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ABSTRACT

This paper reports a case study on treatment of soft clays by dynamic compaction. A special technique adopted in this project allowed massive stiff columns to be formed under the impact locations, and the soils between these impact locations to be replaced and mixed with granular fills, hence creating a composite foundation. The comprehensive field investigation showed that the allowable bearing capacity of the treated ground (as a composite foundation) was 350 kPa, a significant increase compared with that of untreated ground (70 kPa) . The achieved stiffness modulus of the composite foundation was 24 MPa.

KEYWORDS

Soil improvement, soft soils, dynamic compaction, composite foundations.

INTRODUCTION

The method of dynamic consolidation/compaction (DC) was developed by Menard and Broise (1975) from heavy tamping. The scope of application of this method has been extended to saturated clay and alluvial soils. Soil improvement by dynamic consolidation was introduced in China in the late 1970s (Qian, 1980). This technique has been proved to be successful in China for improving ballast/industrial waste fills, natural gravely soils and collapsible loess. However, it was found that the applicability of this technique to saturated clayey soils is still controversial. The dynamic consolidation model proposed by Menard (1975) is more a hypothesis than a theory. It is commonly recognised that without adequate drainage, improvements on deep clayey soils are very limited. There have been a number of new applications (Lee, 1985; Shi, 1985; Broms, 1987) of dynamic compaction on soft ground. In these cases, the purpose of dynamic compaction is not to improve the properties of soils, rather to replace soft soils with granular materials (i.e. sands and stones) so that to form a sand and stone columns under the impact points. As DC construction proceeds and a crater becomes deeper, more materials are filled into a pit to facilitate the pullout of pounder for next blow. By doing so, a massive sand/stone column forms within ground. Whether it is realised or not, the column may work as a drainage channel to shortcut drainage paths and accelerate the dissipation of excess pore pressure caused by impacts of DC. The so formed columns, which are normally of high stiffness and strength and together with the surrounding soils, may form a composite foundation with high bearing capacity. This paper reports a case study on the treatment of soft clays by the dynamic compaction. Special technique was adopted to ensure massive stiff columns formed in treated soils.

GROUND CONDITIONS

A large sinter plant was to be constructed on a landfill site reclaimed from a marsh area of the Yangtze River, Wuhan, China. The ground was submerged below the water level of the Yangtze River for the most times of year. The typical soil profile of the ground is presented in Figure 1. It can be seen that the soil profile consists of 1 to 2 meter thick slag fill, plain fill (loam), warp clay, lacustrine soil and loam. The physical and mechanical properties of warp clay and lacustrine clay are presented in Table 1 and Table 2 respectively. These two soils have very low strength and small stiffness, therefore need to be improved in order to support the loads imposed by the development. The deeper stratum of loam, as the first terrace of Yangtze River, is better in mechanical properties than the above two soils and hence does not need treatment.

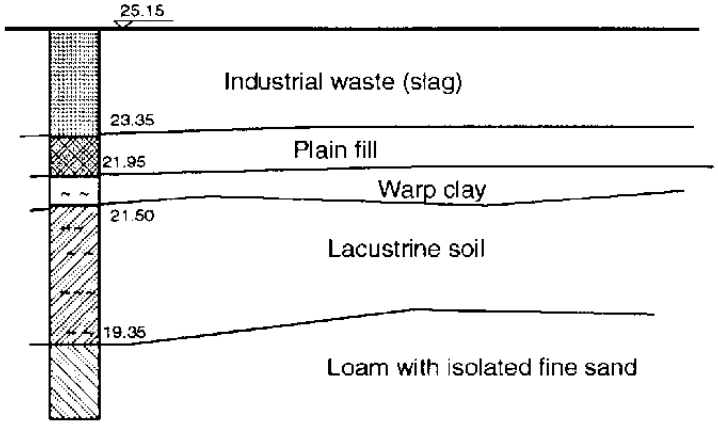

Figure 1 Typical soil profile of the ground

Table 1 Physical properties of the untreated soils

Type of soil	Moisture content (%)	Bulk density (t/m^3)	Void ratio	Plasticity Index	Liquidity Index
Warp soil	52.8	1.75	1.43	23.4	0.93
Lacustrine clay	54.7	1.66	1.59	27.0	0.95

Table 2 Mechanical properties of untreated soils

Type of soil	Modulus of compressibility (MPa)	Allowable Bearing capacity (kPa)
Warp soil	2.2	40-60
Lacustrine clay	2.32	60

TRIAL DYNAMIC COMPACTION

A trial zone was selected to study the validity of the dynamic compaction on the ground concerned. In order to achieve the reasonable good treatment, three primary and one secondary passes of compaction were performed. The arrangement of impact grids for the first three passes are shown in Figure 2. A semi-spherical steel pounder with a diameter of 2 meters and weight of 18 tons, was dropped from a height of 20 meters, making an impact energy for each blow of 3500 kNm. Total of 20 blows were applied for each impact point. Two different grids of 4m and 4.5m were adopted. More slag was filled into craters while the dynamic compaction proceeded. The secondary pass of compaction was carried out by a flat-bottom pounder of 20 tons falling from 10 meters high for 10 blows. The grids were arranged so that the whole area of treated ground was fully covered by the prints of pounder.

In-situ testing and monitoring for the treated ground were carried out to study the effects of the treatment. These techniques included modified dynamic cone penetration tests, static cone penetration tests, Piezometers and pressure cells, and large scale plate bearing tests (3×3 m^2). Test positions are indicated in Figure 2.

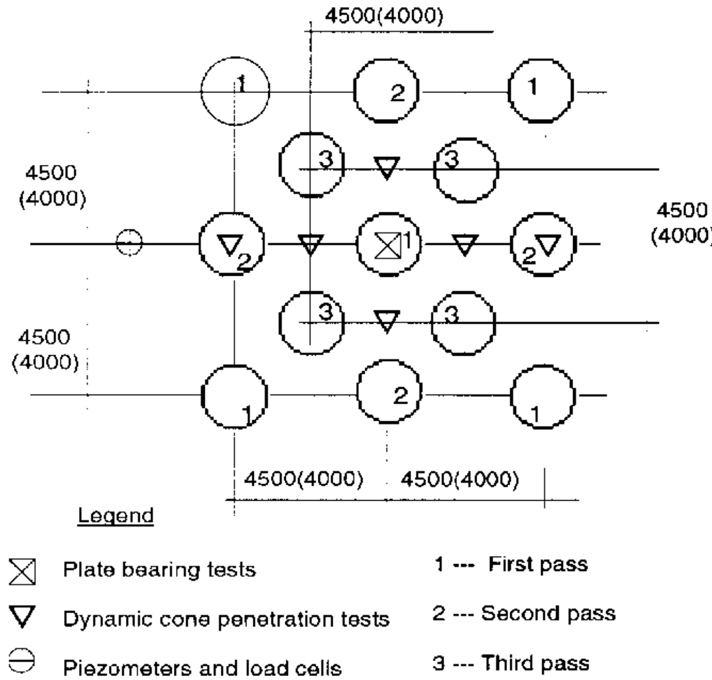

Figure 2 Arrangement of pass grids and test positions

Profile of Treated Ground

Borehole survey conducted on impact points indicated that all material sampled from the depth of 5-6 meters was pure slag. While borehole survey carried out in locations between impact points showed a kind of mixtures of soils and slag. A trench was dug in treated ground and the profile of cross section was outlined in Figure 3. It can seen that massive slag columns of 5-6.6 meter deep and reverse cone shaped were formed under the impact points, and soft soils were squeezed to somewhere between impact points. The materials between the impact points were mixtures of soils and slag, and more slag in upper layer and more soils in lower layer. Some of the soft clay become isolated lumps surrounded by slag. Clearly, a type of composite foundation was formed by the slag columns and the surrounding soils. It was found that the water content of soft soils became smaller than that before treatment. There were two possible reasons: one was due to water absorption of dry slag; two was due to improved drainage provided by slag columns and part of water was expelled from soils under the dynamic forces.

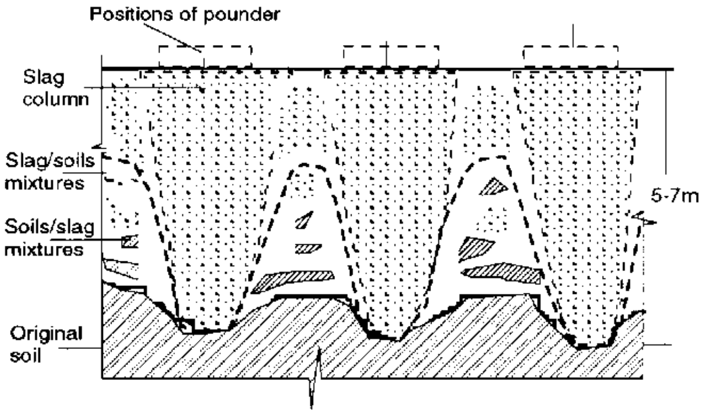

Figure 3 Profile of treated foundation

Plate Bearing tests

The plate bearing tests were carried out on the improved ground. The bearing plate was aligned to the centres of impact points. The area of bearing plate is 3×3 m^2 = 9 m^2, a value similar to the treated area (which is 8 m^2 for 4 m grids and 10 m^2 for 4.5m grids). Hence, the test results of bearing tests may be considered as representative of behaviour of composite foundation. As shown in Figure 4, the as measured load settlement relationships were very linear until the maximum test load of 500 kPa was reached. The modulus of deformation corresponding to 1.5% of width of the bearing plate was in range of 34 to 37 MPa.

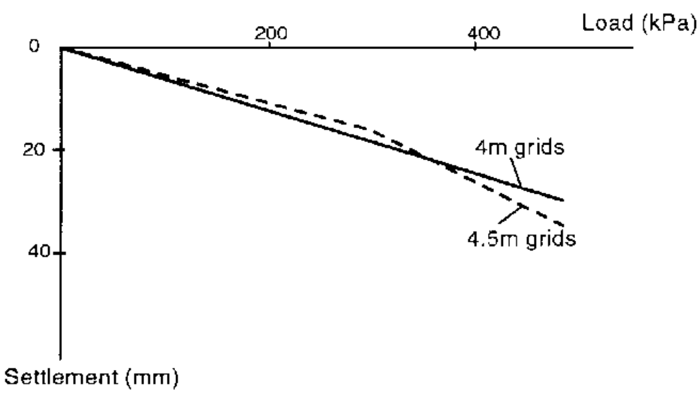

Figure 4 Results of plate bearing tests (3×3m^2)

Modified Dynamic Cone Penetration Tests

Modified dynamic cone penetrometer was used to investigate the strength and stiffness of slag or the mixtures of slag and soils. The weight of the hammer for dynamic cone penetrometer testing is 120 kgs. The test results, denoted as N_{120}, is the number of blows required to achieve a penetration of 10 cms. In order to relate the values N_{120} to the strength and stiffness of the treated soils, a local (Wuhan region) empirical correlation, as summarised in Table 3, was used.

Table 3 Relationships between N_{120} and R, E_s (Wuhan region)

N_{120}	Relative density	Allowable bearing capacity (kPa)	Modulus of compressibility (MPa)
1-5	Slightly dense	150	8
5-25	Medium dense	300	20
>25	Very dense	400	30

The curves of N_{120} vs. depth at the impact points and between the impact points were compared in Figure 5a for 4m grids and in Figure 5b for 4.5 m grids. The results on impact points were averaged from parallel tests on two different slag columns, and the results between impact points were averaged from four parallel tests. The averaged values of N_{120} for tests within depth of 6 meters is 15. According to Table 3, the bearing capacity is 300 kPa, and modulus of compressibility is 20 MPa.

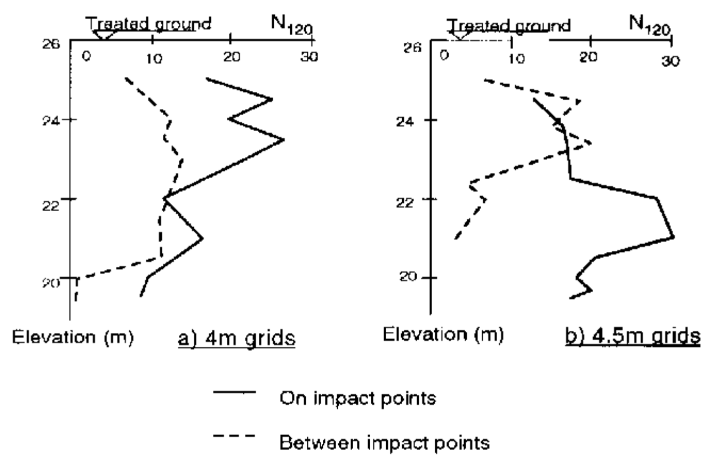

Figure 5 Results of dynamic cone penetration tests

Based on the results of bearing plate tests and modified dynamic cone penetrometer tests, the composite foundation was estimated to have an allowable bearing capacity of 350 kPa and a modulus of compressibility of 24 MPa.

Influence of Dynamic Compaction on Deep Soils

The effect of dynamic compaction on the deep loam soils can be investigated by comparing the change of soil properties after treatment. As shown in Table 4, the increases in density and decreases in moisture content were observed for all soils. The improvement in soil properties may have been contributed by the provision of the shorten drainage paths due to the slag columns and hence excess pore water may have been more readily expelled from soils.

Change of Pore Pressure and Soil Stresses

Four piezometer tips and four pressure cells were installed within depth of 3m to 9m to check the extent and effectiveness of dynamic compaction. The measurements of piezometers indicated that the pore pressures generated by dynamic compaction in soils were so high that zero effective vertical stresses achieved at depth of 4.5 and 6 meters. It is this state of high pore pressures or nearly nil strength that provides the opportunity for soils to be expelled and replaced by slag. The variations of stress registered in pressure cells did not correspond to a total stress change but reflect a local stress change within soil due to dynamic compaction. It was measured that the vertical stress had an increase of 50 to 70 kPa, indicating the soils becoming locally more compacted after dynamic compaction.

Table 4 Comparison of deep soil properties before and after treatment

Type of soils treated	Bulk density (t/m^3)	Moisture content (%)	Void ratio
Loam			
Before	1.92	26.5	0.74
After	2.01	23.5	0.67
Sandy loam			
Before	1.94	27.9	0.79
After	2.03	22.2	0.72
Fine sand			
Before	1.97	23.2	0.68
After	2.03	21.4	0.62

Replacement Ratio

The ratio of the volume of soil replaced by slag to the volume of soil treated is defined as replacement ratio. Based on the amount of slag filled and the elevation increase of the treated ground, the replacement ratio of the treatment was estimated to be about 0.4 to 0.5, considerably higher than that of compaction gravel piles. It worthies noting that some portion of soft soils may be lifted to a higher position than they naturally were. Some water of soft soils has been sucked by unsaturated fills or expelled under dynamic pressure, and part of soft soils has filled pores of fills. Hence the volume of ground swell is less than the volume of compacted slag of being filled.

Applicability

A slag column formed by dynamic compaction is usually large in diameter and high in density, and together with the surrounding soils may form a composite foundation with high bearing capacity. For a small and medium isolated footing, one slag column may be adequate to support the design load of a foundation. For heavy isolated footing, a few densely compacted columns may be a solution. It may be appropriate to use large grids compaction for large foundations. This method is particular advantageous for construction in the area where the designed elevation is higher than the natural surface and fill is required, because, under this circumstance, the operations of dynamic compaction and fill works can be combined.

SUMMARY

Dynamic compaction combined with filling slag appears to be a effective way to treat soft ground. The advantages of this technique have been demonstrated by the following respects:

1. Massive slag columns can be formed under the impact points;

2. Soft soils can be improved in their properties due to formation of slag columns.

3. Composite foundation so formed has excellent strength and stiffness as verified by the plate bearing tests.

There are a few issues required to further investigation, e.g. how the depth of slag columns is influenced by the impact energy and whether higher energy impacts in secondary passes give better treatments.

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