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Seismic Design Considering Soil-Pile-Structure Interaction

Yingcai Han [(1)] and Shin-Tower Wang [(2)]

(1) *Technical Director, Fluor, Vancouver, Canada,* yingcai.han@fluor.com

(2) *President, Ensoft,Inc, Austin,Texas,USA,* stw@ensoftinc.com

Abstract

The state of the art on subject of soil-pile-structure interaction is summarized, and focused on the practical applications in seismic design. The nonlinearity of soil is accounted for approximately using a boundary zone model with non-reflective interface. The ratio of G_i / G_o indicates the nonlinear properties of soil, where G_i and G_o is the shear modulus of soil in the boundary zone and the out zone respectively. The curves of stiffness and damping of soil-pile system *vs* the ratio of G_i / G_o provided in this study. The radiation damping (geometric damping) of foundation is also an important factor in dynamic or seismic design. The soil is assumed normally to be a homogeneous isotropic medium based on the elastic or visco-elastic theory. As a matter of fact, the soil is not a perfect linear elastic medium. It is well recognized in the soil dynamics field that the radiation damping is overestimated with the elastic theory.The effects of radiation damping on seismic response evaluated and the values of damping ratio modified based on a series of dynamic tests of single pile and group pile in the field. A simplified mathematical model of the coupled horizontal and rocking vibration of an embedded foundation was proposed. Only four impedance parameters are used in the displacement expression not six parameters as in traditional method, since the coupled ítems can not be balanced with the superstructure as using the substructure method. The effect of soil-pile-structure interaction was evaluated based on the different conditions. In the first case, the interaction was accounted for fully, that is, all of the soil, pile and structure are flexible. In the second case, the soil-pile system is flexible, but the structure was assumed to be rigid (no deformation in the superstructure). In the third case, the structure is flexible but fixed (or pinned) to the rigid base, no deformation in base soil (without SSI).

As for practical applications, a vacuum tower structure was examined in severe seismic zone as a typical industrial structure supported on pile foundation. The vacuum tower with diameter of 8.5 m and weight of 5,600 KN were installed in a steel frame. There are 25 steel piles in the foundation. Three base conditions were assumed to illustrate the soil-pile-structure interaction: rigid base (i.e. no deformation in the foundation), linear soil-pile system, and nonlinear soil-pile system. The stiffness and damping of pile foundation were calculated with linear and nonlinear soil respectively. A case of liquefaction was discussed for the pile foundation, considering the potential liquefaction in a shallow saturated sand layer. The seismic response were calculated using the response spectrum analysis and time history analysis, and compared with the method of equivalent static loads.

Keywords: soil -pile- structure interaction, nonlinear soil, soil dynamics, structural dynamics, seismic response

1. Introduction

Great advances have been developed on the subject of soil-pile-structure interaction in the past sixty years, and the importance of interaction is recognized widely in the dynamic or seismic design. However, some of the problems are still remained and concerned in practice. One of the interesting topic is how to account for the nonlinearity of soil in an earthquake environment. The plain strain model of soil-pile system has been improved by a boundary zone model. The curves of stiffness and damping of pile foundations are proposed, which vary with the ratio of G_i / G_o to indicate the nonlinear properties of soil, where G_i and G_o is the shear modulus in the boundary zone and the out zone respectively. Another interesting topic is the coupled horizontal and rocking vibration of an embedded foundation (pile cap). A simplified mathematical model was proposed to analyze the coupled vibration using four parameters rather than the traditional six parameters. The radiation damping is also a very important factor to the seismic design and discussed based on dynamic tests.

The effect of soil-pile-structure interaction is evaluated based on an engineering case, and the different soil conditions are considered. In the first case, the soil-pile-structure interaction is accounted for fully, that is, all of the soil, pile and structure are flexible. In the second case, the soil-pile system is flexible, but the structure is assumed to be rigid (no deformation in the superstructure). In the third case, the structure is flexible but fixed (or pinned) to the rigid base, no deformation in base soil (without SSI). Under seismic loads, the vibration of structure with soil-pile-structure interaction is shown in Fig. 1. The dash lines show the original position of the superstructure and foundation. The real lines express the deflections. Δ_1 is the foundation translation. Δ_2 is the foundation rotation, and $\Delta_2 = H \times \theta$, where H is the height of superstructure and θ is the rotation. Δ_3 is the deflection of superstructure.

In case 1, all of the deflections Δ_1, Δ_2 and Δ_3 are accounted for, that is, the flexibility of all soil, foundation and superstructure are included. The soil-pile-structure interaction is considered fully. In case 2, Δ_1 and Δ_2 are accounted for, but Δ_3 is neglected. The soil and piles are flexible, and the mat foundation (superstructure) is assumed to be rigid. Some dynamic analysis of vibrating foundations is done in this way.

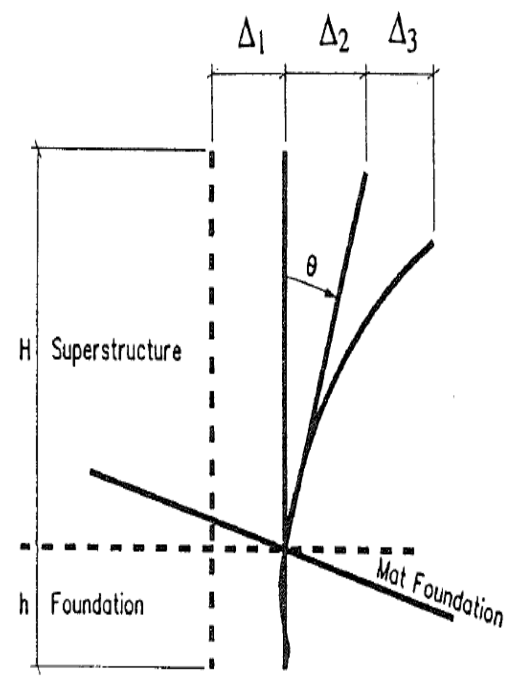

Fig. 1 Soil-pile-structure interaction

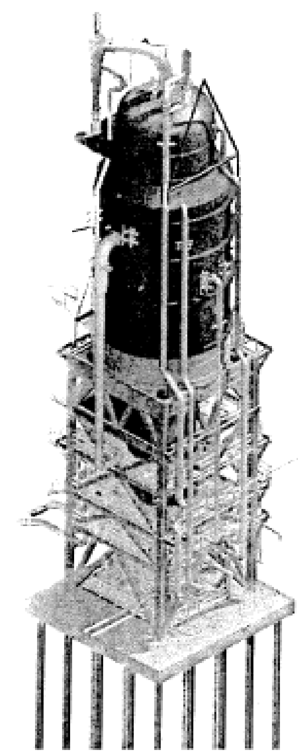

Fig. 2 Vacuum-tower structure on piles

In case 3, Δ_1 and Δ_2 are neglected and only Δ_3 is concerned, that is, the structure is fixed or pinned to the rigid base and no soil-structure interaction to be considered. The seismic analysis was done in this way sixty years ago. The effects of the soil-structure interaction on dynamic or seismic response can be illustrated from the comparison with the three cases. It should be explained that the absolute value of sum of Δ_1, Δ_2 and Δ_3 is not necessary to be larger than that of Δ_3, since their phases are different. The deflection values may be positive in some vibration, and negative in some vibration. So the deflection with soil-pile-structure interaction may be larger or less than that of the superstructure without the interaction as shown later.

As for practical applications, a vacuum tower structure is examined in severe seismic zone as a typical industrial structure supported on pile foundation as shown in Fig. 2. The vacuum tower sets on a steel frame with height of 20 m. There are 25 steel piles in the foundation. Three different base conditions are assumed to illustrate the soil-pile-structure interaction: rigid base (i.e. no deformation in the foundation), linear soil-pile system; and nonlinear soil-pile system. A case of liquefaction of sand layer is discussed for the pile foundation. The seismic response are calculated from the response spectrum analysis and time history analysis considering the soil-pile-structure interaction, and compared with the method of equivalent static loads.

2. Nonlinear Soil – Pile System

Many researchers have made contributions to the subject of soil-pile-structure interaction, such as Dobry & Gazetas [1], Roesset et al [2], Luco [3], Gazetas & Makris [4], Benerjee & Sen [5] and Wolf [6]. Recent alternative approaches were developed on this subject, such as analytical model based on homogenization methods by Boutin & Soubestre [7]. Macro-elements are used to model the soil-pile system by Li et al [8]. Different approaches are available to account for dynamic soil-pile interaction but they are usually based on the assumptions that the soil behavior is governed by the law of linear elasticity or visco-elasticity, and that 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 occur 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. Various numerical approaches are used to model the soil-pile interaction, such as the finite element or boundary element methods. However, the problem is too complex, especially for a group with large number 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, the procedure is developed using a combination of the analytical solution and the numerical solution, rather than using the general FEM. This procedure is considered as an efficient technique for solving the nonlinear soil-pile system. The relationship between the foundation vibration and the resistance of soil layers around the pile was derived using elastic theory by Baranov [9]. 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. Velestsos and Dotson [10] 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 [11], who found that a homogeneous boundary zone with a non-zero mass yields undulation impedance due to reflections of stress wave from the fictitious interface between the two media.

A model for the boundary zone with a non-reflective interface was proposed. The soil in boundary zone have properties smoothly approaching those of the outer zone to alleviate wave reflections from the interface. The details of constitutive model have been described by Han & Sabin [12], not repeat herein. The modulus ratio G_i /G_o is an approximate indicator for the nonlinear behavior of soil. The value of the modulus ratio depends on the method for pile installation, the density of excitation and vibration amplitudes. Further dynamic tests on piles are needed to determine the value of the modulus ratio. The model of the boundary zone with a non-reflective interface has been applied to practice to solve the problem for many projects. However, it should be explained that the method is not a rigorous approach to model the nonlinearity of a soil-pile system. It is an equivalent linear method with a lower value of G_i and a higher value of damping β_i in the boundary zone. With such a model the analytical solutions can be obtained for the impedance functions of a pile, and the software DYNAN [13] was developed based on the approach.

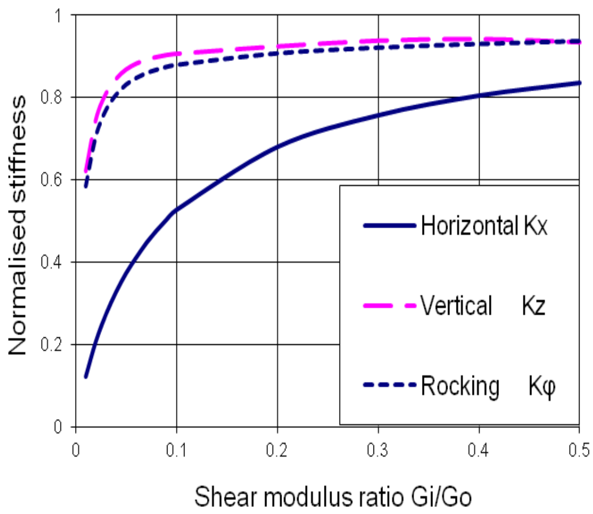

Fig. 3. Normalized stiffness of piles *vs* G_i / G_o

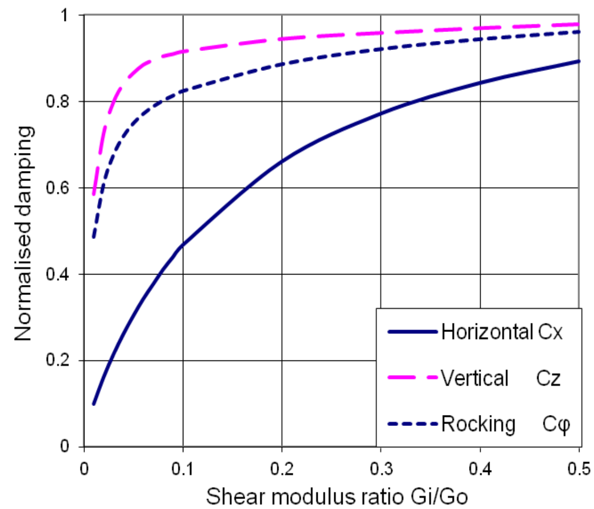

Fig. 4. Normalized damping of piles *vs* G_i / G_o

For the pile foundation under static loads, the differential equation for a beam-column can be solved using nonlinear lateral load-transfer (*p-y*) curves. Nonlinear lateral load-transfer from the foundation to the soil is modeled using *p-y* curves for various types of soil. Unfortunately, the dynamic equations of soil-pile system can not be solved analytically by using the *p-y* curves. An approximate analysis has to be used for the dynamic analysis of pile foundations. The dynamic equations have been solved using the ratio of shear modulus G_i /G_o to indicate the nonlinear properties of soil. The plane-strain model is improved by the boundary-zone approach for the soil-pile system. The nonlinear variation curves of stiffness and damping and range of values for G_i /G_o are discussed in the following. The normalized stiffness and damping of pile foundation varied with G_i /G_o as shown in Figure 3 and Figure 4 respectively. The values of stiffness and damping are generated at frequency 1.0 Hz, and applicable to general pile foundations no matter concrete piles or steel piles.

The stiffness and damping are frequency dependent. The values of stiffness and damping are normalized to show the effects of G_i /G_o. The normalized stiffness and damping are defined as the dynamic stiffness and damping to be divided by static values. It should be explained that the static stiffness can not be generated directly from the program, and the values of stiffness and damping in very low frequency domain such as 0.01 Hz were assumed to be close to as static values. From Figures 3 and 4, it can be seen that the variation of stiffness and damping is larger for horizontal vibration than those for vertical and rocking vibration. It is concluded that the effects of G_i /G_o are more significant on lateral impedances than those on vertical and rocking impedances. Also, it is noted that the stiffness and damping vary gently as $G_i / G_o = 0.25 - 0.5$, and vary sharply as $G_i / G_o < 0.25$. As $G_i / G_o < 0.1$, the stiffness and damping are reduced seriously for all of the vibration modes such as under seismic loads. The value of G_i / G_o depends on the vibration intensity of pile, and the reduction increases with the vibration intensity. The values of G_i / G_o can be estimated based on dynamic tests of pile foundations. It is suggested that $G_i / G_o = 0.25 - 0.5$ for design of machine foundations, and $G_i / G_o < 0.25$ for strong earthquake response. So it can be understood that the shear wave velocity of soil V_s is reduced to about 50% to 70% in the boundary zone corresponding to $G_i / G_o = 0.25 - 0.5$. V_s is reduced to less than 50% corresponding to $G_i / G_o < 0.25$, and V_s is reduced to about 1/3 corresponding to $G_i / G_o = 0.1$.

The group effect of piles is accounted for using the method of interaction factors. The static interaction factors are based on Poulos and Davis [14]. 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 [15]. There are six degrees of freedom for the rigid mat, and lateral vibration is coupled to rocking vibration. It should be explained that the foundations (or caps on piles) are assumed to be rigid. However, in most cases, the superstructures are flexible rather than rigid. The effects of soil-pile-structure interaction on dynamic response of machine foundations were discussed by Han [16]. The dynamic response of the superstructure can be calculated using FEM models by software SAP 2000 [17].

3. Coupled Vibration of Embedded Foundation (Pile Cap)

As for the approximate analysis, the Baranov-Novak method is considered in general as an efficient technique for solving the problem of coupled horizontal and rocking vibration of an embedded foundation. The relationship between the foundation vibration and the resistance of soil layers was derived using the elastic theory. Then, the solutions of coupled horizontal and rocking vibration of embedded footings were formulated. Six vibration parameters for 2-dimensional applications are included in the displacement expression, which are, horizontal stiffness and damping K_x, C_x, rocking stiffness and damping K_φ, C_φ, and cross coupled stiffness and damping $K_{x\varphi}$, $C_{x\varphi}$. However, the foundation embedment conditions are very complex practically. An inverse problem is often used in experimental research: all the parameters of the embedded foundation are to be determined, while the dynamic response is given from measurements. It is difficult to back-calculate for the six parameters in the displacement expressions.

A simplified mathematical model of the coupled horizontal and rocking vibration of an embedded foundation was proposed by Han [18], as shown in Fig. 5 and was implemented in the program. Vibration tests of the foundation with different embedment were conducted and compared with different methods. Based on this method, only four parameters are required in the displacement expression but six parameters are required in Novak's method. The four parameters can be back-calculated from the dynamic response of the foundation using this method. The results by the present method agree with the measured data for the foundation with different embedment. The boundary condition between foundation and superstructure consists of only four impedances, i.e. horizontal stiffness & damping and rocking stiffness & damping, in the substructure method. It should be noted that there are no options of including the coupled terms at the boundary in most of superstructure software, then the coupled items $K_{x\varphi}$ and $C_{x\varphi}$ from foundation part can be not balanced, and have to be eliminated in the analysis of soil-pile-structure interaction.

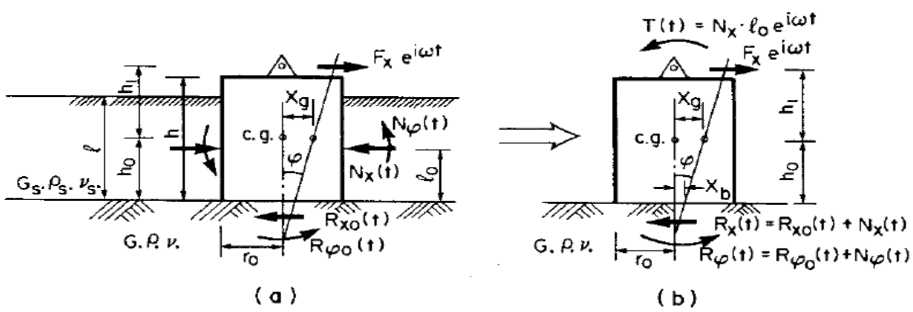

Fig.5. Simplified mathematics model of coupled horizontal and rocking vibration of embedded foundation (pile cap) (a) exciting force and reaction forces acting on the embedded footing (b) equivalent foundation rested on the surface of elastic half-space.

4. Radiation Damping

The radiation damping (geometric damping) is also an important factor in dynamic or seismic design. The elastic-wave energy from foundation vibration dissipated infinitely far away in three dimensions to form the radiation damping. The radiation damping is the dominant energy dissipation mechanism in most dynamically loaded foundation systems, and also in the seismic response. The formula of radiation damping is derived based on elastic theory in which the soil is assumed to a homogeneous isotropic medium. As a matter of fact, however, the soil is not a perfect linear elastic medium as assumed. It is well recognized in the soil dynamics field that the damping is overestimated with the elastic theory. The values of radiation damping have been modified and reduced in the application based on the measurements in practice. To validate the soil-structure interaction, a series of dynamic experiments have been done on full-scale piles, see El-Marsafawi et. Al [19]. The vibration measurements were done on group piles in the field to confirm the theoretical values modified for applications, see Han and Yang [20].

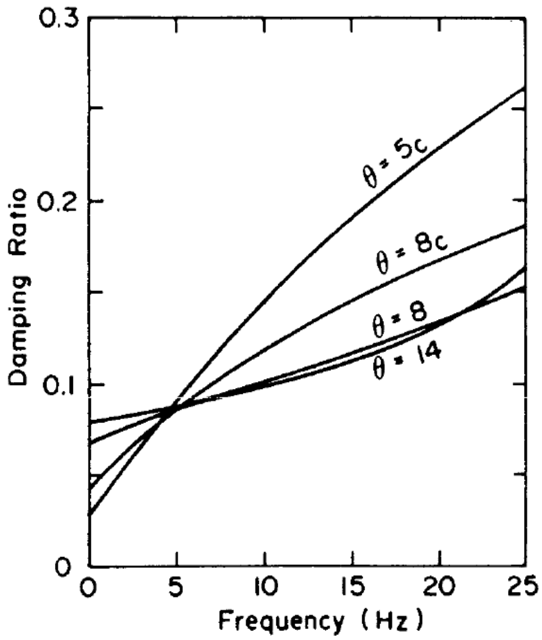

Fig. 6 Horizontal damping ratio of pile

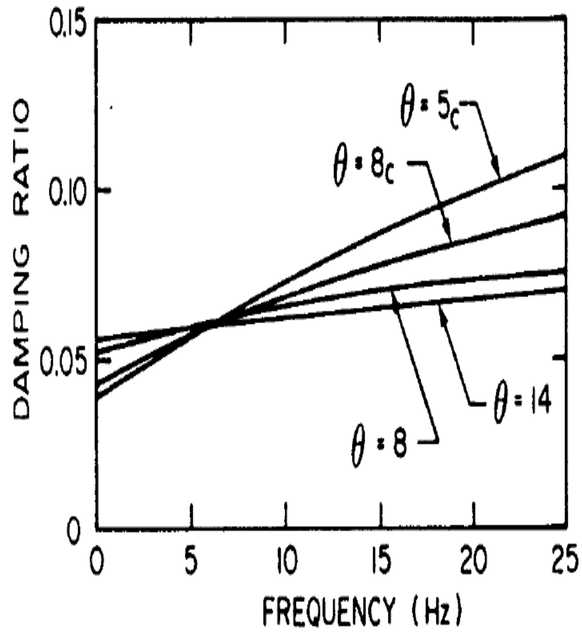

Fig. 7 Rocking damping ratio of pile

The damping ratios were calculated based on the measurements from a dynamic test of steel pile in the field, as shown in Fig. 6 for horizontal vibration, and Fig. 7 for rocking vibration, see Han and Novak [21]. The harmonic excitation loads applied to the pile cap from low frequency to high frequency (25 Hz) with different levels of excitation intensities, where the curves are marked by θ to identify the different values of the dynamic loads. As the bottom of pile cap connected to the ground surface, the excitation intensity is marked by θ = 5c and 8c. As the bottom separated from ground surface, the excitation intensity is marked by θ = 8 and 14. It can be seen that the radiation damping increases with the frequency, and the damping ratio increased from 0.05 to 0.25. The nonlinear properties of soil shown up with the excitation intensities increased in this case.

As known most components of earthquake forces are in the lower frequency domain. The seismic response is affected by the radiation damping, although the damping ratio may be not very high in the fundamental period of earthquake forces. The reduction of radiation damping is different for uncoupled model of single pile and pile group due to the effects of coupled vibration and group effect. So the dynamic experiments were performed to estimate the reduction of damping for the single-pile and group-pile foundations separately.

5. Effects of Soil-Pile-Structure Interaction

Classical empirical methods of the dynamic analysis assume that the foundation acts as a rigid body, such as Barkan model [22]. In this study three conditions of soil-pile-structure system were considered. The first case, the soil-pile-structure interaction is accounted for fully, all of the soil, pile and structure are flexible. The second case, the soil-pile system is flexible, but the table top structure is assumed to be rigid (no deformation in the superstructure). Normally the dynamic analysis for foundations supporting vibrating equipment is conducted in this way. The third case, the columns of table top structure are flexible but fixed (or pinned) to the rigid base, no deformation in base soil (without SSI). In early years the seismic analysis was generally conducted in this way.

A practical case of a table top structure with a reciprocating compressor foundation is examined to illustrate the effects of soil-pile-structure interaction. 47 concrete piles were used to support the reciprocating compressor foundation, and pile diameter is 0.6 m with length of 49 m. The dimension of mat foundation (pile cap) is 16.6 m by 14.35 m, with thickness of 1.5 m. The shear modulus ratio $G_i / G_o = 0.5$ was assumed to indicate the non-linear behavior of soil. The stiffness and damping of piles were generated by the program as shown in Table 1.

Table 1 Stiffness and Damping of Pile Foundation

Stiffness			Damping		
K_x (kN/m)	K_z (kN/m)	K_φ (kN.m/rad)	C_x (kN/m/s)	C_z (kN/m/s)	C_φ (kN.m/rad/s)
2.226×10^{6}	3.227×10^{6}	4.586×10^{8}	1.125×10^{5}	2.667×10^{5}	7.073×10^{6}

Where K_x, K_z, and K_φ are stiffness in the horizontal, vertical and rocking directions, and C_x, C_z, and C_φ are damping constants in the same direction.

The dynamic response of table top structure was analyzed by using the finite element model from SAP 2000 with the input of foundation stiffness and damping as listed in Table 1. The displacement curves calculated at the corners of deck slab are shown in Fig. 8. It should be explained that the response of foundation is a coupled vibration between three translational and three rotational modes, although only horizontal and vertical behavior are described herein. It can be seen that the peak value of amplitude is 426 μm at frequency 5.0 Hz while the amplitude is 47 μm at the operating speed of 6.67 Hz (400 rpm).

For the second case, the deformation of base soil was accounted, but the table top structure was assumed to be rigid. The stiffness and damping of piles were generated as the same as in the first case. The same loads were applied to the structure. The displacement curves calculated at the same points is shown in Fig. 9. It can be seen that the peak value of amplitude is 50 μm at frequency 4 Hz while the amplitude is 25 μm at the operating speed. The deformation of superstructure was not considered since it was assumed to be rigid. It can be seen that the resonant frequency is close to that or a little lower than that in Fig. 8, but the dynamic response is underestimated significantly.

For the third case, the columns of table top structure were pinned to the rigid base (no SSI). The superstructure is flexible but the deformation of base soil was ignored. The structure was subjected to the same loads, and modeled by the same FEM model. The displacement curves calculated at the same points are shown in Fig. 10. It can be seen that the peak value of amplitude is 51 μm at frequency 24 Hz while the amplitude is 5.0 μm at the operating speed. In this case, the resonant frequency is very high since the soil-structure interaction was ignored. The vibration was produced only in the superstructure, and no deformation was considered in the soil-foundation portion. Obviously, it is not true in real situations. The stiffness of structure was overestimated since it was fixed to the rigid base. The damping was underestimated since the energy of vibration transferred though soil (radiation damping) was ignored.

From the above comparison it can be seen that the dynamic response of structure with varied conditions is quite different. Not only the amplitudes are varied at operating speed, but also the resonant frequencies and peak values are very different. As shown in Fig. 8, the peak value is much higher and strong vibration is predicted in the resonant frequency domain. The vibration occurred in the entire superstructure (table top structure) and the soil-foundation portion. It is interesting to note that the values of amplitude calculated with the soil-pile-structure interaction (Fig. 8) are close to that calculated with the rigid superstructure and the flexible soil-pile system (Fig. 9) in a very lower frequency range, such as 0.5 to 2 Hz. However, the difference between the two curves becomes large with frequency increasing. The higher values of amplitudes in Fig. 8 come from some higher modes at some locations of the superstructure.

With the comparisons above, the role of soil, piles and structure in the dynamic response can be identified. The range of material damping ratio for concrete structures is 0.02 to 0.05. The damping ratio was taken as 0.02 for all of the three cases. A higher damping is involved with soil-pile interaction, and the damping comes mainly from the radiation damping of soil.

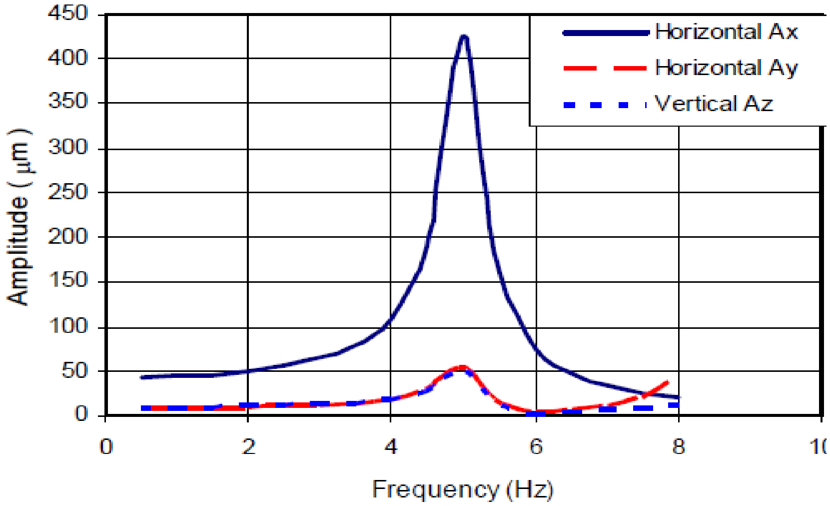

Fig. 8 Dynamic Response of Structure with Soil-Pile-Structure Interaction (Case 1)

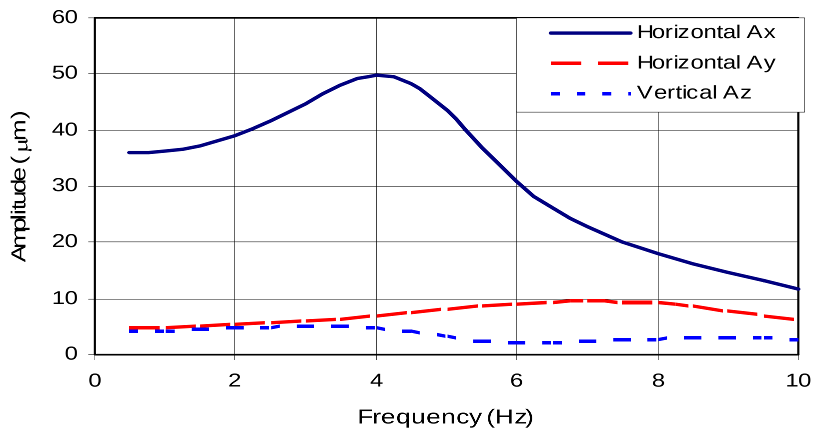

Fig. 9. Rigid Structure Rest on Flexible Piles (Case 2)

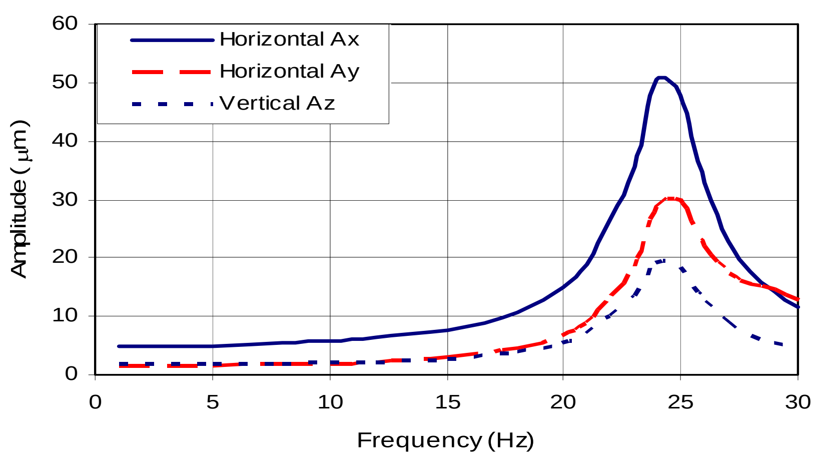

Fig.10. Flexible Structure Rest on Rigid Base (Case 3).

6. Seismic Response of Vacuum Tower Structure

A vacuum tower structure was constructed as shown in Fig. 11 in a seismically active area. At the site, surface soil is soft clay with a depth of 2 m, underlain by a layer of saturate fine sand with a depth of 2 m, followed by some silty clay and dense sand layers with depths of 4 to 8 m in each layer, then bedrock. The depth to bedrock is about 30 m. Soil properties vary with depth and are characterized by the shear wave velocity and unit weight, as shown in Table 2.

The vacuum tower with a diameter of 8.5 m, height of 35 m and weight of 5,600 KN installed in a steel frame with height of 20 m. The concrete mat foundation is 12 x 12 m with a thickness of 1.2 m. The piles are steel HP 360 x 108 with length of 30 m driven to bedrock. Twenty-five piles in a square pattern were fixed to the mat foundation.

Time history analysis was carried out with the soil-pile-structure interaction. A record of horizontal ground acceleration from an earthquake was employed for the time history analysis. The peak value of acceleration is 0.13 g as shown in Fig. 12. The time step is 0.005 second, and duration is 80 second in the earthquake record. The stiffness and damping of the pile foundation were calculated for different base conditions. In the first case a linear soil-pile system is assumed, that is, the soil layers are homogeneous, elastic medium without the weakened zone.

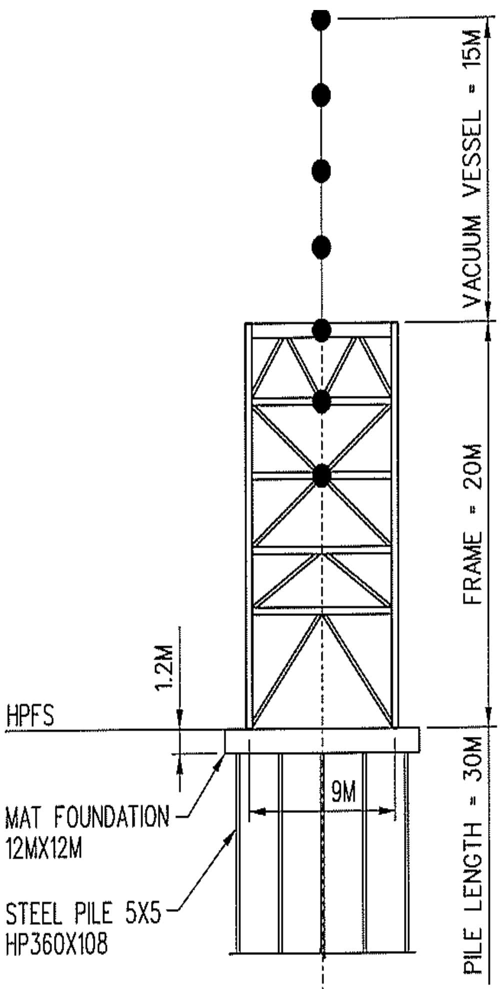

Fig. 11 Model of vacuum tower structure

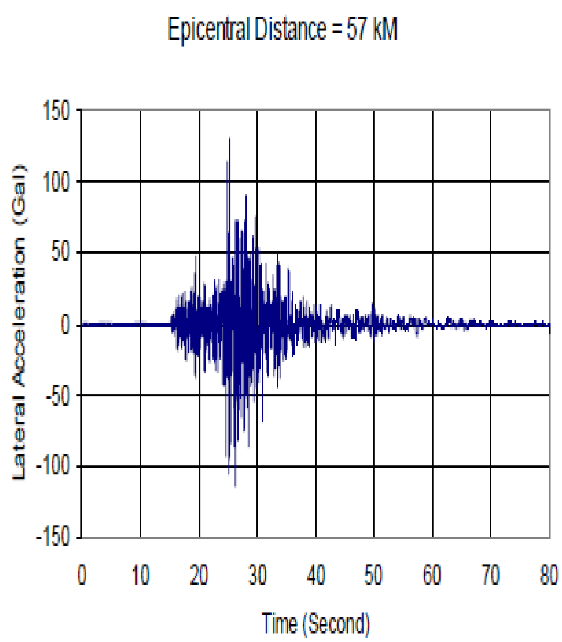

Fig. 12 Horizontal ground acceleration from an earthquake record

Table 2. Soil Properties

Depth (m)	Soil	Unit Weight (kN / m ^{3})	Shear Wave Velocity (m/s)
0 -2	Soft Clay	18	130
2 - 4	Fine Sand	18	140
4 - 12	Stiff Clay	20	300
12 - 16	Silty Sand	19	240
16 - 20	Silty Clay	18	300
20 - 25	Weathered Shale	18	200
25 - 30	Dense Sand	20	300
Below 30	Bedrock	21.5	370

Table 3. Stiffness and Damping of Pile Foundation with Different Soil Status

Soil status	Stiffness			Damping		
	K_x (kN/m)	K_z (kN/m)	K_φ (kN.m/ra)	C_x (kN/m/s)	C_z (kN/m/s)	C_φ (kN.m/rad/s)
Linear	1.283×10^6	3.215×10^6	1.333×10^8	1.244×10^4	1.803×10^4	6.411×10^5
Nonlinear	0.646×10^6	2.877×10^6	1.160×10^8	0.998×10^4	1.005×10^4	3.171×10^5
Liquefaction	0.180×10^6	2.527×10^6	1.006×10^8	0.749×10^4	0.943×10^4	2.787×10^5

In the second case, a nonlinear soil-pile system is assumed, and the boundary zone is considered around the piles. The parameters of the boundary zone were selected as: G_i / G_o = 0.25. In the third case, liquefaction was assumed in the saturated fine sand layer, and the top layer of soft clay has not yielded. Both stiffness and damping are frequency dependent. Since the fundamental period of the structure is closed to 1.0 second, the stiffness and damping were calculated at a frequency of 1.0 Hz. The stiffness and damping calculated are shown in Table 3. Where, K_x, K_z and K_φ are stiffness in the horizontal, vertical and rocking directions, and C_x, C_z and C_φ are damping constants in the same directions. It can be seen that both stiffness and damping are lower in the nonlinear case than those in the linear case, such as the horizontal stiffness reduced to half of that in the linear case. The stiffness and damping reduced further due to the liquefaction of sand layer, such as the horizontal stiffness reduced to 15% of that in the linear case.

To investigate the influence of foundation flexibility on the superstructure, the seismic analysis of the structure was conducted for three different base conditions: rigid base, linear and nonlinear soil-pile systems. The seismic response and forces of the structure were analyzed using a FEM model. The vacuum vessel was modeled as an elastic column with the mass distributed uniformly along its height. The steel structure was modeled using frame elements and the mat foundation was modeled using shell elements. The stiffness and damping of the pile foundation were generated for the three base conditions using the program. The deflection, base shear and overturning moment are calculated using the FEM model, as shown in Table 4. It can be seen that the earthquake forces for the fixed base condition are larger than those for the cases with the soil-structure interaction. The theoretical prediction does not represent the real seismic response, since the stiffness is overestimated and the damping is underestimated for a structure fixed on a rigid base. From the comparison, it can be seen that the maximum values and time histories for the seismic forces and seismic response are different when the foundation is considered as a fixed base or a flexible base.

Table 4. Seismic Response and Seismic Forces with Different Base Conditions

Base Conditions	Amplitude at Tower (mm)	Base Shear (kN)	Overturn Moment (kN-m)
Fixed Base	22.05	807	19,630
Linear Soil	26.30	598	14,980
Nonlinear Soil	26.05	545	14,120

Table 5. Comparison of Seismic Forces and Response by Different Analysis

Method of analysis	Amplitude at Tower (mm)	Base Shear (kN)	Overturning Moment (kN-m)
Time history	22.05	807	19,630
Response spectrum	24.10	897	21,349
Equivalent static forces	20.90	862	20,516

The seismic response and seismic forces were calculated, and the comparison of results from the time history analysis, the response spectrum analysis and the method of equivalent static forces are shown in Table 5. It can be seen that the results calculated are comparable from different methods.

7. Conclusions

The nonlinearity of soil-pile system is complex and important to earthquake engineering. The engineering software DYNAN and SAP 2000 are available to applications in practice.

1. The damping would be underestimated and the stiffness would be overestimated with a rigid base to be assumed. The dynamic response would be underestimated significantly in some case, since the contribution from high modes of structure is ignored, if the superstructure were assumed to be rigid.
2. The nonlinear properties of soil can be accounted for approxamely by the program, using an improved boundary zone model with non-reflective interface. The values of radiation damping have been modified and reduced in the program based on a series of dynamic tests for single pile and group pile in the field.
3. The effects of soil properties were examined for different cases of linear, nonlinear and liquefaction. The horizontal stiffness in nonlinear case reduced to half of that in the linear case. The stiffness and damping reduced further due to the liquefaction of sand layer, such as the horizontal stiffness reduced to 15% of that in the linear case.

8. References

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