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Comparison and Analysis of Dynamic Stiffness Tests of Natural Foundation and Pile Foundation under Forced Vibration

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Abstract: The dynamic stiffness test of foundation and pile foundation is also aimed to provide dynamic design parameters of some important equipment foundation under vibration load.Through the dynamic stiffness test of foundation and pile foundation, the working performance of foundation and pile foundation under vibration load is understood, and the necessary dynamic design parameters of foundation and pile foundation are provided. According to the characteristics of continuous or intermittent vibration of soil and pile foundation, the vibration tests of natural foundation and pile foundation are carried out to measure the compressive stiffness, shear stiffness, bending stiffness coefficient, axial vibration damping ratio and horizontal and rotary coupling vibration damping ratio of natural foundation and pile foundation.Combined with the engineering characteristics of the gas-steam combined cycle power station, the gas turbine is a periodic vibration device. Therefore, this paper mainly studies the comparison and analysis of the dynamic stiffness test of natural ground foundation and pile foundation in forced vibration test.

1. Introduction

Dynamic stiffness characteristic parameters of natural foundation and pile foundation are of great significance for engineering and geoscience research under long-term vibration load [1].In this kind of engineering practice, these parameters are the main basis of pile foundation design.In earth science, it is an important index parameter for calculating foundation stress field, foundation deformation and ground tide stress field [4].

2. Dynamic Stiffness Characteristic Parameters of Natural Foundation and Pile Foundation

2.1 Natural Foundation Dynamic Stiffness Test

This paper takes zhejiang petroleum chemical industry co., LTD. Gas - steam combined cycle power plant project as an example, according to the design requirements of the dynamic stiffness test a set of 2 points, determine the scope of the test point site position by design, test points based processing with anchor bar and anchor hole diameter of 100 mm, depth of 1500 mm, reinforced with diameter of 25 (HRB400), quality of the cast-in-place concrete block, the size is 2.0 m * 1.6 m * 1.0 m, C35 fine stone concrete perfusion pressure.The field test was carried out on March 5, 2020 (earlier than the dynamic stiffness test of pile foundation cap). During the test, the instrument worked normally. The forced vibration test was carried out at each measuring point. Figure 1~2 is a schematic diagram of the arrangement of measuring points [2, 3]. In order to obtain the dynamic characteristic parameters of the above foundation, the following tests were carried out:

1) Horizontal and rotary-coupling forced vibration test;

2) Vertical forced vibration test.

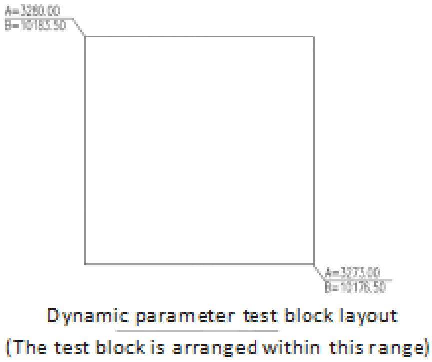

Figure 1: Point Location Layout of Soil Stiffness

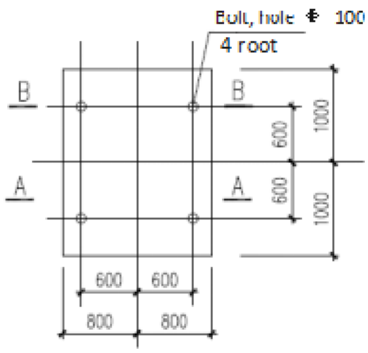

Figure 2: Schematic Diagram of Test Block Layout

2.2 Dynamic Stiffness Test of Pile Foundation Cap

Taking the gas-steam combined cycle power station project of Zhejiang Petrochemical Co., Ltd as an example, according to the design requirements, two double-pile test caps are set in the foundation area of 1# and 3# gas turbine respectively in this dynamic stiffness test. The site location range of test points is determined by design, and the size of pile cap is 4.0m×1.6m×1.2m [5]. Pile foundation adopts perforated cast-in-place pile, pile diameter is 800 mm, bearing layer is weathered tuff, details can be found in this project design document.The field test was carried out from May 26 to 27, 2020. During the test, the instrument worked normally. In order to obtain the dynamic characteristic parameters of the pile foundation mentioned above, the following tests were carried out by referring to the forced vibration test method of natural foundation:

1) Vertical forced vibration test [6];

2) Horizontal and rotary coupling forced vibration test;

3. Setup of Test Instruments and Equipment

3.1 Dynamic Stiffness Test of Natural Foundation Cap

The forced vibration produced by electromagnetic vibrator is used in the test. Data acquisition, recording and analysis are carried out by vibrator, seismograph amplifier and ray recording oscilloscope [7].

In this test, forced vibration is adopted, and electromagnetic exciter is used as vibration source.In order for the excitation force generated by the shaker to be well transmitted to the block, there must be a reliable connection between the shaker and the block.

The vibration picker is installed on the block.In the vertical forced vibration test, two vibration pickers are installed symmetrically vertically to measure the vertical vibration displacement [8]. In the horizontal and rotary coupling free and forced vibration tests, one vibration picker is installed horizontally and two vibration pickers are installed vertically to measure the horizontal vibration displacement and rotation Angle.The excitation frequency is from 10Hz to 80Hz.

The vibration measuring equipment is composed of vibration picker, vibration measuring instrument, CRASV6.2 data acquisition and processing system, microcomputer, printer, etc.

3.2 Dynamic Stiffness Test of Pile Cap

The forced vibration produced by electromagnetic vibrator is adopted in the test. The vibration measuring equipment consists of vibration picker, vibration measuring instrument, CRASV6.2 data acquisition and processing system, microcomputer and so on [9].

In order for the excitation force generated by the shaker to be well transmitted to the block, there must be a reliable connection between the shaker and the block.The vibration picker is installed on the block.In the vertical forced vibration test, two vibration pickers are installed symmetrically vertically to measure the vertical vibration displacement.In the horizontal and rotary coupling free and forced vibration tests, one vibration picker is installed horizontally and two vibration pickers are installed vertically to measure the horizontal vibration displacement and rotation Angle.The excitation frequency starts from 10Hz to 60Hz.

4. Test Method [3]

4.1 Dynamic Stiffness Test of Natural Foundation

The electromagnetic shaker is used as the vibration source.The maximum value of disturbance force is 700N.There must be a reliable connection between the shaker and the cap in order for the exciting force generated by the shaker to be well transmitted to the foundation.

The vibrator is rigidly connected with the top surface of the cap.In the vertical forced vibration test, two vibration pickers are installed symmetrically vertically to measure the vertical vibration displacement.The excitation frequency starts from 12Hz to 80Hz, and the test data is recorded once every 2Hz increase in the excitation frequency.

The vibration measuring equipment is composed of vibration picker, vibration measuring instrument, CRASV6.0 data acquisition and processing system, microcomputer, printer, etc.

4.2 Rayleigh Wave Velocity Test on Foundation

4.2.1 Principle of Method

Rayleigh wave (surface wave) exploration is a new method of geotechnical in-situ testing and exploration.This method uses the correlation between the dispersion characteristics of Rayleigh wave and the physical and mechanical properties of rock and soil to explain many engineering geological problems.Rayleigh wave exploration has been widely used in China and has achieved gratifying results.In 1993, it has been listed as one of the main methods of national engineering exploration.

The point source acting on the semi-infinite space can produce the energy-rich Rayleigh wave, and the vertical component of the Rayleigh wave can be recorded by setting two vertical sensors on the same side of the ground source（Figure.3) .

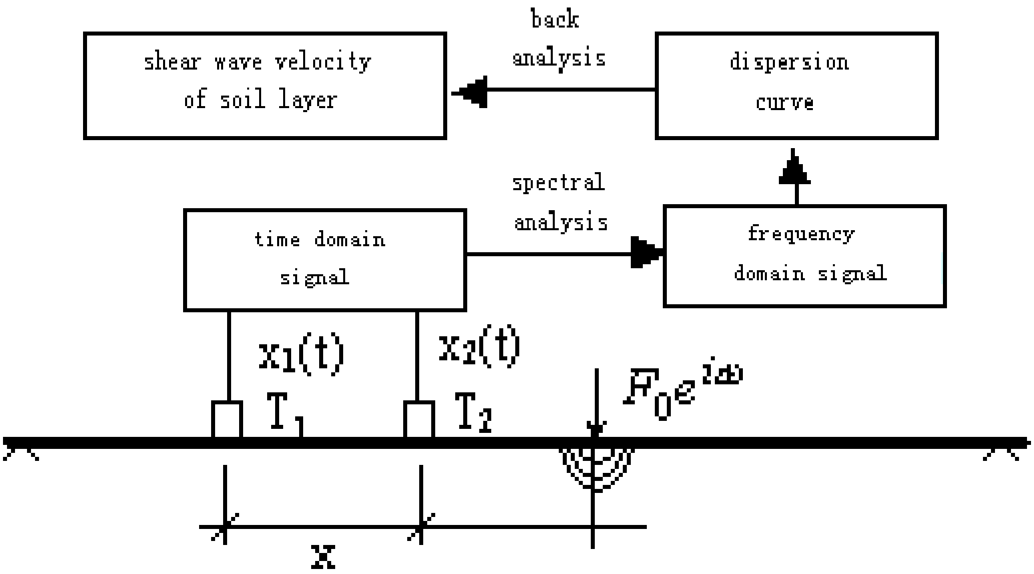

Figure 3: Schematic Diagram of Surface Wave Test

It is convenient to evaluate the signal quality in each frequency band by using coherence function.The coherence function is close to 1 in a certain frequency band, indicating that signal 1 and signal 2 have good correlation in this frequency band.

The Rayleigh wave velocity of the formation between the sensors can be calculated by using the equation below.

$$V_R = \frac{2\pi f \cdot x}{\phi}$$

Type in the V_R --Rayleigh wave velocities in foundations(m/s)

f --The vibration frequency of the source(Hz)

x --Horizontal distance between sensors(m)

ϕ --The phase difference between two signals(rad)

Rayleigh wave velocity can reflect the physical and mechanical properties of the formation with a certain frequency and a depth of half a wavelength.The frequency increases, the wavelength decreases, the survey depth decreases;Frequency goes down, wavelength goes up, depth goes up.Then the relationship between the depth of soil layer and the shear wave velocity is obtained by the reverse analysis method.

4.2.2 Measurement and Analysis Steps

① Method of measurement 1 (steady state method)

1) Select the test site and level it.

2) With the source as the zero point of the survey line, two sensors are arranged on one side of the source.

3) Select the appropriate excitation frequency F, start the shaker, and the sensor receives Rayleigh wave.

4) when two sensors to accept to the vibration wave is differ, showed that two sensors spacing is not equal to Rayleigh wavelength, mobile either detector, makes the collector record waveform in phase, and then under the same frequency, mobile sensors to two wavelengths, three wavelength and so on, the test should be repeated many times, 5 groups commonly can.

4.3 Stiffness Test of Pile Foundation

The dynamic stiffness of pile foundation adopts the hammer free fall as vibration source.Two vibration pickers are symmetrically installed vertically on the surface of the pile cap to measure the vertical vibration displacement on the surface of the pile cap. At the same time, the force and vibration waveform of the pile body at different depths are collected synchronously through the multi-channel signal collector.

The vibration measuring equipment consists of vibration picker, vibration measuring instrument, multi-channel signal collector, CRASV6.0 data acquisition and processing system, computer and so on.

5. Test Results and Analysis [2]

5.1 Data Processing of Foundation Dynamic Stiffness Test Analysis:

According to the Code for Testing Foundation Dynamic Characteristics (GB/T50269-2015) :

1) Experimental data processing of horizontal rotary coupling forced vibration:

① The damping ratio of the first mode of the foundation horizontal reverse steering

$$\xi_{x\varphi 1} = \{\frac{1}{2}[1 - \sqrt{1 + \frac{1}{3 - 4(\frac{A_{ml}}{A})^2}}]\}^{0.5}$$

A_{m1} :Horizontal amplitude of the vibration point of the first vibration type of the foundation horizontal rotary coupling vibration (μm)

A :Horizontal amplitude corresponding to frequency 0.707 f_{m1} (μm)

② Total vibration mass of coupled horizontal rotary vibration of foundation $m_{x\varphi}$

$$m_{x\varphi} = \frac{p(\rho_1 + h_3)(\rho_1 + h_1)}{A_{ml}(2\pi f_{nl})^2} \cdot \frac{1}{2\xi_{x\varphi 1}\sqrt{1 - \xi_{x\varphi 1}{}^2}} \cdot \frac{1}{i^2 + \rho_1{}^2}$$

③ The shear stiffness K_x and bending stiffness of the foundation K_φ

$$k_x = m_{x\varphi}(2\pi f_{nx})^2 , K_\varphi = J(2\pi f_{n\varphi})^2 - k_x h_2{}^2$$

In: $$f_{nl} = \frac{f_{ml}}{\sqrt{1-2\xi_{x\varphi}{}^2}} ; \quad f_{nx} = \frac{f_{nl}}{\sqrt{1-\frac{h_2}{\rho_1}}} ; \quad f_{n\varphi} = \sqrt{\rho_1 \frac{h_2}{i^2} f_{nx}{}^2 + f_{nl}{}^2}$$

$$\rho_1 = \frac{A_x}{\Phi_{ml}} ; A_x = A_{ml} - h_2 \Phi_{ml}$$

f_{nl} : Undamped natural frequency (Hz) of the first mode of coupling vibration of base horizontal rotation(Hz)

f_{ml} : Frequency of basic vibration point (Hz) ; P :Exciting force(kN)

ρ_1: Distance between the rotation center of the first vibration mode of the foundation and the center of gravity of the foundation (m)

h_1 :Height of foundation(m) ; h_2 :distance between center of gravity of foundation and bottom of foundation (m)

h_3 :Distance between the base center of gravity and the horizontal disturbance force of the shaker (m)

i :Rotary radius of foundation(m) ; J :Moment of inertia of foundation pair through its barycenter axis $(t \cdot m^2)$

④The shear stiffness coefficient C_x and bending stiffness coefficient of the foundation C_φ

$$C_x = \frac{K_x}{A_0} , C_\varphi = \frac{K_\varphi}{I}$$

A_0 ::Test base area (m2)

I :Moment of inertia (m4) at the base of the foundation through its centroid axis

According to the field measured data and the above calculation formula, the amplitude and frequency values of horizontal rotary coupling forced vibration of soil are calculated as shown in Fig. 4.The calculated values of horizontal and rotary coupling forced vibration parameters $\xi_{x\varphi 1}$, K_x , K_φ , $m_{x\varphi}$ are shown in Table 1.

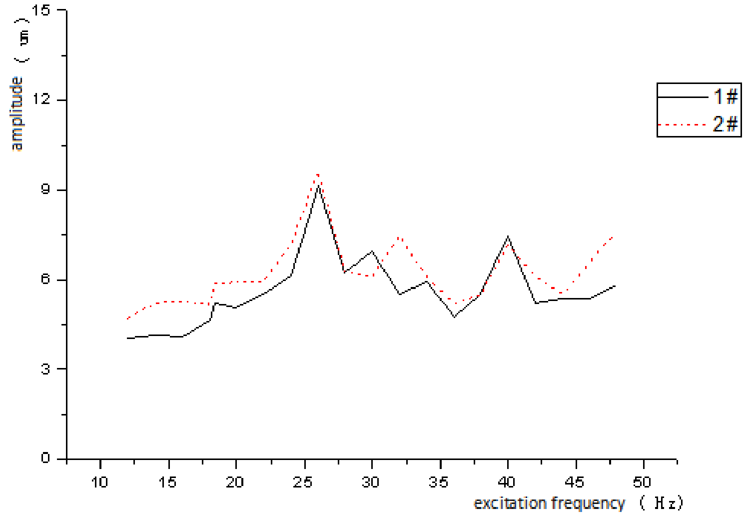

Figure 4: Typical Amplitude - Frequency Curve of Horizontal Forced Vibration of Foundation

Table 1: Forced Vibration Parameters of Horizontal and Rotary

Coupling $\xi_{x\varphi 1}, K_x, K_\varphi, m_{x\varphi}$ *Calculation Table*

place parameter	f_{ml} (Hz)	A_{m1} (μm)	$0.707 f_{ml}$ $(t \cdot rad^2 / s^2)$	A (μm)	$\xi_{x\varphi 1}$	$m_{x\varphi}$ (t)	K_x $(10^3$ kN/m)	K_φ $(10^3$ kN/m)
1#cushion cap	26	9.16	18.38	5.19	0.16	9.19	77.9	270.7
2#cushion cap	26	9.61	18.38	5.87	0.18	7.76	72.8	283.9

2) Vertical forced vibration experimental data processing:

① Base damping ratio ξ_z

$$\xi_z = \frac{\sum_{i=1}^{n} \xi_{zi}}{n}$$

In: $\xi_{zi} = \left[0.5 \left(1 - \sqrt{\frac{\beta_i^2 - 1}{\alpha_i^4 - 2\alpha_i^2 + \beta_i^2}} \right) \right]^{0.5}$; $\alpha_i = \frac{f_i}{f_m}$; $\beta_i = \frac{A_m}{A_i}$

ξ_{zi} :Vertical damping ratio of foundation calculated from point I

f_m :Resonant frequency of vertical vibration of foundation(Hz)

A_m :Resonant amplitude of vertical vibration of foundation (μm)

f_i :Frequency (Hz) of the i-th point on the amplitude-frequency response curve(Hz)

A_i :The amplitude corresponding to the frequency of point I on the amplitude-frequency response curve (μm)

②Compressive stiffness of foundation K_z

$$k_z = \frac{p}{A_m} \cdot \frac{1}{2\xi_z \sqrt{1-\xi_z^{\ 2}}}$$

P:excitation force(kN)

③Compressive stiffness coefficient of foundation C_z

$$C_z = \frac{K_z}{A_0}$$

•④Total vibration mass of vertical vibration of foundation m_z

$$m_z = \frac{P}{A_m (2\pi f_{nz})^2} g \frac{1}{2\zeta_z \sqrt{1-\zeta_z^2}}$$

$$f_{nz} = \frac{f_m}{\sqrt{1-2\zeta_z^2}}$$

According to the field measured data and the above calculation formula, the amplitude and frequency values of vertical forced vibration are calculated as shown in Fig. 5 The calculation values of vertical forced vibration parameters ξ_z, K_z, m_z are shown in Table 2.

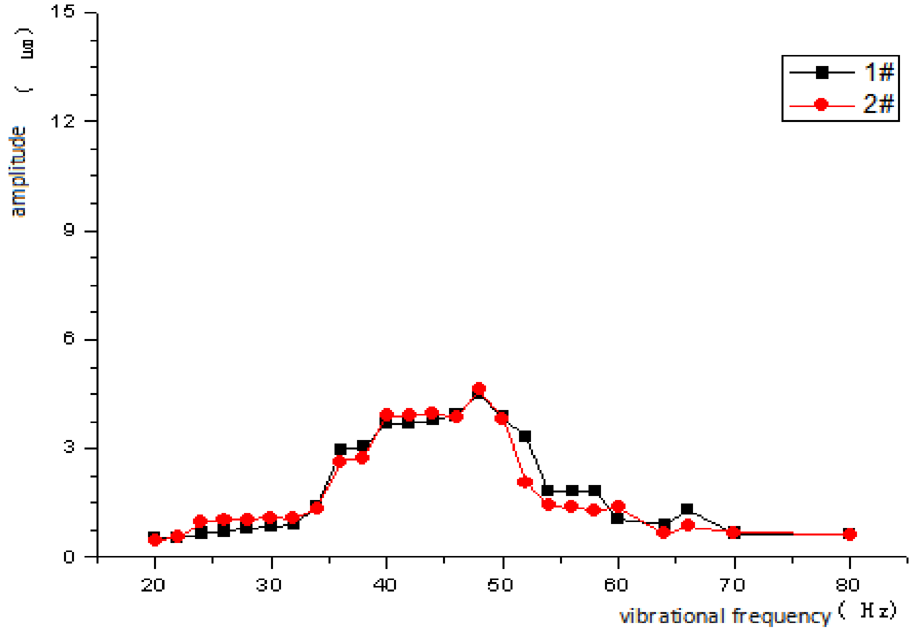

Figure 5: Amplitude-Frequency Curve of Vertical Forced Vibration of Soil

Table 2: Vertical Forced Vibration Parameters ξ_z , K_z , m_z , Calculation Table

place parameter	f_m (Hz)	A_m (μm)	f_1 (Hz)	A_1 (μm)	f_2 (Hz)	A_2 (μm)	f_3 (Hz)	A_3 (μm)	ξ_z	K_z (10^3 kN/m)	m_z (t)
1#	48	4.51	36	2.97	34	1.41	24	0.67	0.106	2306	6.20
2#	48	4.63	36	2.63	32	1.34	26	0.96	0.101	2361	6.36

3) Experimental data processing of horizontal torsional forced vibration:

① Torsional damping ratio of foundation ζ_ψ

$$\zeta_\psi = \left\{ 0.5 \left[1 - \sqrt{1 + \frac{1}{3 - 4\left(\frac{A_{m\psi}}{A_{x\psi}}\right)^2}} \right] \right\}^{\frac{1}{2}}$$

$A_{m\psi}$:Horizontal amplitude of vibration point of first mode of coupled horizontal rotary vibration of foundatio(m)

$A_{x\psi}$: Horizontal amplitude corresponding to frequency 0.707 $A_{m\psi}$ (m)

② Total mass of foundation torsional vibration parameter m_ψ

$$m_\psi = \frac{12 J_t}{l^2 + b^2}$$

In: $J_t = \frac{M_\psi \bullet l_\psi}{A_{m\psi} \bullet \omega_{m\psi}^2} \bullet \frac{1 - 2\zeta_\psi^2}{2\zeta_\psi \sqrt{1 - \zeta_\psi^2}}$; $\omega_{m\psi} = 2\pi f_{m\psi}$

$$f_{n\psi} = f_{m\psi}\sqrt{1 - 2\zeta_\psi^2}$$

③Torsional stiffness of foundation K_ψ

$$K_\psi = J_t \bullet \omega_{m\psi}^2$$

④Torsional stiffness coefficient of the foundation C_ψ

$$C_\psi = \frac{K_\psi}{I_t}$$

According to the field measured data and the above calculation formula, amplitude and frequency values of foundation torsional vibration are calculated as Figure 6;The calculated values of torsional forced vibration parameters ζ_ψ, m_ψ, K_ψ are shown in Table 3.

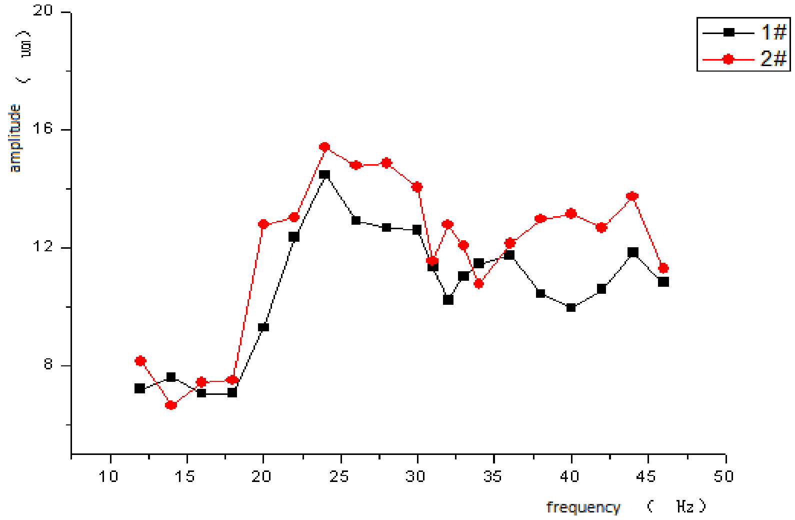

Figure 6: Typical Amplitude - Frequency Curve of Torsional Forced Vibration of Foundation

Table 3: Forced Vibration Parameters of Horizontal and Rotary Coupling ζ_ψ, m_ψ, K_ψ and Calculation Table

place parameter	$f_{m\psi}$ (Hz)	$A_{m\psi}$ (μm)	$0.707 f_{m\psi}$ ($t \cdot rad^2 / s^2$)	$A_{x\psi}$ (μm)	ζ_ψ	m_ψ (t)	K_ψ (10^3 kN/m)	C_ψ (10^3 kN/m^3)
1#cushion cap	24	14.47	16.97	7.05	0.136	0.828	99	74.3
2#cushion cap	24	15.40	16.97	7.47	0.135	0.782	94	70.2

5.2 Data Processing of Pile Foundation Dynamic Stiffness Test Analysis:

According to the Code for Testing Foundation Dynamic Characteristics (GB/T50269-2015) :
1) Vertical forced vibration experimental data processing:

① Base damping ratio ξ_z (Same as the test formula for dynamic stiffness of foundation)

② Total vibration mass of vertical vibration of foundation m_z ,(Same as the test formula for dynamic stiffness of foundation)

③ Compressive stiffness of pile foundation K_z (Same as the test formula for dynamic stiffness of foundation)

④ Compressive stiffness coefficient of foundation C_z (Same as the test formula for dynamic stiffness of foundation)

According to the field measured data and the above calculation formula, the amplitude and frequency values of vertical forced vibration are calculated as shown in Figure 7~8.The calculation values of vertical forced vibration parameters ξ_z, K_z, m_z are shown in Table 4.

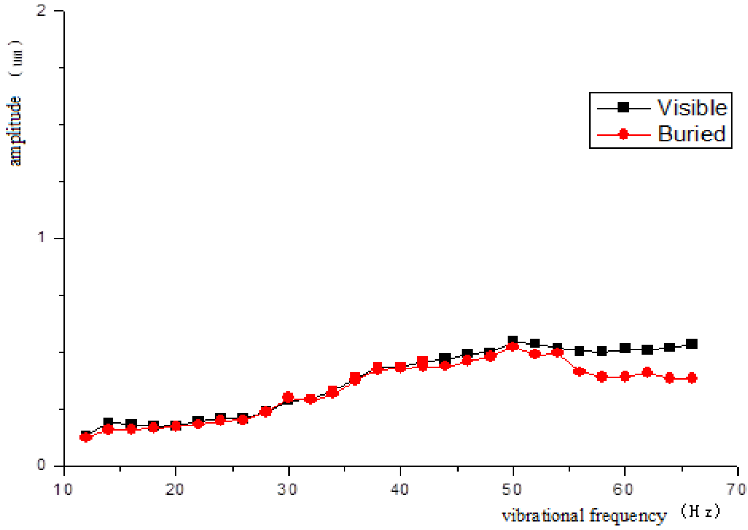

Figure 7: Amplitude Frequency Curve of Vertical Forced Vibration of Open and Buried Gas Turbine Cap

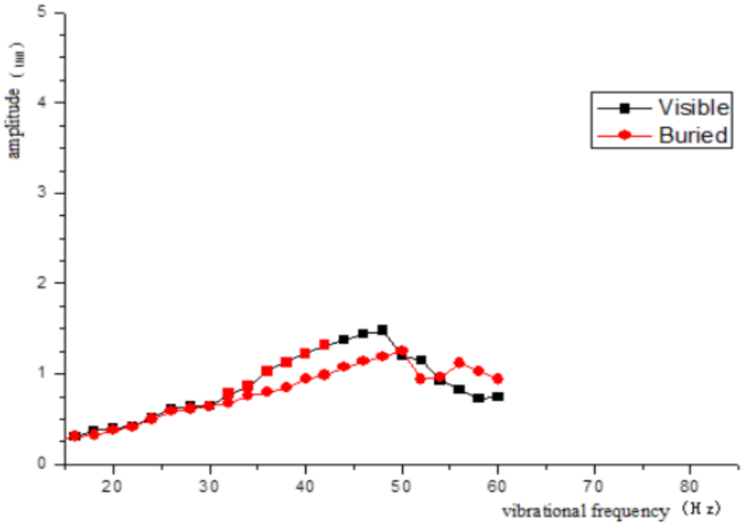

Figure 8: Amplitude and Frequency Curve of Vertical Forced Vibration of Open and Buried Gas Turbine Cap Platform No.3

Table 4: Vertical Forced Vibration Parameters of Cap ξ_z , K_z and m_z

place parameter		f_m (Hz)	d_m (μm)	f_1 (Hz)	d_1 (μm)	f_2 (Hz)	d_2 (μm)	f_3 (Hz)	d_3 (μm)	ξ_z	K_z (10^3 kN/m)	m_z (t)
1#gas turbine	Visible arrangement	50	0.54	40	0.44	36	0.33	24	0.21	0.189	2001	4.71
	Visible arrangement	50	0.52	46	0.46	36	0.37	30	0.30	0.192	2038	4.78
3#gas turbine	Visible arrangement	48	1.48	38	1.12	34	0.86	24	0.51	0.169	812	2.10
	Visible arrangement	50	1.25	46	1.14	36	0.79	30	0.64	0.177	918	2.18

2) Experimental data processing of horizontal rotary coupling forced vibration:

① Damping ratio of the first mode of horizontal reverse steering of foundation $\zeta_{x\varphi1}$ (same as test formula for dynamic stiffness of foundation)

② The total vibration mass of coupled horizontal rotary vibration of foundation $m_{x\varphi}$ (same as the test formula for dynamic stiffness of foundation)

③ Shear stiffness K_x and bending stiffness of foundation K_φ (same as test formula for dynamic stiffness of foundation)

④The shear stiffness coefficient C_x and bending stiffness coefficient of foundation C_φ (same as the test formula for dynamic stiffness of foundation)

According to the field measured data and the above calculation formula, the amplitude and frequency values of the horizontal rotary coupling forced vibration of the pile foundation were calculated as shown in Figure 9~10.The calculated values of horizontal and rotary coupling forced vibration parameters $\xi_{x\varphi1}$, K_x, K_φ, $m_{x\varphi}$ are shown in Table 5.

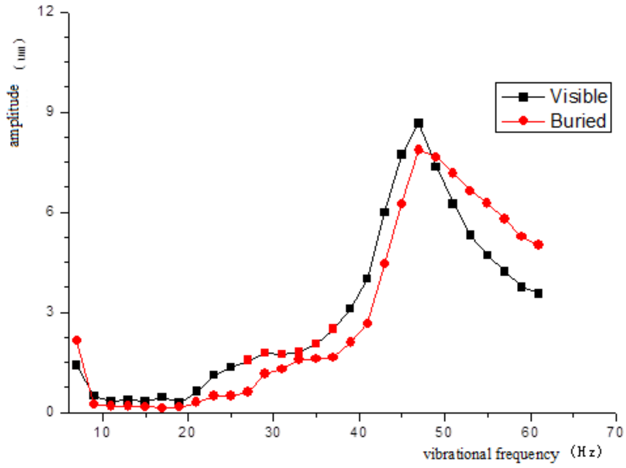

Figure 9: Typical Amplitude and Frequency Curves of Open and Embedded Horizontal Forced Vibration of Gas Turbine Cap Platform 1#

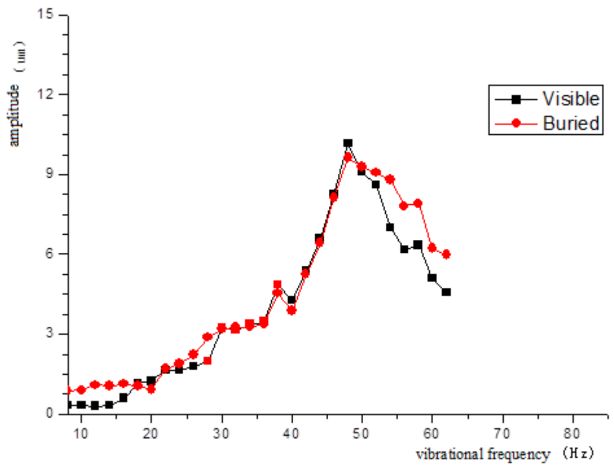

Figure 10: Typical Amplitude and Frequency Curves of Open and Embedded Horizontal Forced

Vibration of Gas Turbine Cap 3#

Table 5: Forced Vibration Parameters of Horizontal and Rotary Coupling,,, Calculation Table

place / parameter		f_{ml} (Hz)	d_{m1} (μm)	$0.707 f_{ml}$ ($t \cdot rad^2 / s^2$)	d (μm)	$\xi_{x\varphi 1}$	$m_{x\varphi}$ (t)	K_x (10^3kN/m)	K_φ (10^3kN/m)
1#gas turbine	Visible arrangement	47	8.65	33.23	1.85	0.05	1.40	162	10121
	Visible arrangement	47	7.85	33.23	1.59	0.05	1.63	190	10050
3#gas turbine	Visible arrangement	48	10.16	33.94	3.36	0.09	0.71	88	10505
	Visible arrangement	48	9.63	33.94	3.26	0.09	0.73	80	10596

5.3 Test Results

5.3.1 According to the Measured Data and the Above Calculation, the Test Results of Foundation Dynamic Stiffness Are Shown in Table 6.

Table 6: Results of Forced Vibration Test

C_z (kN/m^3)	m_z (t)	ζ_z	C_x (kN/m^3)	C_φ (kN/m^3)	$m_{x\varphi}$ (t)	$\zeta_{x\varphi 1}$	C_ψ (kN/m^3)	m_ψ (t)	ζ_ψ
72077	6.20	0.106	24351	253754	9.19	0.16	74300	0.828	0.136
73772	6.36	0.101	22739	266155	7.76	0.18	70200	0.782	0.135

5.3.2 According to the Measured Data and the Above Calculation, the Dynamic Stiffness Test Results of Pile Foundation Are Shown in Table 7.

Table 7: Results of Forced Vibration Test

location		C_z (kN/m^3)	m_z (t)	ζ_z	C_x (kN/m^3)	C_φ (kN/m^3)	$m_{x\varphi}$ (t)	$\zeta_{x\varphi 1}$
1#gas turbine	Visible arrangement	31259	4.71	0.189	2533	118609	1.40	0.05
	Visible arrangement	31845	4.78	0.192	2973	117769	1.63	0.05
3#gas turbine	Visible arrangement	12688	2.10	0.169	1381	123102	0.71	0.09
	Visible arrangement	14350	2.18	0.177	1410	124171	0.73	0.09

6. Conclusion

The test blocks used in the two tests studied in this paper are all cast-in-place concrete blocks, and two methods of horizontal rotary coupling forced vibration and vertical forced vibration are adopted for the analysis (the data of foundation torsional forced vibration is abandoned due to the limitation of test conditions) [7].Table 8 is obtained by analyzing the test data.

The SPSS analysis shows that the compressive stiffness coefficient C_z , shear stiffness coefficient C_x, bending stiffness coefficient C_φ, damping ratio of the first mode of horizontal reverse steering $\xi_{x\varphi 1}$, the total mass of vertical vibration m_z and the total mass of horizontal rotary coupling vibration of foundation $m_{x\varphi}$ are less than those of the foundation.The damping ratio of foundation ξ_z is higher than that of foundation.

Table 8: Suggested Value Table and Comparative Value of Dynamic Stiffness Test Results

Name of Parameter	Signs and Units	Location	Numerical Value	Comparison Value	Sketch
Compressive stiffness coefficient	C_z kN/m^3	The natural foundation	72924	1	
		1#gas turbine	31552	43.27%	decrease
		3#gas turbine	13519	18.54%	decrease
Damping ratio	ζ_z	The natural foundation	0.104	1	
		1#gas turbine	0.19	182.69%	increase
		3#gas turbine	0.17	163.46%	increase
Shear stiffness coefficient	C_x kN/m^3	The natural foundation	23545	1	
		1#gas turbine	2753	11.69%	decrease
		3#gas turbine	1400	5.95%	decrease
Flexural stiffness coefficient	C_φ kN/m^3	The natural foundation	259955	1	
		1#gas turbine	118189	45.47%	decrease
		3#gas turbine	123637	47.56%	decrease
The damping ratio of the first mode of horizontal reverse steering	$\zeta_{x\varphi 1}$	The natural foundation	0.17	1	
		1#gas turbine	0.05	29.41%	decrease
		3#gas turbine	0.09	52.94%	decrease
Total mass of vertical vibration	m_z t	The natural foundation	6.28	1	
		1#gas turbine	4.75	75.64%	decrease
		3#gas turbine	2.14	34.08%	decrease
Total mass of horizontal rotary coupling parameter	$m_{x\varphi}$ t	The natural foundation	8.48	1	
		1#gas turbine	1.52	17.92%	decrease
		3#gas turbine	0.72	8.49%	decrease

In this paper, the experimental study of forced vibration of foundation is carried out by using a certain volume of concrete block as the mass. The experimental conditions are different from the working conditions of foundation cap in actual engineering.In addition, the backfilled downslag thickness (7~11m), uniformity, particle size and other differences are relatively large in the forced vibration test area of foundation bearing platform. At the same time, the test pile adopts perforated cast-in-place pile, and the actual pore shape and theoretical value of the test pile in the downslag layer will be different to some extent, which makes the test data have a certain discretization.

There are certain differences in various working conditions of foundation and foundation cap in this kind of test conditions and foundation cap in actual engineering, so each unit should select the parameters according to the actual situation of the project.At the same time, the proportion of vibration mass of soil is larger than the mass of foundation itself, which cannot be ignored. Therefore, how to value it is worth further study [1].

References

[1] Wang L, Lv JQ, Zhu WJ & Zheng S M. (2011). Measurement and analysis of forced vibration of natural foundation.Geodesy and geodynamics (02) 84-88.

[2] The National Standards Compilation Group of People's Republic of China. Measurement method of dynamic properties of subsoil(GB/T50269-2015)[S]. Beijing:China Architecture and Construction Press,2015 Building Press,2015)
[3] Zhi, L.Y. & Zhi, L.Y. (2018). Experimental study of different types of vibration shakers in ground dynamic testing.Construction Technology (S4),18-21.
[4] Sun, Y.L., Sun, G.J., & Huang, Q. (2014). Research on vertical forced vibration of natural foundation: A case study of vibration test engineering.Journal of Changchun Institute of Technology (Natural Science Edition)(01),13-17.
[5] Liang Feng. (2009). The flow pipe transverse vibration mechanism and control research (Ph.D. Dissertation, Northeastern University).https://kns.cnki.net/KCMS/detail/detail.aspx?dbname=CDFD0911&filename =2010055585. nh
[6] Ge, L., Shen, H., Lin, Z., (2002). Forced vibration of symmetrically cross-laid laminated plates on elastic foundation.Journal of Shanghai jiaotong university (11), 1634-1639 + 1648.
[7] Song L & Zhang J Y. (1997). Solution to the problem of circular thin plate vibration on elastic foundation.Metal Forming Technology (04),34-38+56. Doi.
[8] Liang Fayun,Li Tongda,Qian Yu,Wang Chen & Jia Yajie.(2021).Investigating the seismic isolation effect of the cushioned pile raft foundation in soft clay through dynamic centrifuge tests. Soil Dynamics and Earthquake Engineering.
[9] Gui Lin Sheng,,Cai Li Su & De Hui Liu.(2013).Analysis of Dynamic Performance of Rigid Pile Composite Foundation. Applied Mechanics and Materials.