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Numerical Study on Dynamic Response of Pile Group Foundation of Geotechnical Centrifuge

Quansheng Mao & Tao Yue
Sino-steel Ma'anshan Institute of Mining Research Co., Ltd, Ma'anshan, Anhui, China
State Key Laboratory of Safety and Health for Metal Mine, Ma'anshan, Anhui, China
Huawei National Engineering Research Center Co., Ltd. Shenzhen, Guangdong, China

Dianjun Zuo
Tianjin Research Institute for Water Transport Engineering, Tianjin, China

ABSTRACT: Based on National Engineering Laboratory for Harbor Engineering Structure-Geotechnical Centrifuge Laboratory construction project, the dynamical response of piles foundation under horizontal-rocking vibration was analyzed by using finite element software Abaqus, and the displacement and stress characteristics of piles were discussed with soil between the piles reinforced by high pressure jet piles. The result indicates that in the operation of the centrifuge, foundation changes of vertical load of center pile are very small; the vertical displacement of the pile head is increasing, the vertical displacement of the pile head is no longer changed until the vibration time reaches 3 times period,; the horizontal load of piles varies with sinusoidal, the horizontal displacement amplitude is increasing, , and the vibration amplitude reaches to fixed value at 2 times vibration period .

Keywords: geotechnical centrifuge; horizontal-rocking; pile group foundation; dynamical response; numerical study

1 INTRODUCTION

In deep soft soil area, the rigid pile group was used in large dynamic machine foundation engineering to form a pile cap-pile group-soil interaction mechanics system. Theoretically, the automatic dynamic balancing system on both ends of the rotating system would achieve the static balance when the large beam geotechnical centrifuge run. But in fact, due to factors such as changes of gravity center of test specimen, machining and the other errors, imbalanced force was caused to transmit down to the pile cap via pedestal and anchor bolts. Such effects are mainly demonstrated by horizontal-rocking vibration.

Recent research were mainly studied on piles buried depth [1], soil-pile dynamic interaction [2-3], dynamic resistance [4] and properties of the soil layer in foundation[5] under the effects of horizontal vibration, and a series of computing methods were proposed such as direct method and methods based on interaction of factors. Few researches focused on the dynamic response of pile group under the effects of horizontal-rocking coupled vibration, for examples, Huang Maosong and Zhong Rui [6] used a dynamic Winkler foundation model to deduce the horizontal-rocking dynamic resistance for the part of offshore wind turbine buried in pile group foundation and made a study on the effects of foundation resistance on characteristics of structural resonance.

Based on the background of the construction of geotechnical centrifuge lab, the dynamic response of pile group foundation during large geotechnical centrifuge operation was studied by using finite element software ABAQUS in this paper.

2 PROJECT OVERVIEW

The national engineering lab for port construction projects-geotechnical centrifuge lab is located in Test Zone of Tianjin Academy of Science for Marine Traffic Engineering established by Ministry of Transport in Tianjin Lingang Industrial Zone, with a designed capacity of 500 g·t, a maximum centrifugal acceleration of 250 g and a rotation speed of 0.5% FS·S12 H. The pedestal of centrifuge is based on the foundation of a pile group consisting of cast-in-situ bored piles made of C40 reinforcing bar concrete with diameter D=800mm, length L=32m, thickness of pile cap = 1.5m and the strength grade of concrete is C40. Figure 1 was the main structure of centrifuge.

The soil layers under the foundation pile cap of the centrifuge are shown as follows (from top to bottom): ⑥ the mucky clay, which mainly consists of coastal tidal zone sediments in Group Four of Upper Pleistocene; ⑦ the silty clay layer, which consists of swamp facies sediments in Lower Group of Holocene series, is plastic with medium compressibility; ⑧ the silty clay layer without stratification is plastic with medium compressibility; ⑨ the compacted silt is

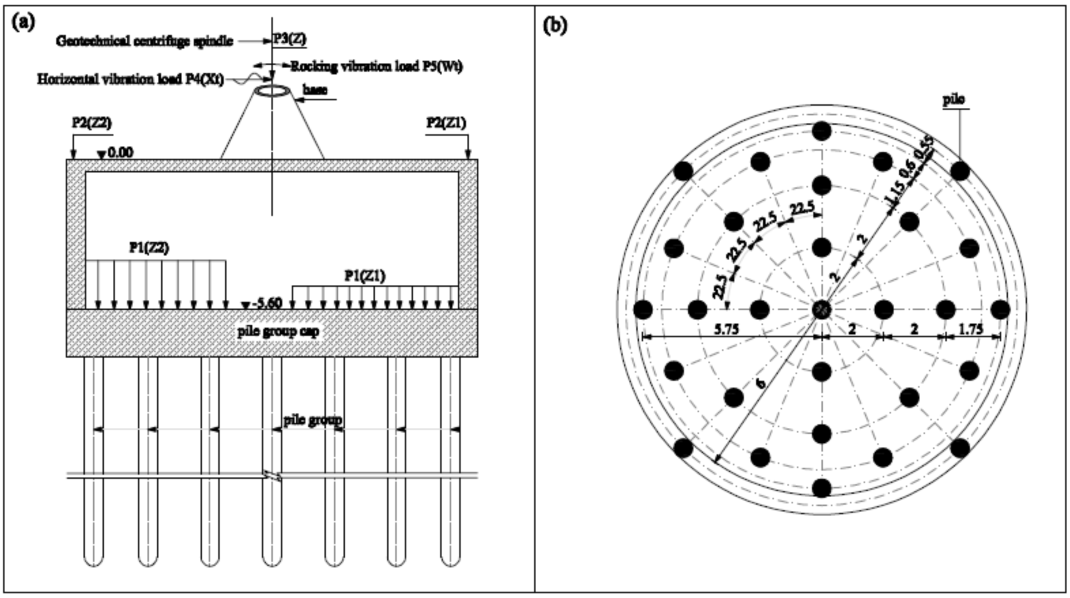

Figure 1. Geotechnical centrifuge room structure and locations of the pile foundation: (a) structure; (b) pile group

Table 1. Soil physical and mechanical index

Soils	ω/%	e_0	γ /kN/m^3	E_{s1-2} /MPa	ω_L /%	ω_p /%	c /kPa	φ /(°)
mucky clay	37.8	1.075	19.7	12.2	40.8	22	13.7	8.9
silty clay	33.1	0.933	19.8	13.2	36.2	21	16.3	23.2
silty clay	32	0.905	18.6	11.7	36.2	21.2	16.7	24.2
silt	30.1	0.851	18.7	12.4	29.4	21.8	6.8	32.1
clay	34.8	0.982	19.7	14.5	40.2	22	21.2	7.9

with medium (comparatively low) compressibility; ⑩ the clay is plastic with medium (relatively high) compressibility. The physical and mechanical indexes of each soil layer were shown in Table 1.

3 ESTABLISHMENT OF 3D NUMERICAL SIMULATION

3.1 *Simplification & establishment of model*

As shown in Figure 1, the geotechnical centrifuge is mainly located on the second floor of the lab while its pedestal is fixed on the bottom slab through embedded bolts. During operation, the horizontal-rocking vibration generated by the centrifuge is transmitted to the ground foundation via the bottom slab; therefore, the building structures above the bottom slab on the second floor and ancillary equipment of the centrifuge are simplified as equal load imposed on the pedestal in order to make the numerical simulation simple; besides, the transmission mechanism of the centrifuge on the first floor is simplified as uniform load and concentrated force acting on the top surface of foundation pile cap.

It is pointed out in Literature [7] that, in order to prevent the settings of boundary conditions of the model from having impacts on the calculation results, the width of one side of the model should be greater than 30D (D is the diameter of the foundation pile) and height should be greater than 2Le (Le is the embedded depth of pile) during the numerical simulation calculation process of pile group foundation; therefore, according to Figure 1, the size of numerical calculation model is determined as 50 m * 50 m * 70 m.

Figure 2 was the diagram of the numerical calculation model based on the finite element software ABAQUS. The origin of coordinates is located at the center of the pedestal; there are 126246 units and 143628 nodes in total. The pedestal of centrifuge, wall of the lab, pile cap and pile group are expressed in 3D eight-node reduction unit (C3D8R) and the soil of foundation is expressed in 3D ten-node coordination unit (C3D10I). As for meshing, the grids of pile cap, foundation piles and the soil within a 2D range around the pile are densified while the soil in other areas is expressed in relatively sparse grids.

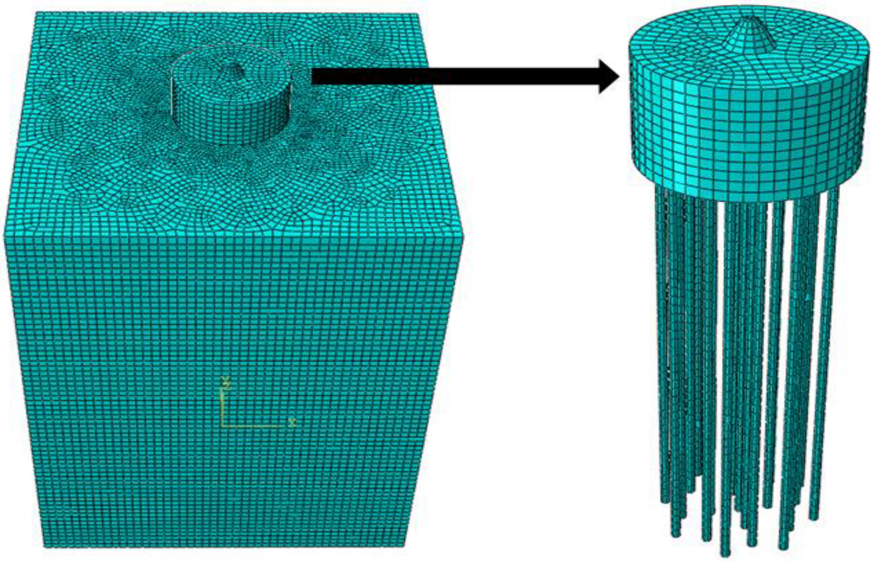

Figure 2. Numerical model of geotechnical centrifuge pile foundation

3.2 *Selection of calculation parameters*

The pedestal of centrifuge, wall of the lab, pile group and pile cap are simulated with elastic model in the pedestal which is 35 CrMo, the elastic modulus is 200 GPa and the Poisson's ratio is 0.30. All of the wall, pile group and pile cap are made of C40 reinforced concrete with an elastic modulus of 32.5 GPa and a Poisson's ratio which is0.20. The soil foundation is simulated with Mohr-Coulomb elastic-plastic model and the density, cohesive force and friction angle consist with the values shown in Table 1. The elastic modulus E is calculated with the following formula [8]:

$$E = (2.5 \sim 3.5) * E_s \quad (1)$$

Where E is elastic modulus; E_s is compression modulus.

Fixed connections are made between the pedestal and the roof slab of building structure, they are also between the top of foundation pile and the bottom of the pile cap; the tip of pile is tied to soil; the side of pile contacts is with soil in face-face limited sliding friction; the frictional angle δ is calculated with the following formula [9]:

$$\delta = \tan^{-1}(\sin\varphi \times \cos\varphi / (1 + \sin^2\varphi))$$

(2)

Where φ is the friction angle in soil, and it is determined according to Table 1.

3.3 *Simplification and application of load*

As shown in Figure 1, the main load generated by running centrifuge is divided into the static load and the dynamic load, the former mainly consists of: (1) The oil pump and foundation load as well as motor and foundation load $P_1(Z_1)$ and $P_1(Z_2)$ act on the top surface of foundation pile cap; (2) the upper structure loads $P_2(Z_1)$ and $P_2(Z_2)$ act on the roof slab of building structure; (3) the model casing and counterweight load on both sides of rocker arm $P_3(Z)$ acts on the main shaft of the centrifuge; the dynamic load mainly consists of the main horizontal vibration load $P_4(X_t)$ and the rocking vibration load $P_5(W_t)$ acts on the main shaft of the centrifuge. According to the design data of geotechnical centrifuge, static loads $P_1(Z_1)$=26.7 kPa, $P_1(Z_2)$=27.8 kPa, $P_2(Z_1)$= $P_2(Z_2)$=50 kN, and $P_3(Z)$=800 kN. The dynamic load is calculated by using following formula:

$$P_4(X_t) = P_{X0} * \sin(\frac{2\pi}{T} t) \quad (3)$$

$$P_5(W_t) = P_{W0} * \sin(\frac{2\pi}{T} t) \quad (4)$$

Where P_{X0} and P_{W0} are respectively the maximum imbalanced horizontal force and the overturning moment imposed on the main shaft of the centrifuge at an acceleration of 250 g, and respectively determined as 250 kN and kN·m; T is the duration of each turn of the centrifuge at an acceleration of 250 g, and it is determined as 0.27 s; t is the vibration time, which shall not exceed 10T under the maximum imbalanced horizontal force and overturning moment during operation of the geotechnical centrifuge. Once such speci-

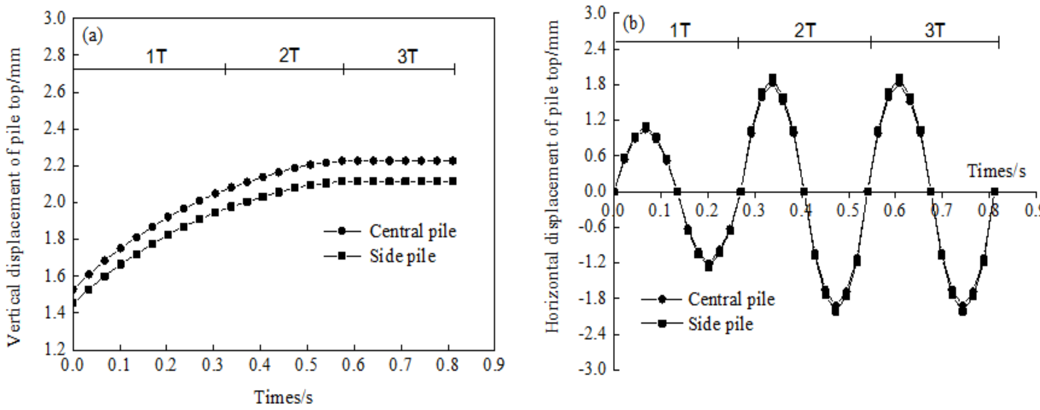

Figure 3. Displacement of pile top and pile foundation: (a) vertical displacement; (b) horizontal displacement

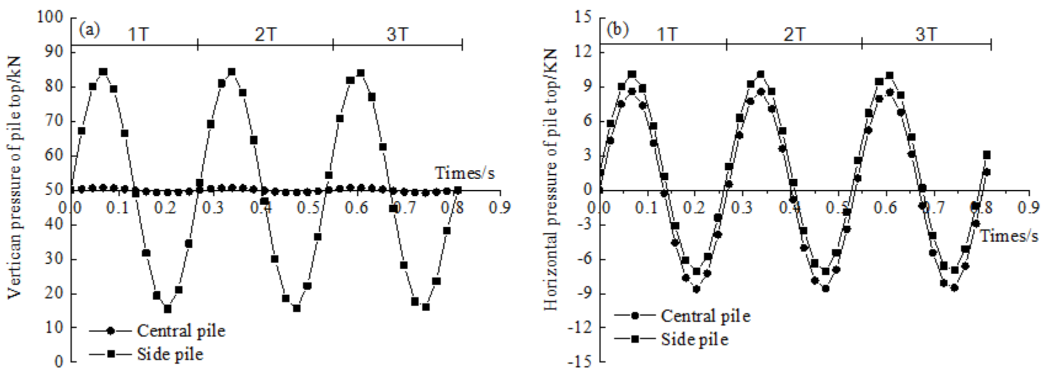

Figure 4. Curve of pressure characteristics of piles: (a) vertical pressure; (b) horizontal pressure

fied time expires, the system will be automatically locked to stop the operation of centrifuge; for numerical calculation in this paper, t is determined as 0~3T.

3.4 *Calculation process*

(1) We generate initial grids of the structure of geotechnical centrifuge lab, pedestal, pile cap foundation and soil layer of foundation for establishment of initial calculation model, apply the displacement constraint boundary conditions at the boundary, and carry out iterative calculation under initial stress conditions of the foundation soil layer to put the system into initial stress balance;

(2) We apply the static load imposed by structure of lab, ancillary equipment of the centrifuge and so on;

(3) We apply the dynamic load generated by horizontal and rocking vibration.

4 RESULTS

4.1 *Analysis of displacement of pile top*

Figure 3 was the diagram of displacement change of pile top in pile group foundation under the effects of horizontal-rocking vibration of the centrifuge. Under the vibration load, the vertical displacement of the pile cap in pile group foundation witnesses rapid increase in the first cycle period, while the second cycle period witnesses slower increasing rate, and it tends to be stable in the third cycle period; it can be determined based on the degree of impacts which is imposed by the vibration load on vertical displacement of each foundation pile that the displacement of piles in the center is slightly larger than side piles. Being different from the change trend of vertical displacement, the horizontal displacement of pile top in the group reflects the characteristics of horizontal-rocking vibration load; the trend is shown with a sine curve which shows that the vibration amplitude of horizontal displacement is low in the first cycle, and such vibration amplitude becomes higher in the second and third cycle periods. Thus it can be concluded that the vibration amplitude of both vertical displacement and horizontal displacement is gradually increased based on the effects of horizontal-rocking vibration of the centrifuge, and it approaches a fixed value; the essence is that the effects of vibration load results in plastic deformation of the soil around pile in a certain depth weaken the pile-soil interaction rigidity.

4.2 *Analysis of the force on foundation piles*

Figure 4 was the diagram of force change which is imposed on foundation piles in pile group based on the effects of horizontal-rocking vibration of the centrifuge. As shown in the figure, the horizontal-rocking vibration acted on the main shaft of the centrifuge has less impact on the center foundation piles in the pile group than that on side piles. The vertical load imposed on side piles can be shown with a sine curve, on which the maximum amplitude is 85.6 kN, which is larger than the average vertical load acted on the center pile (50 kN) by approximate 70%; the vertical load borne by the center pile experiences less fluctuation, and it fluctuates with approximately 1% of the average vertical load, higher or lower. The horizontal load acted on side piles and center piles can be shown with a sine curve, in which the horizontal load on side piles is slightly higher than that on center piles, indicating that the horizontal load acted on the foundation piles is redistributed based on the effects of horizontal-rocking vibration.

5 CONCLUSIONS

Based on the background of the construction of geotechnical centrifuge lab, the dynamic response of pile group foundation during large geotechnical centrifuge operation was studied by using finite element software ABAQUS. The main conclusions were summarized as follows:

(1) While the centrifuge is in operation, little change is witnessed on the vertical load which is imposed on the center piles in the pile group, and the vertical displacement of pile top increases gradually; the vertical displacement of pile top will no longer be changed when the duration of horizontal-rocking vibration reaches up to 3 times of vibration period.

(2) The horizontal load acted on the side piles in the pile group foundation can be shown with a sine curve, in which the horizontal displacement amplitude increased gradually, and the amplitude approaches a fixed value when the vibration duration reaches up to 2 times of the vibration period.

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