Study of Indoor Model Tests of Soft Soil Foundation by Dynamic Drainage Consolidation

Ji-hui Ding, Qi Zhao, Ming-jiang Wu, Meng-jia Xiang, Xing-Gao, Bing-jun Li

Abstract—**Taking the silt clay of the lake bottom as the model test material, the model of indoor dynamic consolidation test is designed, and the law of soil layer resistance and dynamic earth pressure in the process of dynamic consolidation of drainage is studied. On the basis of the definition of soil layer resistance under single tamping energy, the soil body resistance under total tamping energy is defined, and the calculation method of composite soil layer resistance is put forward according to the soil body resistance under single tamping energy. The composite soil layer resistance and the soil layer resistance under the total tamping energy are the ability of resisting soil deformation after dynamic consolidation. The results show that the ratio of the calculation of composite soil layer resistance than the corresponding soil layer resistance under the total tamping energy is respectively 1.08,1.87 and 1.43 when the single tamping energy is 7.5N.m, 12.5N.m, 18.75N.m. The effect of dynamic compaction on soil produce additional earth pressure in the soil body, acts in a very short time, the equivalent of a downward impact load, the ratio between the maximum earth pressure and the rammer bottom pressure increases with the increase of tamping energy and tamping times, the minimum value is 14.32, the maximum value is 88.07.The dynamic earth pressure attenuates rapidly downward and radial, with a horizontal impact range of 3 times the rammer diameter, with the increase of tamping times, the vertical influence depth is 3.4 times the rammer diameter.**

Index Terms—**Dynamic drainage consolidation; Soil layer resistance; Soil body resistance; Dynamic earth pressure**

I. INTRODUCTION

The hydrostatic consolidation method is mainly used to deal with the soft clay of the lake-faces, sea-faces and river-faces in the southeast coast of China, when dealing with this kind of foundation, it is usually carried load step by step, and with the help of the spatial drainage system to improve the drainage characteristics of the soil, the pore water in the soft soil is discharged, and the soil gradually consolidation[1].

The traditional compaction method reinforced the saturated soft clay foundation increase the pore pressure but can not dissipate in time. It is easy to form the "rubber soil" phenomenon[2]. At present, the dynamic drainage consolidation method is used as a pressurized system with shock load, static cover and continuous residual effect. The space network system of drainage causes the pressure of ultra-pore water to dissipate rapidly. Both makes up for the lack of dynamic compaction method is not suitable for reinforcement of saturated soft clay, overcame the dynamic method cannot effectively ruled out pore water pressure after tamping, and simplifies the complex pressurized system in the drainage consolidation method and effectively shorten the construction period and reduce the post-construction settlement. More and more scholars have studied the theoretical calculation, numerical simulation, field experiment and laboratory model experiment.

Jia-huan Qian[3]made the dynamic consolidation instrument to study the dynamic compaction mechanism, the self-stressing pressure of soil samples is simulated by the spring static pressure device, and using combination drop rammer to simulate tamping. The measuring device has three kinds of sensors, such as dynamic stress, dynamic displacement and dynamic pore water pressure. Based on the principle of energy similarity, Ji-hui Ding and Ma Na[4][5]designed dynamic compaction consolidate with the hydraulic method to reinforce the soft soil foundation indoor experiment, and studied the role of dynamic compaction on soft soil consolidation in the background of a soft soil base processing project in a municipal infrastructure. Jian-hua Zhao and Xiao-bin Chen [6] established the laboratory model of a soft soil with a similar ratio of 1:2 based on the similarity criterion in order to study the reinforcement effect of the dynamic drainage consolidation method. Li-hui Li [7]carried out the large-scale indoor model experiment to simulated reinforce saturated dredger soft soil by dynamic drainage consolidation method. Shan-shan Wang [8]carried out a large-scale model test to monitor the amount of settlement and the change of pore water pressure in the soil. An-ming Wang [9] carried out the model experiment based on similar theory based on the specific engineering examples. Ru Xue [10]designed a model experiment reinforce the soil in different tamping energy, different rammer size combinating with different drop distance and different rammer. Increasing the amount of compaction does not improve the reinforcement effect, which will cause the slower the pore pressure to dissipate, and it could destroy the structure of the earth and reduce its capacity. Ji-hui Ding, Qing-song Duan [11] stack precipitation is studied through field dynamic test joint preloading dynamic compaction method to reinforce the effect of dynamic compaction in soft soil subgrade, define the soil layer resistance to complete unit rammer heavy quantity needed per unit area can click the ram lamping. The study shows that the greater the resistance of soil layer, the greater the resistance to deformation of soil layer. With the increase of the ramming number, the soil layer compacts under the compaction rammer, and the soil layer resistance becomes more resistant to deformation. The uniformity of soil layer can be measured by using the parameter that soil body resist deformation in the last tamping. However, due to the different engineering properties of various kinds of ground-based soil, the research on the mechanism of strengthening compaction in China and abroad has not yet obtained satisfactory results. In this article, through indoor dynamic drainage consolidation test, the

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distribution of the tamping energy and dynamical earth pressure in the soil layer in the process of dynamic drainage consolidation, and it is of great significance for the establishment of dynamic compaction theory and design method of the establishment, development and improvement .

II. TEST SCHEME AND MODEL DESIGN

A. Test Model

The indoor test model using customized rigid model box, the box is in a cuboid shape, size $90\text{cm}\times 60\text{cm}\times 50\text{cm}$ .The model box fixed with rigid plates and bolts, the bottom with the rigid plate and wood ,drilling drainage holes on the bottom, the box is as shown in Fig. 1. Taking the silt clay of the lake bottom as the model test material, water content is 43.4%, the density is 1.68g/cm3, plastic limit is 22.6%, liquid limit is 41.7%, plasticity index is 19.1, according to “Code for Geotechnical Engineering Investigation” (GB50021-2001) [12] definition, test of soft soil is clay.

Figure 1. Sketch map of settlement monitoring arrangement

The bottom of the test case is provided with sand drainage, the thickness is 8cm, the soft soil layer is 30cm, the overlying soil layer is 12cm, and the upper and lower surface of the soft soil layer is provided with a layer of permeable geotextile. The arrangement of sensors and the arrangement of the tamping points are shown in Fig. 2.

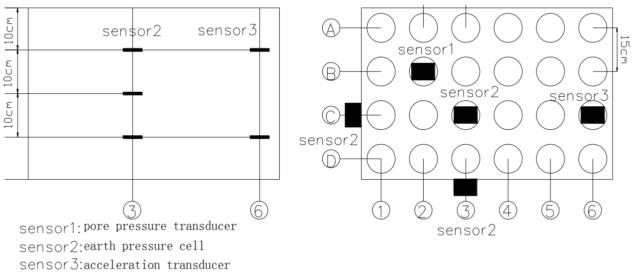


Figure 2. Sketch map of sensor section and plane layout of tamping point

Drainage system adopts plastic drainage plate, plum blossom shape, the width is 2.5cm, the spacing is 16cm, and the upper and lower layers of soft soil layer are made of the drainage layer with medium sand and fine sand 3:1 respectively. A drainage hole is arranged on the lower layer of the model box, so that the water produced by the consolidation of the sludge is discharged smoothly after the loading is convenient.

The pre load preloading method is adopted to test the silt soil before dynamic loading, saturated sand filling thickness of 10cmas a load (about 2kPa). The heavy of rammer is 25N, diameter is 10cm, drop by 30cm, 50cm and 75cm, the corresponding tamping energy are respectively 7.5N·m, 12.5N·m, 18.75N·m.

B. Test Scheme

(1) Soil settlement test during dynamic consolidation

In the model box center, a rigid piece between the soft soil layer and overlying soil layer, the size of $2\text{cm}\times 2\text{cm}$, which is soft soil settlement observation point. Taking a PVC tube through the overlying soil, arranged a rigid piece at the top of the pipe, and the displacement of the soft soil layer is monitored by a strain displacement meter, as shown in Fig. 1.

(2)Dynamic response test during dynamic consolidation

The earth pressure sensors that are used to the test are all strain sensors. The earth pressure measuring instrument adopts BX-1 type earth pressure box. The dimensions are $\varphi 17\text{mm}\times 17\text{mm}$, and the range is 0.5MPa. Data acquisition system adopts Donghua DH3817 static and dynamic data acquisition instrument, which has a acquisition frequency 200Hz.

Through laboratory tests, the contents are as follows:

1. the relationship between tamping settlement and the number of tamping.
2.the relationship between consolidation settlement and time in the process of dynamic consolidation.
3.dynamic characteristics analysis of heavy tamping.

III. ANALYSIS OF TEST RESULT

A. The Relationship between Tamping Energy, Single Tamping Settlement and Soil Body Resistance

The soil body resistance the ability of soil body to resist deformation under unit tamping energy is defined as[12]:

$$p = \frac{E}{AS} \tag{1}$$

Where, p is the resistance to deformation of the soil body under the rammer of single tamping energy, which is the single tamping energy that complete the unit of settlement and unit of area, kN/m^2; E is single tamping energy, kN· m; A is the rammer's bottom area, m^2; S is the tamping settlement, m.

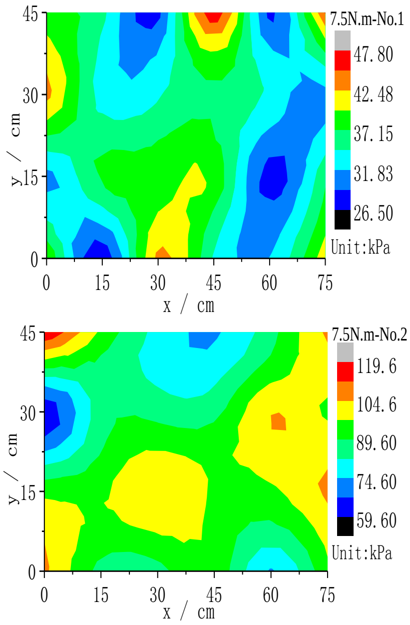


Figure 3. the soil body resistance nephogram when ramming energy is 7.5N·m

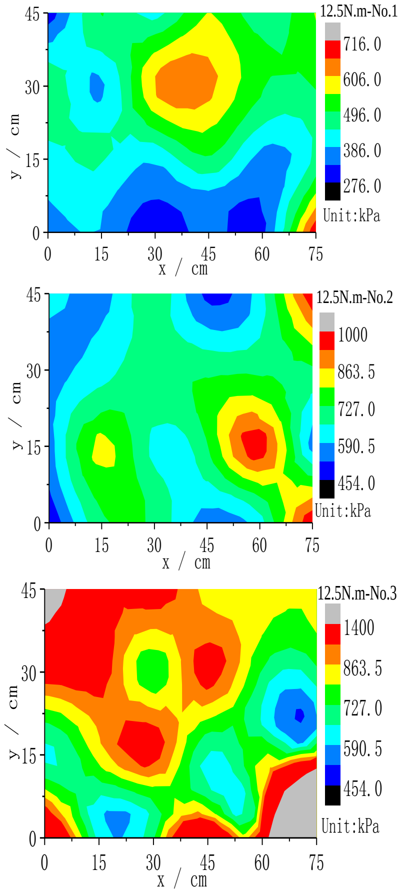


Figure 4. the soil body resistance nephogram when ramming energy is 12.5N·m

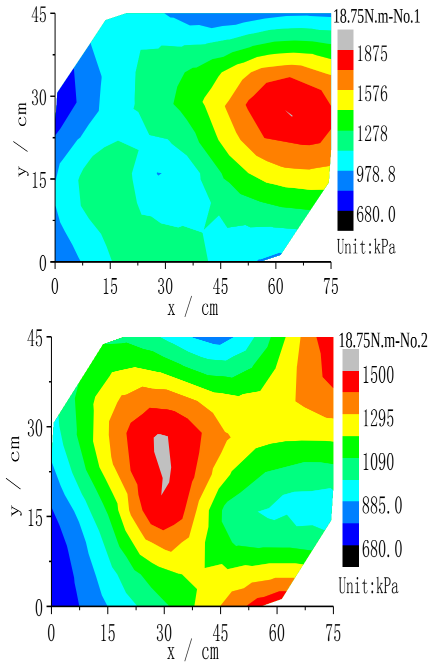


Figure 5. the soil body resistance nephogram when ramming energy is 18.75N·m

Figure3~Figure5 are soil body resistance nephogram under single tamping energy in test area. Table 1 is the resistance of soil body, the ability of soil body to resist deformation, and its value depends on the nature of soil body. When the single tamping energy is 7.5N·m, the resistance of soil is 26.54kPa~47.77 kPa after the first strike, the average value is 35.99kPa, soil layer bearing capacity improvement after the first strike; Soil resistance increased to 59.71kPa~119.43 kPa after second strike, the average value increased to 92.58kPa. When the single tamping energy is12.5N·m, the average resistance of soil body is 452.27kPa after the first strike; The average soil body resistance increased to 683.54kPa after second strike; In the third strike, The average soil body resistance increased to922.87kPa. When the single tamping energy is18.75N·m, the average resistance of soil body is 1123.64kPa after the first strike; The average soil body resistance increased to 1148.14kPa after second strike. The average value of the soil body resistance of the two hit is very close, which is 31 times that of the first strike of the7.5N·m. Therefore, the soil properties are greatly improved after treatment with 7.5N·m, 12.5N·m and18.75N·m. The soil layer resistance of the last strike of dynamic consolidation reflects the properties of the soil layer after treatment. The value of the soil layer can be used to evaluate the effect of the reinforcement of the soft soil layer.

According to the soil body resistance under single tamping energy that the soil under the rammer, the soil layer resistance of the proposed site can be calculated in weighted average by area:

$$p_{\text{area}} = mp_{\text{ave}} + (1-m)p_{\text{soil}} \tag{2}$$

$$m = \frac{nA_p}{A_{\text{soil}}} \tag{3}$$

Where, p_{area} is composite soil layer resistance, which is the soil body resistance under single tamping energy calculated in weighted average by area; p_{soil} is the soil body resistance before site processing; p_{ave} is the average value of the resistance under single tamping energy; A_p is the bottom area of the rammer; A_{soil} the area of the site; m is the area replacement ratio; n is the number of tamping points.

1.Calculation of composite soil layer resistance under 7.5N·m tamping energy:

$$m_1 = \frac{nA_p}{A_{\text{soil}}} = \frac{24\times3.14\times0.05^2}{0.6\times0.9} = 34.89\%$$

$$p_{\text{area1}} = mp_{\text{ave}} + (1-m)p_{\text{soil}}$$
$$= 0.3489\times92.58 + (1-0.3489)\times35.99 = 55.15\text{kPa}$$

The soil body resistance calculated during the first strike of dynamic compaction reflects the characteristics of the soil before treatment, so the resistance under the first strike can be used as the soil layer resistance before treatment.

2.Calculation of composite soil layer resistance under 12.5N·m tamping energy:

Order $p_{\text{ave}} = p_{\text{area1}}$, p_{area} take the soil body resistance that corresponding to the last hit.

$$m_2 = \frac{nA_p}{A_{\text{soil}}} = \frac{24\times3.14\times0.05^2}{0.6\times0.9} = 34.89\%$$

$$p_{\text{area2}} = mp_{\text{ave}} + (1-m)p_{\text{area}}$$
$$= 0.3489\times922.87 + (1-0.3489)\times55.11 = 357.86\text{kPa}$$

3.Calculation of composite soil layer resistance under 18.75N·m tamping energy:

Order $p_{\text{ave}} = p_{\text{area2}}$, p_{area} take the soil body resistance that corresponding to the last hit.

$$m_3 = \frac{nA_p}{A_{\text{soil}}} = \frac{14\times3.14\times0.05^2}{0.6\times0.9} = 17.44\%$$

Statistics	7.5N·m		12.5N·m			18.75N·m	
	No.1	No.2	No.1	No.2	No.3	No.1	No.2
p_{max} /kPa	47.77	119.43	714.29	1000.00	1666.67	1875	1500
p_{min} /kPa	26.54	59.71	277.78	454.55	625.00	681.82	681.82
p_{ave} /kPa	35.99	92.58	452.27	683.54	922.87	1123.64	1148.14
p_{area} /kPa	55.15		357.86			495.72	

$$p_{area3} = mp_{ave} + (1-m)p_{area}$$
$$= 0.1744\times1123.64 + (1-0.3489)\times357.86 = 495.72\text{kPa}$$

Note: p_{max} is the maximum value of soil body resistance under single tamping energy; p_{min} is the minimum value of soil body resistance under single tamping energy.

B. Soil Surface Settlement

The soil layer resistance under the total tamping energy which is the ability of soil layer to resist deformation is defined as:

$$p_{soil} = \frac{E_{soil}}{A_{soil}S_{soil}} \quad (4)$$

Where, p_{soil} is the resistance to deformation of soil layer under total tamping energy, which is the tamping energy on the unit area needed for the dynamic settlement of the unit, kN/m^2; E_{soil} is the total tamping energy applied to the soil layer, kN·m/m^2; A_{soil} the area of the site,m^2; S_{soil} is the instantaneous settlement of dynamic consolidation, m.

Taking into account the four corner boundary effect of the model box, the monitoring data at the center of the model box are analyzed. The first tamping, the tamping is 7.5N·m, and 24 tamping points is loaded, each point 2 strikes; The second tamping, the tamping is 12.5N·m, and 24 tamping points is loaded, each point 3 strikes; The third tamping, the tamping is 18.75N·m, and 12 tamping points is loaded in a way that is spaced jump tamping, each point 2 strikes; The total tamping energy is 360N·m, 900N·m and 450N·m respectively. And the total tamping energy on the unit area of soil layer is 666.7N·m/m2, 1667.7N·m/m^2 and 833.3N·m/m^2.

Table 2 Comparison of soil layer resistance and composite soil layer resistance under total tamping energy

Unit: kPa

Tamping energy	7.5N·m	12.5N·m	18.75N·m
Total tamping energy / N.m	360	900	450
Total tamping energy per unit area / N.m/m^2	666.7	1666.7	833.3
p_{soil} /kPa	51.29	191.57	347.21
p_{area} /kPa	55.15	357.86	495.72
p_{area} / p_{soil}	1.08	1.87	1.43

Fig. 6 is the time variation curve of the settlement of the top of soft soil during dynamic consolidation. When the dynamic compaction is applied, the settlement of 13 mm, 8.7 mm and 2.4 mm can be generated when the single tamping is 7.5N·m, 12.5N·m and 18.75N·m respectively. The stable consolidation settlement is 7.13 mm and 7.42 mm and 2.09 mm respectively. The total settlement of three times dynamic consolidation is 40.74mm.

Table 2 is the comparison of the resistance of soil layer and the resistance of composite soil layer under the total tamping energy calculated according to formula (3), the results show that the resistance of composite soil layer calculated by formula (2) is larger than that of the corresponding soil layer under the total tamping energy, and the ratios are 1.08, 1.87 and 1.43, respectively, when the compaction rate of single tamping energy is 7.5N·m, 12.5N·m and 18.75N·m. The main reason for the difference between the two lies in the error in the test process. When calculating the resistance of composite soil layer, first, the soil body resistance under the rammer is the soil body resistance of the last hit, second, because of the loosening of the soil body at the bottom of the ram during the dynamic consolidation, the resistance of the soil layer is too large, which leads to the final calculation.

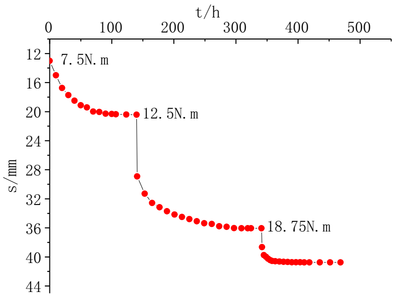


Figure 6. Curves of settlement with time at the top of soft soil under dynamic consolidation

C. *Analysis of dynamic earth pressure*

Fig.7~Fig.9 are the variation curves that change with time about different tamping energy corresponding with earth pressure when the measuring point is located below the tamping point C-3. In Fig.7~ Fig.9, when the tamping energy is loaded to the soil body, additional passive earth pressure is generated in the soil body, the action time is short, and the earth pressure acting on the soil body is equivalent to a downward impact load. When tamping is 7.5N·m, the action time is 48ms;When tamping is 12.5N·m, the action time is 23ms;When tamping is 18.75N·m, the action time is 20ms.The peak value of earth pressure decreases rapidly with the increase of depth (Table 3), and the earth pressure at the measured point is only 1.25%~3.83% of the depth of 10cm at 30cm. Table 3 shows the ratio of peak earth pressure measuring point and rammer on the soil surface static pressure, static pressure generated by the rammer model is 3.185kPa, measuring point depth is 10cm. The ratio increases with the increase of tamping energy and tamping times, the minimum value is 14.32, the maximum value is 88.07.

Table 3 Earth pressure under different tamping energy Unit：kPa

Depth(cm)	7.5N·m		12.5N·m			18.75N·m	
	No.1	No.2	No.1	No.2	No.3	No.1	No.2
10	45.61	76.18	140.17	214.85	280.51	186.45	240.91
20	7.80	8.35	10.89	10.53	10.53	15.43	13.79
30	2.54	2.92	3.09	4.00	4.40	2.54	3.00

Table 4 The ratio between the peak value of earth pressure and the static state of rammer under different compaction energy

Depth(cm)	7.5N·m		12.5N·m			18.75N·m	
	No.1	No.2	No.1	No.2	No.3	No.1	No.2
10	14.32	23.92	44.01	67.46	88.07	58.54	75.64
20	2.45	2.62	3.42	3.30	3.30	4.84	4.33
30	0.80	0.92	0.97	1.25	1.38	0.80	0.94

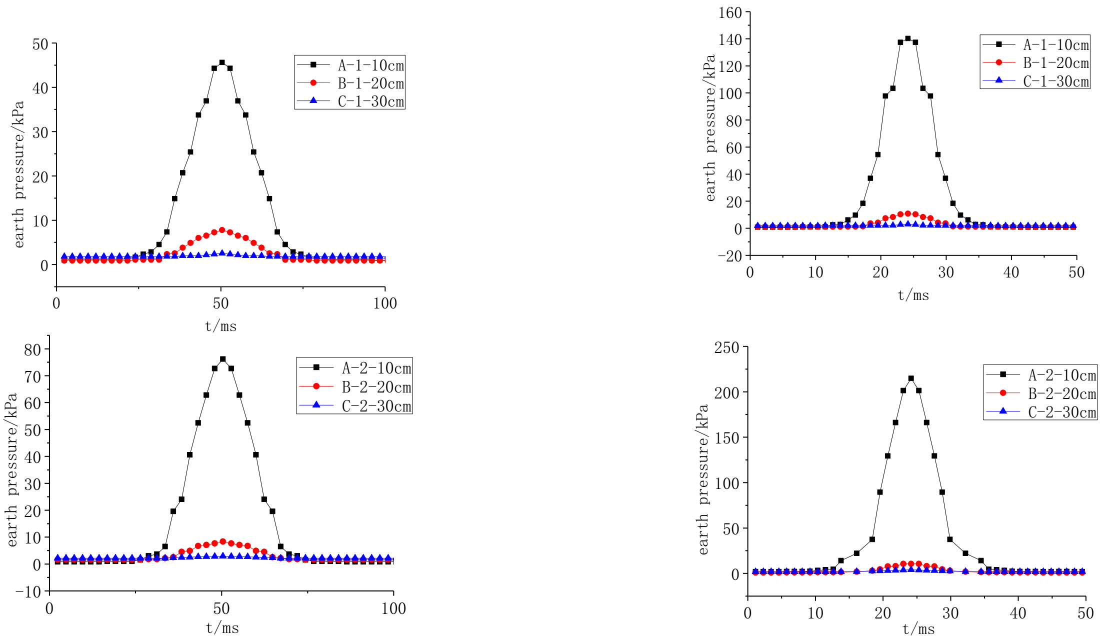


Figure 7. Curves of earth pressure with time in 7.5N·m tamping energy

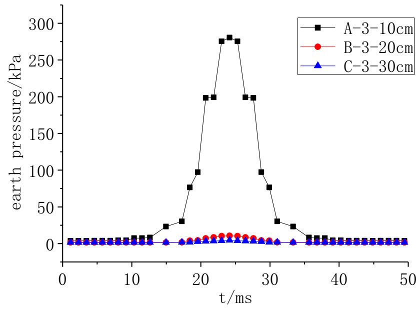
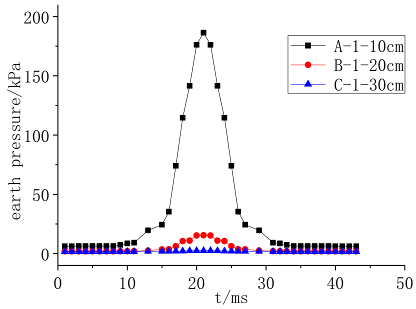


Figure8. Curves of earth pressure with time in 12.5N·m tamping energy



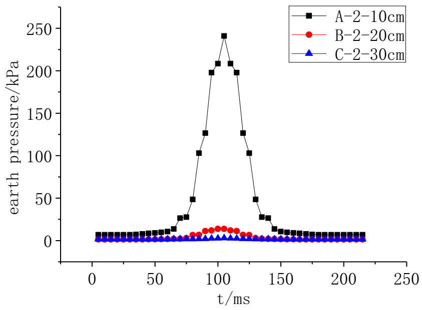


Figure9. Curves of earth pressure with time in 18.75N·m tamping energy

Fig. 10 is a comparison curve of earth pressure peak depth caused by changes in depth and tamping energy. When the depth is 10cm, 20cm and 30cm, the peak value of earth pressure is reduced along the depth. The diameter of rammer D is10cm, and the depth is D、2D、3D,P_{2D}/ P_D is 5%-17%，P_{3D}/ P_D is 1%-3%. From Table 3 shows that the earth pressure at the depth of 30cm peak is 2.5kPa-4.4kPa. According to the linear analysis on the earth pressure at the depth of 20cm, the additional pressure is 0at the depth of 32.8cm-37.2cm and the vertical effect depth depending on additional pressure (the value is 0), the average value is 3.4 times the diameter of the rammer.

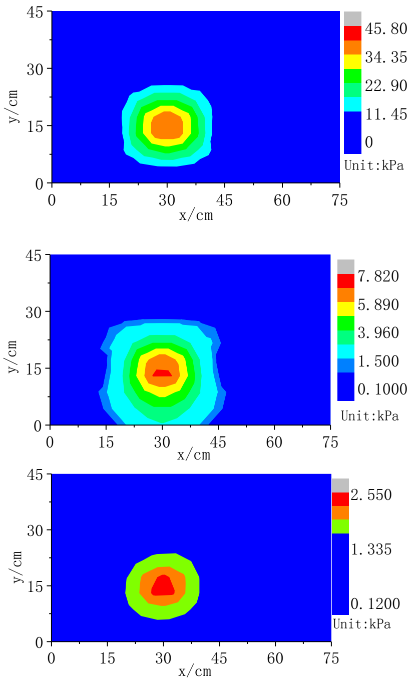


Figure 10. The influence range at the depth of 10cm, 20cm and 30cm by 7.5N.m tamping energy

Fig.11~ Fig.13 is the sketch of the influence range of the earth pressure peak at the depth of 10cm.As the tamping energy is same, the influence area increases with the increase of tamping time. The additional pressure is 0, which is the boundary standard of influence range, and the horizontal influence range is approximately a circular area that is a 3 times the diameter of a rammer.

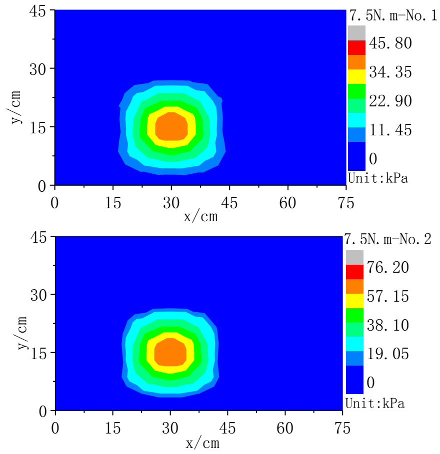


Figure 11. Influence range at the depth of 10cm by 7.5N·m tamping energy

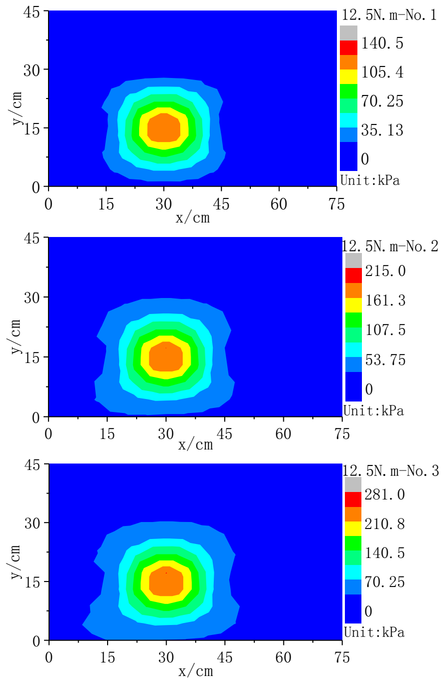


Figure 12. Influence range at the depth of 10cm by 12.5N·m tamping energy

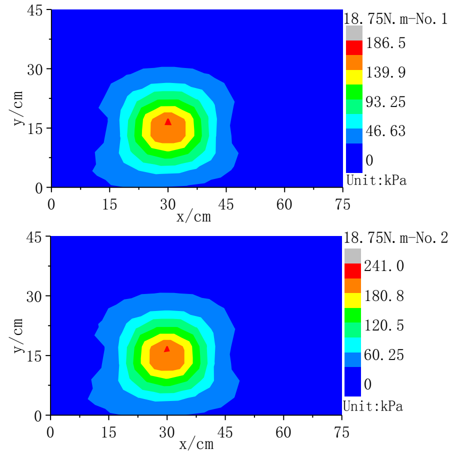


Figure 13. Influence range at the depth of 10cm by 18.75N·m tamping energy

IV. CONCLUSION

The soil body resistance and the soil layer resistance under single tamping energy is analyzed. With the increase of tamping times, the soil body is compacted after rammer tamping, and the soil layer resistance to deformation is enhanced. The uniformity of soil layer can be measured by using the last tamping of soil layer to resist deformation. On this basis, the soil layer resistance under the total tamping energy is defined. A formula for calculating the resistance of composite soil layer is put forward according to the soil body resistance under single tamping energy. When the single tamping energy is 7.5N·m, 12.5N·m and 18.75N·m, the resistance of composite soil layer is larger than that of the soil layer under the total tamping energy, and the ratios are 1.08, 1.87 and 1.43 respectively.

(2)when the tamping energy is loaded to the soil body, additional dynamic earth pressure is generated in the soil body, the action time is short range 18~45ms, and the dynamic earth pressure acting on the soil body is equivalent to a downward impact load. The ratio of peak earth pressure measuring point and rammer on the soil surface static pressure increases with the increase of tamping energy and tamping times, the minimum value is 14.32, the maximum value is 88.07.

(3)For the influence range of tamping process, the additional pressure is 0, which is the boundary standard of influence range, and the dynamic earth pressure peak is reduced along the depth in the vertical direction, the peak at the depth of 20cm is 5%-17% of which at the depth of 10cm, the peak at the depth of 30cm is 1%-3% of which at the depth of 10cm, the vertical influence depth is 3.4 times rammer diameter. In the horizontal direction, the influence area increases with the increase of tamping times as the tamping energy is same, the horizontal impact range is 3 times the rammer diameter.

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Reliability design principle and application of foundation engineering
Achievement:
Hosted and participated in more than ten provincial and prefectural research, has more than ten research achievements. Hebei science and Technology Progress Award：(1)Study on reliability of subgrade bearing capacity in Hebei；(2) Research and development of CAD for foundation engineering design; (3) Study on reliability design theory and application of foundation engineering; (4) Study on reliability design theory and application of composite foundation; (5)Calculation method of dynamic bearing capacity of composite foundation and dynamic characteristics of composite pile foundation; (6)Study and application of mechanical characteristics of composite foundation under seismic loading; (7)Experimental research and engineering application of complete set of composite foundation.

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September 2011-July 2015, Civil Engineering, Studying civil engineering at Hebei University;
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Mingjiang Wu
Education:
September 1988-July 1991, Engineering Eeology, Guilin Institute of metallurgy and geology.
Achievement:
Mainly engaged in geotechnical engineering survey, design, construction, monitoring and research work. Presided over and participated in more than thirty soft soil foundation design, on-site in-situ inspection and construction projects. Fourteen national invention patents were obtained and three provincial and ministerial level scientific and technical prizes were obtained.