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SYNOPSIS

More innovative methods of ground treatment have replaced traditional methods.Dynamic Consolidation, for example, has been applied widespreadly in China. Presented in this paper is a case history of adopting the twice dynamic consolidation method to improve liquefiable saturated loesslike sandy loam deposit, since the site for the Aluminum Material Company which is located at the suburb of Taiyuan, China, is geotechnically adverse. In this project the effective depth of improvement increased significantly.Judged from the in-situ investigation and laboratory triaxial shear test,the liquefaction potential was eliminated as predicted.

INTRODUCTION

After the catastrophic 1976 Tangshan Earthquake,China, engineers found that not only granular soil but also soil containing large amount of plastic fines had experinced liquefaction. Wang (1980) has shown that certain types of clayey materials may be vulnerable to severe loss as result of earthquake shaking. Again, as the infra-structures increase in size and scope, more innovative methods have to be introduced to cope up with the scale of projects encountered. In the project mentioned in this paper, how to eliminate the liquefaction potential of deeply embedded soil layers economically is a practical problem to be tackled. The twice dynamic consolidation had been proved to be applicable.

SITE CONDITIONS

The site for the Aluminum Material Company is located at the suburb of Taiyuan ,China. It is a first class terrace near Fen River, the main geological properties are of alluvium from terrace. Within the exploration area, the site deposit includes four layers as follows:

The first layer is composed of loam and sandy load with medium compressibility, the cone resistance qc=1.20MPa. Its thickness is 3~4m.

The second layer is mainly composed of sandy loam. Its thickness is 4~6m and in the middle part there exists a sandwiched layer of loam of brown yellow or grey. The compressibility is of medium extent, qc=2.2MPa.

The third layer is sandyloam of 4~6m in thickness sandwiched with sand and loam. Its color is brown grey or brown with medium compressibility, qc=3.47MPa.

The fourth is a sand layer which consists of silty sand,find sand,coarse sand, gravel sand and round gravel but sandwiched with the layers of sandyloam and loam. The strength of this layer is rather high, qc=11.63MPa.

The ground water table is 2.2~5.5m below the ground surface.

JUDGEMENT OF LIQUEFACTION POTENTIAL

According to the judgement of liquefaction potential by Chinese Seismic Code (1985 Temporary Revised Version), the saturated sandy loam and sand layers within 3~16m deep below the ground surface are all liquefiable. The fourth soil layer is non-liquefiable. The liquefaction index of the site for main factory biulding is PL=12.5 which is greater than 7 and belongs to liquefaction region of 3rd class.

PROJECT DESCRIPTION AND PLAN OF GROUND TREATMENT

The main factory building consists of two workshops, i.e. continuous moulding workshop and plate-belt workshop. All are bent frames as shown in Fig.1. The foundation embedment is 2m except that for cold rolling machine which is embedded in a depth of 6.5m, and thus is already under the original water table.

Since the seismic intensity of the zone is of degree 8 according to China Intensity Scale of 12 Degrees System, it is decided that for the sake of elimination of risk of liquefaction hazard, the depth of ground treatment should be no less than 10.5m counting from the outdoor ground surface. The residual depth of liquefaction after treatment is less than 4m and the residual liquefaction index is $p_L<3$. But for the foundation of cold rolling machine, the liquefaction potential should be wholly eliminated and thus the required thickness of ground treatment is 15m.

Based on the site conditions, the authors adopted the dynamic consolidation for the whole main factory building with energy per blow of 4000KN-M(a 210KN pounder with a drop of 19m), the base area of round pounder is $6m^2$. In the whole process of dynamic tamping, we used the extension of the field application of dynamic consolidation which is called "dynamic replacement". We filled the tamping pit with naturally graded sand after each pass of tamping to the ground surface and thus large diameter sand pillar can be formed through the soft soil usually down to the required depth or supporting stratum. According to our experience, the effective depth is:

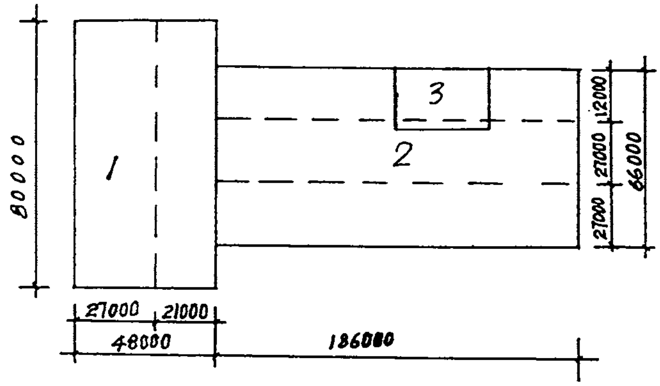
$$D=K\sqrt{WH/10}$$

where W is the weight of pounder (in KN) and H is the drop height (in M), K is an empirical coefficient, for clayey soils and high ground water table, K=0.5~0.6. Here we take K=0.5, and then we get D=10m. For this project, since the requirement is elimination of liquefaction potential and thus higher density of soil is required and therefore we finally take 8m of improvement as the actual effective depth. The elevation of base of foundation is 2m under the indoor elevation. The whole process includes two steps (Fig.2). The tamping pits for the first step are divided into two groups. The first group is marked by a circle "o", which includes 3 passes, with number of blows 5,10 and 10 respectively. While for the second group marked by concentric circles "◎", we ran two passes with the number of blows 10 and 15 respectively.

It should be noted that before tamping an excavation of 2m was run and a layer of naturally graded sand of 0.6m in thickness was spread so as to facilitate the travelling of crane, since the excavated ground is already near the ground water table. Moreover, after the whole 5 passes were completed, the site was filled with plain soil, its thickness was 0.5m. This is to compensate the predicted settement and then carpet tamping (printing one by one) with energy of 1000KN-M per blow was conducted. The dry unit weight was controlled to be $1.65KN/M^3$.

THE TWICE DYNAMIC TAMPING TECHNIQUE

The embedment for the foundation of cold rolling machine is 6.5m. Which is already beneath the ground water table. As stated above, the liquefaction potential should be completely eliminated. Moreover, the dynamic tamping with energy of 4000KN-M per blow can not fulfill this reqiiredment of ground



Notes. 1. continuous moulding workshop
2. plate-belt workshop
3. cold rolling machine

Fig.1 plan of main factory building

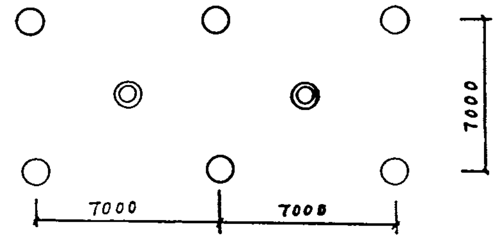


Fig.2 layout of tamping grids

Table 1 SPT values versus time both before and after tamping

depth (M) / time of SPT	0~5	5~10	10~15
before tamping	3.2	5.8	9.1
5 days after tamping	18.9	11.0	11.0
3 months after tamping	18.5	18.2	12.5
9 months after tamping	18.5	17.0	14.25

Table2. Judgement of Liquefaction for Boring Hole No.7

depths of SPT (M)	2.55	3.55	4.55	5.55	6.55	7.55	8.7	9.7	10.7	11.7	13.2	14.7	15.8
Soil layer	2~3.05	3.05~4.05	4.05~5.05	5.05~6.05	6.05~7.05	7.05~8.1	8.1~9.2	9.2~10.2	10.2~11.2	11.2~12.45	12.45~13.95	13.95~15.25	15.25~16.2
values of blow counts N_i	21	11	25	23	17	14	12	10	12	8	15	18	11
content of clay P_c(%)	0	0	13	13	0	1	9.5	11	9	1	12	1	10
critical blow counts N_i'	—	—	—	—	12.3	13.6	8.5	8.3	11.5	18.8	11.6	22.5	—
$(1-\frac{N_i}{N_i'})W_iD_i$	—	—	—	—	0	0	0	0	0	1.7	0	0.1	—
Judgement of Liquefaction	N	N	N	N	N	N	N	N	N	L	N	L	—

Notes: 1. Liquefaction criterion is based on "China Code of Liquefaction Judgement for Saturated Sandy Loam (Temporary Version). P_L=1.8 G.W.L.=-6.2M
2. Energy per blow is 4000KN-M.
3. Date for completion of first step, 5 passes: Sept.10,1986.
4. Date for completion of carpet tamping after first Step:Sept.16,1986
5. Date of investigation for boring hole No.7 : March 20 ,1987.
6. L = Liquefiable
7. N = Nonliquefiable

Table3. Results of liquefaction judgement by Seed laboratory test method

NO. of boring hole	depth (M)	τ_d/σ_3 <MPa>	C_r	$\bar{\sigma}_v$ <MPa>	σ_0 <MPa>	r_d	τ_{dn} <MPa>	τ_{1n} <MPa>	F
25#	5.8	0.395	0.553	0.1086	0.1166	0.913	1.384×10^{-2}	2.372×10^{-2}	1.714
	8.8	0.30	0.553	0.14014	0.17904	0.868	2.02×10^{-2}	2.34×10^{-2}	1.158
	9.8	0.222	0.553	0.15184	0.19984	0.853	2.216×10^{-2}	1.864×10^{-2}	
	10.8	0.285	0.553	0.16264	0.22064	0.838	2.404×10^{-2}	2.563×10^{-2}	1.066
27#	6.2	0.385	0.553	0.11388	0.12488	0.907	1.472×10^{-2}	2.425×10^{-2}	1.647
	8.2	0.28	0.553	0.13548	0.16648	0.877	1.898×10^{-2}	2.098×10^{-2}	1.105
28#	7.8	0.35	0.553	0.13143	0.15834	0.883	1.819×10^{-2}	2.544×10^{-2}	1.398
	8.8	0.32	0.553	0.14233	0.17933	0.868	2.024×10^{-2}	2.519×10^{-2}	1.244
	9.8	0.27	0.553	0.15323	0.20023	0.853	2.22×10^{-2}	2.288×10^{-2}	1.031
	10.8	0.3	0.553	0.16413	0.2213	0.838	2.409×10^{-2}	2.723×10^{-2}	1.13

improvement to a depth of 15m. Therefore the so called twice dynamic tamping technique was applied.this is the second step of the whole process of tamping.

When the above stated first step of tamping which includes five passes were completed, and then after a period of interval ,the heavily compacted area for cold rolling machine foundation was excavated. to a depth of 5.9m below the original outdoor elevation. this surface of excavated pit was already beneath the original ground water table, but no seepage could be seen. Thus the twice dynamic compaction could be conducted on dry ground. The energy of heavy tamping per blow was still 4000KN-M. The tamping grids were as before in the first step but without passes. The twice dynamic compaction was performed at 20 blows consecutively (only filling sand after 10 blows). It should be noted that owing to the first step of heavy tamping, the permeability of a certain layer of the deposit originally below the ground water table became nearly impermeable. Based on our experience, a depth of 2m can be guaranteed. This successful practice proved that it can avoid dewatering and thus reduce the construction cost.

IMPROVING RESULTS

After dynamic compaction we ran SPT tests, laboratory tests and static cone investigations. The results were as follows:
The Main Factory building

The SPT values both before and after heavy tamping as well as their relationships with time were tabulated in Tab.1. We can see from Tab.1 that the first SPT values after 5 days of tamping had been increased significantly. They are 5 times between 0~5m deep, 100% increase between 5~10m deep. and 20% increase between 10~15m deep respectively.The test results for a period of 3 months after tamping had been compared with those of the first test after tamping. These are as follows ; nearly no increase within depth of 0~5m, 100 increase within the depth between 5~10m, some increase between the depth of 10~15m. The SPT values after 9 months showed that there still was progressive increase between the depth of 10~15m but no change in shallow layers. This reveals that the recovery of soil strength has relationship with time and embedment.In summary, for shallow layers, say 0~5m, it can be recovered in 5 days. But for layers of 5~10m deep it requires 3 months. And it should be noticed that even deeper than 10m, there is still increase in strength. The residual liquefaction indexes were all less than 3 with the mean value of 1.7, and thus the design requirement could be fulfilled. The calculated results for boring hole No.7 were shown in Tab.2.

As to that part of tamped area for the foundation of cold rolling machine, the results were all as expected.

LABORATORY TRIAXIAL SHEAR TESTS

In order to obtain the main parameters which affect the liquefaction behavior of compacted loesslike sandy loam, such as time effect, content of clay particles etc., In addition to SPT values the authors conducted laboratory dynamic triaxial shear tests. All the samples were taken from the site of Aluminum Material Company in Taiyuan. The laboratory tests were divided into two groups. The fist group includes heavily tamped soil and the second one consists of reconstituted samples of various clay content. The instrument used is cyclic triaxial device of stress controlled type designed by C.K.Chang of University of California,Berkeley.

1.The laboratory dynamic triaxial tests were run on samples taken from layers 5~10m under the water table. The boring hole numbers are 25#,27# and 28# respectively. The samples after tamping are of 10 groups altogether and the simplified method proposed by Seed was used by the authors for liquefaction judgement, i.e.

$$\tau av = 0.65 a_{max} \cdot \gamma d \cdot rh/g$$

Since the earthquake intensity for design is 8 in Taiyuan , we took amax=0.2 . While for the value of τ_d/σ_3, we took the value corresponing to N=20 .The calculated results were shown in Table 3. We can see that from the calculation judged by Seed's criterion, only the deposit at 9.8M depth of 28 boring hole is liquefiable . and the other layers are nonliquefiable. This shows that the liquefaction resistance behaviour of the deposits has been improved significantly after treatment by dynamic consolidationapproach. In addition, we run SPT field investigations for the boring holesof 25 ,26 , 27 and 28 ,both the autual SPT blow counts and critical values are shown in Table 4. Shown in Fig 3 were the valuesof factor of safety in

Table 4 actual SPT blow counts and critical SPT values

NO. of boring hole	depth (M)	actual N_i	critical N_i	F.O.S.
25*	5.1	21	11.7	1.79
	6.1	22	13.2	1.67
	7.1	11	7.2	1.53
	8.1	16	15.4	1.04
26*	5.0	21	4.7	
	6.8	20	13.0	1.54
	7.85	13	12.7	1.02
	9.15	17	16.7	1.02
27*	5.60	21	12.3	1.71
	6.7	18	13.7	1.31
	7.7	16	15.0	1.07
	9.1	9	8.3	1.08
28*	5.05	21	11.7	
	6.15	19	13.2	1.44
	7.20	15	14.4	1.04
	8.45	9	6.7	1.34

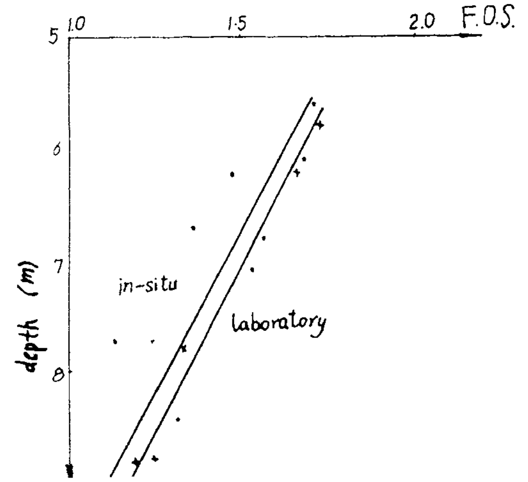


Fig.3 comparison of F.O.S. for in-situ values and laboratory values

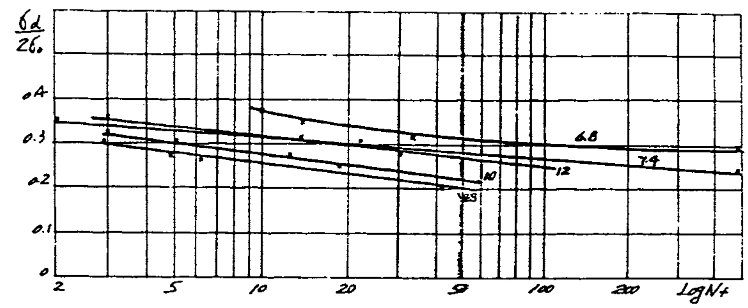


Fig.4 cyclic stress ratio versus number of cycles for samples of different clay contents

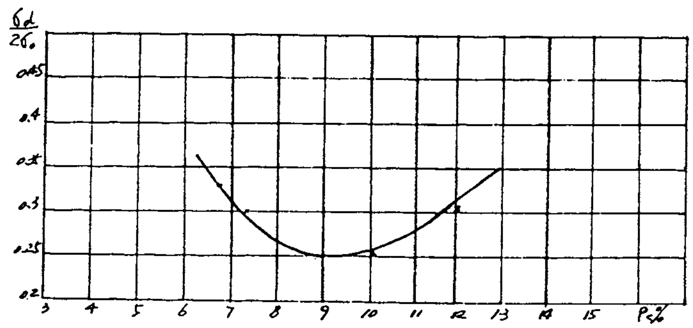


Fig.5 correlationship between cyclic stress ratio and clay contents

laboratory tests versus deepness and those of in-site SPT versus deepness.it can be seen that the values of F. O. S. in laboratory tests are basically parallel to those of in site values. This explains that so far as the trend for factors of safety are concerned, Seed's method and China code are consistent. But the autual values of the former is somewhat greater than thoseof the latter ones.

2.The effect of fine content on the liquefaction resistance behavior

In order to evaluate the effect of clay content on cyclic stress ratio quantitatively, the authors performed laboratory dynamic triaxial tests on 5 groups of soil including 25 samples with different clay content. The test results were shown in Figures 4 and 5. It can be seen that following the increase of clay content, the cyclic shear ratio is not monotonously increased, but with a minimum value at Pc=9%.

Conclusions

1.For improvement of saturated sandy loam deposit and elimination of liquefaction potential, the coefficient used to modify Menard's Formula should be smaller than general conditions, In this project it was 0.4.
2. Filling the tamped pit with sand and increasing the passes of dynamic tamping jointly render the soil layers under water to be progressively consolidated and thus can get the density increased.This approach is applicable to eliminate the liquefaction potential.

3.In case of high ground water table and the required effective depth of improvement being great, the twice Dynamic Consolidation method has been proved to be successful. The technique includes two steps; firstly the conventional dynamic consolidation is conducted, and after a certain period of interval, we excavate the heavily compacted site to a depth noless than 2m. Owing to the first step of heavy tamping, the permeability of a certain layer of the original below the ground water table becomes nearly impermeable, and thus the second step ,i.e. twice dynamic consolidation can be conducted on dry ground and finally the effective depth of improvement could be increased significantly.

4.The factor of safety values evaluated by SPT method (China Code) basically coincides with those by Seed's laboratory test method, but the former is somewhat on the safe side.

5.If we use SPT values as criterion, the time effect for shallow layer is one week or so for stable SPT values. But for deep layers it will be more than 3 months.

6.For this site, the authors found that from experimental test the clay praticle percentage is not in a linear relationship with the liquefaction resistance capacity, but with minimum value for Pc=9%.

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