Experimental Study on Vacuum Dynamic Consolidation Treatment of Soft Soil Foundation

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Abstract. In view of the deficiency of the saturated silt clay foundation reinforced by the dynamic consolidation method, combination the project of soft foundation treatment test area in Tangshan, the reaserch analysed indexes, included groundwater level, pore water pressure, settlement about soil layer and so on, by use of field tests and indoor geotechnical tests, The results showed that the whole reinforcement effect with vacuum dynamic compaction method to blow fill foundation is obvious, due to the result of vacuum precipitation, generally, the excess pore water pressure can be dissipated by 90% above in 2 days around and the effective compaction coefficient can reached more than 0.9, the research work in soft foundation treatment engineering provide a new method and thought to similar engineering.

1. Introduction

The dynamic compaction method is a kind of conventional foundation treatment method, which is widely used in gravel soil, sandy soil, cohesive soil and low saturation silt soil. However, it is not ideal for the treatment of soft clay foundation with high water table, especially the soft soil foundation with high water content, large void ratio, low permeability and low intensity. It is considered that the excess pore water pressure, which is formed in soft soil foundation under the condition of compaction, is difficult to dissipate in time, the result is the loss of shear strength of soil [1-3]. As the active composite drainage consolidation measures, the vacuum dynamic consolidation takes into account the advantages of the dynamic compaction method and the vacuum preloading method, avoiding the damage to the drainage system, the application range of the soft soil foundation treatment method in the coastal area is widened by the accelerated dissipation of excess pore water pressure and the effective consolidation of soft soil.

In view of the existing dynamic foundation reinforcement in the process of excess pore pressure dissipation and hard rubber soil problems of the phenomenon, and based series of achievements has been made in the research on the reinforcement mechanism [4], permeability coefficient variation law of [5, 6], Zhou Jian [7] puts forward the method of dynamic drainage consolidation by combining dynamic compaction and well point dewatering, based on the field test, the mechanism of soil reinforcement is analyzed and discussed, Wang Liming and [8] have also proved that the vacuum dynamic consolidation can achieve good reinforcement effect.

2. Vacuum dynamic consolidation treatment of saturated soft soil foundation

Vacuum dynamic consolidation is suitable for the reinforcement of coastal muddy clay, and the vacuum drainage effect is directly related to the reinforcement effect, due to the impact of compaction and vacuum negative pressure, the pressure difference will be more obvious, then, through multiple times of high vacuum drainage and dynamic consolidation, the water content of saturated soft soil is
reduced. The consolidation mechanism of vacuum dynamic consolidation method is mainly composed of three parts:

1) Vacuum drainage. The saturated soft clay foundation is treated by using vacuum pumping equipment, the saturation of the soil and the excess pore water pressure are reduced by the high vacuum, so that the pore water and pore gas can be discharged quickly, and then the dynamic consolidation efficiency can be enhanced, and the soil consolidation can be accelerated.

2) Dynamic consolidation. Dynamic consolidation is mainly realized by dynamic compaction, which is based on the construction of high vacuum drainage, and pore water and excess pore water pressure can be discharged and dissipated through the permeable channel, therefore, the effect of dynamic compaction is obvious, and the compactness of soil can be increased rapidly.

3) Formation of "over consolidated hard shell layer". The saturated soft clay foundation will accelerate consolidation on the basis of the "negative pressure" produced by high vacuum and the excess pore water pressure generated by dynamic compaction, and low water content, high density features of the over consolidated crust layer is vacuum drainage and dynamic consolidation multiple interactions in saturated soft clay ground surface results can meet the bearing capacity of building foundation soil and settlement.

3. Engineering geological condition
The foundation treatment is located in Caofeidian area of Tangshan. The site engineering geological condition is complex, the upper part of dredger fill in unconsolidation state, and the uneven distribution of site poor engineering properties, engineering geological survey measured soil properties are shown in table 1.

| Soil number | Soil name | Bearing capacity characteristic value (kPa) | Compression modulus \( E_s \) (MPa) |
|-------------|-----------|-------------------------------------------|-------------------------------------|
| ②           | Plain sand | 74                                        | 1.8~4.4                             |
| ②           | Silty clay | 52~89                                     | 2.1~3.9                             |
| ②-3         | Silt       | 71~89                                     | 4.2~5.0                             |
| ③           | sand       | 102~128                                   | 5.1~10.0                            |
| ③-3         | Silt       | 92~108                                    | 4.3~5.0                             |
| ⑤           | sand       | 151~179                                   | 14.1~15.9                           |
| ⑤           | Silty clay | 120~150                                   | 4.0~7.0                             |

4. Process research and test scheme design

4.1 Main process flow
Vacuum drainage and dynamic compaction are the basic requirements of the vacuum dynamic consolidation method, the consolidation of saturated soft soil foundation requires two processes of cycle (figure 1).
4.2 Test scheme

Test area of 2500m$^2$, the foundation treatment using three down three ram, that is, the vacuum drainage and the three times the compaction of alternating, dynamic compaction construction should follow the principle of "from light to heavy, less hit multiple" principle, the depth of reinforcement is controlled by 5–7 m, and the designed load characteristic value is between 160–200 kPa, the distance between tamping points is 4 m, and the interval time is 2–3 days. The other process parameters of vacuum dewatering and dynamic compaction in the test area are shown in table 2.

| Vacuum dewatering required depth (below ground m) | The number of tamping per tamping and tamping energy (kN - M) |
|-------------------------------------------------|--------------------------------------------------------|
| First time 2.5                                   | First 4–5 hit 1000                                     |
| Second times 3.0                                 | Second 6–8 hits 1500                                  |
| Third times 3.0                                  | Third 8–10 hits 2000                                  |

Figure 2 shows the vacuum drainage by deep well (length 6 m) and Asakai (length 3 m) spaced construction scheme, the vertical well spacing of 4 m, the transverse horizontal pipe spacing of 4 m. Considering that the groundwater level of the test site is obviously affected by the flood tide, the pulling out of the vacuum well point pipe should be kept synchronized with the tamping. In order to ensure the drainage of the pore water and the effect of excess pore water pressure dissipation, the well point pipe shall be re inserted and continuously operated for 72 h at the end of each tamping end. The construction time of dynamic compaction shall be controlled, and 3 water level observation holes shall (6 meters deep) be installed on the test site, the observation hole has a filter length of 2 m and it is guaranteed to be observed at least 2 times a day.
The compaction process adopts medium tamping, and the energy can be considered for the convenience of comparing the foundation reinforcement effect, the selection of round hole hammer can avoid the energy dissipation caused by the overlap of the hammer landing. The size of the hammer is 2.5 m, the weight of hammer is 11.5 T, and the distance of the hammer is controlled at 9 m–20 m. The observation of the water table by the pore water pressure meter determines the time interval after tamping, the next dynamic compaction shall be carried out after the excess pore water pressure of the foundation soil is dissipated by 85%–90%.

5. Monitoring and results analysis

The test of vacuum dynamic consolidation process in the test area is divided into three stages: pre strengthening, strengthening and consolidation, the standard penetration test (B4, B5, B6) and static cone penetration test (J4, J5, J6) were carried out before strengthening; pore pressure observation, deep deformation observation and ground acceleration test were carried out in the experiment. The pore water pressure gauge selects the steel string type, altogether 8 (K31~K34, K41~K44), to be buried at different depths (3 m, 5 m, 7 m, 9 m) depending on the need. In order to ensure the validity and integrity of the observation data, and better reflect the characteristics of the deep deformation of the foundation treatment, three groups of deep targets (S1, S2, S3) were embedded in the test area. The ground acceleration test is selected for the test area; After the completion of the vacuum dynamic consolidation test, the test site was carried out through the standard penetration test (hole B4 ′, B5 ′, B6 ′) and static cone penetration test (hole J3 ′, J4 ′, J5 ′), the specific hole layout shown in figure 4.

5.1 Comparative analysis of standard penetration test

In the test area, the ”Three times precipitation, three times ramming” was used to control the impact energy, which was mainly controlled by M 2000 kN, the observation results of standard penetration test before and after vacuum dynamic consolidation (figure 5) show that the number of shallow soil SPT in the foundation soil is obviously improved, and the increase range is mainly between the range of 100%–200%, however, with the deepening of soil layer, the extent of the increase gradually decreased until the deep layer of foundation soil was lost. The strength of foundation soil is increased in the range of 4–9 m after vacuum dynamic consolidation, the depth and bearing capacity of foundation soil can be improved by increasing the depth of precipitation and increasing the energy of compaction, therefore, the depth of precipitation and the corresponding energy level should be arranged reasonably according to the thickness of the soil layer, so as to meet the requirements of the foundation bearing capacity and deformation.
5.2 Analysis of static sounding test results

The resistance curve of the cone head before and after the vacuum dynamic consolidation in the test area (figure 6) shows that the resistance value of the saturated soft clay ground cone in a certain depth range is improved obviously, the strength and compactness of soft soil foundation increased significantly. Before and after the vacuum dynamic consolidation, the resistance curves of the cone head approximately intersect at the depth of 6~7 m, which indicates that the resistance of the cone head before and after reinforcement is not significant, as a result, the effective depth of the foundation reinforcement of the vacuum dynamic consolidation soft soil foundation with "Three times precipitation, three times ramming" is considered as 6~7 m. Because the surface soil is easy to be disturbed in the construction process, which leads to the best reinforcement effect of the soil under the scope of 2~3 m.

5.3 Analysis of pore water pressure variation

The dynamic time history curves of the peak pore water pressure of the pre buried pore water pressure gauges (K31, K32, K33, K34) are shown in figure 7. It is found that during the vacuum dynamic consolidation process, the foundation soil is partly removed from the pore water in the vacuum dewatering process (January 23 ~ 25), the initial pore water pressure decreases and the saturation of the soil decreases, the efficiency of tamping is improved, and there is no rubber soil. The peak value of pore water pressure at different depths increased obviously during the dynamic compaction (January 25~28), the increase of pore water pressure increases gradually with the increase of depth, which can be reflected in the curve; The excess pore water pressure was dissipated in the two vacuum active precipitation process (January 28~31), the excess pore water pressure in the shallow layer of the foundation soil dissipates rapidly, and the excess pore water pressure generated by the dynamic compaction can be dissipated more than 90% in 2 days, the reason is that the "positive pressure" produced by the excess pore water and the "negative pressure" produced by vacuum dewatering and drainage in the foundation soil have a gradually increasing "pressure difference". The drainage effect
of the project is improved, the gap between the dynamic compaction and the construction period is shortened; Pore water pressure variation peak in the subsequent two times of compaction (February 1~2, February 6~14) and again vacuum precipitation (February 4~6) in the construction of the same similar, but then two times of compaction caused by excess pore water pressure decreases.

5.4 Analysis of site deformation characteristics

5.4.1 Test result analysis of tamping pit. The observation and analysis of 4 groups of different tamping energy in the test area were carried out (figure 8): ground settlement and hammer number showed the proportion of positive change, but the change rate decreases gradually, the overall consolidation settlement occurs in the main components of the tamping number is less than 6 when it is struck, therefore, to determine the best overall implementation of foundation treatment of tamping hammer blow number per times contribute to better. The crater near without obvious uplift indicated that soil compaction is approximately equivalent to the crater volume, thus reflecting the soil compaction effect can be directly used to measure the crater volume can reach more than 0.9, calculation of the effective coefficient of compaction. Local failure deformation law of foundation soil showed extensive damage, after the final failure characteristics of elastic deformation and that in times of compaction conditions, with the increase of soil compaction number was significantly increased.

Figure 8. Relation curve of tamping number and tamping quantity.

5.4.2 Deep deformation analysis. Figure 9 shows the deep foundation soil standard Determination of S1, S2 and S3 three groups of deep displacement, through the complete process of vacuum dynamic consolidation settlement observation, the overall soil depth attenuation characteristics of deformation with convergence. The settlement of S1 deep scale soil under 14.084 m is less than 8.9% of the total settlement, but the change of settlement is obvious at the above position (from 472 mm to 14.084 m of the surface soil mass, 42 mm at the depth); S2 deep scale settlement is attenuated from 602 mm (ground surface) to 240 mm (8.1475 m depth), The calculation shows that the settlement below the soil layer still reaches 39.9% of the total settlement; The settlement of S3 deep scale soil decreased from 470 mm (surface) settlement to 177mm (9.965 m depth), and the soil settlement still accounted for 37.7% of the total settlement under 9.965 m. The analysis of the observed curve can be that the depth of soil’s S1 standard position has basically reached the vacuum dynamic consolidation effect, while the S2 and S3 standard has not yet been laid in place, because the bottom still has a large settlement, and the soil below this layer is affected by the compaction of vacuum dynamic consolidation

The observation results show that, in the process of vacuum dynamic consolidation in shock wave and dynamic stress of foundation soil under the action of force more dense, the strength of the foundation soil, stiffness and compression modulus increased significantly, while the soil compression volume growth rate showed reverse decreasing trend, the soil tends to be more dense

6. Conclusion
With the development of the integration of Beijing, Tianjin and Hebei, and as well as the continuous
The strengthening of large saturated soft clay foundation is also highlighted. In the paper, the influence of excess pore water pressure, ground deformation and tamping energy on the soil mass change before and after foundation treatment in the experimental area are systematically monitored and analyzed. The following conclusions have been obtained:

1. The excess pore water pressure and water content in foundation soil can be dissipated and reduced by the combination of vacuum drainage and dynamic compaction. The compaction efficiency is improved obviously and the construction period is shortened.

2. The soil strength and modulus of deformation in the experimental area are obviously improved after vacuum dynamic consolidation, and the risk of soil liquefaction is completely eliminated.

3. The number of vacuum precipitation and tamping energy are closely related to the strengthening effect of foundation soil, and the effect of reinforcement increases obviously with the increase of precipitation number and tamping energy. In the range of influence, the settlement of the tamping pit and the total settlement of the ground increase with the increase of tamping energy and tamping number.

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