Journal of World Architecture, 2026, Volume 10, Issue 1
https://ojs.bbwpublisher.com/index.php/JWA
Online ISSN: 2208-3499
Print ISSN: 2208-3480

Research on Several Issues of Pile Foundations for Dynamic Machinery in Soft Soil Areas

Qing Chen

MCC CISDI Shanghai Engineering Co., Ltd., Shanghai 200940, China

Abstract: The selection of foundation dynamic characteristic parameters is one of the difficulties in the design of dynamic machinery foundations, and the pile foundations for dynamic machinery in soft soil areas have certain particularities. Taking the research on the vibration problem of a dryer foundation in Shanghai as an example, this paper discusses several key issues in the design of pile foundations for dynamic machinery in soft soil areas. Suggestions are put forward for the selection of key parameters, such as vertical compressive stiffness and shear stiffness of pile foundations, as well as for the design of such pile foundations in soft soil areas, which can provide reference for similar engineering designs and research.

Keywords: Foundation dynamic characteristic parameters; Soft soil areas; Foundation vibration

Online publication: March 11, 2026

1. Introduction

In industrial building design, from metallurgy, machinery manufacturing to energy and power generation, from large-tonnage dynamic equipment to precision processing equipment, the vibration control requirements for dynamic machinery foundation design are increasingly higher. The design of dynamic machinery foundations is a specialized and complex work involving two disciplines: civil engineering and mechanical engineering.

China's current *Standard for Design of Dynamic Machine Foundation* (hereinafter referred to as the "Dynamic Code") describes vibration based on the mass-spring-damper theoretical system, and the calculation model of this system is shown in **Figure 1** [1]. This theoretical system focuses on three dynamic parameters: vibrating mass (W), spring stiffness (K), and damping (C). However, there are numerous factors affecting these three parameters, and China's "Dynamic Code" has not well solved the impact of these factors [2–8]. Especially in the design of pile foundations for dynamic machinery in soft soil areas, blindly adopting the recommended values in the code may lead to results completely inconsistent with reality. Taking the research on the vibration problem of a dryer foundation in Shanghai as an example, this paper discusses several issues in the design of pile foundations for dynamic machinery in soft soil areas, which can provide a reference for similar engineering designs and research.

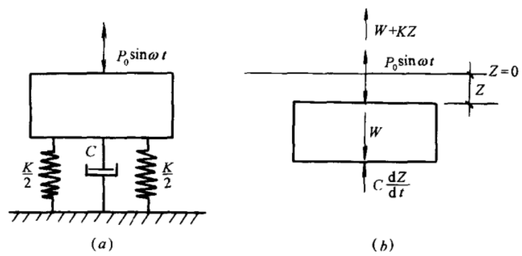

Figure 1. Computational model of damped forced vibration for single-degree-of-freedom system.

2. Project overview

2.1. Equipment data

A coal drying room in Shanghai is equipped with 3 coal dryers, all of which are imported from foreign countries with the same performance. The coal dryers are placed on the top surface of the foundation at an elevation of 4.107 m. The net weight of a single equipment is 36t. A total of 44 springs are installed between the equipment and the foundation, with an angle of 35 degrees between the springs and the horizontal plane. Under normal working conditions, the equipment performs harmonic reciprocating motion driven by the motor, generating both vertical and horizontal exciting forces (along the length direction of the foundation group) on the foundation. The rotational speed of the motor is 528r/min, the double amplitude of the springs is 12.7 mm, and the stiffness of each spring is 1646.9N/mm.

2.2. Foundation design

The foundation of the coal dryer is a wall-type foundation, supported by 14 PHC400 pipe piles with a length of 45 m, and the characteristic value of the single pile bearing capacity is 1150kN. The spacing of the pipe piles in the direction of the horizontal exciting force is 2699 mm, and the spacing in the vertical direction is 1880 mm. The total length of the foundation is 17.193 m, the width is 2.88 m, the elevation of the foundation cap bottom is -1.300 m, the elevation of the wall top is 4.107 m, and the buried depth is 1.750 m. The cross-sectional and longitudinal-sectional views of the coal dryer foundation are shown in **Figure 2** and **Figure 3**.

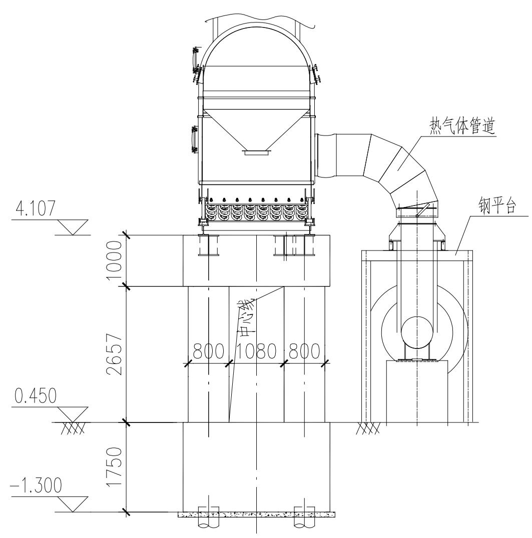

Figure 2. Cross-sectional view of coal dryer foundation.

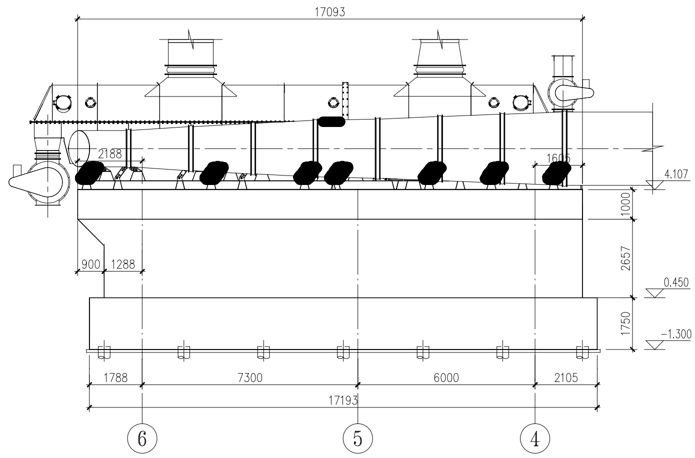

Figure 3. Longitudinal-sectional view of coal dryer foundation.

2.3. Soil layer performance parameters

The project site is located in the Yangtze River Delta alluvial plain, a typical soft soil area. The physical and mechanical property parameters of each soil layer are shown in **Table 1**.

Table 1. Physical and mechanical property parameter table of soil layers

Soil layer No.	Soil layer name	Compression modulus $E_{S0.1\text{-}0.2}$ /MPa	Characteristic value of subsoil bearing capacity f_{ak}/kPa
②	Silty clay	5.0	90
$③_2$	Sandy silt	8.0	80
$③_3$	Mucky silty clay	3.5	65
④	Mucky clay	2.5	-
$⑤_1$	Silty clay	5.0	-
$⑤_3$	Silty clay	5.5	-

The pile foundation bearing layer is the $⑤_3$ silty clay, which is a medium-compressibility foundation soil with slightly higher strength.

3. Foundation vibration exceedance problem

The owner reported that since the commissioning of the coal dryer, the vibration during operation has been relatively large, causing vibration of the adjacent hot gas generator and its pipeline support steel structure, affecting normal production. The owner entrusted a professional testing company to conduct vibration testing on the coal dryer, its foundation, and the hot gas generator foundation. The basic results are as follows: under normal working conditions, the vibration along the length direction of the coal dryer is the largest, and the horizontal longitudinal vibration velocities of the equipment itself, the top surface of the equipment foundation, and the hot gas generator foundation reach 15.83 mm/s, 13.73 mm/s, and 4.14 mm/s respectively. The layout of measuring points on the coal dryer itself is shown in **Figure 4.** The vibration test results (including vibration velocity, amplitude, etc.) of each point are shown in **Table 2**. It can be seen that the vibration velocity and amplitude of the unit have exceeded the limit values.

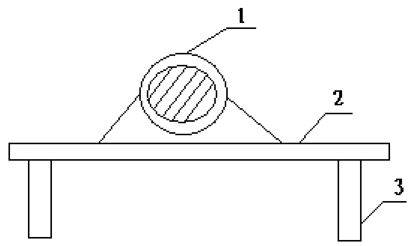

Figure 4. Layout of measuring points.

Table 2. Test data results [7]

Measuring point	Vibration direction	Vibration velocity / mm/s	Vibration velocity limit /mm/s	Amplitude /μm	Amplitude limit /μm
Crankshaft bearing seat	Vertical	7.34	12.6	-	-
	Horizontal longitudinal	15.83	12.6	-	-
	Horizontal transverse	5.52	12.6	-	-
Top surface of foundation	Vertical	4.84	12.6	483	228
	Horizontal longitudinal	13.73	12.6	733	228
	Horizontal transverse	2.72	12.6	165	228
Bottom of wall	Vertical	3.75	12.6	-	-
	Horizontal longitudinal	13.08	12.6	667	228
	Horizontal transverse	1.29	12.6	94	228

4. Checking calculation of foundation dynamic characteristics

4.1. Calculation of exciting force

The total exciting force of the coal dryer can be calculated by the following formula:

$$\begin{aligned} P &= AK \\ &= 12.7\ \text{mm} \times 0.5 \times 1646.9\ \text{N/ mm} \times 44 \\ &= 4.601 \times 10^5\ \text{N} \end{aligned} \tag{1}$$

The supporting springs form an angle of 35 degrees with the horizontal plane, so the total exciting force can be decomposed into vertical and horizontal exciting forces:

$$P_Z = P_{sin}(35°) = 2.639 \times 10^5\ N \tag{2}$$

$$P_x = P_{cos}(35°) = 3.769 \times 10^5\ N \tag{3}$$

According to the rotational speed of the motor, the circular frequency of the unit vibration is (unit: rad/s):

$$\omega = 2\pi \times \frac{528}{60} = 55.292 \tag{4}$$

Therefore, the relationship between the exciting force of the unit and time can be written as a harmonic function (unit: kN):

Vertical exciting force:

$$P_z(t) = 263.9\, sin(55.292t) \quad (5)$$

Horizontal exciting force:

$$P_x(t) = 376.9\, sin(55.292t) \quad (6)$$

4.2. Selection of foundation dynamic characteristic parameters

According to the *Standard for Design of Dynamic Machine Foundation*, the foundation dynamic characteristic parameters can be determined by on-site tests. However, this project has been put into operation, and on-site tests cannot be carried out, so it is necessary to select them according to the actual situation of the project.

4.2.1. Vertical compressive stiffness of pile foundation

China's "Dynamic Code" adopts the design theory of rigid piles. However, some studies have pointed out that the vertical compressive stiffness of pile foundations calculated considering the elastic deformation of the piles themselves is more in line with reality [9,10]. To better reflect the actual situation, the vertical compressive stiffness of the pile foundation in this project is proposed to be calculated by the following formula [2]:

$$k_{pz} = \varepsilon(k_\tau + k_s) \quad (7)$$

Where k_{pz}: Vertical compressive stiffness of the pile foundation (kN/m); k_s: Compressive stiffness of the soil at the pile tip (kN/m); ε: Consider the interaction between the pile and the soil, the elastic influence coefficient of the pile; k_τ: Shear stiffness between the pile and the soil around the pile (kN/m).

4.2.2. Shear stiffness of pile foundation

According to Article 3.4.17 of the "Dynamic Code", the shear stiffness of the pile foundation can be taken as 1.4 times the shear stiffness of the corresponding natural foundation. This regulation is relatively general and does not consider the influence of the properties of the soil at the bottom of the cap, pile type, number of piles, pile spacing, etc. Relevant studies have pointed out that when the cap is not separated from the underlying soil, the shear stiffness of the pile foundation is the parallel action of the pile-soil shear stiffness and the shear stiffness of the soil at the bottom of the cap, namely [5]:

$$k_{px} = k_{pile} \times k_{soil} \quad (8)$$

This calculation method can better reflect the actual situation, so the shear stiffness of the pile foundation in this project is proposed to be calculated by the above formula.

Considering that the backfill quality around the foundation of this project is difficult to meet the requirements of the "Dynamic Code", the shear stiffness of the pile foundation does not temporarily consider the improvement effect of the foundation burial depth.

4.2.3. Other parameters

Other parameters are selected with reference to the "Dynamic Code".

4.3. Results of foundation dynamic characteristics calculation and analysis

The checking calculation of the foundation dynamic characteristics is carried out using the finite element software SAP2000, and the calculation model is shown in **Figure 5**. The model adopts solid elements with a minimum element size of approximately 0.5 m. The model performs time-history analysis according to the harmonic functions of the exciting forces (**Equation 5** and **Equation 6**), and the dynamic responses of each node of the foundation group are obtained through calculation.

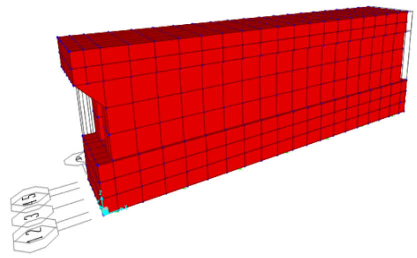

Figure 5. SAP2000 computational model.

According to the calculation results, the first mode of the foundation group is in the X direction (horizontal exciting force direction), and the second mode is in the Z direction (vertical direction). The natural frequencies of the foundation group and the vibration velocity of the top surface of the foundation are shown in **Table 3**. It can be seen from the table that the first natural frequency of the foundation group is less than the vibration frequency of the equipment, indicating that the stiffness of the foundation in the horizontal direction is weak, leading to excessive vibration in the horizontal direction. The second natural frequency of the foundation group is more than 40% higher than the vibration frequency of the equipment, and the vertical vibration of the foundation group is relatively small. At the same time, the calculated vibration velocity of the top surface of the foundation is relatively close to the measured value, indicating that the selection of calculation parameters is relatively reliable.

Table 3. Calculation results

Calculation item	Calculated value	Measured value
First natural frequency of foundation group f_1 /Hz	5.32	-
Second natural frequency of foundation group f_2 /Hz	12.55	-
Vibration frequency of coal dryer f_0 /Hz	8.8	-
Vibration frequency ratio f_1/f_0	0.60	-
Vibration frequency ratio f_2/f_0	1.43	-
Horizontal vibration velocity of foundation top surface /mm/s	16.1	13.73
Vertical vibration velocity of foundation top surface /mm/s	5.2	4.84

In summary, the dominant vibration direction of the foundation group is the horizontal direction, and the main reason for the excessive horizontal vibration of the foundation group is the weak shear stiffness of the foundation in the horizontal direction.

5. Discussion on relevant issues in the design of pile foundations for dynamic machinery in soft soil areas

5.1. Vertical compressive stiffness of pile foundations

When calculating the vertical stiffness of pile foundations, China's "Dynamic Code" adopts the assumption of rigid piles, and the vertical stiffness increases proportionally with the increase of pile length. Relevant experiments have shown that the compressive stiffness of pile foundations increases to a certain extent with the increase of pile length, but not proportionally with the pile length (L) [3]. From the test data, under dynamic loads, the pile itself deforms, especially when the soil quality is poor and the slenderness ratio of the pile is large, the deformation of the pile body cannot be ignored. For example, in this project, the thickness of the soft soil layer is relatively large, and the pile length reaches 45 m. In this case, the influence of pile body deformation on the pile foundation stiffness should be considered.

Equation 7 gives the calculation formula for compressive stiffness considering the deformation of the pile itself. Its basic assumptions are: the pile is vertical and elastic; the surface of the pile is in close contact with the soil; the soil around the pile is a linear elastic body composed of infinite thin layers. In this project, if calculated according to the "Dynamic Code", the vertical compressive stiffness of a single pile is Kz = 6.39e8N/m, which is 1.8 times the compressive stiffness calculated considering the elastic pile (Kz = 3.544e8N/m), showing a significant difference. Therefore, it is worth noting that the dynamic response calculated by the "Dynamic Code" for the vertical compressive stiffness of pile foundations may be smaller than the actual value. Based on the experience of this project, it is recommended to calculate the vertical compressive stiffness of pile foundations according to **Equation 7**.

5.2. Shear stiffness of pile foundations

When calculating the shear stiffness of pile foundations, China's "Dynamic Code" generally takes the shear stiffness as 1.4 times the shear stiffness of the corresponding natural foundation. This method is conditional, i.e., the soil at the bottom of the cap must not be separated from the cap. In fact, 1.4 times is also an empirical value, and some documents take this value as 1.2 times. Simply taking the shear stiffness as a multiple of the shear stiffness of the natural foundation is theoretically questionable, as it completely ignores the influence of factors such as the properties of the soil at the bottom of the cap, pile type, number of piles, and pile layout. In soft soil areas, it is easy for the soil at the bottom of the cap to separate from the cap. At this time, using the "Dynamic Code" for calculation may lead to inaccurate results.

In response to the above situation, some studies have given the calculation method for the shear stiffness of vertical pile foundations [8,9]. This calculation method considers two cases: no pile cap or the pile cap is separated from the underlying soil, and the pile cap is not separated from the underlying soil. In the case of separation, only the shear stiffness of the pile itself is considered; in the case of non-separation, both the shear stiffness of the pile itself and the shear stiffness of the soil are considered.

In this project, if the separation between the cap and the underlying soil is considered, the calculated shear stiffness of the pile foundation is Kx = 9.29e6N/m, which is almost an order of magnitude smaller than the shear stiffness calculated without separation (Kx = 5.385e7N/m). At the same time, in the case of non-separation, the calculated shear stiffness of the pile foundation is about 1.21 times higher than that of the natural foundation, which is also smaller than the value specified in the "Dynamic Code".

5.3. Design suggestions for dynamic machinery foundations

A typical feature of coal dryer foundations is that both horizontal and vertical exciting forces are large, and they are harmonic vibrations. In metallurgical structure design, the vibration modes of machinery, such as horizontal vibrating screens and crushers are similar to this. When pile foundations are used in soft soil areas, the vertical stiffness of the foundation is generally easy to meet, and the key lies in improving the horizontal shear stiffness of the foundation. To improve the horizontal shear stiffness of pile foundations, the following measures are recommended:

(1) Increase the pile diameter, number of piles, etc., to improve the stiffness of the piles themselves. Since the shear stiffness of vertical piles mainly depends on the properties of the soil in the upper part of the foundation piles, replacement or reinforcement of the soil in the upper part of the foundation piles can be considered in soft soil areas. If the treated foundation itself can meet the vertical bearing capacity requirements, the treated foundation can be directly used instead of pile foundations;

(2) Inclined pile foundations can be considered in soft soil areas: Increase the foundation burial depth to improve the constraint effect of the soil around the foundation; Take measures to ensure the compaction quality of the backfill around the foundation as much as possible; Set reinforced concrete rigid floors around the foundation to improve the constraint effect of the floor on the foundation.

6. Conclusion

In the design and calculation of dynamic machinery foundations, the accuracy of the selection of foundation dynamic characteristic parameters is directly related to the success of the design of dynamic machinery foundations. Generally, under the condition that the applicable conditions of the national "Dynamic Code" are met, the foundation dynamic characteristic parameters can be conservatively selected according to the code. However, pile foundations in soft soil areas have their particularities, especially the compressive stiffness and shear stiffness of pile foundations, which need to be calculated according to the actual situation, and tests are necessary if conditions permit. When designing dynamic machinery foundations dominated by horizontal exciting forces in soft soil areas, special attention should be paid to whether the shear stiffness of the pile foundation meets the requirements. If necessary, the shear stiffness of the pile foundation can be improved by increasing the pile diameter and number of piles, adopting inclined piles, reinforcing the soil around the piles, etc., to meet the horizontal vibration resistance needs.

Disclosure statement

The author declares no conflict of interest.

References

[1] Ministry of Housing and Urban-Rural Development of the People's Republic of China, 2020, Standard for Design of Dynamic Machine Foundation: GB50040-2020, China Planning Press, Beijing.

[2] Ba Z, Fu Z, Han Q, et al., 2023, Concept, Theory and Application of Vibrating Mass for Large Complex Dynamic Machinery Foundations. Journal of Earthquake Engineering and Engineering Vibration, 43(3): 56–68.

[3] Yan W, 2022, Dynamic Stiffness Test and Analysis of PHC Piles in Soft Soil Areas. Electric Power Survey & Design, 2022(4): 71–76.

[4] Chen L, Tan Z, Qiu J, 2020, Analysis of the Influence of Pile Dynamic Stiffness on Low-Arranged Gas Turbine Foundations. Electric Power Survey & Design, 2020(6): 32–37.

[5] Xuan Y, Wei Q, 2020, Discussion on the Application of m-Method Linear Finite Element to Simulate Pile Stiffness.

Building Materials & Decoration, 2020(7): 258–259.

[6] Ministry of Housing and Urban-Rural Development of the People's Republic of China, 2015, Code for Testing Dynamic Properties of Foundations: GB/T50269-2015, China Planning Press, Beijing.

[7] Shanghai Baosteel Industrial Testing Co., Ltd., 2020, Coal Dryer Test Report.

[8] Liu W, 2020, Comparison of Calculations for Dynamic Equipment Foundations Between Chinese and European Codes. Science and Technology Innovation Herald, 17(14): 101–102.

[9] Yao L, 2020. Numerical Calculation Analysis and Design of Dynamic Machinery Foundations. Construction & Design for Engineering, 2020(20): 3–7.

[10] Fang Y, 2023, Research on Static and Dynamic Responses of Gas Turbine-Pedestal-Pile Foundation Three-Dimensional Finite Element, thesis, Fuzhou University.