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Impacts of pit excavation on foundation piles in deep silty soil by centrifugal model tests

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Abstract: The foundation pit excavation of a power plant located along the Yangtze River in Jiangsu province is selected to study the interaction mechanism between piles and soils during excavation of foundation pits in deep silty soft soil. Thus an indoor centrifugal model test with the similarity ratio of 1:50 is designed. The influence of foundation pit excavation on existing pile and surrounding soil in deep silty soft soil are analyzed from different aspects including the pile strain, pile displacement, pile top displacement, surface settlement and soil deformation influence range, pile bending moment and pore water pressure. Results from the centrifugal test and the excavation of the foundation pit in situ are compared and analyzed. It shows that when the shear strength of silty soft soil in the upper part of the layered foundation is relatively high, the pile foundation is subjected to a large force and it is prone to the breakage accident during the excavation process. Two extreme values of pile strain occur near the excavation depth and the interface between the silty soil and the underlying soil layer. Due to the influence of the pile, the pore water pressure of the soil near the excavation face changes smoothly, but the pore water pressure of the soil after the pile changes drastically with the excavation. The interaction between piles and soils mainly lasts 48 hours after excavation before the restoration of stability. The test results match with the field measured data, which can provide a reference for the design and construction process of the foundation pit in deep and thick soft soil.

Keywords: deep silty soft soil stratum; foundation pit excavation; centrifugal model test; foundation pile deformation; interaction between piles and soils

1 Introduction

During the excavation of foundation pit in the deep and thick soft soil, the horizontal slip of the deep and thick soft soil aside of pit caused by the gravity and external load effects presses the foundation pile, which may cause a large displacement and even breaking accident. The horizontal displacement in the soil caused by the excavation of foundation in the mucky soft soil can attain 10%–20% of the excavation depth. A large lateral stress can be induced by such a large lateral displacement, resulting in a serious deformation and even breaking of the foundation pile with a large diameter[1−3].

A power plant in Jiangsu Province along the Yangtz river is selected as the study area. The upper stratum at the boiler room is composed of the plastic-flow mucky soil with a thickness of 9–15 m. The lower stratum at the boiler room is composed of sand and silty clay layers. The bearing stratum of pile tip is the moderately weathered slate. The bored pile in the foundation of boiler room is formed by the churning drive with a diameter of 800 mm. The pile tip in the bedrock is more than 800 mm. The excavation depth of foundation pit in the boiler room is 3.75 m and two stages of excavation are applied, i.e., the excavation thickness is 1 m during the first stage, and it excavates to the basement during the second stage. Inclination and displacement of some foundation piles are found. The measured minimum displacement is 4 mm and the maximum value is 782 mm. The displacement of most foundation piles points is found at the excavation side[4], see detailed statistical results of pile displacements in Table 1.

Table 1 Classified statistics of pile position offset

Offset of pile / mm	Number of piles	Percentage to the total piles / %
0–99	94	20.2
100–150	115	24.7
151–300	199	42.7
301–500	50	10.7
501–800	8	1.7

Detection of low strain after removing the pile heads show that about 50% of piles are defined as the III type because serious defects are found at 4–6 m under the pile top. Then other three piles with a large displacement offset are selected to

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be checked after excavation. The steel casing with a large diameter is sunk into the soil surrounding the pile. The water flushing method is applied to remove the mucky soil between the steel casing and the pile. It is found that the horizontal crack, with a length accounting for 60% of the circumference of the pile shaft and the maximum width is 8 mm, exists at 4.2–5.5 m below the top of the designed piles (i.e., 7.95–9.25 m from the ground surface). The cutting section of the pile shaft at the cracks is flat. The crack cuts through some gravels in the concrete. Most cutting sections present the stain of muddy water. A few cutting sections present the fresh surfaces (see Fig. 1). It demonstrates that the horizontal cracks at the pile shaft form under the horizontal stress induced by the flow of the mucky soil during the excavation of foundation pit. Most cracks basically locate above the interface of soft and hard layers.

The centrifuge test is designed to simulate the excavation of foundation pit in the mucky soil in order to study the mechanism of pile displacement, broken pile induced by the unloading of foundation pit excavation in the muddy soft soil, and the deformation mechanism of foundation piles and surrounding soil. Thus a reasonable controlling strategy can be presented.

Fig.1 Horizontal crack and section of pile at the crack caused by excavation

2 Design of centrifugal model test

2.1 Experimental apparatus

The large geotechnical centrifuge LXJ-4-450, which has a maximum acceleration of 300*g*, an effective rotation radius of 5.03 m, an effective load of 1.5 t and an effective load capacity of 450 *g*·t, is applied in the test, see Fig. 2.

Fig.2 Geotechnical centrifugal model testing machine

Based on the factors such as site size and model box size etc., the similitude ratio is designed as N=50, and the proportion relationship of other parameters in the centrifugal model test[5] is shown in Table 2.

Table 2 Proportional relationship of parameters in the test

Parameters	Prototype	Model	Parameters	Prototype	Model
Length	1	$1/N$	Force	1	$1/N^2$
Area	1	$1/N^2$	Stress	1	1
Volume	1	$1/N^3$	Strain	1	1
Consolidation time	1	$1/N^2$	Displacement	1	$1/N$
Velocity	1	1	Soil pressure	1	$1/N$
Accelerated velocity	1	N	Specific mass	1	1
Mass	1	$1/N^3$	Weight density	1	N

2.2 Design of excavation apparatus

The excavation should be completed under the condition of high speed operation of centrifuge, and the actual stress state of soil before excavation also should be considered, thus the apparatus to simulate earthwork excavation is designed[1, 6–12]. The hydraulic cylinder plunger supports the excavation baffle, and the excavation baffle supports the mucky soil. The double-acting cylinder is used in the hydraulic pump. The hydraulic cylinder plunger is pushed into the designated position before the test. The hydraulic control valve is automatically locked, and the control system is connected to the console through the centrifuge slide ring. It speeds up to the desired acceleration value (N=50g). After the stabilization of the rotation speed, the control switch is turned on, and the excavation baffle is pulled back to the specified position by the hydraulic cylinder plunger. The excavation starts when the silt loses the support of the baffle. The excavation device is shown in Fig. 3.

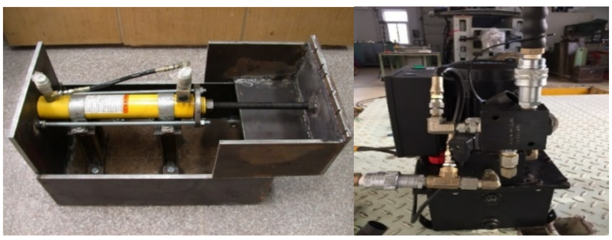


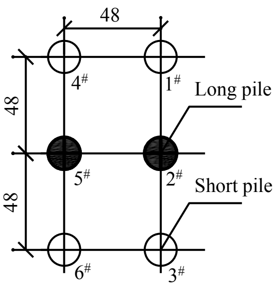
Fig.3 Pictures of excavation device

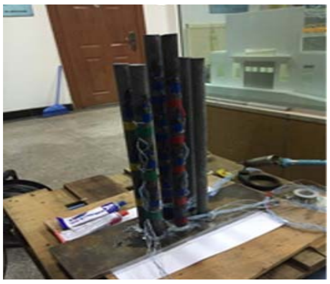
2.3 Model piles

The model piles, which are poured by mixtures of gypsum, sand, barite powder, fly ash, cement and other materials at a certain proportion[1], are used to simulate the reinforced concrete piles in the field. The material can strictly meet the requirement of geometric similitude ratio. The elastic modulus of the model pile, which can be regarded as the similitude material, is comparable with that of the prototype reinforced concrete. The artificial stone material can simulate the fracture of pile. The kaoline in the artificial stone material has a strong adhesion, making a certain bending stiffness of the artificial stone material. Thus it can simulate the characteristics of the steel bar in the pile to a certain extent. The parameters of model pile used in the test are shown in Table 3.

Table 3 Basic parameters of model pile

Parameters	Elastic modulus E / GPa	Diameter of model pile/ mm	Length of model pile/ mm
Artificial stone material	30	16	410/450



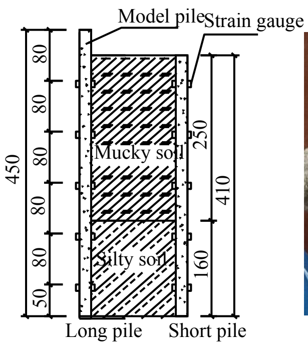


(a) Relative position of model piles(unit: mm) (b) Installation effect

Fig.4 Relative position of model piles and the installation effect

The model pile is fixed on a pre-drilled steel plate to simulate the fixed end formed by the pile end embedded in the bedrock. Meanwhile, the pile body should be remained vertical and fixed in the process of model formation. The installation position and effect of the model piles are shown in Fig. 4. Among them, 2# and 5# piles are long with a length of 450 mm. The short piles 1#, 3#, 4#, and 6# on both sides have a length of 410 mm. Based on the similitude ratio, the length of long pile is 22.5 m, and the length of short pile is 20.5 m.

Before the experiment, a strain gauge is fixed to the model pile (see Fig. 5) and connected to the data collection box using a single-bridge and the wire.



(a) Adhesive position of stran gauge (unit: mm) (b) Adhesion effect

Fig.5 Adhesive position and adhesion effect of strain gauges

2.4 Model box and sample preparation

The dimension of the model box is 1 350 mm, 400 mm and 910 mm in length, width and height, respectively. One side of the model box is filled with soil, and the excavation apparatus is placed on the other side[1]. The lubricant is painted on both sides of the model box before the soil filling to eliminate boundary effects.

The soil used in the test is divided into two parts. The upper mucky soil is sampled from the construction site of a thermal power plant in Jiangsu Province of China. The lower silty clay is obtained from Shijiazhuang. The test soil is the remolded soil. When the sample is prepared, the model pile is fixed at the bottom of the model box, and then the configured lower layer of soil is compacted to a specified height layer by layer till the thickness attains 160 mm. Finally, the mucky soil and water is mixed by proportion and put into the mixer to form the remolded soil. The upper layer is smoothed to arrange the sensors in place. The centrifuge is turned on and the mucky soil is consolidated at a low speed. The test starts when the thickness of mucky soil reaches 250 mm.

The main physical and mechanical parameters of model foundation soil are shown in Table 4.

Table 4 Main physical and mechanical indexes of model foundation soils

Type	ω / %	ω_L /%	ω_P / %	I_L	I_P	ρ_d / (g/cm^3)	c / kPa	φ / (°)
Mucky soft soil	52.2	43.5	22.9	1.29	22.6	1.21	9.66	20.38
Silty clay	20.4	25.2	17.8	0.29	7.4	1.83	25.13	29.13

2.5 Layout of sensors

During the test, the laser rangefinders, the strain gauges, and the miniature pore pressure sensors are arranged both on the model box and the model pile to measure the displacement of the pile shaft, the soil settlement, the strain of pile shaft, and the pore water pressure in the soil during the test. The arrangement of strain gauges is shown in Fig. 5, the pore water pressure sensor is installed at the interface of two layers of soil, the plane position is shown in Fig. 6, and the arrangement effect of the pore water pressure gauge and laser rangefinder is shown in Fig. 7.

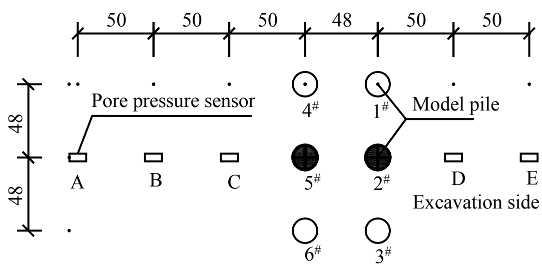


Fig.6 Layout plan of pore pressure sensors (unit: mm)

(a) Pore water pressure sensors (b) Laser rangefinder

Fig.7 Arrangement effect of pore pressure gauges and laser rangefinder

2.6 Experimental process

The centrifuge is in operation under 50*g*. After the soil sample is fully consolidated, the hydraulic device starts and the baffle is removed to simulate the in situ excavation process of the foundation pit. After the baffle is removed, the accessible excavation depth is 150 mm, which is equivalent to an on-site excavation depth of 7.5 m. The mucky soil under the excavation surface is 100 mm in thickness, and the silty clay has a thickness of 160 mm, which is equivalent to the thickness of 5 m and 8 m in the field, respectively.

It is stable for 5 minutes after excavation to simulate the actual excavation period of 8 days and the sensor data is recorded.

3 Results of centrifuge model test

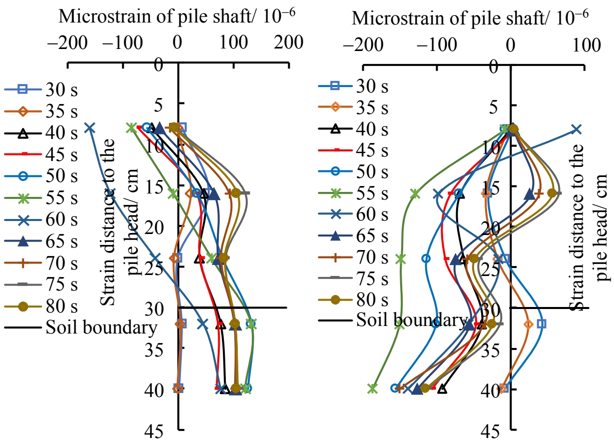
The shear strength of the mucky soil in the upper model is measured in two tests under 6 kPa and 16 kPa, respectively. When the shear strength is 6 kPa, the plastic flow of mucky soil around the pile is obvious and the interaction between the soil and the pile is so small that the data variation obtained from the sensors is not obvious. It demonstrates that the shear strength of mucky soil plays a significant role in the foundation pile stress.

Parameters include the strain of model pile, displacement of pile shaft and pile top, pore water pressure, the affected zone induced by the excavation etc., are obtained and analyzed. Using the mucky soil with a shear strength of 16 kPa, the representative piles of 2# and 5# (long middle pile) are selected to compare with that of the 6# pile (short border pile).

3.1 Strain of pile shaft

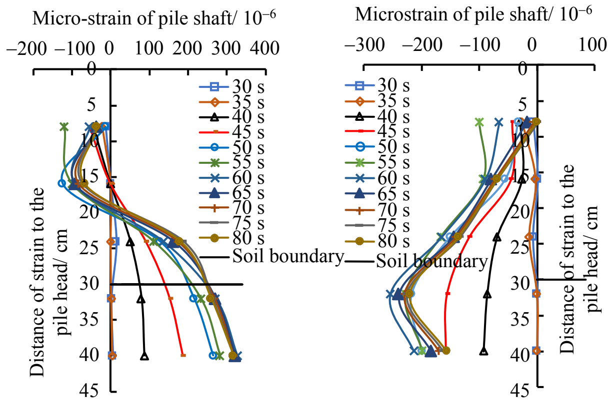
Strain variations of pile shafts (e.g., 2#, 5# and 6#) with depth are shown in Figs. 8–10. The 2# and 5# piles are middle piles and 6# pile is the border pile.

Two extreme strain values of tensile and compressive strain for 2# pile shaft in the front row occurs at the depth of 18 cm and 32 cm, respectively, which are corresponding to the excavation depth and the bottom location of mucky soil. Extreme value of tensile strain for 5# pile in the back row occurs at 18 cm, while the extreme value of compressive strain occurs at 32 cm. The strain variation of 6# pile with depth is gentle and no extreme value appears. Moreover, the strain values at deep depth is greater than that of the shallow depth.



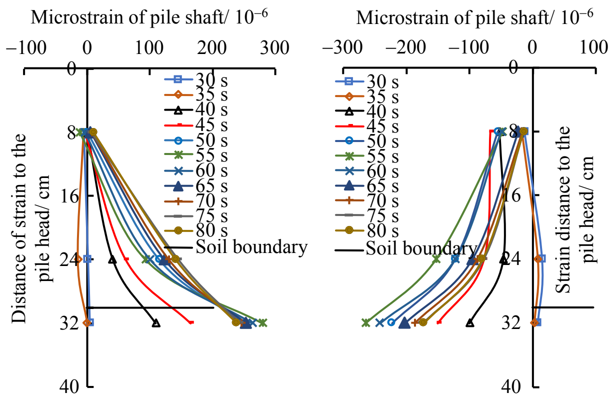
(a) Tensile strain (b) Compressive strain

Fig.8 Variation of pile strain with depth (pile #2)



(a) Tensile strain (b) Compressive strain

Fig.9 Variation of pile strain with depth (pile #5)



(a) Tensile strain (b) Compressive strain

Fig.10 Strain variation of pile with depth (pile #6)

The top of the 2# and 5# piles is 40 mm higher than that of the filling surfaces in the model. The top of 6# pile is under the filling surface. The tensile strain of 5# pile is larger than that of the 6# pile. It demonstrates that the pile head above the excavation surface is much longer, impact of the thrust force caused by the mucky soil on the pile is much larger during the excavation process. The stress concentration occurs, resulting in the broken of the piles. Two positions of stress concentration appear in the 2# pile that is close to the excavation side, one is located around the excavation depth, and the other is located below the interface of mucky soil and underlying soil.

3.2 Displacement of pile shaft

The curvature distribution of model pile at every moment during the excavation process is calculated based on the strain gauge. Then the deformation of model pile during the excavation process is calculated[13]. The displacement of prototype piles is computed based on a similitude ratio of 50, see Fig.11.

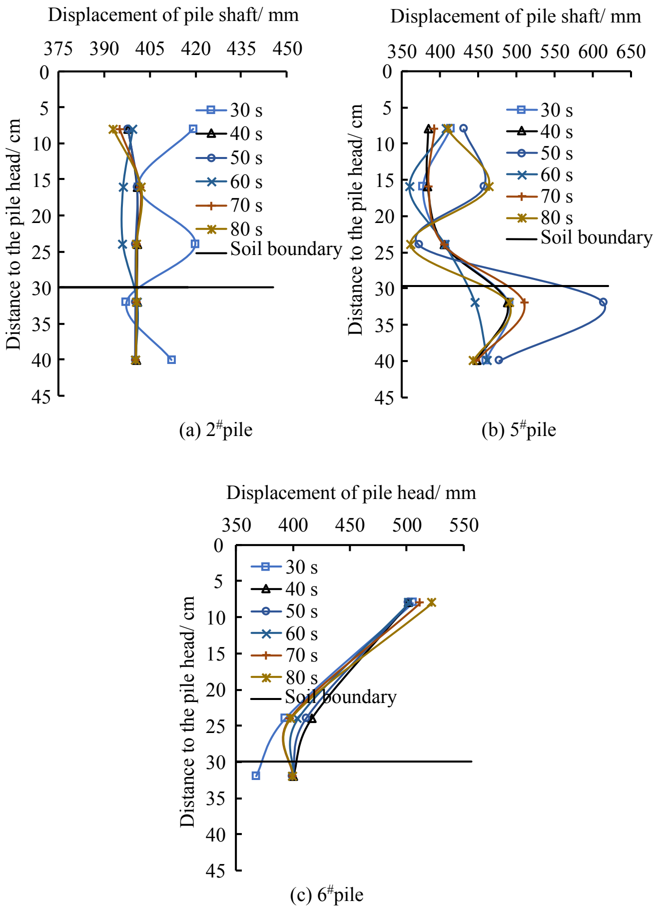


Fig.11 Variation of pile displacement with depth

It is shown in Fig.11 that the displacement curves of 2# and 5# piles are similar. The displacement of pile shaft in 2# pile is obvious at the excavation point. The maximum displacement of both the pile head and soil layer boundary exceed 420 mm. With time, displacement of pile tends to be gentle till the failure of pile shaft. The displacement process of 5# pile obviously lags behind, demonstrating that both the back piles and sludge squeeze the front piles which firstly occurs the extreme displacement values at the excavation moment. However, no extreme displacement values occur at the boundary of soil layer for 6# pile (border pile). The displacement at the top of pile is large, while it is small at the bottom of pile. It is found that the difference of displacement curves of border pile (short pile) and middle pile (long pile) is large in three piles. It implies that the length of pile shaft above the excavation surface plays a significant role in controlling the displacement of pile shaft.

After the excavation of foundation pit, the exposure part of the pile head in the field presents a large inclination. The displacement of foundation pile separates the foundation pile and soil body behind the pile. A crack with the width of more than 10 cm forms in the soil at the back of the pile (see Fig. 12). The displacement morphology of the pile shaft above the fracture surface of the foundation pile in the field presents a large top part and a small bottom part, which is in accordance with the displacement morphology of the 6# pile. The excavation is carried out backwards by sequence along one side and is applied in the field. Multiple foundation piles under the same cushion cap present their relationships with the side piles one by one during the excavation process. It is different from the model tests when three foundation piles are excavated simultaneously.

(a) Inclination of foundation piles (b) Soil cracks behind the pile

Fig.12 Inclination of pile and the soil crack behind pile after excavation

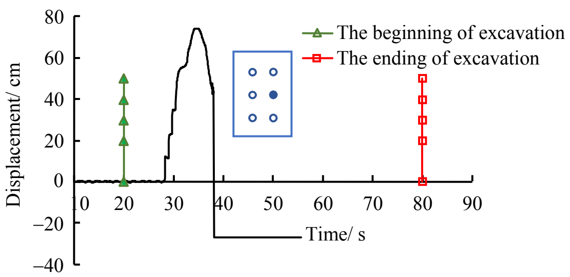
3.3 Variation of pile top displacement

The displacement of pile top for two long piles i.e., 2# and 5#, whose tops are higher than the filling soil surface, is measured by the laser rangefinder. Fig. 13 shows the variation curves of pile top displacement with time.

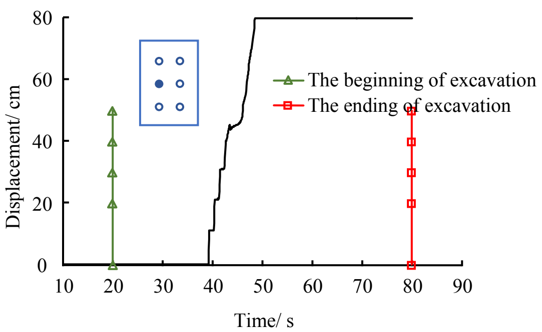
It shows in Fig.13 that the displacement of pile head concentrates in 2# pile after 28 s. The maximum displacement 14.76 mm occurs at 33 s, corresponding to the practical displacement of 73.8 cm in the field. The opposite directional displacement emerges after the maximum displacement, which may be induced by the rolling-over of the pile head after the failure of pile shaft. Obvious displacement occurs after 38 s for the 5# pile head. The maximum displacement reaches 15.92 mm after 48 s, corresponding to the practical displacement 79.6 cm in the field, which is equivalent to measured maximum displacement 78.2 cm of pile top in the field. Displacement exceeds the range of laser rangefinder after breaking of two piles.

Two rows of piles are pulled out after experiments. It is found that the rupture phenomenon appears in piles. The rupture location is 2 cm under the boundary of mucky soil and overlying soil. The 80% area of the fracture surface in the foundation pile is characterized as the connected fractures after excavation, while only 20% of the area for the foundation pile is linked by the concrete (see Fig. 1). This may be caused by the simplification that only the similitude of material elastic modulus of model pile is considered in the tests.

Based on the rupture time of two piles and the time proportion of similitude theory, it is estimated that maximum displacements of the piles at the front and back row occur at 9 h and 19 h after excavation of foundation pit in practical engineering.



(a) 2# pile



(b) 5# pile

Fig.13 Variation of pile top displacement with time

3.4 Affected region of surface subsidence and soil displacement

Figure 14 shows the variation curves of surface subsidence with time (the subsidence value is enlarged based on similitude ratio).

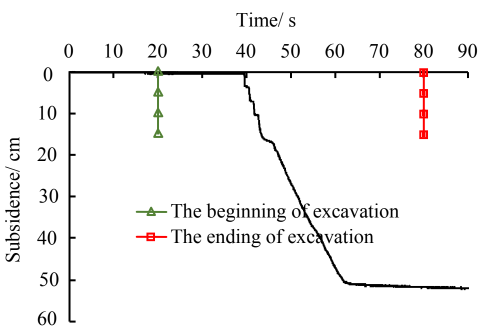


Fig.14 Variation of surface settlement with time

It can be shown in Fig.14 that the surface subsidence has no obvious time effect, which is different from the variation rules of the pile shaft displacement. The subsidence starts at 38 s in the curve, and it nearly presents a linear state after 60 s and the changes of subsidence is not obvious. It is shown from the similitude relationship that the displacement occurs after 12.5 h of the excavation. The surface displacement process lasts about 27 h and the surface displacement behind the pile basically completes in 48 hours after the excavation. It demonstrates that the interaction between the pile and soil after the foundation pit excavation in the thick and deep mucky soil mainly occurs in 48 h and it tends to be stabilized. It is approximately matched with the evolution time of the measured pile displacement in the field and the surface fractures behind the pile. The maximum subsidence amounts at two monitoring points of subsidence can reach 52.5 cm and 53.8 cm, respectively.

The affected area of the soil displacement can be determined by the forms of the fractures at the model surface of soil and development after the tests. There are mainly two types of fractures on the surface of the model soil after tests, one is the longitudinal crack perpendicular to the excavation surface, and the other is the transverse fracture parallel with the excavation surface that is the dominated type. The fractures parallel with the excavation surface are mainly distributed in the soil within a distance of 29 cm behind the pile. The development extension of main fractures is larger than the thickness of the top mucky soil (25 cm). Based on the similitude principal, the impact region caused by excavation is larger than 15 m, which is basically equivalent to the real fractures in the field (see Fig. 15) .

Fig.15 Distribution of surface cracks after excavation of foundation pit

3.5 Variation of bending moment of pile shaft

Figure 16 shows the variation curve of the bending moment of pile shaft with time. The positive value represents that the bending is towards the excavation side, and vice-versa. The variation forms of the bending moment for the 5# and 6# piles are similar. The bending moment supported by the pile shaft increases with time and depth. It tends to be stabilized after the

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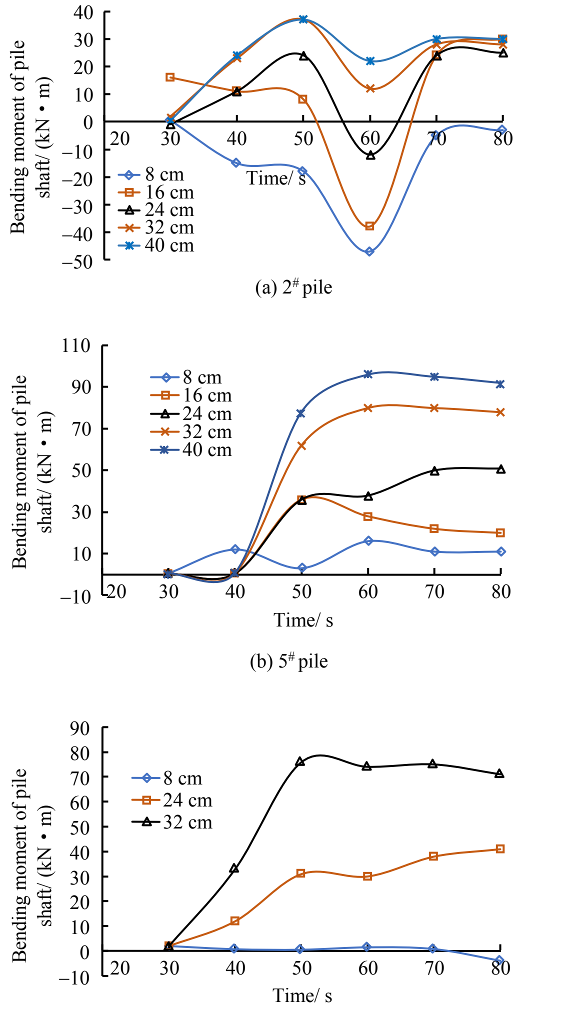
peak values. The bending moment at the middle pile is larger than the side pile, demonstrating that the variation of the bending moment supported by the pile shaft is very strong at the beginning of excavation when it is the key period to guarantee that the pile shaft not to be destroyed. The variation form of the bending moment for the 2# pile close to the excavation surface is different from that of the 5# pile. The negative bending moment occurs in the shallow depth, while the positive bending moment occurs in the lower middle part. With time, two extreme maximum values appear in the pile shaft. The top pile shaft is characterized as the negative bending moment, while the lower middle part of the pile is characterized as the positive bending moment. The bending moment finally tends to be stabilized.



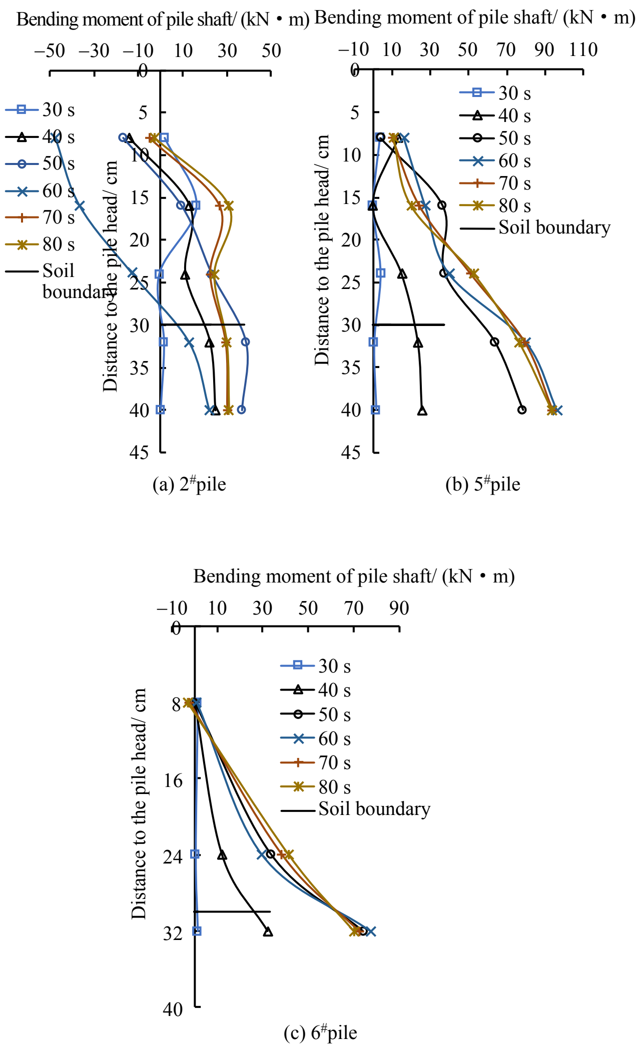
(a) 2# pile

(b) 5# pile

(c) 6# pile

Fig.16 Variation of pile bending moment with time

Figure 17 shows the envelop curve of the bending moment of pile shaft with depth. It presents that the maximum bending point of the pile shaft is located at the 2 cm below the boundary of the mucky soil and underlying soil. The maximum bending moment of the experimental pile shaft for the 2#, 5# and 6# piles are 38.6 kN • m, 93.4 kN • m and 77.4 kN • m, respectively. It implies that the bending moment of front piles is smaller than that of the back piles, and the bending moment of side piles is smaller than that of the middle piles. The response of the bending moment for the pile shaft of the 2# pile that is close to the excavation side is faster than that of the 6# pile which is far away from the excavation side. It demonstrates that the front piles are firstly pushed by the mucky soil at behind. After the interaction between the pile and soil weakens, the back piles are undergoing the force. At the beginning of the excavation, the bending moment of the excavation surface reaches the maximum value and it decreases over time. The bending location gradually moves downwards. Because the length of the 6# pile is short, the bending moment of the upper parts of the pile keeps nearly constant during the excavation process. The bending moment gradually increases with depth. Therefore, it is efficient to avoid the failure of the pile shaft by decreasing the length of the pile shaft above the excavation surface during the excavation process.



(a) 2# pile

(b) 5# pile

(c) 6# pile

Fig.17 Variation of pile bending moment with depth

3.6 Pore water pressure

Figure 18 shows the variation curves of the pore pressure perpendicular to the excavation surface. The variation characteristics of the pore water pressure can be divided into two parts including the front and back of the model pile. The variation of pore water pressure in front of the pile is not obvious, while dramatic changes of pore water pressure are found at the back of the pile with the excavation and it reaches to a maximum value of 12.8 kPa. Thus it is better to apply the excavation at both sides to reduce the impact of super pore water pressure on the pile shaft.

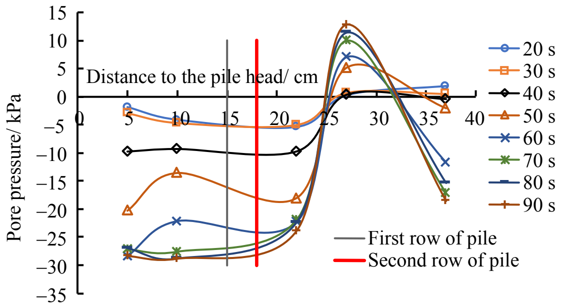


Fig.18 Cross-section of pore pressure

4 Conclusions

The pit excavation of a boiler room at a power plant located at the Yangtz river of Jiangsu province is used as the background. The geotechnical centrifugal model test is applied to study the broken pile phenomenon induced by the excavation of foundation pit in the stratum that is composed of deep and thick mucky soil in the upper part and the lower soil layer with a good engineering property. Some conclusions can be drawn as follows:

(1) The centrifugal model test is useful to simulate the impacts of foundation excavation on the foundation piles. The possible location of broken pile in the tests is consistent with the field observation.

(2) When the shear strength of the mucky soil at the upper part of the foundation is low, the plastic flow of mucky soil around the pile occurs due to the excavation of foundation pit and its interaction with the pile is small. When the shear strength of the mucky soil at the upper part of the foundation is high, the interaction between the pile and soil plays a significant role in the foundation pile of pit. Thus the broken pile accident occurs easily during the excavation process.

(3) The strain and bending moment of pit foundation piles increase with the buried depth. Two extreme displacement values, i.e., one is at the excavation depth, the other is at the interface between the mucky soil and the underlying soil, occur at the pile shaft during the excavation process. The extreme bending moment value occurs at the interface between soil layers. There are two broken locations of the foundation piles during the excavation. One is located at the excavation depth, the other is located at the interface between the silt soil and the underlying soil layer.

(4) The length of foundation piles has a great impact on the pile stress at the depth shallower than the excavation depth. A smaller foundation pile length at the location shallower than the excavation depth is helpful in weakening the failure of pile shaft during the excavation process.

(5) The interaction between the pile and soil in the foundation of deep and thick mucky soil mainly occurs in 48 hours after the excavation of foundation pit, and it tends to be stabilized afterwards.

(6) Due to the existence of foundation pile in the pit, the pore pressure in the front and back of the piles presents different variation characteristics during the excavation process. The pore pressure in the soil close to the excavation face changes strongly. Therefore, the soil in the front and back of the foundation pile of pit should be kept balance during the excavation of foundation pit in the deep and thick silt soil.

References

[1] DU Chen-xiang. Experiment study on the deformation of pile foundation by excavation in thick mucky soft soil[D]. Shijiazhuang: Shijiazhuang Tiedao University, 2016.

[2] YANG Min, ZHU Bi-tang. Preliminary analysis of collapse accident caused by stacking in a factory[J]. Chinese Journal of Geotechnical Engineering, 2002, 24(4): 446–450.

[3] NIE Qing-ke, HU Jian-min, WU Gang. Deformation and earth pressure of a double-row pile retaining structure for deep excavation[J]. Rock and soil mechanics, 2008, 29(11): 3089–3094.

[4] WANG Guo-hui, ZHOU Jin-fa, GUO Yue-liang, et al. Influence and treatment of foundation pit excavation on foundation piles in muddy foundation[J]. Architecture Technology, 2011, 42(Suppl.11): 161–163.

[5] QI Tai-yue, GAO Bo, MA Liang. Centrifugal model test for ground surface subsidence caused by metro tunneling in saturated soft clay strata[J]. Journal of Southwest Jiaotong University, 2006, 41(2): 184–189.

[6] QIAN Jian-gu, MA Xiao, LI Wei-wei. Centrifuge model test and in-site observation on behaviors of side-grouting uplift pile[J]. Rock and Soil Mechanics, 2014, 35(5): 1241–1246.

[7] ZENG You-jin, WANG Nian-xiang, ZHANG Wei-min, et al. Centrifugal model test of micro-pile foundation in soft soil area[J]. Chinese Journal of Geotechnical Engineering, 2003, 25(3): 242–245.

[8] XU Qian-wei, MA Xian-feng, ZHU He-hua, et al. Centrifugal model test on extra-deep foundation pit excavations in soft ground[J]. China Civil Engineering Journal, 2009, 42(12): 154–161.

[9] ZHOU Qiu-juan, CHEN Xiao-ping, XU Guang-ming. Centrifugal model test and numerical simulation of soft foundation pit[J]. Chinese Journal of Rock Mechanics and Engineering, 2013, 32(11): 2342–2348.

[10] LI Ming, ZHANG Ga, HU Yun, et al. Centrifuge model tests on excavation-induced failure of slopes[J]. Rock and Soil Mechanics, 2010, 31(2): 366–370.

[11] HU Qi, LING Dao-sheng, CHEN Yun-min, et al. Study of loading characters of pile foundation due to unloading of deep foundation pit excavation[J]. Rock and Soil Mechanics, 2008, 29(7): 1965–1970.

[12] NIE Qing-ke, LIANG Jin-guo. Design theory and application of double-row pile retaining structure in deep foundation pit[M]. Beijing: China Architecture & Building Press, 2008.

[13] MA Xian-feng, ZHANG Hai-hua, ZHU Wei-jie, et al. Centrifuge model tests on deformation of ultra-deep foundation pits in soft ground[J]. Chinese Journal of Geotechnical Engineering, 2009, 31(9): 1371–1377.