Dynamic Soil-Pile-Structure Interaction

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ABSTRACT

The largest compressor train in North America was installed for a new ethylene production plant at the Nova Chemicals Facility located near Joffre, Alberta. To illustrate the effect of soil-pile-structure interaction, the dynamic behavior of the structure using a flexible piled foundation is compared to the same structure fixed to a rigid base in this paper. Both field and laboratory tests were carried out to investigate the soil properties including down hole seismic tests to provide soil shear wave velocities at different depths. Different design options are considered and an optimum design selected to limit vibration and produce a safe, economic system. The method and procedure used in this study can be applied to the design of tall buildings, bridges and offshore platform with soil-pile-structure interaction under seismic, blast, sea wave and other dynamic loads.

KEYWORDS

Pile foundations, dynamic analysis, flexibility, foundations, vibration in higher frequency, soil-structure interaction, table top structure, soil-pile-structure interaction, structural design.

INTRODUCTION

It is now well-recognized that the foundation on which a structure is constructed may interact dynamically with the structure resulting in maximum deflections and stresses in the system are significantly different from results obtained if the structure is considered to be on a rigid foundation. Years ago, such interaction effects on dynamic or seismic response of a structure was considered of little consequence and ignored. Even in recent years, the effect of foundation flexibility on the dynamic response of a superstructure is still not considered to be important by various authorities or engineers when analyzing vibrating machine foundations. For instance, the following quote is by the Task Committee on Turbine Foundations, (1987). "If the dynamic load is a high-frequency force such as a rotating unbalance, the effect of the base mat is small, that is, the base mat acts as a fixed base for the foundation. Therefore, the foundation may be adequately analyzed by using a model where the columns are assumed to be fixed at the mat (no translation and no rotation)." According to such specifications, the effects of the "mat" foundation portion are not considered important and only the superstructure needs to be considered when subjected to the high-frequency unbalanced forces.

The largest compressor train in North America was installed on a concrete table top for a new ethylene production plant at the Nova Chemicals Facility located near Joffre, Alberta. The centerline of the machine shaft is 10.67 m above grade. The machine weighs 2,780 KN, and operates at speeds in excess 3,000 rpm. The concrete table top structure is constructed on a piled mat foundation.

The details for the design of table top structure were described by Han et al (1999). In this paper, the analysis results for the table top structure is used to demonstrate the significance of the foundation interaction and how the assumption of a rigid foundation may lead to erroneous results. The dynamic behavior of the elevated concrete structure attached to the flexible piled foundation is compared to the same structure fixed to a rigid base to illustrate the effect of soil-pile-structure interaction. Both field and laboratory tests were carried out to investigate and determine the soil properties including seismic down hole tests to provide soil shear wave velocities at different depths and impulse response tests to investigate the integrity of the pile shafts. Several options for the piled mat foundation and table top structure are considered and discussed. An optimum design is then selected to limit vibration and produce a safe, economic system. The relationship between static behavior and dynamic behavior of the table top structure is discussed to provide guidelines for the design of this type of structure.

The rotating machinery is supported by an elevated concrete

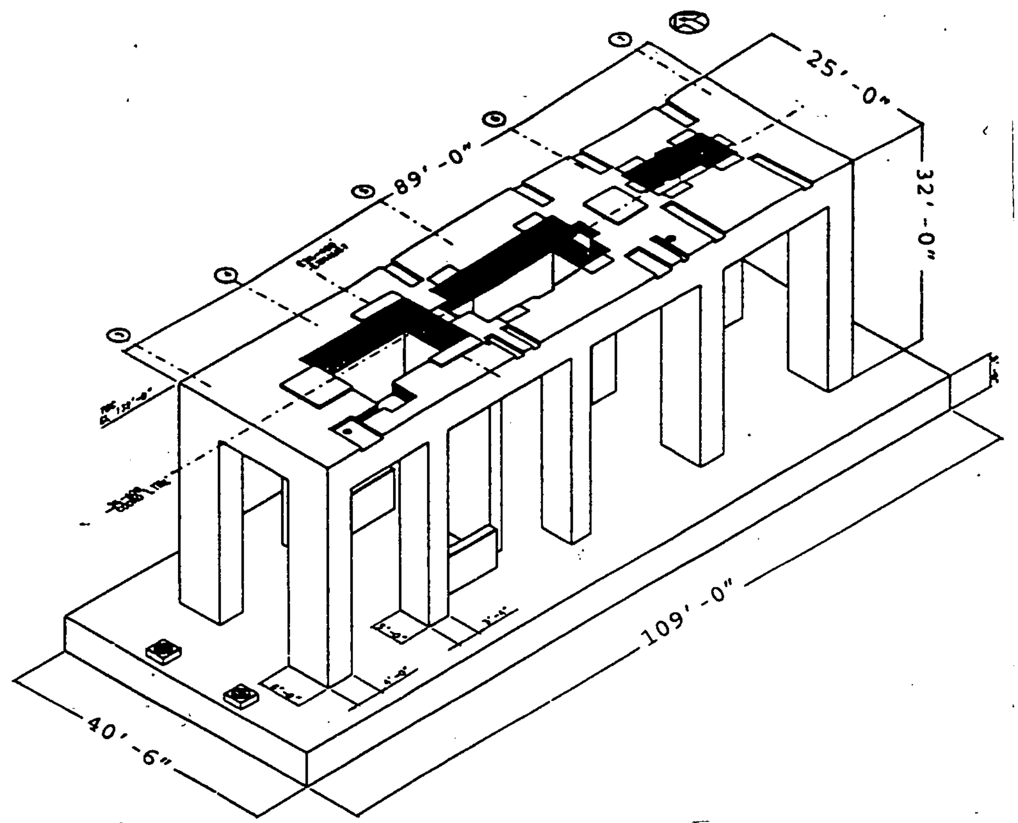

Figure 1. Layout of Elevated Compressor Table Top Structure

table top structure as shown in Figure 1, attached to a piled mat foundation. The superstructure is modeled by means of the finite element method, and the soil - pile system is represented by the spring and damper with six degrees of freedom. The unbalanced forces from the rotating machine shaft produce vibration in both the superstructure and the pile foundation. The dynamic analysis for the table top structure is a typical problem of soil-pile-structure interaction.

SOIL-PILE-STRUCRUAL INTERACTION

For practical design purposes, the evaluation of soil-pile-structure interaction can be done following a simple procedure based on the substructure method. The soil-pile interaction analysis is conducted separately to yield the piled mat foundation stiffness and damping. The dynamic response for the table top structure is then obtained by means of finite element analysis that includes input of foundation stiffness and damping. This type of analysis was described by Novak, (1991). The effect of soil-pile-structure interaction on tall buildings in seismic environment was investigated in time domain by Han and Cathro, (1997).

The deformation of the table top structure in vibration is sketched in Figure 2. The dashed lines represent the original shape and location, and the solid lines represent the deformation. The displacements consist of three portions: the foundation translation Δ_1, the foundation rocking Δ_2, and the superstructure deflection Δ_3. Where, $\Delta_2 = H \times \theta$, H is the height of superstructure and θ is the foundation rotation. In the case of the fixed base, the soil-structure interaction is ignored, $\Delta_1 = \Delta_2 = 0$. In the case of the flexible footing, the soil-structure interaction is accounted for. To illustrate the effect of soil-pile-structure interaction, both cases, fixed base and flexible footing, are considered in this study. The detail of the effect of foundation flexibility will be discussed later.

The dynamic analysis is divided into two steps. Determination of stiffness and damping of the pile foundation is the first step, but the difficulty is how to evaluate the soil-pile interaction. A number of approaches are available to account for dynamic soil-pile interaction but they are usually based on the assumption that the soil behavior is governed by the law of linear elasticity or visco-elasticity and the soil is perfectly bonded to a pile. In practice, however, the bonding between the soil and the pile is rarely perfect and slippage or even separation often occurs in the contact area. Furthermore, the soil region immediately adjacent to the pile can undergo a large degree of straining, which would cause the soil-pile system to behavior in a nonlinear manner. Both theoretical and experimental studies have shown that the dynamic response of the piles is very sensitive to the properties of the soil in the vicinity of the pile shaft (Han and Novak, 1988).

A rigorous approach to the nonlinearity of a soil-pile system is extremely difficult and therefore approximate theories have to be used. Novak and Sheta (1980) proposed including a cylindrical annulus of softer soil (an inner weakened zone or so called boundary zone) around the pile in a plane strain

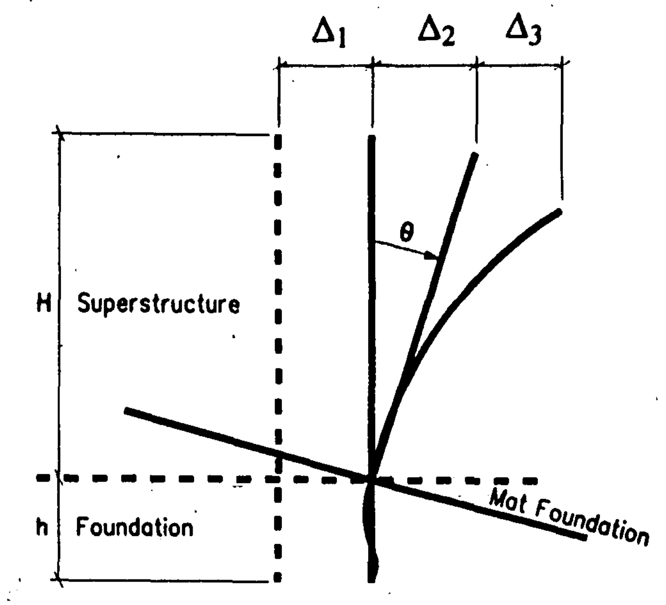

Figure 2. Deformation of table top structure in vibration

analysis. One of the simplifications involved in the original boundary zone concept was that the mass of the inner zone was neglected to avoid the wave reflections from the interface between the inner boundary zone and the outer zone. To overcome this problem, Velestsos and Dotson (1988) proposed a scheme that can account for the mass of the boundary zone. Some of the effects of the boundary zone mass were investigated by Novak and Han (1990) who found that a homogeneous boundary zone with a non-zero mass yields undulation impedance due to wave reflections from the fictitious interface between the two media.

The ideal model for the boundary zone should have properties smoothly approaching those of the outer zone to alleviate wave reflections from the interface. Consequently, such a model for the boundary zone with non-reflective interface was proposed by Han and Sabin (1995). The model of non-reflective interface assumed that the boundary zone has a non-zero mass and a smooth variation into the outer zone by introducing a parabolic variation function, which may be best fit with use of experimental data. Dynamic investigations of piles indicated that the boundary zone model is applicable to both granular and cohesive soils (Han, 1997).

Using the impedances of the soil layer, the element stiffness matrix of soil-pile system can be formed in the same way as the general finite element method. Then the overall stiffness matrix of a single pile can be assembled for different modes of vibration. For analysis of soil-pile interaction, the DYNA4 program was developed by Novak. Following the similar way, DYNAN program is developed by the author using the non-reflective boundary model. For linear elastic vibration, the results from DYNA4 and DYNAN do not have too much difference. For nonlinear vibration, such as seismic environment, DYNAN is better than DYNA4 since the mass in boundary zone is accounted for (see Han, 1997). To generate the stiffness and damping of the pile foundation, both programs are used in this study.

The validity of the model of soil-pile interaction has been verified using full-scale pile foundation tests. Field tests of the piles were carried out at the Institute of Engineering Mechanics, Harbin, China (El-Marsafawi et al., 1992).

The group effect of piles is considered using the dynamic interaction factor method. The dynamic interaction factors were presented in a chart form by Kaynia and Kausel (1982).

STIFFNESS AND DAMPING OF PILES

The soil profile where the compressor is being installed consists of two clay till layers overlying bedrock. The upper clay till is brown and 4 to 5 m thick underlain by a grey till. The bedrock formation under the clay till starts around 11.0 m below grade. In the upper 2 to 3 m of the bedrock formation, the bedrock is very weak, and moderately to highly weathered and fractured. Ground water was encountered at 11.5 m. Down hole seismic tests were carried out to provide shear wave velocities in both the clay till and the bedrock.

Drilled end bearing concrete piles with belled bottoms were used throughout the construction project. The typically length of the piles is 11 m, with the underside of the bell resting on top of the weathered bedrock. The bearing capacity of such piles presented no problem for the compressor foundation. However, the belled piles did not provide the stiffness required for the compressor foundation, since the shear wave velocity at the depth of 11 m was only 200 to 300 m/s. To achieve a higher stiffness for the foundation, straight shaft piles socketed into competent bedrock to a depth of 15 m below grade were used. The shear wave velocity at that depth was measured to be over 600 m/s. Tremie concrete was used for the cast-in-place concrete piles below groundwater level.

44 piles with a 0.914 m diameter were arranged into 4 rows of 11 piles. A spacing ratio of 3.9 in transverse direction and 3.3 in longitudinal direction were used. The pile heads were fixed to a concrete cap (mat foundation) with a thickness of 1.5 m. The dynamic response for a foundation using belled piles resting on top of bedrock (floating pile) versus socketed straight shaft piles is shown in Figure 3 for the amplitudes of lateral vibration, and Figure 4 for the amplitudes of rotation vibration. It can be seen that the peak value for both translation and rotation of the floating pile is much larger than that for the socketed pile. This indicates a much smaller damping ratio for the floating piles. The larger vibration amplitudes from the floating piles will result in larger vibrations of the table top. With the socketed piles, the energy was transferred to the competent bedrock, so that the peak values of vibration are much smaller. Consequently, the option of socketed straight shaft piles was adopted.

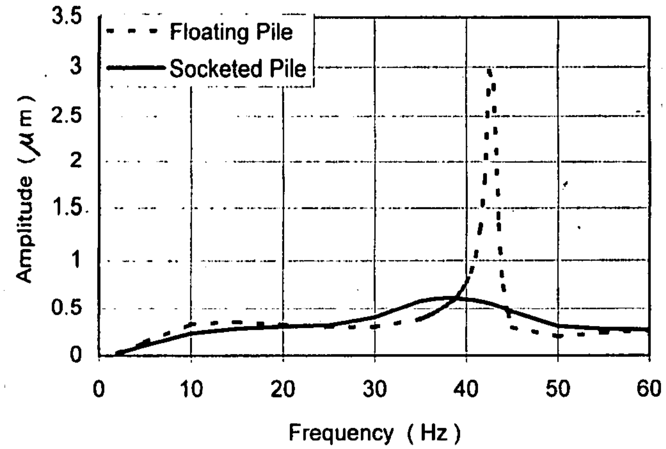

Figure 3. Transverse amplitudes for different pile foundations.

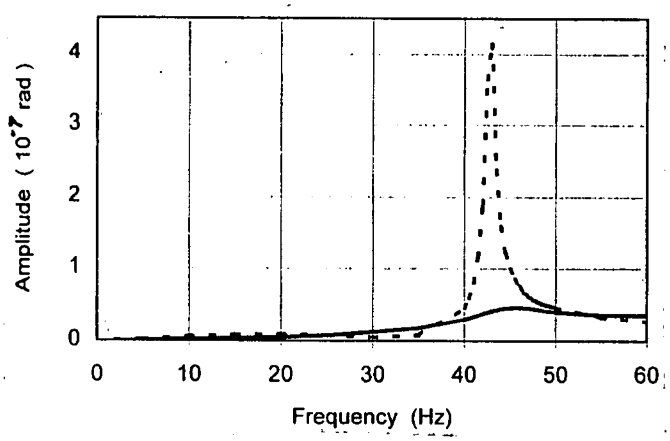

Figure 4. Rocking vibration for different pile foundations.

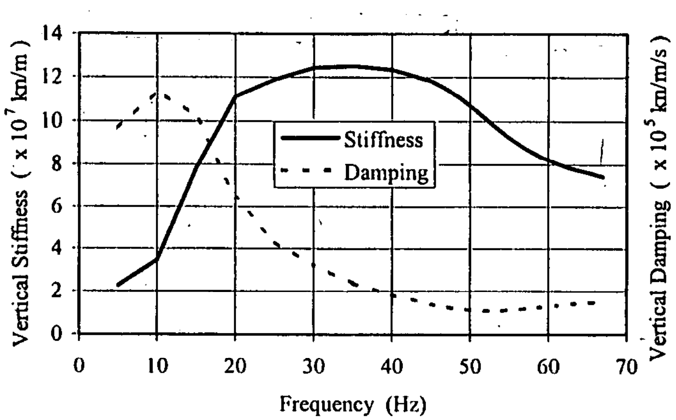

Figure 5. Vertical stiffness and damping of pile foundation

The bearing capacity of the socketed piles depends on the adhesion resistance between the bedrock and the concrete shaft. The allowable shaft adhesion is 100 kpa from depth of 10 m to 13 m, and is 300 kpa from depth of 13 m to 15 m. The total loads consisting of the table top concrete structure, machinery, and foundation mat, is less than half of the bearing capacity of the piles.

For dynamic soil-pile interaction, the stiffness and damping are frequency dependent. The vertical stiffness and damping of the foundation is shown in Figure 5 as an example.

ANALYSIS AND DESIGN OF TABLE TOP STRUCTURE

The initial geometry of the concrete table top structure was estimated based on experience and published guidelines, such as suggested by Arya, et al, (1981). Usually, the height of table top is not over 6 m and column spacing should be less than 3.6 m. The thickness of the deck (top beams) should be not less than one fifth of the clear span. All columns should be stressed almost equally. The flexural stiffness of the beams should be at least twice the flexural stiffness of the columns.

In the guidelines, the mass of the top half of the structure should not be less than the mass of the supported machine, and the total mass of the structure including the mat should not be less than three times the mass of machine.

The actual geometry of the structure was dictated by a number of factors including equipment size, piping layout, anchor bolts, and clearance for installation. The weight of the deck is 5,840 KN, which is larger than the machine weight . The weight of the top half of the structure (deck and half columns) is 8,230 KN, which is three times the machine weight. It should be noted that the mass of the structure used in this case is different from that based on the general guidelines.

For the concrete design, the compressive strength is 30 Mpa, and the dynamic modulus of elasticity is 35,900 Mpa, Poisson's ratio is 0.25, and the damping ratio is 0.02. Minimum reinforcement governed for most beams and columns, since the cross-sections were large.

The finite element program SAP2000 nonlinear version was used for the dynamic analysis of the table top structure, including the stiffness and damping parameters of the pile foundation. The centrifugal machine produced harmonic excitation on the table top structure, so the dynamic response can be solved in a frequency domain conveniently. Although the harmonic steady-state analysis can be done with the program, the structural damping is assumed to be zero. (This is a limitation imposed by SAP2000.) The structural damping should be accounted for, therefore, a time history analysis had to be used for the harmonic vibration. Sine and cosine time functions were used for the dynamic vertical loads and horizontal loads respectively, with a phase difference of 90 degrees.

Both the larger compressor and the smaller compressor were driven by the turbine. The turbine and larger compressor run at the same speed, 3,415 rpm (56.92 Hz); and the smaller compressor runs at speed of 4,928 rpm. The value of unbalanced forces were taken as 25% of the rotor weights (as specified by the vendor), and the maximum values are 23, 32 and 9 KN for the turbine, the larger and the smaller compressor respectively. In the dynamic analysis, the unbalanced forces are frequency dependent. If the frequency ω_1 is lower than the operating frequency ω_0, the unbalanced forces were reduced by $(\omega_1/\ \omega_0)^2$, such as in the case of machine shut down or start up. Since the smaller compressor provides small excitation and run at a different speed, the effect of phase change from the smaller compressor was ignored. The dynamic response of table top structure was mainly controlled by the turbine and the larger compressor, operating in phase or out-of-phase.

The concrete table top structure can be modeled by means of solid element or frame element. In this study, the frame elements were used to model the superstructure, the mat foundation was modeled by using shell elements. The damping parameters of the pile foundation were inputted using nllink element.

There are many factors affect the dynamic behavior of the table top structure. Some may play an important role in the dynamic response and some may be not important. It is unnecessary to account for all of the factors involved. Consequently, the mat foundation modeled with the shell elements was constrained as a rigid plate. The stiffness and damping of the pile group were input at the center of mat.

Table 1. Maximum amplitudes on the deck

Direction	Vertical	Transverse
Load Case	In Phase	Out-of-Phase
Frequency (Hz)	51	53
Amplitude (μm)	3.94	4.58

Table 2. Maximum amplitudes at the mid-height of columns

Direction	Transverse	Longitudinal
Load Case	Out-of-Phase	In Phase
Frequency (Hz)	61	49
Amplitude (μm)	7.46	8.91

Thus, the flexibility of the mat foundation was ignored, but the group effect of the piles was accounted for. From the dynamic finite element analysis, the maximum amplitudes on the deck are shown in Table 1 and the maximum amplitudes at the mid-height of columns are shown in table 2, respectively.

The vibration criteria given by the vendor was a max velocity of 2.54 mm/s. In accordance to the velocity, the amplitude limit should be 6 – 9 μm. From the results shown in the above table, it can be seen that the dynamic response meets the vibration limit, with the largest amplitudes at the columns.

EFFECT OF FOUNDATION FLEXIBILITY

To illustrate the effect of foundation flexibility, the dynamic behavior of the compressor supported by the table top structure attached to a flexible piled foundation is compared to the same structure fixed to a rigid base. The vertical, horizontal and rocking vibration were calculated in the frequency domain from 5 Hz to 68 Hz. In the case of the flexible footing, the stiffness and damping parameters are frequency dependent, i.e., the dynamic soil-pile-structure interaction is considered. In the case of fixed base, there is no soil-pile-structure interaction. The comparison for the deck with different base conditions is shown in Figure 6 for vertical response and Figure 7 for lateral vibration, respectively.

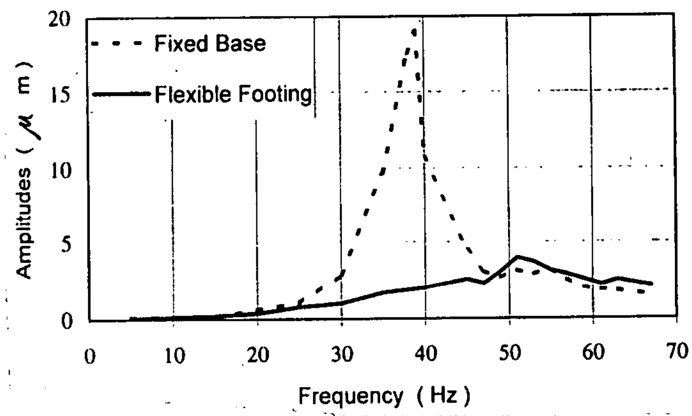

Figure 6. Effect of foundation flexibility on vertical dynamic response of deck.

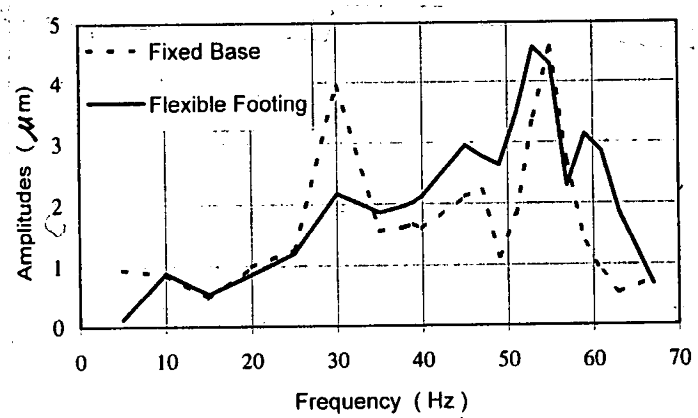

Figure 7. Effect of foundation flexibility on lateral dynamic response of deck

From Figure 6, it can be seen that the vertical dynamic response with the soil-pile-structure interaction is very different with that on the fixed base. The peak value of amplitude with the fixed base is almost five times of that with the flexible footing. The reason is that the damping ratio of the flexible system is increased greatly, so called radiation damping, due to the energy dissipated from the foundation and soil when the soil-pile-structure is considered. In the case of fixed base, the vibration energy is reflected from the base.

The only damping in the fixed base is the material damping of concrete, which is smaller. Also, the vertical natural frequency was changed due to the soil-pile-structure interaction. In the case of the fixed base, the frequency of the vertical vibration mode is 38.6 Hz. $f_m / f_n = 1.47$, where f_m is the operating speed of machine and f_n is the vertical natural frequency. In the case of the flexible footing, the vertical natural frequency is 23.9 Hz, and $f_m / f_n = 2.38$. With the soil-pile-structure interaction, the natural frequency of the table top is far away from the operating frequency.

From Figure 7, it can be seen that the lateral dynamic response with the soil-pile-structure interaction is close to that of the fixed base in the frequency domain of machine operation. However, the amplitude of the flexible foundation is about half that of the fixed base at the frequency of 30 Hz. In the case of fixed base, the natural frequency of lateral vibration mode $f_n = 7.24$ Hz, and the operating frequency of machine $f_m = 56.92$ Hz, $f_m / f_n = 7.86$. In the case of flexible footing, the lateral natural frequency is 4.82 Hz, and $f_m / f_n = 11.81$. In both cases, the lateral natural frequencies are far away from the operating frequency and the foundation flexibility has a smaller influence on the lateral vibration in the frequency domain of machine operation.

CONCLUSIONS

(1). The soil-pile-structure interaction is complex, any part of the soil, the piles, or the superstructure may play an important role in the dynamic response of the table top structure. In this study, the soil-pile-structure interaction might affected the vertical vibration in the higher frequency domain, and affected the lateral vibration in the lower frequency domain. For large and important structures a dynamic analysis including soil-structure interaction is necessary.

(2). For the case of a significant elevated concrete table top supporting rotating machinery, any part of the soil, the piles, and/or the superstructure may play an important role in the dynamic response. Attention should be paid to both the foundation design and the superstructure design, even for the high-frequency rotating machines.

(3). The piled mat foundation and table top structure provided in this study are safe, economic and meet the vibration criteria. The method and procedure used in this study can be applied to the design of tall buildings, bridges and offshore platform under seismic, blast, sea wave and other dynamic loads.

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