Thessaloniki-GREECE 2007

**4th International Conference on**
**Earthquake Geotechnical Engineering**
June 25-28, 2007
Paper No. 1717

# ADVANCED DYNAMIC ANALYSIS FOR ELEVATED CONCRETE FOUNDATION

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## ABSTRACT

The soil-structure interaction may play an important role in the dynamic analysis of elevated concrete foundation (table top structure). The dynamic analysis should be not only advanced in theory but also practical in engineering. In this study, the dynamic response is investigated based on a large reciprocating compressor installed on table top structure. Subsoil in the site consists of very soft silty clay/sand, with lower shear wave velocity of 100 m/s. Jet grouting procedure was adopted to improve the soft soil. Both field and laboratory tests were carried out to investigate the soil properties including cross-hole tests. Several options of the pile foundation design are considered.

The soil-pile-structure interaction is accounted for by means of the substructure method. Two commercial softwares are used in this case. At first, stiffness and damping of the pile foundation are generated from a computer program DYNAN, and then input into a finite element model by program SAP2000. The dynamic behavior of the structure on the flexible piled foundation is compared to the same structure fixed to a rigid base to illustrate the effect of soil structure interaction.

Keywords: Dynamic soil-pile-structure interaction, pile foundation, soil dynamics, structural dynamics, nonlinear vibration

## INTRODUCTION

The elevated concrete foundation (table top structure) is often used to support vibrating machinery. The dynamic response of such structures is complex, since any part of the soil, the foundation (piles), or the superstructure may play an important role. The foundation on which a structure is constructed may interact dynamically with the structure itself to the extent that the maximum deflections and stresses in the system are significantly different from values that would have been developed if the structure were on a rigid foundation.

In this study, the dynamic response is investigated based on a large reciprocating compressor installed on the table top structure supporting by piles. The weight of compressor machine and motor is 3,660 kN, with power of 23,600 HP, operating in lower frequency domain.

Very soft soils are involved in the site. Subsoil consists of very soft silty clay/sand, with lower shear wave velocity of 100 m/s. Jet grouting procedure was adopted to improve the soft soil. Several options for the piled mat foundation and table top structure are considered and discussed. Both field and laboratory tests were carried out to investigate and determine the soil properties including cross - hole tests to provide soil shear wave velocities at different depths.

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The unbalanced forces from the machines produce vibration in both the superstructure and the pile foundation. The dynamic analysis for the table top is a typical problem of soil-pile-structure interaction. For practical design purposes, the evaluation of soil-pile-structure interaction can be done following a simple procedure based on the substructuring method. The soil-pile interaction analysis is conducted separately to yield the piled mat foundation stiffness and damping. The dynamic response of 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 Han et al, 1999. The effect of soil-pile-structure interaction on tall buildings in seismic environment was investigated in time domain by Han, 2002.

To examine the soil-pile-structure interaction, different conditions are considered. In the first case, the soil-pile-structure interaction is accounted for fully. In the second case, no deformation in base soil (no SSI) and the columns of table top structure were fixed (or pinned) to the base. In the third case, the dynamic soil-pile interaction is accounted for, but the table top structure is assumed to be rigid (no deformation in the superstructure). The stiffness and damping of pile foundation are frequency dependent and generated from a program, and dynamic response of the superstructure is calculated using FEM model. From the comparisons, the role of soil, piles and structure in the dynamic response can be identified.

## DYNAMIC SOIL- PILE-STRUCTURE 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 behave in a nonlinear manner.

Many effects have been spent on the numerical analysis with 3D Finite Element Method (FEM) to model the soil-pile interaction. However, it is too complex, especially for group piles in nonlinear soil. A rigorous approach to the nonlinearity of a soil-pile system is extremely difficult and time consuming.

As an approximate analysis, Novak - Han model is used widely, and considered as an efficient technique for solving the nonlinear soil-pile system (Han, 1997). The procedure is developed using half analytical and half numerical solution rather than using 3D FEM.

The relationship between the foundation vibration and the resistance of the side soil layers was derived using elastic theory by Baranov (1967). Both theoretical and experimental studies have shown that the dynamic response of piles is very sensitive to the properties of the soil in the vicinity of the pile shaft. 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 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, Han and Sabin (1995) proposed such a model for the boundary zone with a non-reflective interface.

The impedances of the composite layer are derived from the plane-strain assumption. The outer zone medium is homogeneous, isotropic, and viscoelastic, with frequency independent material damping; within the boundary zone, the complex shear modulus, $G^*(r)$, varies parabolically, as expressed by the function $f(r)$. The variation of $G^*(r)$ is continuous at the boundary, both the function itself and its derivatives, so that no reflective wave can be produced at the interface. The interface is referred to as the "non-reflection boundary".

The properties of the soil medium for each region are defined by the complex-valued modulus

$$G^*(r) = \begin{cases} G_i^* & r = r_0 \\ G_o^* f(r) & r_0 < r < R \\ G_o^* & r \geq R \end{cases} \tag{1}$$

and

$$\begin{cases} G_i^* = G_i(1 + i\,2\beta_i) \\ G_o^* = G_o(1 + i\,2\beta_o) \end{cases} \tag{2}$$

in which $G_i$ and $G_o$ = shear modulus of the inner and outer zones; $r_o$ = radius of pile; $R$ = radius of boundary zone; $r$ = radial distance to an arbitrary point; $\beta_i$ and $\beta_o$ = damping ratio for the two zones; and $i$ = root (−1).

With the impedance of the soil layer, the element stiffness matrix of the 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, included three translations and three rotations. The dynamic stiffness and damping of a single pile can be expressed in terms of complex stiffness, such as for vertical vibration

$$K_v = (E_p A/r_o) f_{v1} + i\omega (E_p A/V_s) f_{v2} \tag{3}$$

in which $E_p$ is the Young's modulus of the pile; $A$ is the cross-section area of the pile element; $\omega$ is the circular frequency; $V_s$ is the shear wave velocity of the soil. $f_{v1}$ and $f_{v2}$ are the dimensionless stiffness and damping parameters.

The group effect of piles is accounted for using the method of interaction factors. The vertical static interaction factors are based on Poulos and Davies (1980). The horizontal static interaction factors are due to El-Sharnouby and Novak (1986). The dynamic interaction factors are derived from the static interaction factors multiplied by a frequency variation, and the frequency variation of interaction factors is based on the charts of Kaynia and Kausel (1982).

To investigate the soil-pile-structure interaction, a series of dynamic experiments have been done on full-scale piles in the field, including single piles and groups (Han & Novak ,1988, and El-Marsafawi et al, 1992).

The governing equations of a soil-pile-structure system can be given in a standard form,

$$[m]\{u\} + [c]\{u\} + [k]\{u\} = \{p(t)\} \tag{4}$$

With a substructure method, the matrices of mass, stiffness and damping can be divided into two parts, the foundation portion and the superstructure portion. Then, the equation (4) can be rewritten as,

$$
\left[\begin{array}{c|cc} \boldsymbol{m} & \boldsymbol{m}_i & \boldsymbol{m}_i\boldsymbol{h}_i \\ \hline \boldsymbol{m}_i^{\mathrm{T}} & m_b+\sum_1^n m_i & \sum_1^n m_i h_i \\ (\boldsymbol{m}_i\boldsymbol{h}_i)^{\mathrm{T}} & \sum_1^n m_i h_i & I+\sum_1^n m_i h_i^2 \end{array}\right]\left\{\begin{array}{c}\ddot{\boldsymbol{u}} \\ \hline \ddot{u}_b \\ \ddot{\varphi}\end{array}\right\}+\left[\begin{array}{c|cc} \boldsymbol{c} & \boldsymbol{0} & \boldsymbol{0} \\ \hline \boldsymbol{0}^{\mathrm{T}} & c_{xx} & c_{x\varphi} \\ \boldsymbol{0}^{\mathrm{T}} & c_{\varphi x} & c_{\varphi\varphi}\end{array}\right]\left\{\begin{array}{c}\dot{\boldsymbol{u}} \\ \hline \dot{u}_b \\ \dot{\varphi}\end{array}\right\}+\left[\begin{array}{c|cc} \boldsymbol{k} & \boldsymbol{0} & \boldsymbol{0} \\ \hline \boldsymbol{0}^{\mathrm{T}} & k_{xx} & k_{x\varphi} \\ \boldsymbol{0}^{\mathrm{T}} & k_{\varphi x} & k_{\varphi\varphi}\end{array}\right]\left\{\begin{array}{c}\boldsymbol{u} \\ \hline u_b \\ \varphi\end{array}\right\}
$$

$$
=\{p(t)\} \tag{5}
$$

in which $\{u\}$ is the displacement vector, and $\{p(t)\}$ is the load vector,. The matrices $[m]$, $[k]$ and $[c]$ list all the mass, stiffness and damping constants of the superstructure, $I$ is the total mass moment of inertia, $h_i$ is the height of ith floor, and $\{0\}$ is the null vector.

The foundation properties are incorporated as shown in equation (5). $m_b$ is mass of foundation; $u_b$ and $\varphi$ are horizontal translation and rotation; $k_{xx}$, $k_{x\varphi}$, $k_{\varphi x}$ and $k_{\varphi\varphi}$ are stiffness coefficients of the foundation and $c_{xx}$, $c_{x\varphi}$, $c_{\varphi x}$ and $c_{\varphi\varphi}$ are damping coefficients of the foundation.

The parameters of soil-foundation system are considered separately. The stiffness and damping are generated by the DYNAN program and are then input into the finite element model. A finite element program, SAP2000, is used to generate the dynamic response of superstructure.

It should be explained that the foundations (or caps on piles) are assumed to be rigid. In most cases, the superstructures are flexible rather than rigid. By means of a substructure method, the dynamic response of the superstructure is calculated using a finite element program, such as SAP2000, and the stiffness and damping of the foundation can be generated from the DYNAN program (2003). With this procedure, the seismic or dynamic response of the structure can be calculated in time domain or frequency domain (Han, 2001).

## STIFFNESS AND DAMPING OF PILE FOUNDATION

Based on site observations and drilling records, the subsoil consists of silty sand and very soft silty clay. The cross-hole tests were carried out to provide shear wave velocities in different depth, and the velocities measured are shown in Table 1.

Table 1. Shear Wave Velocity Measured in Natural Soil

| *Depth (m)* | *Shear Wave Velocity (m/s)* |
|---|---|
| *0 - 5* | *100* |
| *5 - 15* | *150* |
| *15 - 20* | *209* |
| *20 - 35* | *239* |
| *35 - 50* | *280* |

With the poor soil properties, the vibration amplitudes of foundation will be over larger as described later. The soft soils have to be treated in this site. Two methods were tested, pressure grouting and jet grouting. The test results showed that the improvement is much better by jet grouting than that by pressure grouting. The spacing of column jet grouted is 1.2 m. The grout consists of ordinary Portland cement and the cement content is 400 kg/m$^3$.

Concrete pile foundation was used in this case. The dimension of mat (pile cap) is 16.6 m by 14.4 m as shown in Fig. 1. Two options of pile foundation were considered. In option 1, 8 by 7 places were planned for piles and 9 places were deleted in the centre area. The spacing is about 2.1 m. Total 47 piles were placed, with diameter of 0.6 m and length of 49 m. In option 2, 6 by 5 places were planned. Total 30 piles were placed, with diameter of 0.9 m and length of 20 m. The spacing is bout 3.1 m.

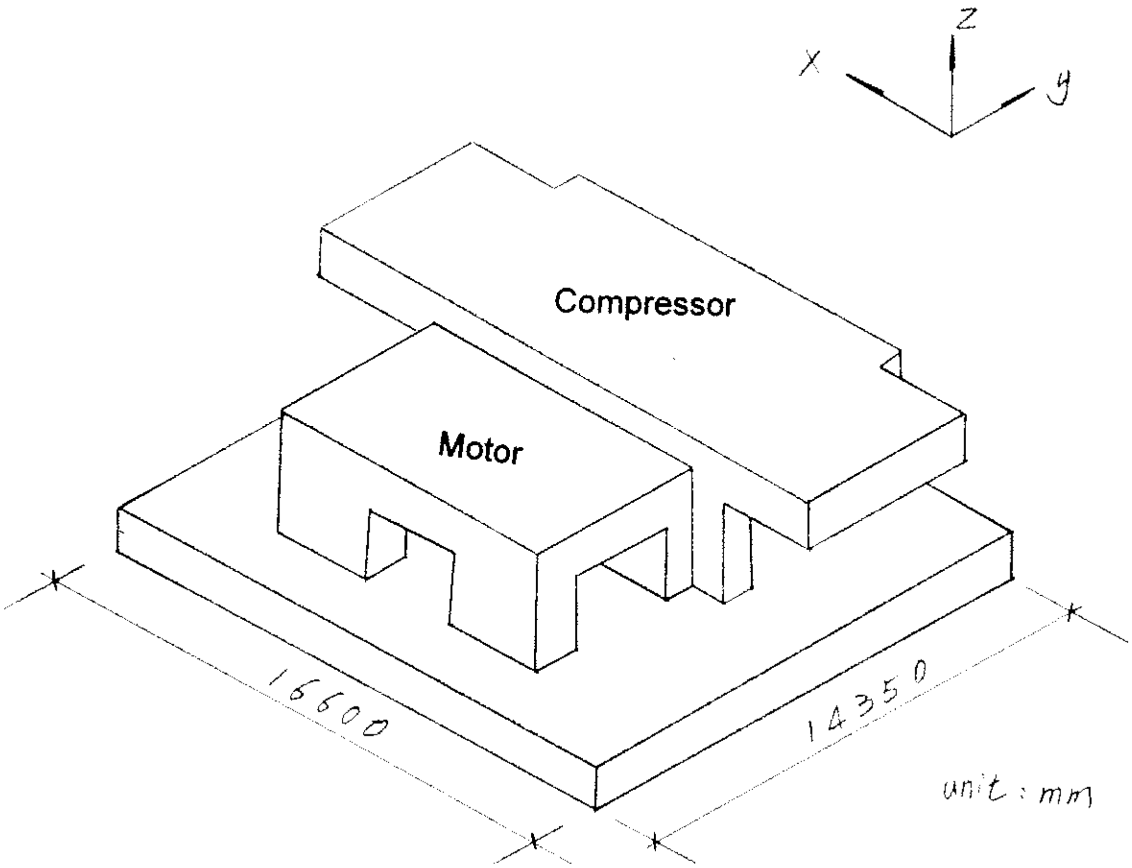


Fig. 1 Foundation of Reciprocating Compressor

The shear wave velocity was measured to be 180 m/s after grout improvement, and the depth of treatment is 15 m. Stiffness and damping of foundation are increased with the treatments, based on option 1 piles, as shown in Fig. 2. The horizontal stiffness and damping are shown in (A), and vertical shown in (B).

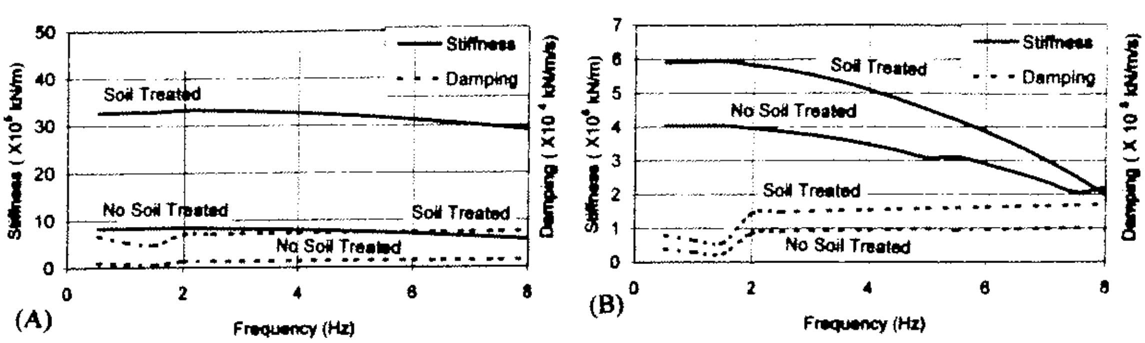


Fig. 2. Effects of Soil Treatment on Stiffness and Damping of Pile Foundation
(A) Horizontal Vibration; (B) Vertical Vibration

The stiffness and damping are frequency dependent. It can be seen that both stiffness and damping are increased with the soil treated. Especially for lateral, the horizontal stiffness is increased about four times for piles in the soil treated than that in the natural soil. As for option 2 piles, the stiffness and damping are also increased significantly, and more improvement obtained by the piles with bigger diameter.

## VIBRATION OF TABLE TOP STRUCTURE

As shown in Fig.1, the thickness of deck slab under compressor is 2.0 m, and the top of slab is 4.9 m above grade. The thickness of deck slab under motor is 1.5 m, and the top of slab is 3.9 m above grade. The thickness of concrete walls (columns) is about 1.4 m.

The compressor and motor are installed on the top of elevated foundation, and the machine weight is 3,660 kN. The weight of concrete foundation is 24,000 kN. 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 ratio was used for most slabs and columns, since the cross-section is large.

The unbalanced forces of reciprocating compressor are defined by vendor. Under load order 1, $M_x$ = 589 kN-m, and $M_z$ = 1,876 kN-m, operating speed is 200 rpm (3.33 Hz). Under load order 2, $F_x$ = 101.4 kN, and $M_y$ = 110.6 kN-m, operating speed is 400 rpm (6.67 Hz). Where, $F_x$ is the lateral force in X direction, $M_x$, $M_y$ and $M_z$ are the moments about X, Y, and Z axes. The directions of X, Y and Z are defined as shown in Fig. 1. The machine shaft for compressor and motor is placed in Y direction. The challenge for foundation design is that the values of unbalance force are quite large and running in lower frequency domain.

The harmonic response is produced by the unbalanced forces. The dynamic analysis of the table top structure can be done using the finite element model, with input of stiffness and damping of the pile foundation. There are two ways to model the soil-structure interaction. One way is the harmonic steady-state analysis, and the dynamic response is obtained in frequency domain. Frequency-dependent link property is defined which includes stiffness and damping of foundation. Another way is the time history analysis for the harmonic vibration. Sine or cosine time functions are defined for the dynamic response. The stiffness and damping are frequency-dependent in the time history analysis.

The mat foundation was modeled by shell elements, and the damping parameters of pile foundation were inputted by using nllink element. There are two ways to model the mat. In one way, the shell elements for mat were constrained as a rigid plate. There are six degrees of freedom for the rigid mat, and lateral vibration is coupled to rocking vibration (Han, 1989). The stiffness and damping of the pile group were input at the center of mat. Thus, the deflection of mat foundation is ignored, but the group effect of the piles is accounted for. In another way, the mat foundation is modeled by the shell elements and to be flexible. The stiffness and damping for individual pile are inputted at the actual locations. More works have to be done in this way. By comparison, the difference is quite small between the two ways. The contribution from mat deflection can be ignored, since the mat is quite rigid. The top deck slabs are modeled by using shell elements, and the columns are modeled by using frame elements, as shown in Fig. 3.

The four corners at top slab are taken as the reference points 1, 2, 3 and 4 as shown in Fig. 3. The maximum amplitudes on the points are calculated for different soil conditions and different options of piles design. The amplitudes calculated for the case of natural soil (no soil treated) are shown in Table 2, and for the case with soil treated are shown in Table 3.

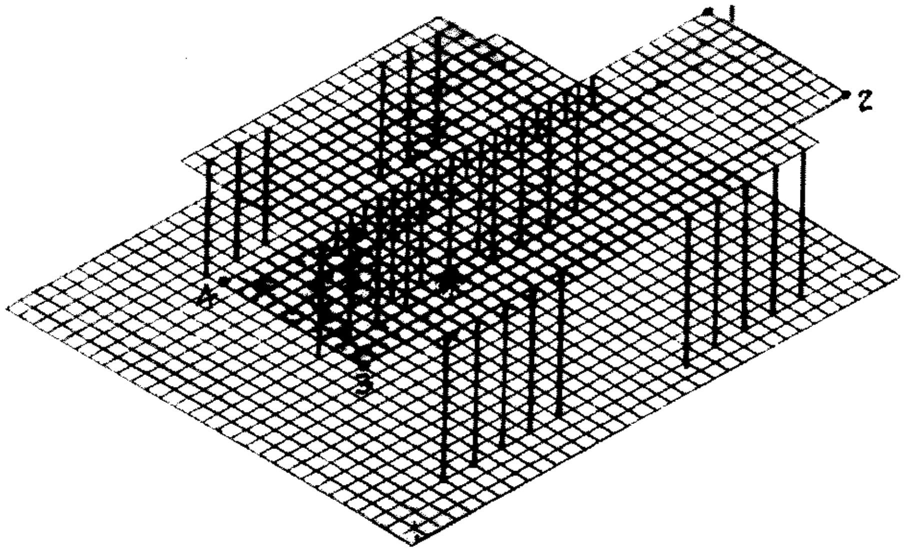


Fig. 3 Table Top Structure Modeled by Combination of Frame and Shell Elements

Table 2. Amplitudes for the case of natural soil (μm)

| *Piles* | $A_x$ | $A_y$ | $A_z$ |
|---|---|---|---|
| Option 1 | *253* | *513* | *39* |
| Option 2 | *137* | *318* | *30* |

Table 3. Amplitudes for the case with soil treated ((μm )

| *Piles* | $A_x$ | $A_y$ | $A_z$ |
|---|---|---|---|
| Option 1 | *111* | *96* | *18* |
| Option 2 | *102* | *89* | *16* |

In which, $A_x$ , $A_y$ and $A_z$ are the amplitudes in direction of X, Y and Z respectively. The amplitudes calculated are produced by both loads order 1 and order 2. From Table 2, it can be seen that the amplitudes are over large, not meet the vibration limit by the building code. The very soft soils are involved within top 15 m, and soil property is too poor. Using the piles with larger diameter in Option 2, the amplitudes are reduced significantly. Higher values of stiffness and damping are provided by the piles with larger diameter. From Table 3, it can be seen that the amplitudes are reduced significantly with soil treated. The stiffness and damping of pile foundation are increased greatly by the jet grouting.

The finite element models used in above dynamic analysis are combination with frame and shell elements. Since the cross-section of the structure is quite large, the overlapping mass in the frame elements was accounted for by reducing the mass density of concrete. An analysis based upon the centerline-to-centerline (joint-to-joint) geometry of frame elements may overestimate deflections in some structures. This is due to the stiffening effect caused by overlapping sections at a connection. It is more likely to be significant in concrete than in steel structures. A rigid-end factor can be specified to assume the connection to be rigid for bending and shear deformation. Typically the value for "rigid" would not exceed about 0.5. In this study, a rigid-end factor of 0.4 is specified.

The solid element (3D) model is appropriate to model concrete structures with larger cross-sections, as shown in Fig. 4. By comparison, the results agree with each other from the two types of FEM models (Han and Histon, 2003). The combined element model, including frame and shell elements, is good enough to accurately generate dynamic responses. The method of using the combined elements saves cost and time.

From the calculation results in Table 2 and 3, it can be concluded that the soil-structure interaction plays a very important role in the dynamic response of table top structure. Different dynamic response is produced by different base conditions. Over large amplitudes of structure are expected in the case with natural soil, and the vibration can be reduced greatly by the soil improvement, jet grouting. Meanwhile, larger stiffness and damping are provided by piles with large diameter. Especially, as the soil properties are poor. the vibration can be reduced significantly by the piles with large diameter.

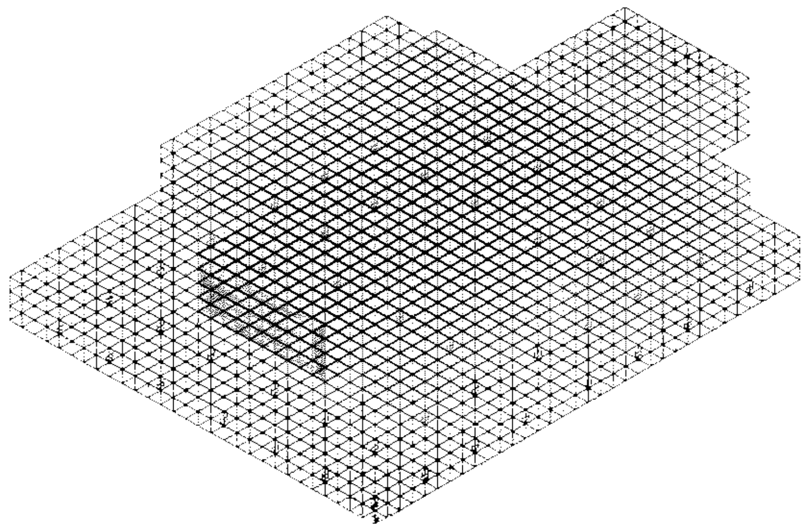

Fig. 4 Table Top Structure Modeled by Solid Elements.

## INVESTIGATION ON SOIL-PILE-STRUCTURE INTERACTION

To examine the soil-pile-structure interaction, different base conditions are considered. In the first case, the soil-pile-structure interaction is accounted for fully, as described in this study. In the second case, no deformation in base soil (no SSI) and the columns of table top structure were fixed (or pinned) to the base. The procedure has been used for many years that the soil-structure interaction is considered to be less important and ignored. In the third case, the dynamic soil-pile interaction is accounted for, but the table top structure is assumed to be rigid (no deformation in the superstructure). In some program of soil-foundation system, the mat (pile cap) is assumed to be rigid.

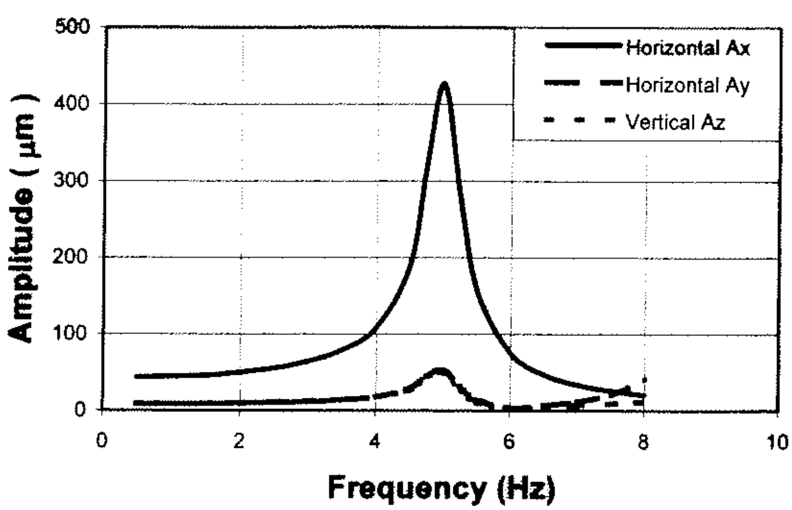


Fig. 5 Dynamic Response of Structure with Soil-Pile-Structure Interaction

In the first case, the soil-pile-structure interaction is accounted for fully, and included vibration in both foundation and superstructure. The option 2 for pile foundation is assumed, that is, 30 piles, with diameter of 0.9 m and length of 20 m. It is assumed that the structure subjects to dynamic load order 2 only, that is, $F_x$ = 101.4 kN, and $M_y$ = 110.6 kN-m, operating speed is 400 rpm (6.67 Hz). The dynamic response curves at the corners of deck slab are shown in Fig. 5.

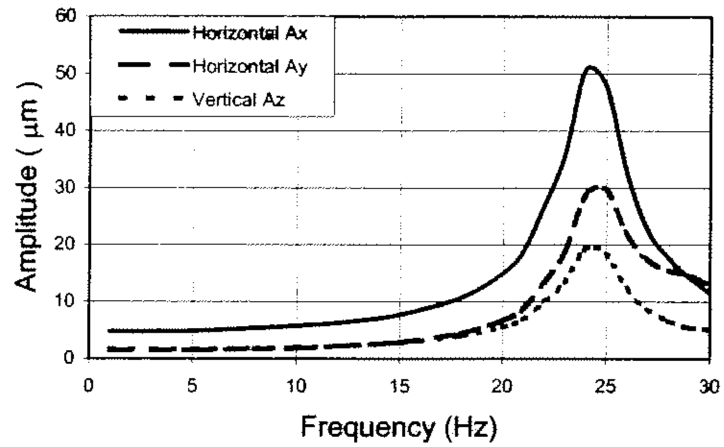


Fig. 6 Dynamic Response of Structure without SSI

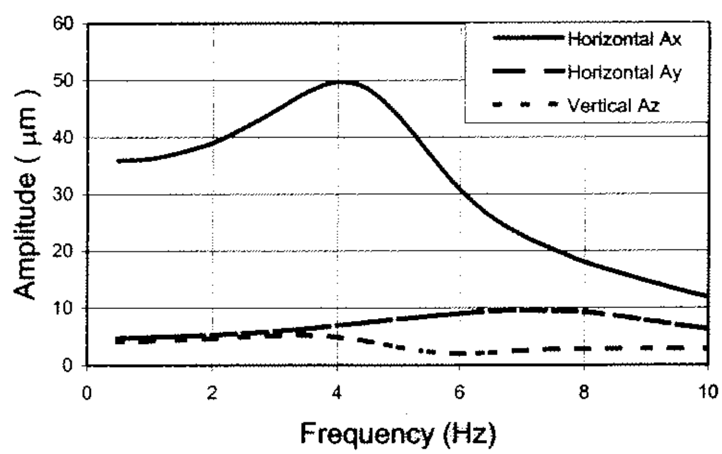


Fig. 7 Dynamic Response of Rigid Structure with Flexible Soil-Pile System

From Fig. 5, it can be seen that the peak value of amplitude is $A_x$ = 426 μm at frequency 5.0 Hz. At operating speed of 400 rpm (6.67 Hz) under load order 2, amplitude $A_x$ = 47 μm.

In the second case, no deformation in base soil (no SSI) and the columns of table top structure were pinned to the base. The same loads are applied to the same structure, and the structure is modeled by the same FEM. The dynamic response calculated at the same points is shown in Fig. 6.

From Fig. 6, it can be seen that the peak value of amplitude is $A_x$ = 51 μm at frequency 24 Hz. At operating speed of 400 rpm (6.67 Hz) under load order 2, amplitude $A_x$ = 5 μm.

In the third case, the dynamic soil-pile interaction is accounted, but the table top structure is assumed to be rigid (no deformation in the superstructure). The same loads are applied to the structure. The dynamic response calculated at the same points is shown in Fig. 7. It can be seen that the peak value of amplitude is $A_x$ = 50 μm at frequency 4 Hz. At operating speed of 400 rpm (6.67 Hz) under load order 2, amplitude $A_x$ = 25 μm.

The dynamic response is very different from above three figures. Not only the amplitudes calculated at operating speed are different, but also the resonance curves are different. As the structural columns pinned (or fixed) to the base, no soil-structure interaction, the resonance frequency is very high as shown in Fig. 6. The vibration is produced only in the superstructure, and no deformation in soil-foundation portion. Obviously, it is not true. As the table top structure is assumed to be rigid, the peak value is very low as shown in Fig. 7. The vibration is accounted for in the soil-foundation portion, but no deformation in the superstructure portion. A higher damping is involved in the dynamic response, and the damping comes mainly from the radiation damping of soil. As the soil-pile-structure interaction is accounted for, the peak value is much high and strong vibration is predicted in some frequency range (4 - 6 Hz) as shown in Fig. 5. The vibration occurred in entire table top structure and soil-foundation portion. In very lower frequency range, such as 0.5 - 2 Hz, the values of amplitude calculated with soil-pile-structure interaction (Fig. 5) are closed to that calculated with rigid superstructure (Fig. 7). However, the difference between the two curves becomes large with frequency increasing. Based on the comparisons, the role of soil, piles and structure in the dynamic response can be identified.

Material damping also called internal or hysteretic damping, and this is the energy loss within the material due to inter particle friction. The range of material damping ratio for concrete structures is 0.02 to 0.05. The material damping was taken as the same in the above three cases as 0.05.

## CONCLUSIONS

The soil-pile-structure interaction plays an important role in the vibration of elevated concrete foundation, and peak values of amplitude with SSI are much higher than that with other boundary conditions. The soil properties, design of the piles and the superstructure have a critical effect on the maximum amplitude of vibration.

The model of fixed (or pinned) base, no soil-structure interaction, can not lead to a reasonable solution. The resonance frequency calculated is much high with such a base condition, since the stiffness of structure is overestimated.

The model with rigid superstructure and flexible soil-pile system can not lead to a better solution, and the dynamic response is underestimated greatly. The deformation is needed to be considered in both portions of the soil-pile system, and the superstructure. From the comparisons in this study, the role of soil, piles and structure in the dynamic response can be identified.

Nonlinearity of soil is considered approximately using the model of soil-pile with non-reflective boundary. The dynamic analysis of soil-pile-structure interaction can be accounted for using the two commercial softwares.

The vibration of machine foundation is over large in the poor soil conditions. The amplitudes calculated are larger than the vibration limit defined by building code. The soft soil has to be improved for the elevated machine foundation. The soil properties can be improved greatly by the jet grouting, and both of stiffness and damping are increased. Higher values of stiffness and damping can be provided by piles with larger diameter. Especially, as the soil properties are poor, the option of pile foundation design with large diameter is better.

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