cycle of dynamic compaction, the settlement for both Sub-divisions B11 and B12 was 42 cm, 6 cm, and 7 cm, respectively. For both Sub-divisions B13 and B14, the settlement was 35.3 cm, 29.5 cm, and 8.9 cm, respectively. As can be seen, in all cases the first cycle of dynamic compaction had induced about 50% of total surface settlement.

4.3.2 Pore pressure monitoring results

Representative pore pressure response is shown in Figure 8 and Figure 9 with HVDM and with PVD, respectively. It can be seen that pore pressure dissipation rate is very high when vacuum is applied. With HVDM, dissipation of pore pressure occurred very rapid. Within 3 to 4 days, 90 % of pore pressure had been dissipated. In contrast, the site with PVDs only, it took about 10 to 14 days to dissipate pore pressure completely.

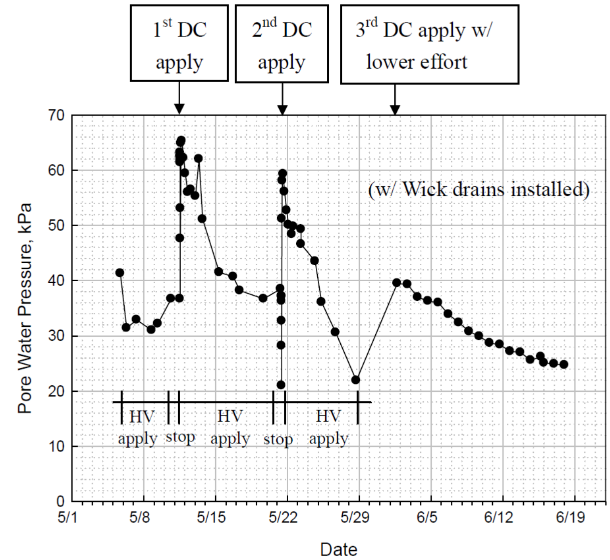

Figure 8. Pore pressure response due to PVDs and vacuum dewatering.

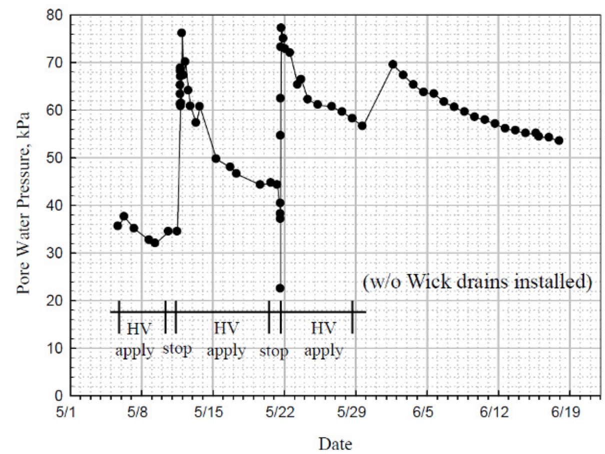

Figure 9. Pore pressure response due to PVDs and variation.

4.3.3 Groundwater observation

The original groundwater elevation was about -0.735 m. After the first cycle of HVDM, the groundwater elevation was lowered to -2.3 m. There was not much of further groundwater elevation change due to the subsequent cycles of HVDM.

4.3.4 Water content

In the hydraulically filled fly ash layer, the water content was reduced from 54.7 % to 39.9 %, with an average of 15 % reduction. In the clay mud layer, the water content was lowered from 53 % to 36 %, with an average of 17 % reduction. In the silty sand layer, the water content did not change. Therefore, it can be concluded that HVDM can reduce water content down to 5 to 6 meter from ground surface. However, HVDM would not affect the water content in the soil layer that is 10 m or deeper from ground surface. No benefits of consolidation or densification are expected for the soils at or greater than this depth.

4.3.5 Vacuum pressure monitoring

The vacuum pressure can reach about 0.5 to 0.8 MPa in the beginning; however, the vacuum pressure would reduce as the elapsed time of vacuum consolidation increases. The smallest vacuum pressure observed was about 0.2 to 0.4 MPa.

4.4 Evaluation of Improvement Results

Sub-divisions B11 and B13 were subjected to higher impact energy and less number of impact, while Sub-division B13 had PVD installed. Sub-division B12 and Sub-division B14 were subjected to lower impact energy but with larger number of drops. Sub-division B14 had PVD installed. The average improvement of the entire site B is as follows. In layer 1-2, cone resistance increased from 0.74 MPa to 2.51 MPa, with an improvement ratio of 3.37. In layer 1-3, the cone resistance increased from 0.21 MPa to 0.35 MPa, with an improvement ratio of 1.66. In comparing B13 to B11 or B14 to B12 (i.e., zones with PVD and zones without PVD), it can be seen that cone resistance can be in average 10 to 20 % higher in zones with PVD than in zones without PVD.

5 SUMMARY AND CONCLUSIONS

In this paper, recent advances in soft clay improvement techniques using principles of vacuum dewatering and deep dynamic compaction were described. Specifically, a series of invention that is commonly referred to as “High Vacuum Densification Method (HVDM)” was described in this paper. The work principles of HVDM and its two variations, in a form of preloading/HVDM and HVDM/composite foundation respectively, were presented in detail. The distinctive features and potential benefits in terms of cost and time saving of using HVDM, in comparison to the traditional method of PVDs with fill preloading, were elucidated. Two case studies were presented at the end of the paper, in which Case I presented a successful use of HVDM to improve large area for Pudong Airport Runway No. 2 and Case II presented the monitoring and evaluation results of a pilot testing program at the Ningbo Port Project. In Case II, site monitoring data confirmed the beneficial effects of HVDM in reducing water content and in increasing cone resistance, thus providing in-depth understanding of the working principles and soil improvement mechanisms of HVDM.

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