Dynamic-static drainage consolidation method on silty ground

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ABSTRACT
The treatment of a silty ground for petroleum product storage facilities in Guangzhou China with dynamic-static drainage consolidation method is presented. The soft ground has been improved under the dynamic and static forces and their residual effects through drainage with a system of horizontal drainage (crisscross ditches and wells) and vertical plastic strip drains. The pore water pressure, soil pressure, settlement, field vane shear strength, bearing capacity through plate load tests and laboratory determined physical-mechanical properties measured before and after the treatment have clearly shown that this method can significantly strengthen the silt ground within reasonable time frame.

RÉSUMÉ
Le traitement de la terre limoneuse pour des installations d'entreposage de pétrole à Guangzhou en Chine avec la méthode de consolidation de drainage dynamique-statique est présenté. La terre molle a été améliorée grâce aux forces dynamiques et statiques ainsi que leurs effets résiduels suivant le drainage par un système horizontal (fossés et puits croisés) et par le drainage vertical par bande de plastique. Les essais de chargement à la plaque et les mesures physico-mécaniques pré- et post-traitement de laboratoire ont manifestement démontré que la pression interstitielle, le tassement, la résistance au cisaillement et la capacité de charge peuvent renforcer de manière significative la terre limoneuse dans un délai raisonnable.

1. DYNAMIC-STATIC DRAINAGE CONSOLIDATION METHOD

Dynamic compaction and static drainage consolidation methods are proven soil improvement techniques. While the dynamic compaction method is suitable for application to granular soils, it is inapplicable to soft clay. The static drainage consolidation method is applicable to soft clay but it usually requires complicated drainage systems and a long time for the consolidation process to complete. Therefore the dynamic-static drainage consolidation method was invented in recent years for strengthening clayey soils to remove the shortcomings of separately using the dynamic compaction and the static drainage consolidation methods (Li 2006 and Ye 2002). This method combines the dynamic energy from compaction and consolidation by means of the static drainage system to improve soft clayey soil. It has the advantage of high quality, low cost and short construction time. The basic idea of the method is as follows. A horizontal drainage system (crisscross ditches, wells and a layer of sand on the ground surfaced) and a vertical drainage system (vertical plastic s) are first installed to improve the drainage condition. The soft ground is then improved under the dynamic and static forces and their residual effects to form high pore water pressure gradient followed by dissipation of the pore water pressure that leads to consolidation settlement and increased soil strength.

2. PROJECT OUTLINE (GUANG 2006)

Located in the Nansha area, Guangzhou, China, the project is built for petrifaction storage. The total treated area is 149 thousand m2 of which 137 thousand m2are for storage tank area, and the rest for access roads. The site was originally a pond with silt covering the surface of the whole area and the ground water level was high. The geological condition of the whole area is poor which the average silt layer is 12.0m ,and the maximum depth of silt is 16.7m ; water content is 45.8~114%; void ratio is 1.517~2.992. The treatment began in April 2006. Because of rain and complicated site conditions, the treatment process was quite difficult. An observational method for the construction was part of the design requirement. Therefore, in situ monitoring and inspection had been conducted during construction in order to provide timely data to check the effectiveness of the treatment and to guide any adjustment to the construction plan.

3. PROJECT DESIGN

3.1 Dynamic process and parameters

3.1.1 Layout of tamping point and tamping passes

Zheng et al. (2000) show that increasing the number of tamping passes and decreasing the number of drops of tamping at each location produce better results in the improvement of soft clay ground. In this project, a total of four tamping passes were conducted. The first three passes were performed at tamping points at a spacing of 5.5m. The last pass was performed with an overlapping distance of 0.75 hammer diameter. The layout of tamping points is shown in Figure 1.

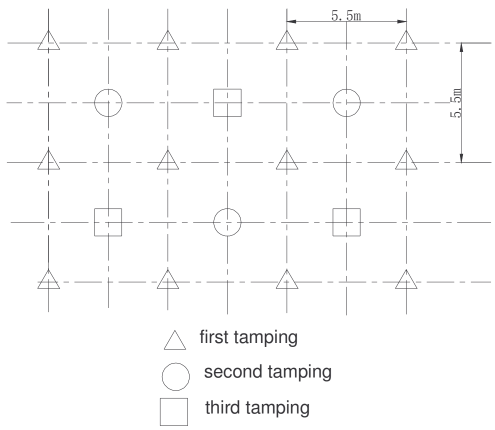

Figure 1 Layout of temping locations at the test area

The number of drops at each tamping location was determined by the settlement and pore water pressure generated from the tamping as measured at the site. The duration between each tamping pass was mainly governed by the dissipation of generated pore water pressure after tamping.

3.1.2 Tamping energy

A circular hammer had been used in this project. The hammer was 2.4m in diameter, 75cm in height and 150kN by weight. There were a few evenly scattered ventilating holes on the hammer, which reduced the contact area by 2.5%. Because the permeability and strength of the soft clay are low, low energy is used in the first pass of tamping in order to minimize the destruction to the soil structure. The tamping energy was increased in the subsequent passes to reach deeper ground after the strength of shallow ground has been improved by the first tamping pass (Zhou et al. 2005). Four passes were used in this project based on the results of test tamping prior to the actual tamping of the entire site. The tamping energy for the first, second, third and last tamping was set at 900kN.m, 900kN.m, 1200kN.m and 600kN.m, respectively.

3.1.3 Criterion for terminating tamping

The number of hammer drops for each tamping location is determined by the settlement and pore water pressure generated during the tamping. The general criterion based on Ye et al. (2003) are as follows: (1) the bulging of soil mass around the tamping pit is not obvious, (2) the lateral displacement near tamping pit is not excessive, and (3) the settlement caused by the last pass tamping should be less than that of the current pass to avoid destructuring the soil.

3.2 Drainage system

3.2.1 Horizontal drainage system

The horizontal drainage system was composed of 1.0m thick layer of coarse and medium sand placed on top of the original ground surface, crisscross ditches and shallow wells. The bottom width of the ditches is 0.4 m with a 1% slope to the shallow wells. Fill material used in the ditches was uniformly graded gravel of 3~5cm diameter, and was wrapped with permeable fiber. The shallow wells were set along the length of the ditches at a fixed interval. The wells were filled with reinforced cages of an external diameter of 490mm. A reinforced cage was composed of 12 6mm-diameter longitudinal reinforcing bars and lateral reinforcing hoop of 10mm-daimeter bars at an interval of 300mm. The cage was wrapped with iron or plastic net on the side and its bottom was wrapped with geofabric. Gravel was placed around the reinforced cage as a filtrating material. The wells and the ditches were well connected with the bottom of the wells deeper than that of ditches. Water collected in the well was pumped away timely during the construction to ensure the water depth was less than 60cm.

3.2.2 Vertical drainage system

Plastic strip drains were used for the vertical drainage system. The strips were arranged at a square pattern of 1.4m sides. The strips reached an average depth of 12.0m. The bottom of the strip was secured into the soft soil layer for at least 0.5m and the top 20cm stood out of the sand layer. The location deviation of the strips was kept less than 50mm and the vertical deviation set less than 1.5% of the total strip length. The strip inside soil must be kept clear. The machine for installing the strips was equipped with a recorder to record the installed length of strip.

4. EFFECTIVENESS OF IMPROVEMENT

The excess pore water pressure, settlement profile, earth pressure, vane strength, static cone penetration were monitored during and after construction. Plate load tests were performed after construction. The physical-mechanical properties such as water content, void ratio, unit weight, coefficient of compressibility, modulus of compression, etc., have been measured before and after construction.

4.1 Results on excess pore water pressure

Monitoring the dissipation of the excess pore water pressure provides an effective way of controlling the construction schedule. Typical results from monitoring the excess pore water pressure 3.5m under the surface in the storage tank area are given in Figure 2. The variation of excess pore water pressure with time shows that the excess pore water pressure dissipated quickly after each tamping pass using the method of increased duration between the passes and decreased number of drops at each tamping location combined with the drainage systems. The excess pore water pressure dissipated by 62%, 73% and 71% after the first, second and third tamping, respectively, suggesting that the drainage system has been effective. The maximum increment of excess pore water pressure is 40kPa, occurring after the second pass. The small increment suggests that the soil structure has not been damaged. Figure 2 also shows that the dissipation of excess pore water pressure still continues right after the overlapped or the final tamping. The pore water pressure is 22kPa a month after the final overlapped tamping. This is 10kPa less than the original pore water pressure. This phenomenon shows that the residual effects of the dynamic and static forces are very obvious and important for the acceleration of soft ground consolidation, and it is the advantage and feature of this method.

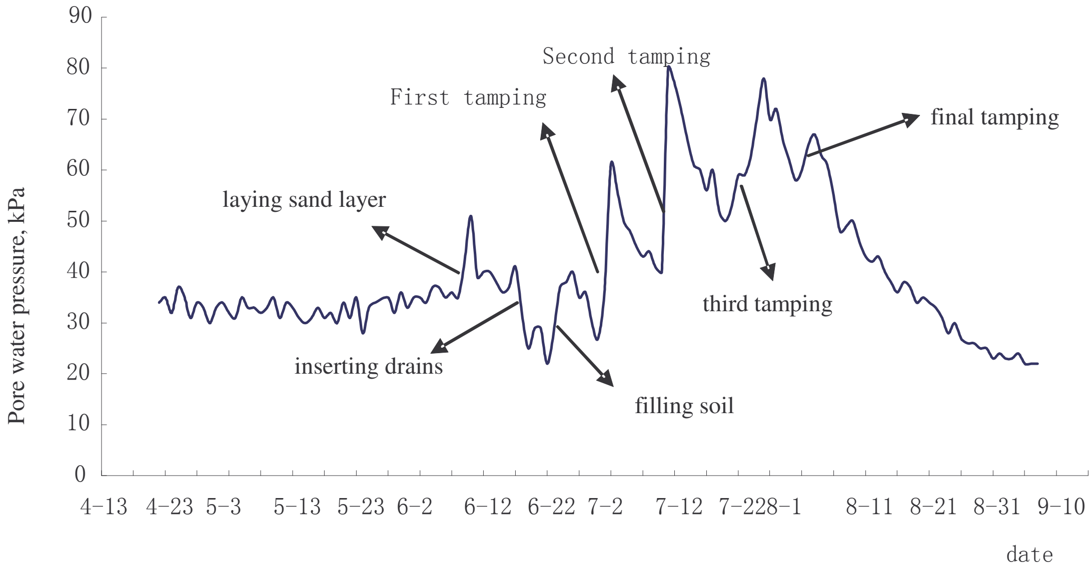

Figure 2 Typical measured excess pore water pressure

4.2 Results on soil pressure

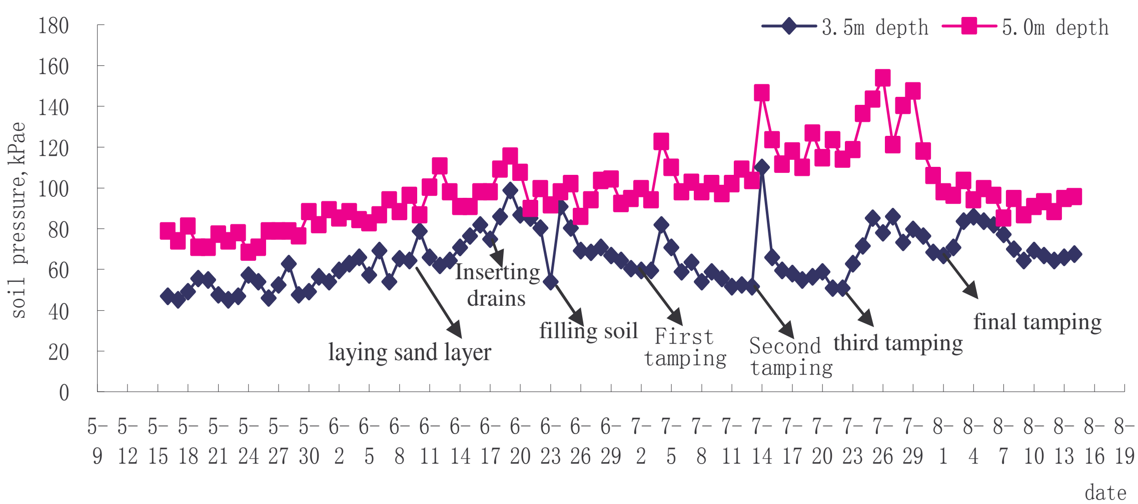

Figure 3 Typical measured soil pressures in oil tank area

The typical curves of horizontal soil pressure in Figure 3 show that the soil pressure increases after each tamping, and the increment in deeper soil is larger than that in shallower soil. The maximum increment occurs after the second tamping pass with values of 66kPa and 36kPa at the depths of 3.5m and 5.0m, respectively. This trend accords with that of the excess pore water pressure. The tamping load increases the soil pressure of soft ground. The residual effects of the dynamic and static forces form a nice pressure gradient to accelerate the dissipation of the excess pore water pressure.

4.3 Results on settlement

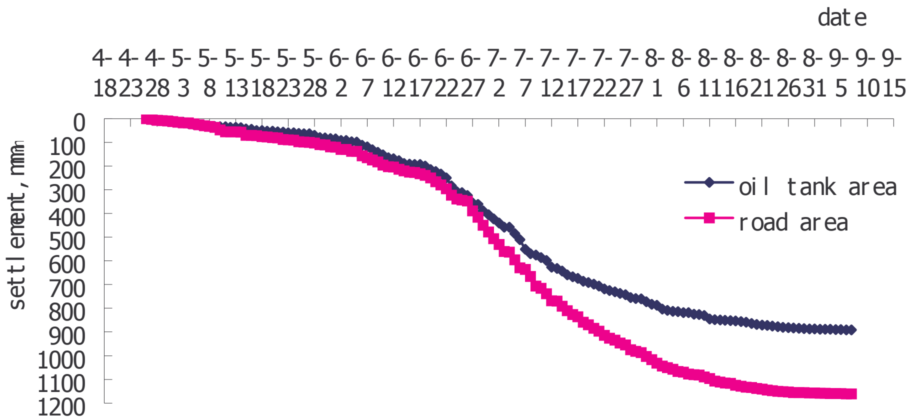

Figure 4 Typical monitoring data of settlements in oil tank area

Ground settlement increases gradually with the dissipation of excess pore water pressure. The settlement is also an important measure of soil improvement. The typical measured settlement (3.5m under the original ground surface) in Figure 4 shows that the increment of settlement increases steadily during the construction. This is caused by the dissipation of the excess pore water pressure after tamping, leading to consolidation settlement. When tamped again, new excess pore water pressures were generated that would give rise to more settlement. The settlements in the tank storage area and in the road area are 780mm and 1040mm, respectively after the overlapped tamping. These values finally increase to 890mm and 1150mm, respectively, which shows that the residual effects of the dynamic and static forces are very obvious and important for the acceleration of soft ground consolidation, the consolidation settlement caused by the residual effects are 12.3% and 9.6% of the total surface settlement in the tank storage area and in the road area, respectively.

4.4 Results on field vane shear strength

Field vane shear tests for measuring the undrained strength were conducted before, during and after the tamping process. The test results for the silt stratum under the tank storage area are shown in Figure 5. There has been a definite strength increase during and after the tamping. The most dramatic increase is found at 4m depth where the undrained strength changes from 4.0kPa to 11.9 and 24.8kPa. The strength increases ranges from 1.8 to 5.2 times the original values. There is also a corresponding decrease in the sensitivity.

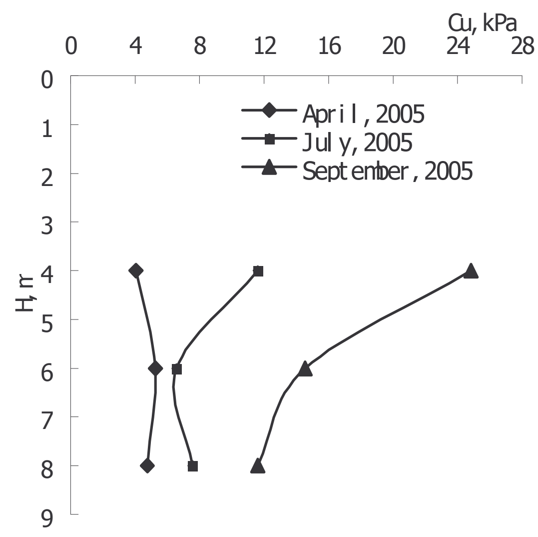

Figure 5 Field vane strength profiles in silt stratum (storage tank area)

4.5 Results on Cone Penetration Test (CPT)

The test results on CPT before, during and after tamping in the tank storage area are shown in Figure 6. The results again show that the silt stratum has been improved by varying degrees. The effect of improvement reached the depth of 11m. and there is 0.7~2 times increase in the Ps of silt stratum.

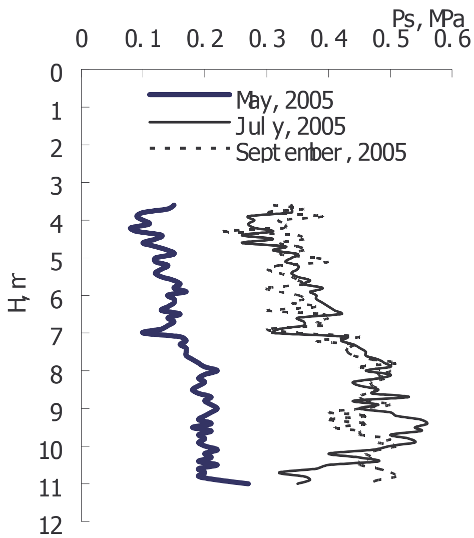

Figure 6 Profiles of CPT resistance (storage tank area)

4.6 Results on plate load test

The results on the plate load test (square plate with 1.0m width) show that the bearing capacities are increased to 180kPa and 120kPa in the road area and the oil tank area, respectively（figure 7and figure 8）, Both have exceeded the design requirement. The compactness and uniformity of the soil have been improved.

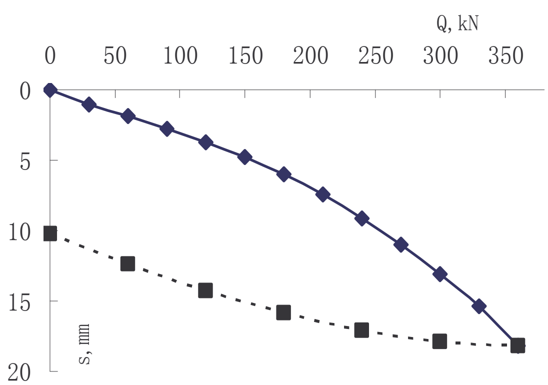

Fig.7 Q~S curves in road area

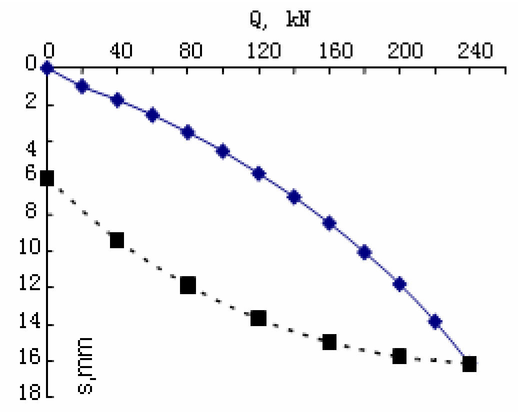

Fig.8 Q~S curves in oil tank area

4.7 Comparison of physical-mechanical properties

The physical-mechanical properties of the soil before and after the tamping treatment have been summarized in Table 1. There are substantial decreases in the water content, void ratio and coefficient of compressibility and definite increase in bulk unit weight and modulus of compression.

The above test results therefore suggest that the application of the dynamic-static drainage consolidation method is successful for application on the silty soil.

Table.1 Comparison of physical-mechanical properties before and after improvement

Item	Water content ω,%		Void ratio		Bulk unit weight g/cm³	
	range	average	range	average	range	average
before	45.8~114.0	75.0	1.517~2.992	2.087	1.35~1.67	1.50
after	45.5~75.9	57.3	1.013~1.862	1.465	1.55~1.81	1.67
ratio of increase	-23.6		-29.8		11.3	

Item	Coef. of compressibility av, MPa-1		modulus of compression Es, MPa-1	
	range	average	range	average
before	1.450~5.016	2.434	0.744~1.969	1.452
after	0.931~2.241	1.332	1.250~2.52	2.05
ratio of increase	-45.3		41.2	

5. CONCLUSIONS

The method of combining dynamic compaction and static drainage consolidation has been devised and applied to a silty ground. The two processes and their residual effects generate excess pore pressures which readily dissipated through drainage with a system of horizontal drainage (crisscross ditches and wells) and vertical plastic strip drains. The dissipation hence leads to increased strength. The pore water pressure, settlement, field vane shear strength, bearing capacity through plate load tests and laboratory determined physical-mechanical properties measured before and after the treatment have clearly shown that this method can significantly strengthen (up to 5.2 time of its original value) the silt ground within reasonable time frame.

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