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Consolidating Dredge Soil by Combining Vacuum and Dynamic Compaction Effort

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ABSTRACT: Escalating lands are being reclaimed at coastal areas by dredging soils from sea or rivers. Such formed lands are often characterized as presenting high water content, high void ratio, high compression, worst disturbance and weak bearing capacity, and thus cannot be directly used as a bearing deposit. It is time consuming to consolidate such lands by relying on naturally occurring evaporation and hydraulic dissipation. Enhanced engineered technology has to be introduced to expedite the dredge consolidation process. A technology, known as high vacuum densification method (HVDM), was developed to treat the dredge soil in a time-efficient and cost-effective means. Its principle is to consolidate the soil by combining vacuum effort and dynamic compaction. The vacuum effort is used to pump the moisture out of the soils in steps; and the drained soils are densified by dynamic compactions. Soils amenable to HVDM can be treated to favorable conditions meeting both strength and deformation requirements. Besides the principles and the construction procedures of HVDM, cases studies were also presented in this paper, which demonstrates the attractive merits of HVDM in contrast to comparable soil treatment methods.

INTRODUCTION

In the past decade, land reclamation from sea or river waterway has been escalating at coastal areas of China, which brings forth challenging soil treatment issues pressing geotechnical communities. Once dredged from sea and waterway, the dredge soil is characterized presenting high water content, high void ratio, high compression, worst disturbance and weak bearing capacity, which leads the dredge land unqualified for the use as a jobsite or a bearing deposit where buildings shall be rested on. To consolidate a large-scale dredge land using a time- and cost-effective means is challenging the current available soil treatment technologies.

Dynamic compaction may be unanimously chosen as the first option to implement the land consolidation. This technology, however, is limited to treatments of unsaturated sandy soils of low water content (Zheng et al. 2000, Shi et al. 2006). The dredge soil often comprises saturated silty and/or clayey soil of high water content and low hydraulic conduction, which impedes the efficient dissipation of excess pore water pressure resulted due to compactions. As a result, a rubber soil phenomenon may be incurred if the dynamic compaction is used to treat the dredge soil. Additional related but limited soil treatment technologies include composite foundation (e.g., in-place mixing columns), which is relatively high in cost, and drainage-consolidation methods (e.g., vacuum-surcharge preloading), which often takes relatively long duration to consolidate the jobsite and extra expenditure if backfilling is required (Editor Committee 1994).

In this study, a soil treatment technology, known as high vacuum densification method (HVDM), is described. HVDM was developed to efficiently consolidate dredge soil by combining vacuum and dynamic compaction effort. The principles, procedures and practices of HVDM are presented in brief.

DESCRIPTION OF METHOD

Principles

Soil dry density is regarded as one the soil properties indicating the relative compaction of the soil. The higher the dry density, the more compacted the soil. HVDM is a method to compact the soil into its maximum dry density, and equivalently, the most densified condition. Fig. 1 demonstrates the soil densification progress in relation to compaction implementation and moisture content variation occurred to a jobsite treated by HVDM. The jobsite soil starts from state A, which presents a relatively high moisture content and low dry density. By reducing the moisture content, the soil is converted into state B, where the soil is subjected to N1 blows at its optimal moisture content and densified into state C. By alternating the two steps, i.e., moisture reduction and dynamic compaction, the soil would further follow routes C-D-E and E-F-G. After three runs, the jobsite soil is converted into state G, which presents significantly low moisture content and high dry density, relative to its initial state A. That is, a substantial consolidation is completed.

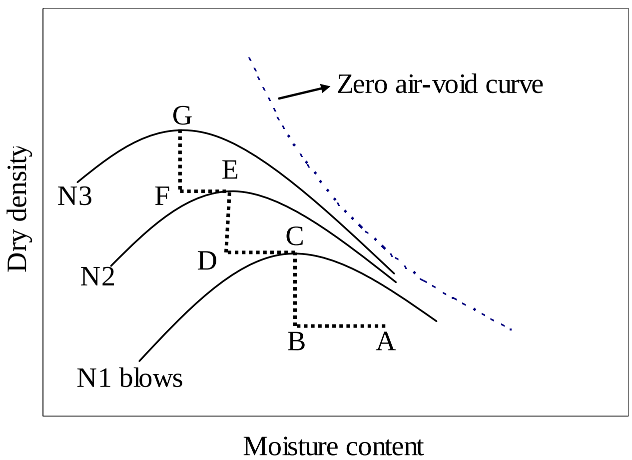

FIG. 1. Schematic of soil compaction.

The above concept is implemented by construction procedures of HVDM. Each HVDM run consists of two steps, i.e., moisture reduction and dynamic compaction. In the steps of moisture reduction (i.e., A-B, C-D and E-F), HVDM employs vacuum effort to suck or drain the soil moisture out (Fig. 2). In the steps of dynamic compaction (i.e., B-C, D-E and F-G), HVDM employs conventional dynamic compaction procedures to densify the soil (Fig. 2). In each HVDM run, the vacuum effort leads to negative pore pressure in the soil around the vacuum pipes, whereas the dynamic compaction leads to positive pore pressure. The two opposite pore pressures form a lateral pressure gradient in influenced soils if the vacuum and compaction spacing are well designated on the jobsite. The pressure gradient is generated to expedite the pore pressure dissipation and moisture discharge.

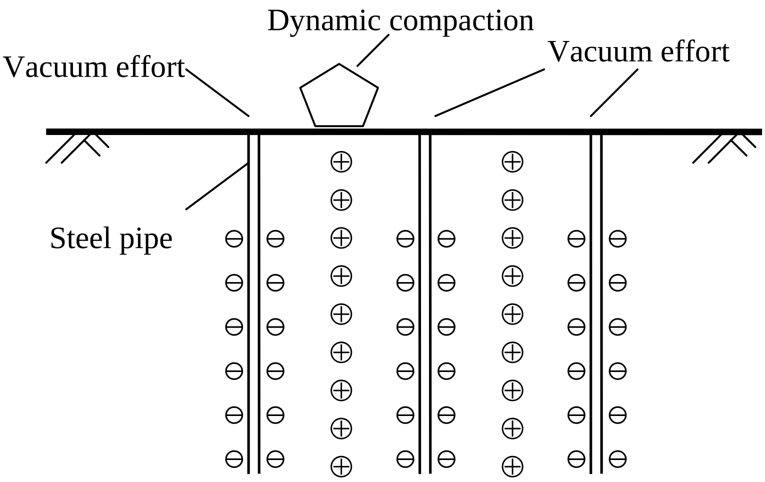

FIG. 2. Diagram of HVDM operation.

Most often, a restoration break is allowed between HVDM runs (i.e., at states C and E), during which the soil strength gains to eliminate the occurrence of a rubber soil. The number of HVDM run is dependent on the compaction energy and the influential depth of the machinery, the construction time allotted, and most importantly, the bearing capacity required for the jobsite or individual section of the jobsite. Generally, for a newly dredge soil, three runs are needed to attain a soil bearing capacity of 80-100 kPa and a consolidation degree of 80-90%.

Facilities and Procedures

The facilities used in HVDM treatments include vacuum facilities, compaction facilities, monitoring devices and sometimes, prefabricated vertical drain (PVD). Vacuum facilities mainly include vacuum system, vertical hollowed-out steel pipes and horizontal main collection pipes. Compaction facilities include crane compactors, bulldozers, rollers or vibrators, etc. Monitoring devices are used to measure the pore water pressure variation in the HVDM progress. PVD is used as an aid facilitating the moisture discharge.

Fig. 3 shows a construction flow chart in a typical HVDM treatment. The treatment starts with the jobsite preparation, in which the site is leveled off, cleaned, and exposed to a site shallow exploration. The hollowed-out steel vacuum pipes are installed in array to depth of 6-8 m. Discharge system is hooked up on the ground. Vacuum systems are laid out independently to charge designated portions of the jobsite.

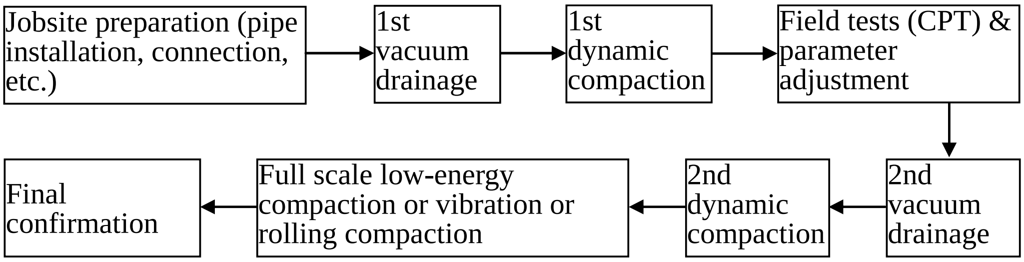

FIG. 3. Construction flow chart in a typical HVDM treatment.

The 1^{st} HVDM run starts with the 1^{st} vacuum drainage, which lasts until the soil moisture content of the treated stratums is close to the 1^{st} optimal moisture content (i.e., the abscissa of state B in Fig. 1). Uninstall the steel pipes, and run the 1^{st} dynamic compaction. Certainly, the energy of the dynamic compaction is decided by trial-and-error via indoor and field compaction tests. After the 1^{st} HVDM run, field confirmation tests (e.g., CPT) are conducted. In terms of the monitoring data and CPT data, a restoration break is estimated and allowed prior to the next HVDM run. Likewise, one or two more HVDM runs are carried out to eventually consolidate the subsurface into a hard shell.

Merits

HVDM enables the dredge soil consolidated in a time-efficient and cost-effective means. Firstly, a pressure gradient is repetitively yielded between the positive pressure (i.e., excess pore water pressure by dynamic compactions) and the negative pressures (i.e., vacuum effort), and being over 1 atm (i.e., over 101 kPa), which is equivalent to a backfill surcharge of 5 m high. Such pressure is able to force out pore moisture in relatively impermeable soils at an expedited rate. Plus, vacuum effort help reduces moisture content in an active manner, instead of the passive manner imposed by conventional methods (e.g., the surcharge preloading method). As a result, the time elapse on water discharge and soil restoration is favorably saved from 3-4 weeks (e.g., in a vacuum-surcharge preloading method) to 5-10 days. According to the experiences, only 10-25 days are required for a treatment unit, which is merely 1/3 to 1/2 of the construction time a general method needs. Meanwhile, low-cost energy machinery, saved labor force, and reduced procedure and time yield substantial saving in cost, which is around 40% to 80% the cost of comparable methods.

Secondary, the influential depth of HVDM leads to the formation of a hard shell of 6-8 m deep in the subsurface. The hard shell is over-consolidated and firm, which helps improve stress distribution conditions (i.e., hardness, thickness and angle). As a result, the post-treatment settlement and differential settlement are controlled. Furthermore, the soil moisture content and saturation degree is decreased in steps. Plus, the soil strength gains via the moderate compaction effort. Occurrence of rubber soils is eliminated. Concurrently, HVDM is a mechanical process which neither uses chemical additions nor discharge environmental unsafe emissions or effluents.

Lastly, a jobsite subjected to HVDM treatment favors a further foundation formation. For instances, the treated jobsite can be formed into an enhanced composite foundation by backfilling stones or gravels, i.e., stone columns. The over-consolidated soils of 6-8 m deep lead to the increased friction between columns and soils. The field test data indicated that the site bearing capacity reached up to 210 kPa.

CASE STUDIES

A jobsite for a port lies close to the Yangtze River in eastern China. The jobsite consisted of the reclamation formation of farmland and dredge soil. The water level was about 0.6 m beneath the ground surface. The main soil profile of the jobsite included: 1) top layer, drained silty fine sand, 1-3 m thick, 2) clay and silty clay, on average 1-2 m thick and 34% water content, void ratio of 0.9, 3) silt and mucky soil with siltage, 0-6 m thick, 43% water content and 1.16 void ratio, and 4) fine sand, medium compaction, good bearing capacity. Deposits beneath were the inter-layers of soft soil and sandy soil.

The end use of the jobsite was to stack steel products and freight containers. According to designs, the soil bearing capacity needed to attain 120 kPa, and 150 kPa for some locations.

A pilot treatment was conducted by using HVDM on a trial patch of 20×20 m. Vacuum pipes were arranged in array of 3.5×4.0 m. The 1st vacuum drainage lasted 11 d. The 1st compact energy was 3000 kN-m at a drop spacing of 7.0×7.0 m and 8 blows each drop location. The drop penetration depth should be less than 2 m. After leveling off the ground, the 2nd vacuum drainage was conducted immediately with identical drainage layout. After 10 d drainage, the 2nd compaction was performed at the energy of 1800 kN-m. The drop spacing was 2.5-3.5 m in quincunx layout. Six blows were conducted each drop location, and the drop penetration depth should be less than 1 m. The ground leveling procedure should be done again after compaction. In order to increase the soil bearing capacity to 150 kPa and form a homogeneous hard subsurface shell, a third HVDM run was conducted. A high energy vibratory roller was finally used to further compact the subsurface of the jobsite.

The site elevations prior to the treatment and after the 1st, 2nd and 3rd compaction were monitor to measure the ground settlement. The segmental settlements were 23.2 cm following the 1st HVDM run, 32.2 cm following the 2nd HVDM run, 10.4 cm following the 3rd HVDM run. The cumulative settlement was 65.8 cm. It is indicated the majority of the consolidation was complemented in the first two HVDM runs in this jobsite.

Field CPT tests and laboratory soil tests were conducted prior to and after soil treatments. Table 1 shows the results of main soil physical and mechanical parameters. It is indicated that the physical and mechanical properties of clayey soils were improved clearly. But the parameter values for sandy soil were decreased, which is associable with the un-accessibility of undisturbed sandy soil samples. Based on the increase of void ratio Δe and the formula $\Delta\sigma' = \Delta e / a = E_s \Delta e / (1 + e_0)$, the effective stress were estimated to increase in the order of over 120 kPa for both silty clay and muddy clay with silty sand, which met the working load of 120 kPa. Meanwhile, the specific penetration resistance increased obviously for the soil deposit up to 10 m, in particular, the deposit of 3-5 m deep. The increase is more effective in sandy soil than in clayey soil. Based on the experience relating CPT test data to soil bearing capacity, the bearing capacity of the shallow deposit was increased from 80-100 kPa to 160 kPa, which met the design requirement.

Table 1. Soil Physical and Mechanical Properties Before and After Treatment.

Layer	Status	Water content w (%)	Specific gravity r_d (kN/m^3)	Void ratio e	Compression modulus Es (MPa)	Specific penetration resistance Ps (MPa)
Alluvial sand	Before	29.4	14.40	0.841	16.53	3.02
	After	32.0	13.86	0.911	16.78	7.18
Silty clay	Before	32.1	14.32	0.898	8.29	1.51
	After	28.5	14.91	0.807	10.15	2.95
Muddy clay with silty sand	Before	41.1	12.91	1.110	4.15	1.05
	After	38.0	13.30	1.050	5.45	1.65
Silty sand	Before	32.7	14.36	0.896	11.56	4.46
	After	31.9	14.31	0.906	10.72	6.81

CONCLUSIONS

HVDM is an enhanced dredge soil treatment method, which expedites the soil consolidation process by coupling two mutual and alternate efforts, i.e., vacuum drainage and dynamic compaction. High moisture content of dredge soils can be decreased in steps, and concurrently, the soil strength gains by the densification effect. Principles and practices indicate that HVDM is able to consolidate high water content dredge soil in a time-efficient and cost-effective means.

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