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EFFECTIVENESS OF DYNAMIC COMPACTION ON LIQUEFIED FOUNDATION IN HIGHWAY PRACTICE

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ABSTRACT

In this paper, the in-situ dynamic compaction tests with different values of single-drop-compaction energy are performed on a liquefiable ground encountered in highway engineering practice. Excess pore pressure, total surface settlement and lateral deformation under dynamic compaction impact are measured and analyzed at different conditions, such as single drop-compaction-energy, drop numbers, depth of soil layer etc. The standard penetration test (SPT) is used for investigating the compaction effectiveness. The investigation results indicate dynamic compaction technique is an effective way for improving liquefiable ground in highway engineering practice. Relatively small single-drop-compaction energy and relatively more drop numbers should be adopted for improving natural sedimentary liquefiable ground with dynamic compaction. The in-situ dynamic compaction tests show that the effective effect range by dynamic compaction impact depends on the single-drop-compaction energy. It is also found that the measured maximum lateral deformation has a good linear relationship with the total vertical surface settlement.

INTRODUCTION

It has been well documented that dynamic compaction is an effective technique of ground improvement (Menard and Broise, 1975; Leonards et al., 1981; Liu et al., 2000). The equipment for dynamic compaction is simple, and the construction performance is easy. A heavy weight (W) of 100*kN* ~ 400*kN* is dropped from a height (H) of 6*m* ~ 40*m*. The impact energy formed by dropping the heavy hammer densifys the treated soils into a state of low void ratio, consequently increasing the strength and decreasing the compressibility.

Lian-Xu highway is a main road in Jiangsu Province of China. Relatively loose silty soils are widely deposited around Xuzhou area of Jiangsu Province. The construction of the Lian-Xu highway encounters such a ground. It is well known that earthquake occurs often in China. For high-class highway construction, ground improvement for liquefiable ground is essential. Dynamic compaction technique is an economical and effective way in improving liquefiable loose sandy ground (Liu et al., 2000). In this study, the in-situ tests of dynamic compaction are performed to investigate the effectiveness of dynamic compaction for improving liquefiable ground in highway engineering practice.

PROPERTIES OF FIELD TESTING GROUND

The in-situ experimental site is located at Xuzhou area of Jiangsu Province. The typical physical properties of the soil layers under ground surface are shown in Table 1. The water table was about 0.3 *m* under ground surface. Figure 1 shows the plasticity chart for the soil layers in the in-situ testing ground. It can be seen that all of the soils lie above the A-line. Figure 2 shows the sedimentation compression curve for the investigated ground. The intrinsic compression line (ICL) proposed by Burland (1990) is also shown in the same figure for comparison. Burland (1990) has proposed a so-called intrinsic compression line (ICL) for reconstituted soils which can be expressed in the following equation.

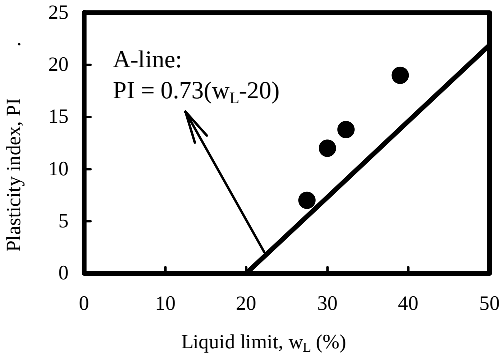

Fig. 1. Plasticity chart of in-situ testing ground.

$$I_v = 2.45 - 1.285(x) + 0.015(x)^3 \qquad (1)$$

Table 1. Typical Physical Properties of Natural Ground.

Soil layer	Depth m	Unit weight kN/m^2	Natural water content %	Liquid limit %	Plastic limit %
Yellow-brown silty soil	0~4	19.5	28.3	27.5	20.5
Gray silty soil	4~8	19.6	27.3	32.3	18.5
Gray silty soil and sand	8~11	19.2	24.5	30.0	18.0
Red dilluvial clayey soil	>11	19.0	29.2	39.0	20.0

where x = logp in kPa and p represents the applied consolidation stress. The void index I_v is defined in the following equation (Burland, 1990).

$$I_v = (e - e^*_{100})/(e^*_{100} - e^*_{1000}) \quad (2)$$

where e*100 and e*1000 are the void ratios corresponding to the consolidation pressures of 100*kPa* and 1000*kPa*, respectively, of remolded (or reconstituted) soils, and can be approximately calculated by the following equations (Burland, 1990).

$$e^*_{100} = 0.109+0.679e_L - 0.089e_L^2 +0.016e_L^3 \quad (3)$$

$$(e^*_{100} - e^*_{1000}) = 0.256e_L - 0.04 \quad (4)$$

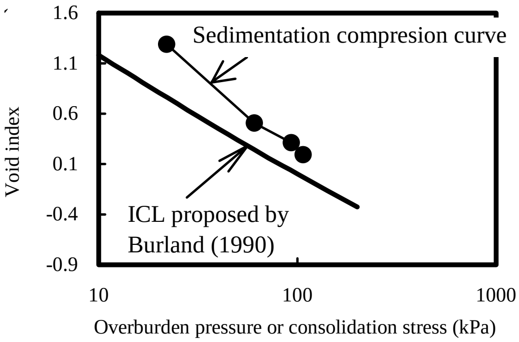

Fig. 2. Sedimentation compression curve of natural ground.

From Fig. 2 it can be seen that that the sedimentation compression curve lies above the ICL. This result indicates that the soils in the investigated natural ground are affected by the effects of soil structure. It is interesting to note that even the loose silty soils lies above the ICL. This result is consistent with the sandy soils affected by soil structure reported by Mitchell (1986).

The in-situ standard penetration tests were performed at 8 holes at the investigated ground. The measured N values at different depths for 8 holes are shown in Table 2. The liquefaction potential of the ground was judged based on the Anti-earthquake Design Standard of Road Engineering (JTJ004-89) (Ministry of Transport, 1990). The results are also shown in Table 2. It can be seen that the upper layer ranging from the ground surface to the depth of about 7*m* is liquefiable. And the lower layer below the depth of about 7*m* is not liquefiable. Hence, ground improvement is needed for improving the upper layer soils. Dynamic compaction technique is adopted for its low-cost and easy-performance.

DYNAMIC COMPACTION TESTS

Single point compaction tests are performed with four different values of single compaction energy E. The values of *E* are 1500*kN•m*、2000*kN•m*、2500*kN•m* and 3000*kN•m* respectively. The typical relationships between excessive pore pressure and drop number are shown in Fig. 3. The excessive

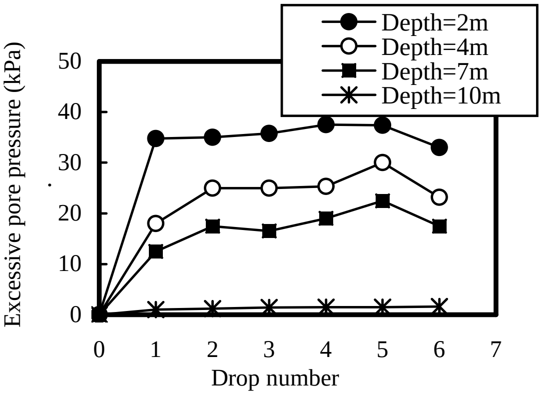

Fig. 3. Excessive pore pressures under single compaction energy of 1500kN•m (at a horizontal distance of 4m from the compaction point).

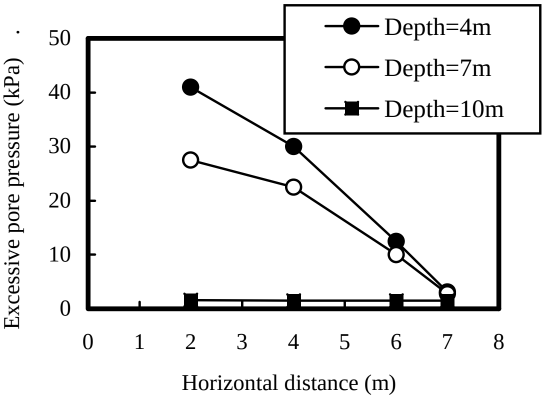

Fig. 4. Typical excessive pore pressures distributions along horizontal distance under single compaction energy of 1500kN•m.

Table 2. Liquefaction Potential of Natural Ground (judgment based on JTJ004-89).

Hole	Depth m	Measured N value	Clay content (<0.005mm) %	Anti-liquefaction critical N value (Calculated based on JTJ004-89)	Judgment
G1	2.6~2.9	3	5.5	7.1	Liquefiable
	4.7~5.0	5	5.0	7.8	Liquefiable
G2	2.3~2.6	4	5.6	6.9	Liquefiable
	4.6~4.9	5	5.1	7.7	Liquefiable
	6.3~6.6	8	5.7	7.5	Not liquefiable
G3	2.1~2.4	4	5.2	6.9	Liquefiable
	4.9~5.2	5	5.0	7.8	Liquefiable
G4	2.5~2.8	4	4.5	7.5	Liquefiable
	5.5~5.8	5	4.9	7.9	Liquefiable
	8.5~8.8	12	5.4	7.3	Not liquefiable
	10.0~10.3	16	5.6	7.2	Not liquefiable
G5	1.9~2.2	4	5.1	6.9	Liquefiable
	5.5~5.8	4	5.6	7.6	Liquefiable
	7.3~7.6	7	6.7	7.2	Slightly liquefiable
G6	2.6~2.9	4	5.3	7.2	Liquefiable
	5.2~5.5	4	5.8	7.5	Liquefiable
	7.3~7.6	10	6.7	7.1	Not liquefiable
G7	2.6~2.9	4	6.2	6.8	Liquefiable
	5.3~5.6	4	5.0	7.8	Liquefiable
G8	2.5~2.8	5	5.6	7.0	Liquefiable
	5.4~5.7	4	5.3	7.7	Liquefiable

pore pressure decreases with the increase in depth. At the depth of 10m, the excessive pore pressure can be neglected. In addition, the excessive pore pressure at the same depth increases the drop numbers when the total compaction energy does not exceed a critical value. When the total compaction energy exceeds the critical value, the excessive pore pressure induced by dynamic compaction does not increase even decreases with the increase in drop number. The single point dynamic compaction tests under other single compaction energy show similar results. Based on the limited data in this study, the critical value of total compaction energy is about 8000 *kN•m.*

Figure 4 shows the typical excessive pore pressure distributions along the horizontal distance from the compaction point under single compaction energy of 1500 *kN•m*. It can be seen that the excessive pore pressure decreases with the horizontal distance. From Figs. 3 and 4 it can be known that there is an effect area when the impact load is loaded on the ground. Based on the limited data obtained in this study, the vertical effect depth can be approximately expressed by modified Menard's equation [= $\alpha\,(WH)^{1/2}$]. The coefficient α is obtained as 0.53 herein. The horizontal effect distance can be expressed by the following simple equation [= β E]. The coefficient β is obtained as about 0.0045 (kN^{-1}).

It should be mentioned that dynamic compaction have two beneficial effects. One is from the 'hammering' occurs local to the impact, which forms a dense plug of soils immediately below the drop mass. The other is achieved from the outgoing highenergy ground waves to more considerable depths (Pan and Selby, 2002). In addition, dynamic compaction impact will dense the soils in a relatively shallow layer, but may damage the soil structure in the underlying layer. In the relatively deeper layer, the increase in strength caused by decrease in void ratio may not compensate the lose in strength due to the damage of soil structure. As aforementioned, the soils in the investigated are affected by soil structure. In fact, most natural soils are affected by the effects of soil structure during their depositional and postdepositional processes (Leroueil et al., 1979; Schmertmann, 1991). Hence, relatively small single compaction energy and relatively large drop numbers should be adopted for improving the ground with dynamic compaction. From Fig. 3 it can be known that effect depth of single compaction energy of 1500*kN•m* reaches 7m, which covers the liquefiable layer. Hence, single compaction energy of 1500*kN•m* and drop numbers of 5 are suggested for the investigated ground with dynamic compaction.

GROUND IMPROVEMENT WITH DYNAMIC COMPACTION

The heavy hammer impact will dense the ground. Ground surface settlement and lateral deformation occur under the dynamic impact loads. Figure 5 shows the relationships between the total surface settlement and the drop number for different values of single compaction energy. Figure 6 shows the relationships between the maximum lateral deformation and the drop number for different values of single compaction energy. It can be seen that the total surface settlement and the maximum lateral deformation increases with the increase in drop number. Figure 7 shows the relationship between the total surface settlement and the maximum lateral deformation. The total surface settlement has an approximately linear relationship with the maximum lateral deformation. Their ratio is about 9. Above results indicate that dynamic compaction is a powerful technique for densifying the investigated ground.

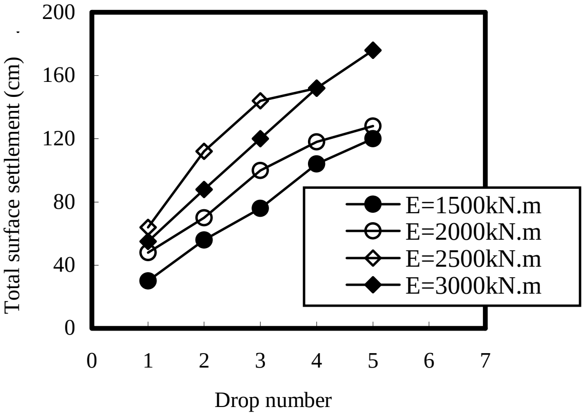

Fig. 5. Total surface settlement.

The in-situ standard penetration tests (SPT) were performed on the treated ground by dynamic compaction. Figure 8 shows the comparison in measured N values before and after treatment. It can be seen the measured N values by SPT for treated ground are larger than those the ground before treatment by dynamic compaction. The improvement extent decreases with the increase in depth. When the depth reaches 7m, the measured N values for treated ground are only slightly larger than those before treatment. This result is consistent with the measure result of excessive pore pressure. The liquefaction potential of the treated ground by dynamic compaction is judged based on the Anti-earthquake Design

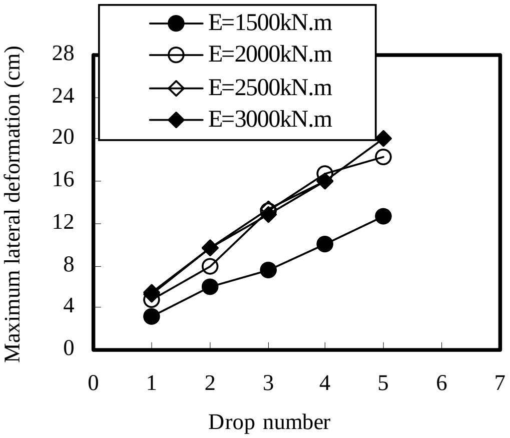

Fig. 6. Maximum lateral deformation.

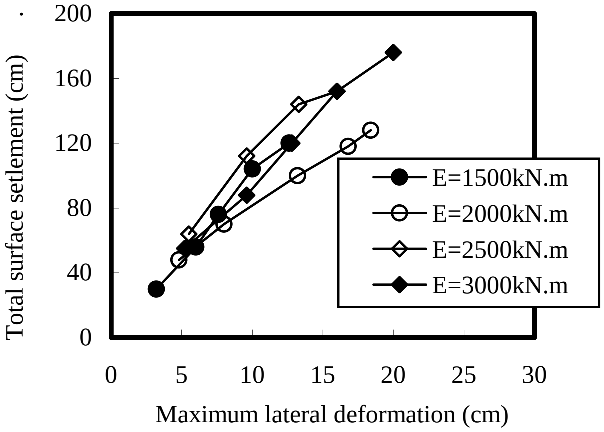

Fig. 7. Relationship between total surface settlement and maximum lateral deformation.

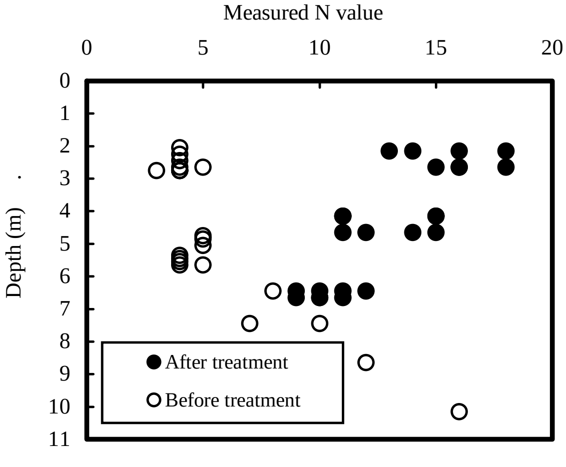

Fig. 8. Comparison in measured N value.

Table 3. Liquefaction Judgment for Treated Ground Based on JTJ004-89.

Depth m	Measured N value	Clay content (<0.005mm) %	Anti-liquefaction critical N value (Calculated based on JTJ004-89)	Judgment
2.5~2.8	16	5.3	7.2	Not liquefiable
4.5~4.8	11	6.1	7.2	Not liquefiable
6.5~6.8	10	5.8	7.5	Not liquefiable
2.0~2.3	14	4.9	7.1	Not liquefiable
4.0~4.3	15	5.3	7.6	Not liquefiable
6.3~6.6	12	5.5	7.7	Not liquefiable
2.5~2.8	16	5.1	7.2	Not liquefiable
4.5~4.8	14	5.4	7.6	Not liquefiable
6.5~6.8	10	5.7	7.5	Not liquefiable
2.0~2.3	18	5.0	7.2	Not liquefiable
4.0~4.3	15	5.5	7.6	Not liquefiable
6.3~6.6	9	5.8	7.7	Not liquefiable
2.5~2.8	18	5.8	7.0	Not liquefiable
4.5~4.8	15	5.7	7.5	Not liquefiable
6.5~6.8	11	5.3	7.4	Not liquefiable
2.0~2.3	13	6.0	8.3	Not liquefiable
4.0~4.3	11	5.3	7.6	Not liquefiable
6.3~6.6	11	5.1	7.9	Not liquefiable
2.5~2.8	15	5.2	7.2	Not liquefiable
4.5~4.8	12	5.6	7.6	Not liquefiable
6.5~6.8	9	6.1	7.4	Not liquefiable
2.0~2.3	16	5.1	7.0	Not liquefiable
4.0~4.3	11	5.3	7.6	Not liquefiable
6.3~6.6	10	5.9	7.5	Not liquefiable

Standard of Road Engineering (JTJ004-89) (Ministry of Transport, 1990). The results are shown in Table 3. It can be seen that all the soils of the treated ground are not liquefiable. Hence, dynamic compaction is effective technique for improving liquefiable ground.

CONCLUSIONS

The main conclusions obtained in this study are as follows.

1) The relatively loose silty soils lie above the intrinsic compression line (ICL) proposed by Burland (1990) based on the experimental data of reconstituted soils. This result indicates that the naturally deposited silty soils are affected by the effects of soil structure.
2) The relatively loose relatively soils deposited at the upper layer at Xuzhou area in China with a thickness of about 7m are liquefiable. The construction of Lian-Xu highway passes the problematic ground. Dynamic compaction technique is adopted for ground improvement.
3) The excessive pore pressure at the same depth increases the drop numbers when the total compaction energy does not exceed a critical value. When the total compaction energy exceeds the critical value, the excessive pore pressure induced by dynamic compaction does not increase even decreases with the increase in drop number.
4) There is an effective effect area by dynamic compaction loads. The effect depth in vertical direction and effect distance in horizontal direction depends on the single-drop compaction energy.
5) Relatively small single-drop-compaction energy and relatively more drop numbers should be adopted for improving natural ground by dynamic compaction technique.
6) The total surface settlement and the maximum lateral deformation under dynamic compaction impact increase with the increase in drop number. The total surface settlement has an approximately linear relationship with

the maximum lateral deformation. Their ratio is about 9 based on limited data obtained in this study.

7) Standard penetration test (SPT) is a powerful way for investigating the effectiveness of ground improvement by dynamic compaction.

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