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SYNOPSIS: The improvement of liquefaction foundations in seismic region has been concerning many engineers. The authors had carried out experimental studies on the improvement of saturated silty and fine sand foundtions at the suburbs of Beijing by vibroflotation method. The test results are described and the improvement effects are evaluated in this paper.

INTRODUCTION

Numbers of seismic disasters Liaonan, Tangshan, Tanjing as well as those abroad indicate that structure on loose saturated sand foundation had failed occasionally due to foundation liquefaction. Methods, both analytical and experimental, for evaluating liquefaction potential of liquefiable foundation have been well developed in the past twenty years. However, the measures for treating liquefiable soil deposit have not achieved so much progress. Among the common measures preventing sand liquefaction, vibroflotation is one of the adequate methods and has experienced a number of earthquakes. However, the mechanism of vibroflotation, the evaluation of its improvement effects and the criterion of aseismic design and analysis of vibroflotation improvement have not been understood very well. In engineering practice the design parameters are often determined by in-situ tests which have been proved very expensive. Therefore, it is quite necessary to raise the understanding for the vibroflotation mechanism, improve the design and construction methods and properly evaluate the vibroflotation effect through a great number of experiment research both in situ and laboratory. The authors had carried out vibroflotation tests in three experimental sites at the suburbs of Beijing including the in-situ measurement of soil dynamic response during vibroflotation, standard penetration test before and after vibroflotation improvement and static loading test. The conclusions of these three test are described.

EXPERIMENTAL SITES AND TEST METHODS

Sites.

The experimental sites locate at the southeastern suburbs of Beijing with subsoil layers of loose sand. Within 10m under the ground surface is mainly silty fine sand intercalated with cohesive soil intercalations of various thickness and consists of sand of about 30m thick, free water surface 1-3m. The silt fraction in the surface silt and sand is less than 10%,

coefficient of uniformity less than 5, mean diameter D50 about 0.1mm, natural relative density 50-55%, standard penetration test blow count less than 10 within 8m under ground surface. The seismic intensity of the sites is VIII. The foundation is considered liquefiable according to the criterion of Chinese code. The subsoil profiles are shown in Fig. 1.

Test Methods.

The soil dynamic response (acceleration and excess pore water pressure) are mainly measured in site A and the routine soil tests (bearing test, standard penetration test and static cone penetration test) were made in site B and site C.

The ZCQ--II vibroflot was employed with exciting force of 7t and 10t. The soil dynamic response during vibroflotation was measured by two methods : (1) Single hole vibrating with measurement done at different distances form the hole. (2) The measuring devices were fixed at certain spots with vibroflotation from distance approaching the measuring spots. The data measured included ground surface acceleration of three directions X,Y,Z, soil acceleration and dynamic pore water pressure.

TEST RESULTS

The Variation of Ground Surface Acceleration.

Fig.2-5 show the ground surface acceleration at different distance from the different depth. It can be seen that the surface acceleration attenuated with the increase of the measuring distance .and the attenuation may law be approximately expressed by exponential function. The measuring records showed that the vibration energy of the vibroflots distributed within soil in a wave form with larger amplitude in all X,Y and Z directions.
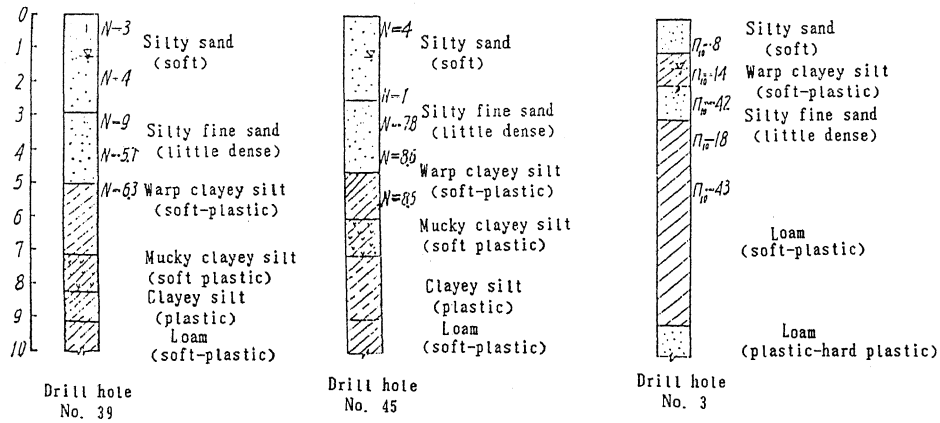
Fig.1 Profiles of experimental sites
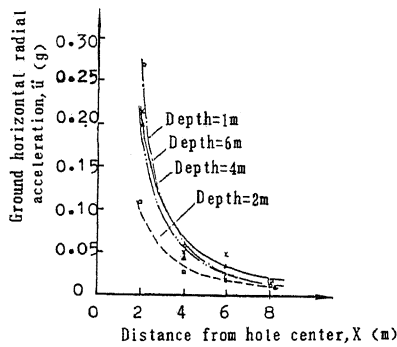N=standard penetration blow count n_{10}=sounding blow count

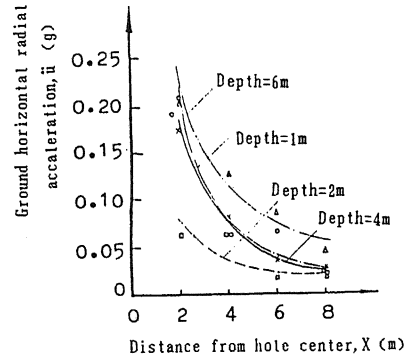Fig.2 Distribution of ground horizonal radial acceleration nearby the vibroflotation hole (site B)

Fig.3 Distribution of ground horizontal radial acceleration nearby the vibroflotation hole (Site c)
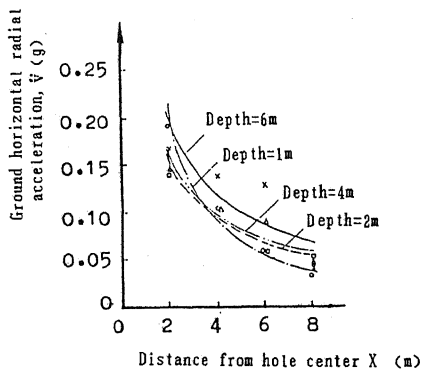

Fig. 4 Distribution of ground tangential acceleration near by the vibroflotation hole (Site C)
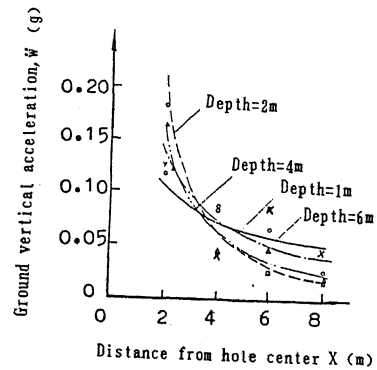

Fig. 5 Distribution of ground vertical acceleration near by viboflotation hole (Site C)

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The Variation of Dynamic Pore Water Pressure and Acceleration in Soil.

Fig. 6 shows the relationship between the excess pore water pressure at 2m below ground surface and the distance from the vibroflot hole during vibroflotation. Due to the difference of the soil properties in the two sites, the pore water pressure measured at site A and site C were somewhat different while the attenuation laws of excess pore pressure and acceleration were basically consistent. Fig. 7 has shown the histories of the horizontal radial acceleration and excess pore pressure at 2m deep below ground surface when the vibroflot penetrated uniformly into 6m deep and than drew back to the ground surface. It can been seen that the acceleration and excess pore pressure in soil 0.875m away from the center of vibroflotation hole reached maximum (amax=0.35g, umax=0.32kg/cm^2 ,pore pressure ratio u/σ_v =0.99) and the soil completely liquefied when the vibroflot penetrated 3m deep into the ground. However the pore pressure ratio 1.05m away from the hole center was only 0.48. It can be thus concluded that the liquefaction range located within 0.875-1.05m from the center of vibroflot hole in the C site condition during vibroflotation operation. Pore water pressure ratio at 2m deep maintained high during the process of continuing penetration and drawing back to the ground surface without filling.

Ground Acceleration and Excess Pore Pressure before and after Vibroflotation Improvement.

The changes of horizontal radial acceleration of ground surface in site B before and after vibroflotation improvement are demonstrated in Table 1.

Table 1. Ground Surface Acceleration Changes before and after Vibroflotation Improvement (g)

Dis-tance m	Mea-suring spot	Vibroflotation time (sec.)				
		Begin	10	30	60	120
4.6	before vibro-flotation	.019	.027	.031	.031	.039
4.6	between piles	.129	.105	.105	.116	.129
4.6	pile top	.172	.172	.172	.164	.140

The excess pore pressure changes in site A before and after vibroflotation improvement are shown in Table 2.

Table 1 and Table 2 show that after vibroflotation the ground acceleration increased while the excess pore pressure reduced remarkably, while indicate that the vibration of vibroflots had made the surrounding soil denser and the pile-soil composite foundation stiffer.

Table 2. Pore Pressure Ratio before and after Vibroflotation

Dis-tance case (m)	2m below A pore press. ratio (KPa)		2m below B pore press. ratio (KPa)		3.6m Below B pore press. ratio (KPa)	
I 8.6	0.90	4.5	1.25	3.6	3.65	4.0
8.6	0.20	4.5	0.35	3.6	0.90	4.0
II 5.9	2.10	10.	2.50	12.	5.90	5.9
5.9	0.20	10.	0.20	12.	1.00	5.9
III 3.6	4.20	4.2	5.00	3.5	12.60	3.6
3.6	1.00	4.2	1.40	3.5	3.50	3.6

* In each case, the first and the second line are the data before and after vibroflotation respectively.

Effects of Foundation after Vibroflotation Improvement [1].

The P-S curves of bearing test before and after vibroflotation improvement are shown in Fig. 8 Foundation allowable bearing capacity are listed in Table 3. It can be seen that the bearing capacity after vibroflotation improvement had increased by more than 60%, the deformation had reduced by 1/3--2/3 and the allowable bearing capacity of the pile--soil composite foundation had multiplied more than 2.3 times.

The results of static cone penetration test are shown in Fig. 9 which indicates that the effects of vibroflotation were unremarkable in the surface layer, sandy loam intercalation and mucky soil but remarkable if the bearing stratum was fine sand, Ps average value tripled. The standard penetration results were roughly consistant with those of static cone penetration test. The blow count in fine sand might raise from 7.6 before vibroflotation to the maximum of 24 after improvement, relative density Dr to 85% [1].

Table 3. Bearing Test Results before and after Vibroflotation

	Type	Allowable bearing capacity [R] and compression modulus Es	
		[R] (KPa)	Es (KPa)
soil	No.1 B*	196.13	8727.90
	No.1 A*	319.70	14808.04
	No.2 B*	171.62	9316.32
	No.2 A*	317.74	15690.64
pile	NO.1	588.40	26576.02
	No.2	661.95	29616.08

B*: before vibroflotation
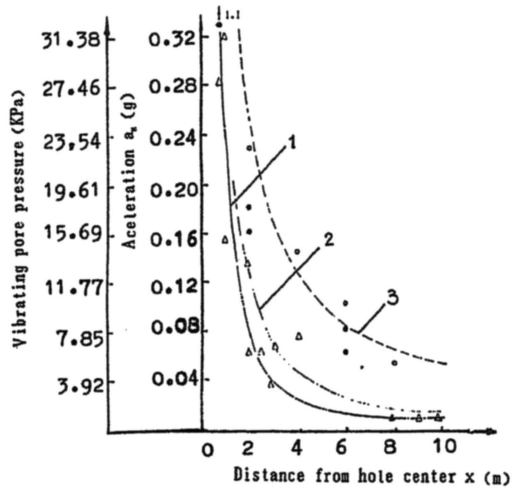A*: after vibroflotation

Fig.6 Distribution of vibrating
pore pressure at 2m depth

1. Pore pressure in site C

2. The measured pore pressure in site A

3. The average of acceleration a_s

o The average of aueajured
  a_s in site C

△ The measured pore pressure P
  in site C

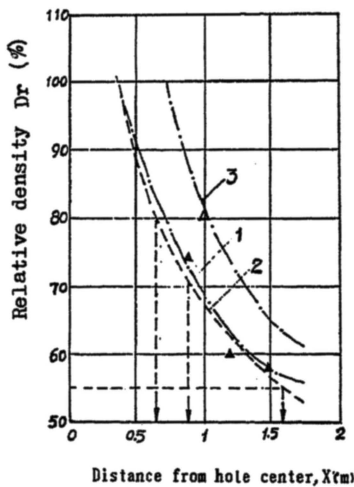• The horizontal radial acceleration at
  the depth of 2m in site C

Fig.7 Variation of acceleration and pore
pressure within soil

Fig.8 Bearing test results before and
after vibroflotation improvment

1. D'appolonia's single pile
   curve. (D_r is the average of
   these at 1.2, 1.8, 2.5m depth)

2. D'appolonia's densified curve,
   distanse between holes 2.44m .

3. D'appolonia's densified curve,
   distance between hole 1.83m .

▲ Predicted according to the
  single pile in Dongfang
  Chemical plant, Beijing (D_r
  is the average within 1~4 depth)

△ Data from Dongfang Chemical Plant,
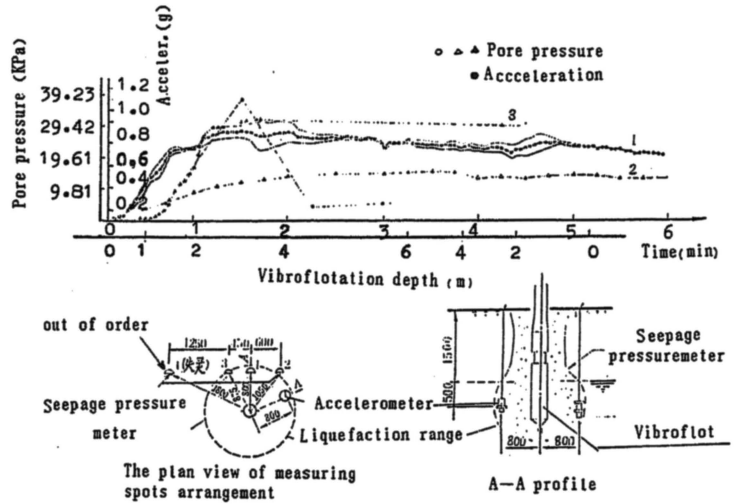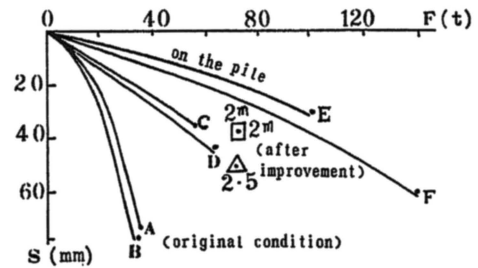 Beijing,distance between holes
  1.80m .

Fig.9   S.C.P. test results before and after
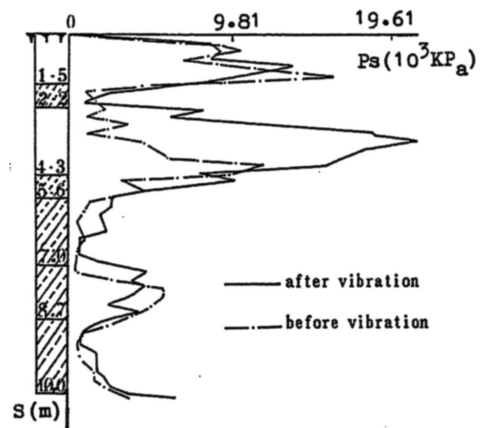vibroflotation

Fig.10   Relationship between distance
and relative desnsity of sand
surrounding the piles

EVALUATION OF SOIL LIQUEFACTION RESISTANCE AFTER VIBROFLOTATION IMPROVEMENT

Densification Effect.

According to the test results the sand within 0.5 m radius from the center of vibroflotation hole had completely liquefied subjected to vibroflotation by 10t ZCQ--II and consequently densified significantly under the composite function of vibroting force, confining pressure and the vibrating compacting of fillings. The soil 0.9m away from the hole center, despite influenced remarkably by vibration did not reach liquefaction condition. It can be assumed therefore the density of the surrounding soil decreased rapidly with the increase of the distance from the holes.

In order to evaluate quantitatively the changes of density in sand after gravel pile improvement, D'appolonia [2] assumed the density curves of soil surrounding single pile as shown in Fig. 10. The vibroflotation test results in a chemical plant in Beijing are also shown in the figure, which are more or less conformable with D'appolonia's. Accordingly, from the point of view of liquefaction resistance, the effective range of vibroflotation improvement should be predicted in the light of the anti-liquefaction critical relative density of sand in various countries and regions. According to the creteria suggested by Engineering Mechanics Institude, SINICA, the anti-liquefaction relative density of sand Dr is 50%, 70% and 80% for the earthquake intensity zone VII, VIII and IX respectively. The effective improvement range surrounding single pile to resist liquefaction may be obtained from Fig. 10 as 1.6m for seismic intensity zone VII, 0.9m for VIII and 0.66m for IX. The effective range should be enlarged moderately when pile group effect is considered [3].

Dranage Effect of Gravel Piles.

After vibroflotation improvement the sand surrounding vibroflotation holes had densified, the foundation stiffness enhanced and the excess pore water pressure lowered obviously. It was known through in-situ data that all of the recorded excess pore pressure had reduced more than 3.5 time after locating the gravel piles. During actural earthquake the percolation path would be shortened due to the location of gravel piles, which makes the excess pore pressure induced by earthquakes dissipate easier and consequently decreases the soil liquefaction potential.

Effect of Pre-vibration.

The laboratory tests indicated that the liquefaction resistance of sand foundation may be increased after being subjected to vibrations [4]. The vibroflots operated by vibration force of 10t were generally arranged within distance less than 2.5m. the ground acceleration 2m away from vibroflots was 0.27g and 0.019g for those 8m away, which means that the surrounding soil would undergo times of previbratings for some dozens of minutes during the whole operation. These previbrations would be beneficial to decreasing liquefaction potential.

The Influence of Vibroflotation Operation on the Nearby Building.

The influence of vibroflotation operation on the nearby buildings depends upon the magnitude of vibration force, site condition and the allowable vibration standard of the building. The test records in this site shows that the minimum safety distance for common building should be more than 5m when 10t ZCQ--II vibroflots are employed [5].

CONCLUSIONS

The following conclusions could be drawn from this study:

1. Before and after the vibroflotation, the dynamic response of soil foundation appears remarkable difference during the action of the same vibration force. Comparing the gravel pile-soil composite foundation improved with the nature foundation, as its enhanced stiffness and shortened percolation path, increased vibrating acceleration, reduced dynamic strain and the excess pore water pressure in the soil layer lowered more than 3.5 times for the composite foundation.

2. Under the condition of applied vibroflot the effective improving radius (from the center of the pile) of anti-liquefaction around the single-pile are 1.6m, 0.9m and 0.6m with the earthquake intensity of VII,VIII and IX, respectively.

3. Modification should be taken when the application of the influence coefficient curves proposed by D'appolonia,E to evaluating the relative density of the center of piles group.

4. After vibroflotation. the measured N-value of loose saturated silty and fine sand layer is higher than the liquefaction critical value Ncr of earthquake intensity VIII. the bearing capacity of soil between the piles is 60% more and the composite foundation is 2.3 times more than natural foundation, the compressing a modulus Es increases 50-70%.

5. Since the soil properties have taken place considerable changes after improvement of vibroflotation, the effect of the soil parameter change must be considered in seismic response analysis when the large area foundation improved by the vibroflotation.

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