A case study on the dynamic-static drainage consolidation method

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ABSTRACT
The dynamic-static drainage consolidation method is a rapid and cost-effective method to strengthen very soft fine-grained soils. It is based on combining the dynamic compaction method and the static consolidation accelerated with an adequate drainage system in both the vertical and horizontal directions. This paper discusses the method as it applies to a petroleum storage site that features very soft mud of strength as low as 8 kPa. A field experiment was conducted to study the effects of the number of tampings and the number of passes on the success of this method. The excess pore water pressures, settlements and field vane strengths resulting from the application of the method were measured. A comparison on the cost and duration for successful application on this and three other methods is also presented. Analysis of the results of measurements at the site and the comparison leads to the conclusions that this method gives excellent results in terms of cost and time for strengthening the very soft mud. In addition, For a given total compaction energy, better result is obtained by increasing the number of passes with corresponding decrease in the number of tamping in each pass and limiting the compaction energy at a point for each pass to less than 1000kN.m.

RÉSUMÉ
La dynamique statique drainage est une méthode de consolidation rapide et rentable de renforcer très doux à grains fins, des sols. Il est basé sur la combinaison de la méthode de compactage dynamique et la statique de consolidation accélérée avec un système de drainage approprié à la fois dans les directions verticale et horizontale. Ce document traite de la méthode, telle qu'elle s'applique à un site de stockage de pétrole que les caractéristiques très doux de boue de la force que de 8 kPa. Une expérimentation a été menée afin d'étudier les effets du nombre de tampings et le nombre de passes sur le succès de cette méthode. L'excès d'eau des pores des pressions, des colonies de peuplement et sur le terrain scissomètre forces résultant de l'application de la méthode ont été mesurés. Une comparaison sur le coût et la durée de mise en application réussie sur ce point et trois autres méthodes sont également présentées. Analyse des résultats de mesures sur le site et la comparaison aboutit à des conclusions que cette méthode donne d'excellents résultats en termes de coût et de temps pour le renforcement de la boue très doux. En outre, pour un total de compactage énergie, meilleur résultat est obtenu en augmentant le nombre de passes avec diminution correspondante du nombre de bourrage dans chaque passage et en limitant le compactage d'énergie en un point pour chaque passage à moins de 1000kN.m.

1. INTRODUCTION

The dynamic-static drainage consolidation method is a newly developed soil improvement technique based on combining the traditional dynamic compaction with the static consolidation method (Li 2006 and Ye 2002). While the dynamic compaction method is suitable for application to granular soils, it is inapplicable to soft clay. The static consolidation method is applicable to soft clay but it usually requires extensive drainage systems and a long time for the consolidation process to complete. By combining the two methods in recent years into one known as the dynamic-static drainage consolidation, the limitations of the individual methods are relaxed. Hence the combined method can be used to strengthen clayey soils, with the advantages of high quality, low cost and short construction time. Existing experience has shown that the key parameters for the successful application of this method (Xing et al. 2008, Jia et al. 2007, and Gong et al. 2007) are the number of hammer drops (tamping) at a point, number of passes and a properly designed drainage system. This paper discusses the application of this method to a site with very soft clayey soil of undrained strength as low as 8kPa.

2. PROJECT DESCRIPTION

Located in the Nansha area, Guangzhou, China, the project was built for petroleum storage. The total treated area was 149,000 m^2 of which 137,000 m^2 was for the storage tank area, and the rest for access roads. The site was originally a pond with mud covering the surface of the whole area and the soil profile is given in Table 1. The thickness of the mud layer averaged 12.0 m with a maximum of 16.7m. The soil treatment began in April 2006. Because of the complex site condition, a small typical area at the site was chosen for an experimental study to determine the most efficient set of parameters for application to the entire site. The study area was monitored with piezometers and settlement gauges during the treatment process. The resulting increase in undrained strength was measured using the field vane shear test.

Table.1 Soil profile at the Nansha site

Soil layer[Δ]	Soil description	Thickness m	Water conten t %	Density g/cm^3	Void ratio	Undrained shear strength kPa	Coefficient of compressibility a_v in 1-2 MPa range MPa^{-1}
Fill	Unevenly spread, high water content and clay content	0.0~2.0					
Mud	Plastic and extremely soft, water content 45.8~114%, void ratio 1.517~2.992	6.5~18.7	75.0	1.60	2.087	7.4	2.434
Silty clay	White and grey plastic clay of alluvial origin,	0.5~10.8	28.2	1.96	0.760	21.9	0.352
Sandy clay	White and grey stiff soil of residual origin	0.5~12.1	21.8	2.01	0.621	31.2	0.177
Completely decomposed granite	White and grey and dark red, slakes in water	0.8~9.8	17.1	2.03	0.538		0.125

Δ As the name of the soil layer goes down the table, the depth where the soil is located increases in accordance with the thicknesses of the soil layers.

3. DESIGN OF EXPERIMENT

3.1 Parameters for the dynamic process

The dynamic process included the total energy to be applied at each point, choice of hammer size, the number of hammer drops (tamping) at a point for a pass, the spacing of the points and the number of passes. A layer of granular soil was placed on the ground surface to serve as a compaction cushion. In this project, fine sand was used because availability. The fine sand has permeability lower than that of coarse sand which is more commonly used in this type of project.

3.1.1 Layout of tamping point, number of tamping and number of passes

Based on past experience (Zheng 2000 and Zhou 2005), more efficient treatment can be reached for a given total applied energy by decreasing the number of tamping by the drop of hammer and increasing the number of passes with practical limits. In this experimental study, three sets of compaction schemes were adopted as shown in Table2.

Each scheme was applied to an area of about 15m×15m, consisting of 9 tamping points. Piezometers and settlement gauges were installed in each area to measure excess pore water pressures and settlements at different depths. Field vane shear tests were conducted before, during and after treatment at each area.

Table 2 Comparison of experimental tamping schemes

	Number of tamping per pass		
	3 passes, Scheme 1	4 passes, Scheme 2	5 passes, Scheme 3
No. of tamping in the first pass	3 drops□1200 kN.m	2 drops□800 kN.m	2 drops□800 kN.m
No of tamping in the second pass	2 drops□1000 kN.m	2 drops□700 kN.m	1 drops□500 kN.m
No. of tamping in the third pass		2 drops□700 kN.m	1 drop□500 kN.m
No. of tamping in the fourth pass			1 drop□400 kN.m
No. of tamping in the final (overlapping) tamping	2 drops□600 kN.m	2 drops□600 kN.m	2 drop□600 kN.m

Note: 1. For each pass, tamping was performed at a spacing of 5.5m except for the overlapping tamping in which the tamping was performed with an overlapping distance of 0.75 hammer diameter.
2. The total compaction energy was kept constant in each compaction scheme.

A circular hammer was used in this project. The hammer was 2.4m in diameter, 75cm in height and 150kN by weight. There were a few evenly located ventilating holes on the hammer, which reduced the contact area by 2.5%.

3.1.2 Criteria for terminating tamping at a point

The number of tampings at a point is determined by the soil deformation generated by the tamping. The tamping will stop when any of the following criteria is fulfilled. (1) The soil mass around the tamping pit starts to bulge up, (2) the lateral displacement near the tamping pit becomes excessive, or (3) the settlement due to the current drop of hammer is larger than that of the last drop, as this is indicative of the soil being destructured.

3.2 Drainage system

The basic idea of the dynamic-static drainage consolidation method is to apply the dynamic energy from compaction to generate excess pore pressure. By installing an adequate system of drainage both in the vertical and the horizontal directions, the excess pore pressure can readily dissipate, leading to consolidation settlement and hence shear strength increase.

3.2.1 Horizontal drainage system

The horizontal drainage system was provided by the fine sand cover that also served as a compaction cushion. This cover was composed of a 1.0m thick layer of fine sand placed on top of the original ground surface with crisscross ditches and shallow wells. The bottom width of the ditch is 0.4m with a 1% slope draining to the shallow well. The ditch was filled with uniformly graded gravel of 3~5cm diameter, wrapped with permeable fabric. The shallow wells were set along the length of the ditches at a fixed interval. A reinforced cage of external diameter of 490mm was placed in the well. The cage was wrapped with an iron or plastic net on the outside, and with geofabric at the bottom. Gravel was placed around the reinforced cage as a filter. Water collected in the well was pumped away timely during the construction to ensure the water level in the well was at a depth greater than 60cm.

3.2.2 Vertical drainage system

Plastic strip drains were used for the vertical drainage system. 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 silty clay below the mud layer for at least 0.5m and the top 20cm of the strip stood freely out of the sand cover. Efforts were made to ensure the location deviation of the strip should be less than 50mm and the strip inclination is less than 1.5% from the vertical. The inside of the strip was kept clean. The machine for installing the strip was equipped with a recorder to record the installed length of the strip.

3.3 EFFECTIVENESS OF IMPROVEMENT

The excess pore water pressure and settlement profile were monitored during and after tamping. Field vane shear tests were conducted before, during, and after treatment to check the effectiveness of improvement.

3.3.1 Results on excess pore water pressure

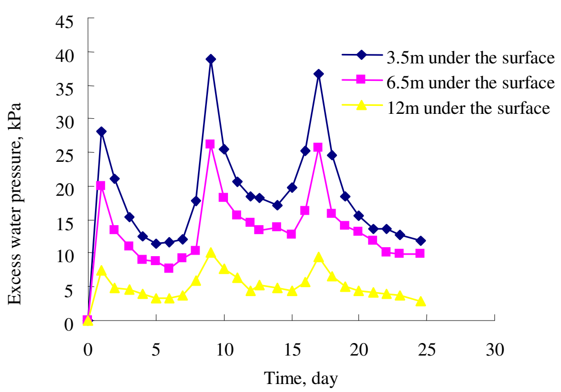

Fig.1 Excess pore water pressure during 3 passes (Scheme 1)

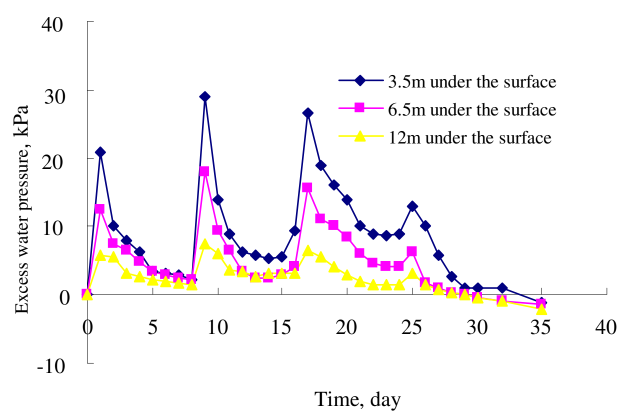

Fig.2 Excess pore water pressure during 4 passes (Scheme 2)

Monitoring the dissipation of the excess pore water pressure provides an effective way of guiding the construction schedule and assessing the effectiveness and depth of improvement. Results from monitoring the excess pore water pressure 3.5m, 6.5m and 12.0m under the surface are given in Figures 1, 2 and 3. The variation of the excess pore water pressure with time shows that the dissipation process occurred quickly after each tamping pass. The excess pore water pressure at shallow depth is higher than that at greater depth. The fact that excess pore water pressure is measurable at 12.0m depth under the surface after each tamping pass suggests that the effect of tamping has reached that depth.

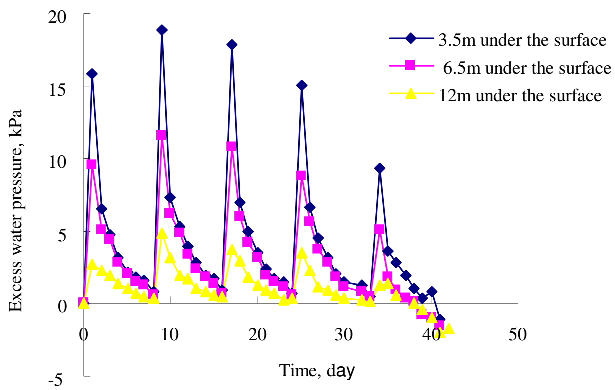

Fig.3 Excess pore water pressure during 5 passes (Scheme 3)

In compaction Scheme 1 in which 3 tamping passes were applied, the maximum excess pore water pressure of about 40kPa is observed. The dissipation rate of this excess pore water pressure is, however, slower than those in other schemes. In this scheme, for example, the excess pore water pressure after 7 days of the first tamping pass at 3.5m, 6.5m and 12.0m depths has dropped respectively to 59%□57% and 54% of its initial value. For compaction Scheme 2 (4 passes) and Scheme 3 (5 passes), the maximum excess pore pressure generated is about 30kPa and 20kPa, respectively. Seven days after the first pass, the excess pore pressure has dropped by more than 70%. This observation suggests that for the given total compaction energy, Schemes 2 or 3 may be more effective than scheme 1.

For the same compaction energy, the excess pore water pressure of later tamping passes is less than that of the earlier pass and the dissipation rate of the excess pore pressure is slower. For example, for compaction Scheme 2 with 4 passes, the results as shown in Figure 2, show that the excess pore pressure generated and the subsequent dissipation rate for the third pass are 5.4% and 4.7% less than those, respectively, for the second pass under the same compaction energy of 700kN.m. The possible reason for this is that increasing hardening of the surface cover due to repeated compaction tends to spread the impact load more evenly at depth, hence decreasing the in of excess pore pressure. Furthermore, the hardened cover will have a lower permeability that slows down the consolidation process and decreases the dissipation rate.

The excess pore water pressure became negative after the overlapping (final) tamping for Schemes 2 and 3 with 4 and 5 tamping passes, respectively. This is because the additional stress in the soil formed by the repeated impulsive loads of tamping and the static load of the sand cushion to cause pore water to expel from the drainage system, so the pore water pressure after the overlapping tamping is less than that of the original value. This phenomenon further supports the notion that Schemes 2 and 3 are more effective than Scheme 1.

3.3.2 Results on settlement

Settlement is also an important measure of soil improvement. Settlement increases gradually with the dissipation of excess pore water pressure. The settlements at various depths for scheme 2 with 4 tamping passes are shown in Figure 4. As expected, the settlement increases with time and the settlement rate decreases with time and depth. The increase of settlement on the surface is the fastest and the settlement increases at different depths are consistent with the dissipation rates of the excess pore pressures. As the excess pore pressure dissipates to a steady point after a pass, so is the settlement. When a subsequent tamping is applied, new excess pore water pressures are generated and more settlements follow. The final settlement tends to be stable suggesting that the tamping energy of each passes is appropriate.

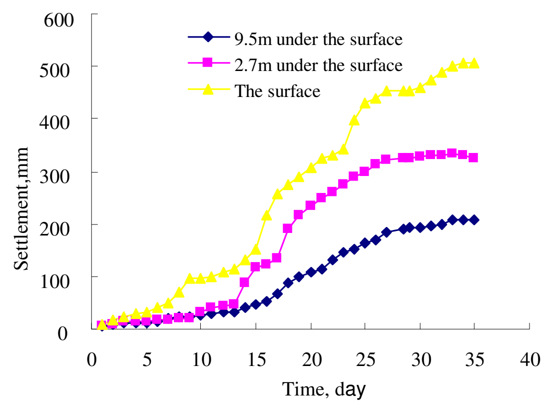

Fig. 4 Settlements at different depths after of 4 passes

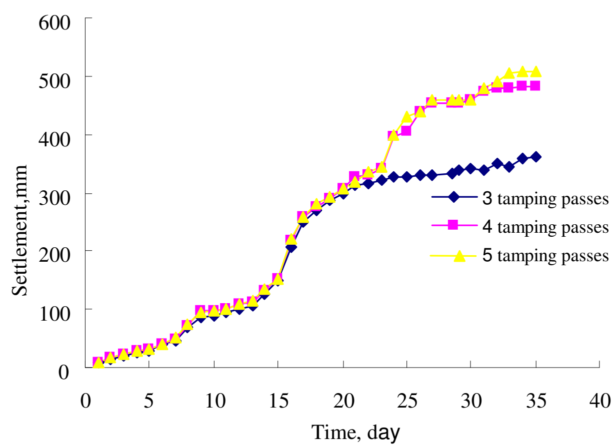

Fig. 5 Surface soil settlements of different numbers of passes

The surface settlements for different compaction schemes with different tamping passes are shown in

Figure 5. The variations of the settlement trends are again consistent with the excess pore pressure generation. The

settlement magnitude increases with the number of passes even though the total compaction energy is kept constant but the increase is not linear. For example, there is a 27% increase in settlement from Scheme 2 (4 passes) to Scheme 1 (3 passes). However, there is only a 4.8% settlement increase from Scheme 3 (5 passes) to Scheme 2 (4 passes). Therefore it is beneficial to increase the number of passes with corresponding decrease in the number of tampings at a point. In this case record, however, other considerations such as the time required for more passes and the associated cost led to the adoption of Scheme 2 for the project.

3.3.3 Results on field vane shear strength

The field vane shear test results before, during (after the first pass) and after tamping (15 days after the final overlapping tamping) of 4 tamping passes are shown in Figure 6. The shear strength of the soft clay before tamping is very low, with a maximum of only 8.5 kPa. 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 7.5 kPa to 12.0 kPa (during tamping) and finally to 25.8 kPa (after tamping). The strength increases range from 1.6 to 3.5 times the original values.

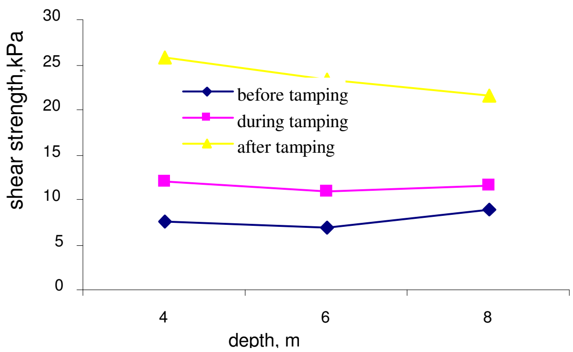

Fig. 6 Shear strength measured before, during and after tamping passes 4 tamping passes (Scheme 2)

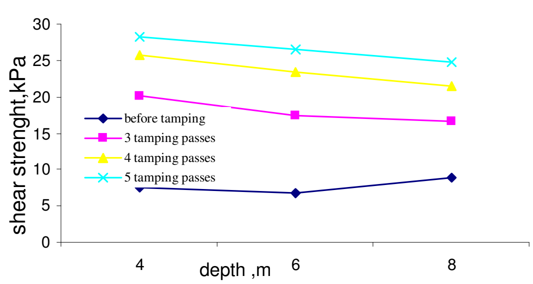

Fig. 7 Measured shear strength of different (Schemes 1, 2 and 3)

Field vane shear test results at 15 days after the final overlapping tamping for Schemes 1, 2, and 3 (3, 4, and 5 passes, respectively) are given in Figure 7. The results show that the strength at different depth increases with the tamping pass and the strength increase at shallow depth is higher than that at deeper depth. After 5 tamping passes (Scheme 3), the strength increases are 3.8, 3.7 and 2.9 times those before treatment at 4m, 6m and 8m depths from the original ground surface, respectively. This shows that the improvement decreases with depth. The strength gain decreases with the increase of tamping pass. For example, the strengths of 4 tamping passes (Scheme 2) at 4m, 6m and 8m under the surface increase by 31%, 34% and 30% compared with those of 3 tamping passes (Scheme 1). Meanwhile the strengths of 5 tamping passes (Scheme 3) at 4m, 6m and 8m under the surface increase by only 12%, 13% and 15% compared with those of the 4 tamping passes. The most dramatic increase is found in Scheme 2 (4 tamping passes).

4. COMPARISON OF VARIOUS METHODS

A comparison of different possible methods for strengthening the site has been conducted and the results are summarized in Table 3. All these methods produce acceptable improvement of the site for the project. The results are expressed in terms of the required duration for the successful application of the methods and the cost per unit area to be strengthened. The results show that the conventional preloading with plastic strip drains will be the cheapest with the dynamic-static drainage consolidation method being a close second. However the required duration of the preloading method will be 3.3 times longer than that of the dynamic-static method. Therefore, consideration of the total cost and the associated construction time required, the dynamic-static method is the most competitive.

Table 3 Comparison among different methods

Type of method	Required duration days	Cost Yuan/m^2
Dynamic-static drainage consolidation	45	65
Vacuum preloading	90	140
Plastic strip together with preload	150	55
Sand drains together with preload	150	70

Note: The 4 different methods are based on the drains (plastic strips or sand) reaching the same depth of 10m

5. CONCLUSIONS

This paper considers the dynamic-static drainage consolidation method which is based on combining the dynamic compaction method and the static consolidation method for the rapid and cost effective strengthening of very soft clay with strength as low as 8 kPa. A field experiment has been conducted to study the influence of the parameters that influence the performance of this method. Analysis of the measured excess pore pressures, settlements and field vane strengths before, during and after the treatment leads to the following conclusions.

1) For a given total compaction energy, better result is obtained by increasing the number of passes with corresponding decrease in the number of tampings at a point.

2) Four tamping passes and the tamping energy level at a point for each pass less than 1000kN.m produce the best result for the case study present in this paper.

3) The undrained strength of the soil was raised from about 8 kPa to 25 kPa.

4) The dynamic-static drainage consolidation is found to give excellent results in terms of cost and time for strengthening the very soft fine-grained soil.

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