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INNOVATIVE SOFT SOIL IMPROVEMENT BY VACUUM DE-WATERING AND DYNAMIC COMPACTION

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Recently, an innovative soft soil improvement method was advanced in China by integrating and modifying vacuum consolidation and dynamic compaction ground improvement techniques in an intelligent and controlled manner. This innovative soft soil improvement method is referred to as "High Vacuum Densification Method (HVDM)" to reflect its combined use of vacuum de-watering and dynamic compaction techniques in cycles. Over the past ten years, this innovative soft soil improvement technique has been successfully used in China and Asia for numerous large-scale soft soil improvement projects, from which enormous time and cost savings have been achieved. In this presentation, the working principles of the HVDM will be described. A discussion of the range of fine-grained, cohesive soil properties that would make them ideal for applying HVDM as an efficient ground improvement method will be discussed. The economic benefits and environmental benefits of HVDM are elucidated.

Keywords: Ground improvement, Soft clays, In-situ improvement.

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 the population is large and infrastructure development is proceeding at a heightened pace, the need for a fast, economical in-situ improvement for soft cohesive soils in a large-scale is clearly evident. The traditional methods of soft cohesive soil treatment 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) rammed aggregate piers, (e) thermal treatment, (f) chemical mixing, (g) electro-osmosis, and (h) deep dynamic compaction. Despite the availability of various methods of in-situ improvements listed above, the method of incorporating PVDs with fill preloading appears to be the most widely used technique throughout the world, even though the vacuum consolidation method has gained some interest recently. In large-scale applications — such as land reclamation using dredged materials, port facility construction, economic zone development along coastal areas, petro-chemical plants near shorelines, steel mills, 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 cannot be economically obtained.

The application of vacuum to facilitate consolidation in saturated fine-grained soils has been used either alone by means of PVDs or in combination with the static surcharge load using fill materials (Kjellman 1952, Holtz 1975). The effectiveness of vacuum consolidation with or without surcharge loading is highly dependent upon soil permeability and the efficiency of the vacuum system. The desired degree of soil improvement and the allowable time duration for completion can also play an important role in determining if vacuum consolidation can be a viable soil improvement method for a project. The use of deep dynamic compaction technique in saturated fine-grained soils has not been widely accepted, even though the validity of its working mechanisms has been demonstrated (Menard 1975).

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 it 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.

In this paper, the working principles of this ground improvement method are described. The distinguishing features of this method and its advantages and limitations are elucidated. It should also be noted that this method is limited to treating soft soils to depths up to 8 to 10 meters. For treating the soft soils with depth greater than 8 meters or for achieving much higher improved strength, the HVDM technology for shallow soft soils has been extended to two additional innovative techniques or the conventional surcharge loading with prefabricated vertical drains (PVD) is required.

2 HVDM CONSTRUCTION SEQUENCES

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 collected for quality assurance and quality control (QA/QC) purposes. Figure 1 provides a schematic drawing of HVDM using vacuum consolidation and deep dynamic compaction. The HVDM consists of the following steps:

Step 1: Conduct detailed geotechnical investigation at the project site. Evaluate and determine the 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 cone penetration testing (CPT) or standard penetration test (SPT) to establish baseline values prior to commencing the 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 (DC) 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.

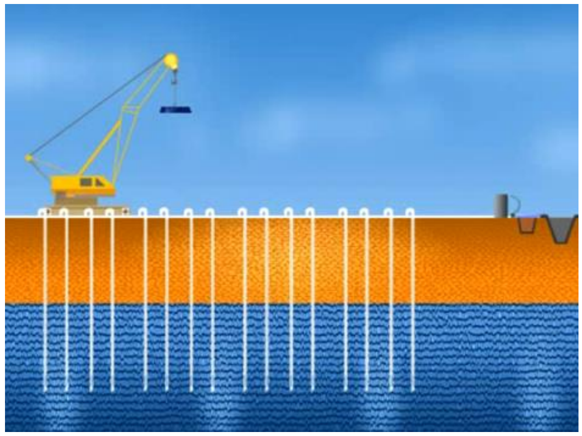

Figure 1. Schematic showing the HVDM method.

Step 2: Install vertical vacuum pipes and horizontal drainage pipes. The vertical vacuum pipes can be installed using several different methods, such as using a vibratory hammer and a mandrel or employing a hydraulic system to directly push vacuum pipes into ground. It is noted that vacuum pipes are steel pipes, typically 2.5 to 3-cm outside diameter, and 0.3-cm in thickness. The vacuum pipes contain perforated holes and are wrapped with a geotextile fabric for filtration purposes. The horizontal drainage pipes are typically polyvinyl chloride (PVC) pipes, 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 pipes and horizontal drainage pipes.

Step 3: Apply the first cycle of vacuum to reduce water content in the influence zone. In this phase, 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 to 80 kPa, depending upon the efficiency of vacuum consolidation. It is noted that the highest vacuum pressure that can be exerted 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 to 25 kPa. Therefore, this phase of vacuum dewatering is primarily used for making the site accessible for equipment to carry out the next phase of work (i.e., deep dynamic compaction). The time required for completing this cycle of vacuum consolidation is dictated by the spacing of vertical vacuum pipes and by the horizontal hydraulic conductivity of the soils. In addition, smearing effects (soil disturbances due to installation of vertical vacuum pipes) need to be taken into account. This phase of work is typically completed within seven days before proceeding to the next phase of work.

Step 4: Apply deep dynamic compaction to create a crater and to generate positive pore water pressure. The direct impact from the heavy tamping creates a crater, resulting in displacement of soils and a 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 a rapid increase in 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. Decisions regarding these parameters need to be made based on site monitoring results to ensure that the soils underneath the bottom of the crater do not suffer from undrained shear failure or the so-called “rubber soil” phenomenon. A typical dimension for a tamper is about 1 to 1.5 meters in diameter, and the weight can vary from 20 to 70 tons. The tamper drop height varies from 10 meters to approximately 20 meters. Useful correlations between crater depth, soil properties, influence zones, and tamper energy are available and 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-m^2 coverage area.

Step 5: Apply the second cycle of vacuum to facilitate a rapid dissipation of pore pressure and to further reduce the 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 will create a very high pore pressure gradient, which in turn helps to facilitate accelerated dissipation of the pore water pressure resulting in reduced water content. The duration of this phase is generally seven 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 the HVDM process. Evaluation of the outcome of ground improvement at this stage would allow for adjusting the operational parameters (spacing and depth of vacuum pipes, dynamic compaction energy level and grid spacing of tamping points, etc.) in the next cycle of the HVDM process.

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

HVDM utilizes the combination of active drainage, consolidation, and densification principles in. In order to be successful, this ground improvement method needs to be executed in a controlled manner based on the feedback obtained using on-site monitoring data.

In summary, the aforementioned method is a repeated process that uses a combination of vacuum consolidation/dewatering and dynamic compaction, applying increased tamper impact energy with each successive cycle to achieve the desired density and the required depth of treatment. In addition, on-site monitoring plays a key role to ensure that not only the soil properties before and after ground improvement are monitored but also that the operational parameters (e.g., the spacing of vacuum pipes, the energy of the tamper, and the duration between each stage of vacuum consolidation) are optimized. Past case histories indicate about 30% cost savings compared to conventional methods and about 50% reduction in construction period again compared to conventional methods. HVDM is a mechanical process, which adds no new materials into the soil thus it is environmental safe. Further details can be found in Liang *et al.* (2015).

3 TECHNOLOGICAL INNOVATION

The HVDM method embodies at least four technological innovations that are worthy of mention. First, the HVDM method successfully utilizes an intelligent combination of cycles of well-designed vacuum dewatering and dynamic compaction to create not only a very high pore water pressure gradient to expedite pore pressure dissipation, but also to provide active drainage conduits through an innovative, airtight vacuum pipe system. HVDM technology essentially extends the applicable range of a vacuum well drainage method into highly impermeable soils with permeability in the order of 1×10^{-6} to 1×10^{-7} cm/sec.

The second distinctive innovation of the HVDM method is that it breaks the barrier limiting the use of dynamic compaction in soft, saturated cohesive soils.

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 in the order of 3 to 4 m. Thus, the stresses transmitted to the underlying soil layer are reduced, which would place less stringent requirements on the soil improvement for this underlying soil layer.

The fourth breakthrough hinges on the ability 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 (in contrast to leaving the PVDs in place) the post treatment water drainage path is restricted to the 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 system illustrated that clearly minimizes the post treatment total and differential settlements.

4 ADVANTAGES AND LIMITATIONS

Some of the interesting advantages of using a combination of vacuum consolidation and dynamic compaction include (a) enhancing the vacuum well drainage techniques in fine-grained soils with relatively low permeability due to the enhanced pore pressure gradient created by combining the dynamic compaction-induced positive pore pressure and vacuum-induced negative pore pressure, (b) overcoming the common obstacle that dynamic compaction could not be applied to saturated cohesive soils due to the ability to lower the groundwater table and the creation of unsaturated soil zones through vacuum dewatering/consolidation, and (c) expediting pore pressure dissipation due to the creation of a high pore pressure gradient as a result of the combination of negative vacuum pore pressure and positive pore pressure generated by the dynamic compaction. The anticipated results include the following: (a) the creation of a highly over-consolidated clay layer near the ground surface by the deep dynamic compaction effort and the influence zone and (b) eliminating the post-treatment vertical drainage path as a result of withdrawing the vacuum pipes from the ground after completion.
There are some limitations of the vacuum consolidation/dynamic compaction method. The treatment depth is generally limited to 10 m due to the limit of the influence zone of deep dynamic compaction and the loss of vacuum efficiency when exceeding that depth. Also, fine-grained soils that contain a large portion of organic materials would not be suitable for this method due to the pronounced secondary compression (creep) that could not be treated. The range of permeability of the fine-grained soils that can be suitable for this treatment method is limited to a minimum of about 10^{-6} cm/sec.

HVDM technology for shallow soft soils has been extended to two additional innovative techniques: 1) Preloading plus HVDM for deep soft soils and 2) HVDM plus Composite Foundation for job sites requiring high bearing capacity.

5 SUMMARY AND CONCLUSIONS

In this paper, recent advances in ground improvement techniques for fine-grained soils involving the combined use of vacuum consolidation/dewatering and deep dynamic compaction (HVDM) were described. The mechanisms of HVDM technology for ground improvement are as follows: Dynamic compaction in nearly saturated contractive soils generate positive pore water pressure, which when coupled with vacuum induced negative pore pressure, can expedite drainage of water from the soil mass, thus increasing density and undrained shear strength of the treated soil.

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