Influence of the Soil–Structure Interaction on the Fundamental Period of Large Dynamic Machine Foundation

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SUMMARY:
Dynamic machine foundation codes generally use the fundamental period of foundation to assess their response to dynamic loading. This parameter is generally calculated using empirical formulas provided by the codes. These formulas generally ignore the soil flexibility, which could drastically affect the fundamental period and consequently their overall dynamic response. This paper includes an investigation of the influence of the soil–structure interaction (SSI) on the fundamental period of dynamic foundations. The behaviour of both the soil and the foundation is assumed to be elastic. The soil-foundation system is modelled using viscous-spring artificial boundary. Analysis shows that the influence of the SSI on the fundamental frequency of dynamic foundation depends on the soil–foundation relative rigidity K_{SF}. The SSI should not be ignored when the rigidity of the foundation is large enough.

Keywords: dynamic foundation; fundamental period; relative rigidity; soil-structure interaction

1. INTRODUCTION

In the modern industrial plant design, the high precision dynamic machine has high vibration requirements for the dynamic foundation. The high speed rotation caused by the large dynamic machine will affect the accuracy and effect of the test on the machine. Therefore, it is very important to obtain the natural frequency of the machine foundation by the modal analysis.

Dynamic machine foundation codes generally use the fundamental period of foundation to assess their response to dynamic loading. This parameter is generally calculated using empirical formulas provided by the codes. These formulas generally ignore the soil flexibility, which could drastically affect the fundamental period and consequently their overall dynamic response. Soil-foundation interaction may affect the dynamic properties of the foundation.

The objective of this study is to analyze and interpret available fundamental period to evaluate the effect of soil-foundation interaction on foundation response for a range of geotechnical and foundation conditions. A companion paper describes the soil–structure interaction of buildings, and a paper discusses the limit of considering dynamic soil-structure interaction. In this paper, a comparison of a dynamic machine foundation between before and after strengthening is studied to find the influence scope of soil-foundation interaction.

2. MODEL OF THE DYNAMIC MACHINE FOUNDATION

The study is carried out based on the dynamic machine foundation of an industrial plant laboratory in Beijing in People’s Republic of China. Fig. 1 shows the sectional view and the shear-wall distribution of the foundation before strengthening. The foundation consists of a three-layer reinforced concrete shear wall structure above ground and a mass concrete foundation under ground. The concrete strength grade of the structure and the foundation is respectively C30 and C25. The dimensions of the shear walls and the floor slabs are shown in the Fig. 1.

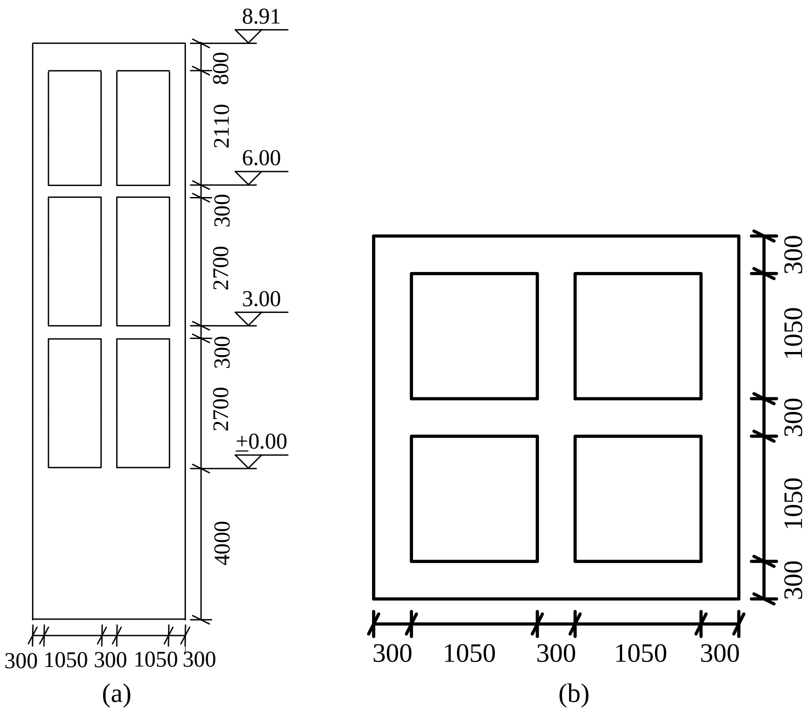


Figure 1. The dynamic machine foundation before strengthening where the figures are in unit of mm. (a) The sectional view of the foundation. (b) The shear-wall distribution of the foundation.

Fig. 2 shows the sectional view and the shear-wall distribution of the foundation after strengthening. Based on the original foundation, the new one increases a series of shear walls (6000mm-height, C25), a series of floor slabs (300mm-thickness, C25) and three retaining walls (300mm-thickness, C30).

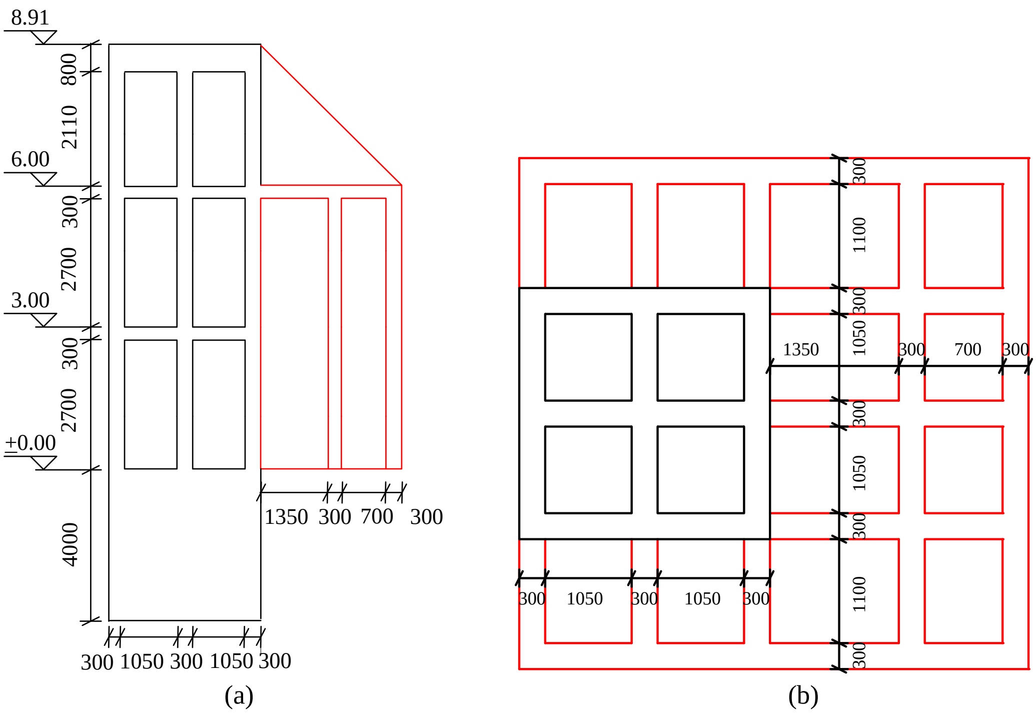


Figure 2. The dynamic machine foundation after strengthening where the figures are in unit of mm. (a) The

sectional view of the foundation. (b) The shear-wall distribution of the foundation.

On the top of the three-layer reinforced concrete shear wall structure is a large dynamic machine. The weight of the machine is 10^4kg and the altitude of the mass centre is 10500mm. The machine can be thought rigid body approximately.

In the original design, the results from numerical simulation and field measurement of the dynamic machine foundation before strengthening are essentially consistent. However, the results show significantly different after strengthening. The following will analyze and explain this phenomenon.

3. ORIGINAL ANALYSIS OF THE FOUNDATION

3.1. Numerical analysis model

The original analysis of the foundation is based on the assumption of rigid soil, for the convenience of modelling and calculation. The FEA software MSC.Marc is used for analysis. The shear walls, the retaining walls and the first two layers floor slabs are simulated with SHELL139, the third layer floor slabs are simulated with SHELL138, and the mass concrete foundation is simulated with SOLID7. The analysis models of the foundation and dynamic machine are shown in Fig. 3. The density ρ and Poisson ration ν of concrete is 2500kg/m^3 and 0.2, and the elasticity modulus E of C30 and C25 concrete is 3.0×10^7kN/m^2 and 2.8×10^7kN/m^2 respectively.

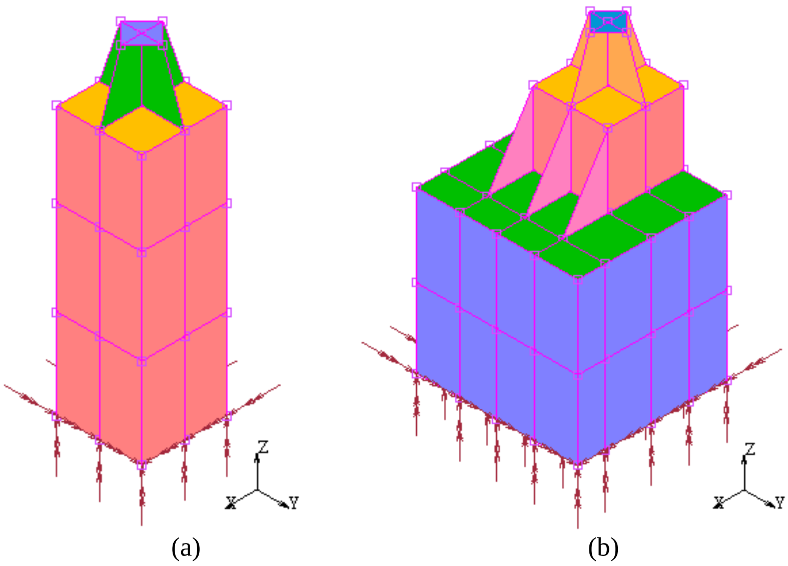
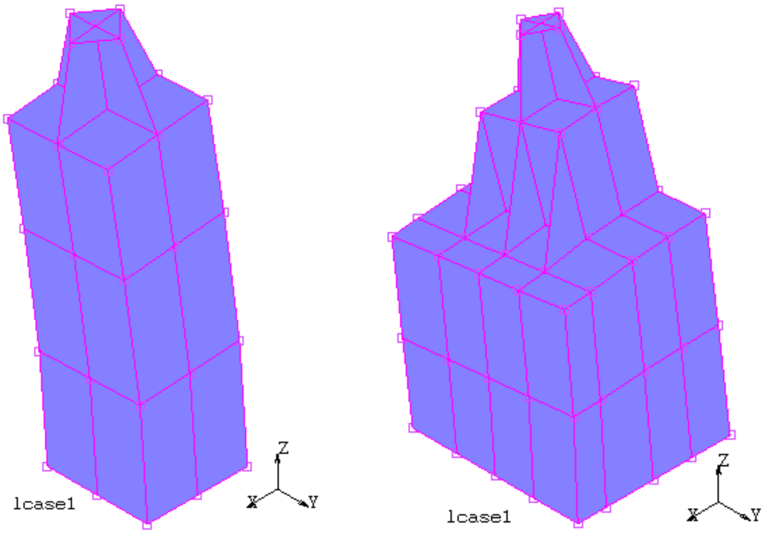


Figure 3. The FEA analysis models of foundation based on the assumption of rigid soil. (a) The foundation before strengthening. (b) The foundation after strengthening.

3.2. Modal analysis

Modal analysis of the two models is made and the results are shown in Fig. 4. The result shows that the foundation after strengthening has a larger integral rigidity, and the fundamental period of the strengthened foundation is about twice the other one. The new walls lead to good strengthening effect.

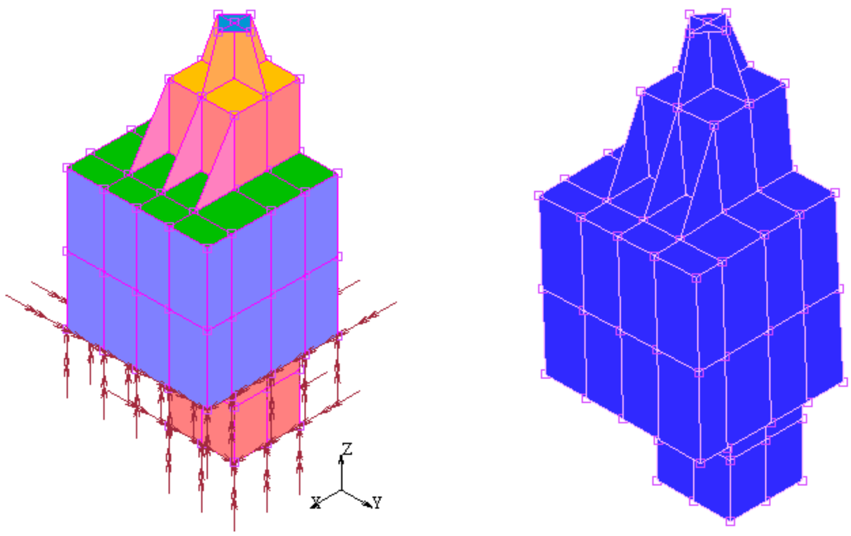


(a) f_1=16.31Hz (b) f_1=32.20Hz

Figure 4. The fundamental modal and frequency of foundation based on the assumption of rigid soil. (a) The foundation before strengthening. (b) The foundation after strengthening.

3.3. Considering the connection between wall and ground

During the construction process, the original foundation and the ground established a reliable connection through the mass concrete, and it can be approximated that the original fundamental fixed on the ground (fixed connection). During the strengthening process, the new walls could not be completely fixed to the ground, so the new walls are set to be articulated to the ground in the simulation process, and it does not bind its rotational degree of freedom. The analysis model and result is shown in Fig. 5. As the new walls in the construction process cannot form a reliable connection with the ground, so the overall stiffness of the small, self-resonant frequency is reduced.



(a) (b)

Figure 5. The analysis model and result of foundation considering the connection between wall and ground. (a) The analysis model. (b) The fundamental modal and frequency (f_1=29.84Hz) of foundation.

3.4. Discussion

The basis frequencies of rigid-assumption foundation are shown in Table 1. In this section, the rigid foundation assumption is used in the modelling analysis.

The stiffness of the dynamic foundation is relatively small before strengthening, so the modelling analysis with rigid foundation assumption does not produce much error. However, the stiffness of the dynamic foundation has been significantly improved after strengthening, and then the ground will play an important role in the natural frequencies of the dynamic foundation. In order to calculate the natural frequency of the dynamic foundation accurately, we must consider the soil-structure interaction. Soil-structure interaction will be considered in the next section and the simulation analysis will based on the establishment of the soil-foundation interaction model.

Table 1. The basis frequencies of rigid-assumption foundation

Analysis model	Fundamental frequency	Second frequency	Third frequency
rigid-unstrengthened	16.31 Hz	16.31 Hz	48.37 Hz
rigid-strengthened	32.20 Hz	32.59 Hz	62.27 Hz
hinged-strengthened	29.84 Hz	30.94 Hz	60.64 Hz

4. FURTHER ANALYSIS CONSIDERING SOIL-STRUCTURE INTERACTION

4.1. Introduction of artificial boundary

When using the finite element method for solving soil-structure dynamic interaction problems, we generally require the interception of the limited size of the computational domain from the infinite medium. And realize the simulation of the infinite foundation by the introduction of artificial boundaries in the finite computational domain boundary. Viscous-spring artificial boundary is a local artificial boundary. It can overcome the low-frequency drift caused by the viscous boundary, and it can simulate the elastic recovery properties of semi-infinite medium away from the artificial boundary. The artificial boundary has good stability in low and high frequency, and it is convenient in application.

Viscous-spring artificial boundary can be modelled as a continuous distribution of parallel spring-damper system; Fig. 6 shows the 3D viscous-spring artificial boundary. In order to apply viscous-spring artificial boundary more easily, we can use the equivalent solid elements to replace the spatial distribution of spring-damper elements in finite element. In practical operation, we can expand a certain thickness of the solid elements along the normal of the existing finite element model boundary, and fix the outer layer of the boundary. The model is shown in Fig. 7.

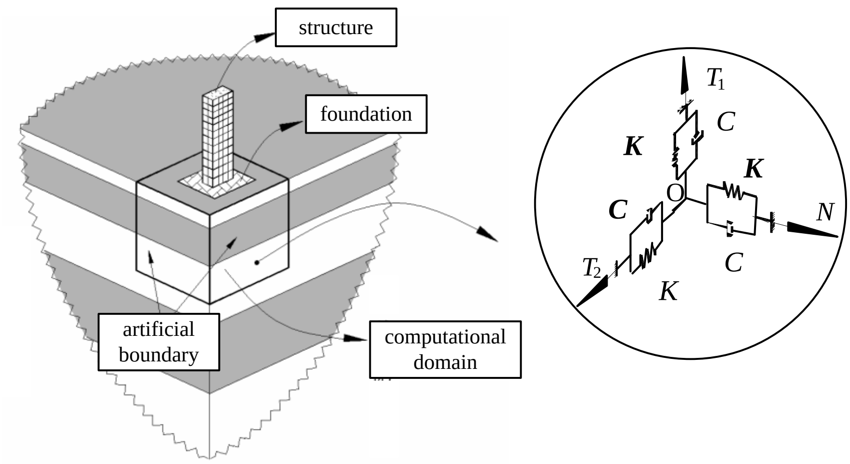
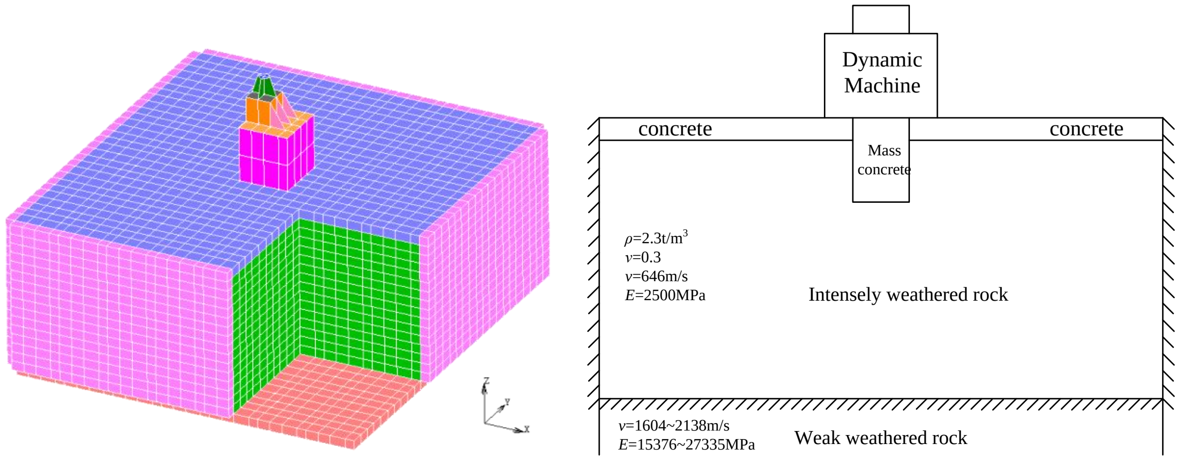


Figure 6. The model of 3D viscous-spring artificial boundary

4.2. Numerical analysis model

Fig. 7 shows the model of soil-foundation interaction and the properties of the soil layers.

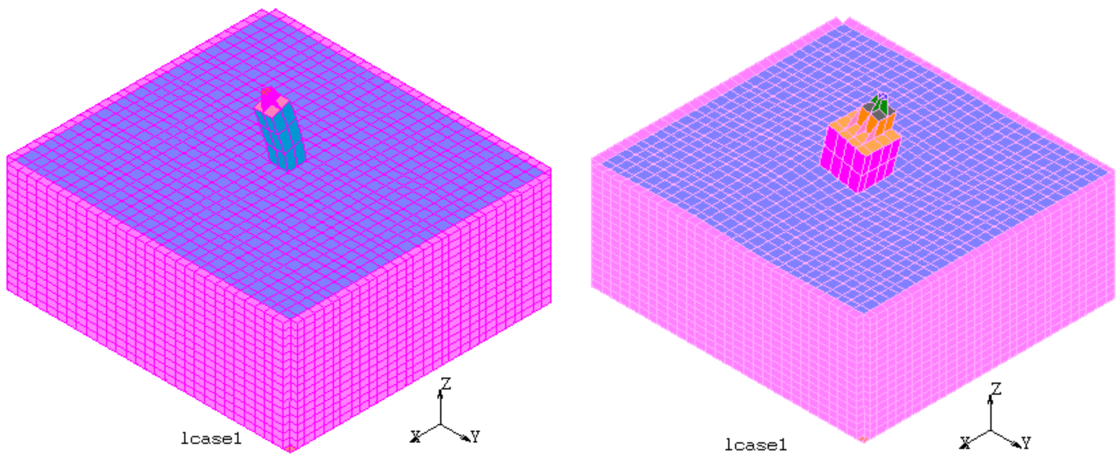


(a) (b)

Figure 7. The FEA analysis model considering soil-structure interaction. (a) The model of soil-foundation interaction. (b) The properties of the soil layers.

4.3. Modal analysis

Modal analysis of the two models is made and the results are shown in Fig. 8. The result shows that the foundation after strengthening has a larger integral rigidity, and the fundamental period of the strengthened foundation is about twice the other one. The new walls lead to good strengthening effect.



(a) f_1=16.31Hz (b) f_1=32.20Hz

Figure 8. The fundamental modal and frequency of foundation considering soil-structure interaction. (a) The foundation before strengthening. (b) The foundation after strengthening.

4.4. Discussion

The basis frequencies of foundation considering soil-structure interaction are shown in Table 2. Compare the results between the rigid foundation assumptions model and the soil-structure interaction model, we can be found that, the natural frequencies of the soil-structure interaction model are significantly lower. The stiffness of the foundation before strengthening is small, and the impact of the SSI is relatively small. The stiffness of the foundation after strengthening has a substantial increase, and the impact of the SSI is relatively large. Similarly, the basis frequencies of the foundation after strengthening are significantly higher than that before strengthening. The SSI model is closest to the actual project, and it is the best indicator of the dynamic characteristics of the dynamic foundation. Through analysis, when the soil modulus is 2500MPa (shear wave velocity of 646m/s), the first three natural frequencies are 17.16Hz, 17.25Hz and 45.42Hz.

Table 2. The basis frequencies of foundation considering soil-structure interaction

Analysis model	Fundamental frequency	Second frequency	Third frequency
unstrengthened	11.33 Hz	11.37 Hz	41.78 Hz
strengthened	17.16 Hz	17.25 Hz	45.42 Hz

5. CONCLUSION

It can be found from the analysis of the dynamic foundations that:

a. The fundamental frequencies of the dynamic foundation before strengthening are consistent between numerical simulation and field measurement, but the result is quite different after strengthening.
b. The stiffness and the frequency of the foundation improve after strengthening whether consider the soil-structure interaction or not.
c. Before strengthening, the rigidity of the foundation is relatively small to the ground, and the affect of the SSI is also small. After strengthening, the rigidity of the foundation is significant, and the affect of the SSI is also large. And this is the reason why the numerical simulation result cannot match the field measurement result after strengthening.

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