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Innovative Soft Clay Improvements Using Vacuum and Dynamic Compaction

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ABSTRACT

An innovative soft clay improvement technique involving the use of vacuum and dynamic compaction (commonly referred to as HVDM) has been advanced in China in the past five to six years. In this paper, the working principles and main technology breakthrough of the HVDM are presented, followed by a brief discussion of a successful case. The benefits of the HVDM in comparison with the conventional PVD (Prefabricated Vertical Drains) and surcharge preloading are evident in savings in both construction time and money.

1. INTRODUCTION

In the past, the application of vacuum to facilitate consolidation in saturated cohesive soils has been used either alone or in combination with static surcharge loading (Holtz, 1975). The effectiveness of vacuum consolidation with or without surcharge loading is highly dependent upon soil permeability and the specific vacuum application techniques, as well as the desired degree of improvement and the allowable time duration for completing improvements. The dynamic compaction (DC) technique, although was mentioned by Menard (1975) as a feasible technique for use in saturated cohesive soils, has not been widely accepted by the U.S. Federal Highway Practice Manual for use in cohesive soils. The combined use of vacuum and dynamic compaction has never been used previously for treating cohesive soils. However, recently, an intelligent manner of combining the vacuum and dynamic compaction has been advanced in China for successfully treating a vast area of soft saturated clay deposits for land reclamation, highway, and harbor projects. This innovative soft cohesive soil improvement technique has been patented and referred to as "High Vacuum Densification Method (HVDM)" to reflect its combined uses of vacuum and dynamic compaction techniques (Chang, et al. 2010). The purpose of this paper is to describe the working principles of the HVDM, followed by a brief summary of a successful project in China.

2. WORKING PRINCIPLES OF HVDM IN COHESIVE SOILS

The general construction method of HVDM is illustrated as a flow diagram in Figure 1. First, as shown in Figure 2, it involves installation of perforated steel pipes into the ground as vacuum pipes. Next, specially designed and air tight elbow connectors are used to connect vertical vacuum pipes with the horizontal PVC pipes, which in turn are connected to vacuum pumps for vacuum dewatering of the soils. Figure 3 provides a photo of the horizontal PVC pipe network at a project site. Once vacuum dewatering has successfully reduced water content of clays to the extent that the degree of saturation is in the range of 85 to 90%, then dynamic compaction (see Figure 4) is commenced to not only densify the soil but also to generate positive pore water pressure in the soil zone influenced by DC. The combination of negative pore pressure generated by vacuum and positive pore pressure generated by dynamic compaction can create a very high pore pressure gradient which in turn expedites dissipation of pore water pressure and further reducing water content and void ratio of the soils in the affected zone. Since pore pressure gradient is greater than that can be generated by vacuum only, the rate of pore pressure dissipation with HVDM principles can be very fast. It should be pointed out that the HVDM is a repeated process of vacuum and dynamic compaction, with each successive cycle involving the use of higher tamper impact energy to achieve the desired density and depth of treatment. To ensure the success of the HVDM, experience and calculation based methods have been developed to assist engineers to determine the appropriate tamper energy at each round of DC and the optimum vacuum duration in between each round of DC. Furthermore, on-site monitoring and observation on the variation of pore water pressure, water content, groundwater elevation, and CTP cone resistance is conducted not only for QA/QC purposes but also for real-time feed to allow engineers to adjust the HVDM operation parameters.

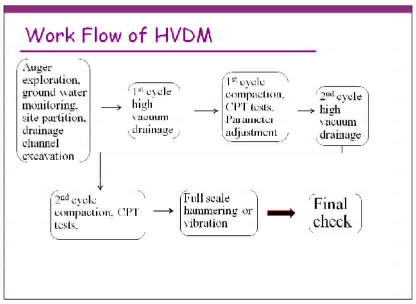


Fig. 1: Work Flow of HVDM

Fig. 2: Vacuum Pipe Installation

Fig. 3: Array of PVC Pipes

Fig. 4: Dynamic Compaction at a Job Site

3. TECHNOLOGY BREAKTHROUGH

HVDM method embodies at least four technology breakthrough that is worthy of mentioning. First, the HVDM method successfully utilizes an intelligent combination of cycles of well designed vacuum dewatering and dynamic compaction to create not only very high pore water pressure gradient to expedite pore pressure dissipation, but also to provide active drainage conduits through the air tight innovative vacuum pipe system. With this generation of high pore pressure gradient and the ability to shorten the pore water drainage path, the HVDM technology essentially extends the applicable range of vacuum well drainage method into highly impermeable soils with permeability in the order of 1×10^{-7} cm/sec.

The second distinctive breakthrough of the HVDM is its breaking the barrier of limiting the use of dynamic compaction in soft, saturated cohesive soils. The main reason that dynamic compaction can be applied to advantage in saturated soft clay is due its combined used with vacuum well dewatering. The vacuum well dewatering is effective in reducing water content in cohesive soils to the point that the degree of saturation is about 75 % to 85 %. Therefore, dynamic compaction can be executed in such a way to avoid rubber soil phenomenon. As shown in Figure 5, a finite element simulation of equivalent static loading on cohesive soil deposits with 100 % and 75 % degree of saturation indicated that there is significant difference in the volume of the plastic zone. With the reduction of degree of saturation in the cohesive soils down to 85 %, HVDM effectively captures the advantages of dynamic compaction while avoiding its limitations.

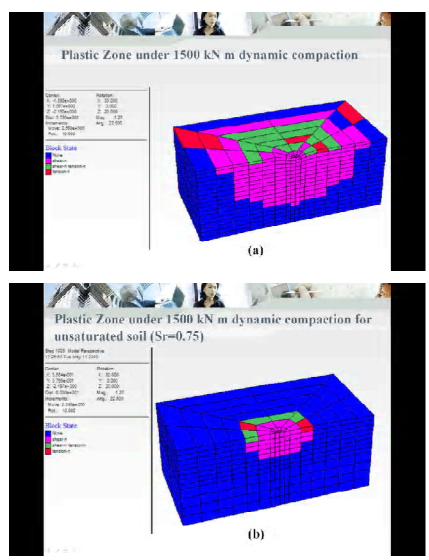


Fig. 5: Finite Element Simulation Results of Stress Contours Under Simulated Load for (a) S= 100 % and (b) S=75 %

The third distinctive feature of the HVDM is the actual densification achieved due to dynamic compaction, which in turn creates a very hard and over-consolidated top layer with thickness to the order of 3 to 4 meters. As illustrated in Figure 6, the presence of this hard, over-consolidated clay layer serves as an effective stress diffuser to spread the surface load with a wider angle of alpha. Therefore, the stresses transmitted to the underlying soil layer are reduced, which would place less stringent requirement on the soil improvement for this underlying soil layer.

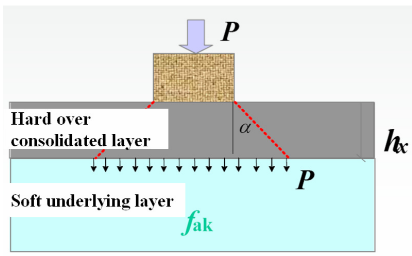
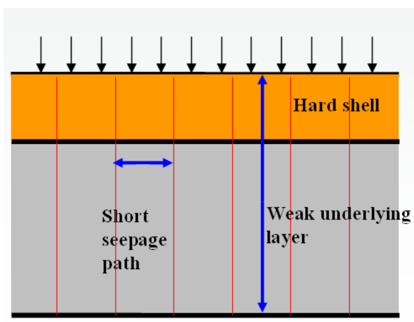
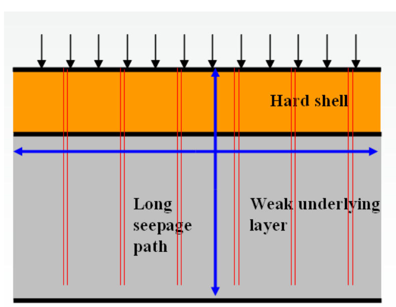


Fig. 6: Effective Stress Distribution Due to Hard Over Consolidated Top Clay Layer



(a) PVD left in place



(b) Vacuum pipes with drawn

Fig. 7: Comparison of Drainage Path: (a) PVD Left in Place and (b) Vacuum Pipes with Drawn

The fourth breakthrough is hinged on the ability of being able to retrieve the vacuum pipes during and after the ground improvement at the site. With the production of hard, over-consolidated clay, which is essentially impervious, in conjunction with the retrieval of vacuum pipes (contrast to leaving PVD in place); the post treatment water drainage path is restricted to horizontal direction. As a result, even with additional pore pressure generation due to surface structure loads, the rate of pore pressure dissipation under this restrictive drainage condition would be very slow. Thus, the HVDM can improve a soft clay site with a product illustrated in Figure 7 that clearly minimizes the post treatment total and differential settlements.

4. A SUCCESSFUL CASE

Since its early applications in China around 2005, the HVDM method has been used extensively in China, mostly for land reclamation and roadway constructions. In the past several years, the HVDM technology has been successfully used in projects in Vietnam and Indonesia. The total accumulated area of treatment by the HVDM method has exceeded 70 million square meters. In this section, a successful project of HVDM application is presented.

The project is located in the Ningbo Zhenhai Harbor District involving about 740,000 square meter of land improvement for the use as storage yards and transportation roads. The soil profile at the site includes 2 meter thick loose sand at the top, underlain by about 1.7 m thick hydraulic fill of fly ash with SPT N values in the range of 2. Underneath the fly ash layer is a layer of 2.3 m thick of soft to very soft clay mud, which is underlain by a layer of 1.2 m thick of sandy and clayey silt, and finally underlain by a fairly deep deposit of silty sand. The HVDM method was used to achieve the specified performance criteria: (a) improve bearing capacity of silty sand layer to 80 to 100 KPa, (b) improve cone penetration resistance of the fly ash layer by a factor of 2.5, and (c) increase cone penetration resistance of soft clay mud by a factor of 1.5.

The HVDM treatment of the site involves three stages of high vacuum dewatering and three stages of dynamic compaction (i.e., two stages of spot compaction and a final stage of full coverage compaction to iron out wrinkles). The vacuum pipes are of 6 meter and 3 meter in length, respectively. The spacing of 6 m long vacuum pipes is a 3.5 m by 3.5 m grid pattern, while the spacing of the 3 m long vacuum pipes is a 3.5 m by 2.25 m grid pattern. The selected dynamic compaction procedure includes the first stage of tamping using 800 kN-m energy with 3 consecutive tamper drops at each tamping location, followed by the second stage of tamping using 1200 kN-m energy and 2 consecutive tamper drops.

The monitoring results and on site observations indicated that the HVDM method has effectively achieved the required performance criteria. It is worthy of mentioning that total ground subsidence due to the HVDM treatment process is in the neighborhood of 1.5 m, which is accomplished in about one month of time. A summary table of soil properties at the site before and after HVDM ground treatment is presented in Table 1.

Table 1: Soil Properties Before and After HVDM

Soil Type	*Treat-ment*	*W_n (%)*	*γ_d (kN/m^3)*	*Void Ratio*	*Compression Modulus (MPa)*
Pond fly ash	Before	54.7	14.8	1.826	9.06
	After	39.9	18.1	1.110	11.58
Clay mud	Before	53.0	17.3	1.449	2.51
	After	35.5	18.6	0.995	5.47
Silty sand	Before	27.7	19.6	0.759	9.12
	After	26.3	19.6	0.738	15.52

The HVDM method has successfully achieved the required performance with the accompanying savings in both time and money, compared to the conventional PVD and surcharge preloading techniques.

5. CONCLUSIONS

The technology of the HVDM soft cohesive soil improvement method has been advanced in China in recent years, with its rapid expansion into the neighboring countries to provide economical soft soil improvement method with savings in both construction time and construction cost. The advantages of the HVDM method, compared to the conventional prefabricated vertical drains (PVD) and surcharge preloading techniques are as follows: (a) the vertical vacuum pipes are re-usable and can be easily connected to the horizontal PVC pipes and the vacuum pumps to form a closed vacuum system for dewatering, (b) there is no need to bring in surcharge load as the dynamic compaction provides the means of generating positive pore water pressure and mechanical densification of the soft clays, and (c) the combined negative pore pressure from vacuum and positive pore pressure from dynamic compaction facilitate expeditious dissipation of pore pressure and resulting fast consolidation of the clay soil deposit, (d) there is no need for a special construction requirement to carry out the work in the field, which is contrast to the necessity of a special equipment to install PVDs, and (e) compared to PVD, vacuum pipes function as a better conduit for vacuum and dewatering.

Finally, the many successful applications (as demonstrated by an illustrative case presentation herein) have provided evidences of the simplicity and effectiveness of the HVDM methods in improving the soft cohesive soil sites. The method can also be considered as a green technology, as it involves no use of chemical additives.

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