Dynamic behavior of turbine foundation considering full interaction among facility, structure and soil

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SUMMARY
In this paper a comprehensive investigation on the dynamic characteristics of turbine-foundation-soil system is performed. To consider the soil effect and facility vibration, a sophisticated finite element model was constructed. All the major components of the system, including shaft, rotors, journal bearings, deck, piers, foundation mat, piles, and soil medium, have been included. Full interaction between the facility, the foundation, and the soil medium, is considered. A 1000MW turbine-foundation-soil system is analyzed under excitations from rotor unbalances and earthquakes. The influence of soil-structure interaction (SSI) on the response of the system is explored by using three-dimensional viscous-spring boundary elements. It is found that the effect of SSI strongly influences the displacements and internal forces of the system under rotor unbalance excitation. Under seismic excitation, however, although the presence of soil does affect the displacements of the system, the effect on the acceleration and internal force is minimal.

Keyword: turbine-foundation-soil system, soil-structure interaction, dynamic behavior

1. INTRODUCTION

A turbine-generator set and its foundation constitute a rather complicated system, which consists of shaft, rotors, journal bearings, deck, piers, mat, piles and the underlying soil medium, as illustrated in Figure 1. The deck and the piers, on which the turbine-generator set is anchored, are usually designed in steel, reinforced concrete, or prestressed concrete. The deck carries the machinery on the top and provides enough space below to install the auxiliary equipment such as condensers and pipes. The spatial frame configuration of the deck and piers is commonly referred to as the turbine-generator pedestal. The dynamic behavior and seismic response of such a system is determined by the interaction of all the components. The foundation not only should have a sufficient bearing capacity to support the turbine machine and its auxiliary equipment, but also be designed to limit the vibration amplitudes of the shaft, the rotors, and the bearings within the acceptable level. Excessive vibration amplitudes and deflections may cause serious damage if rotor blades hit the casing.

Early analyses of turbine-foundation systems were conducted based on very simplified models such as lumped mass systems. With the development of the finite element method, three-dimensional elements were introduced to model the deck and piers. The influence of the soil-structure interaction, if ever considered, was estimated crudely by introducing spring and dashpot coefficients of the elastic half-space solution. For years afterward, scientists put forward artificial boundaries, such as viscous-spring boundaries, to solve the problem caused by reflection at the edges of soil computational domain and successfully employed this method in 2D and 3D numerical simulation.

In this paper, a numerical model of the complete turbine-foundation-soil system is established using three-dimensional solid elements. All the major components of the system, including the rotors, shaft, bearings, the deck, the columns, the foundation mat, the optional piles, and the soil medium, are incorporated. The turbine-generator, the foundation superstructure and the soil medium are modeled by finite elements. The underlying soil is a layered medium with viscous-spring boundaries at edges of the computational domain. Seismic excitation is introduced by the inversion from free ground motion to soil medium boundaries.

The response of a typical 1000MW turbine-generator-foundation system subjected to rotor unbalance and seismic load is presented. The influence of soil-structure interaction, which has been conducted roughly in previous studies, is investigated.

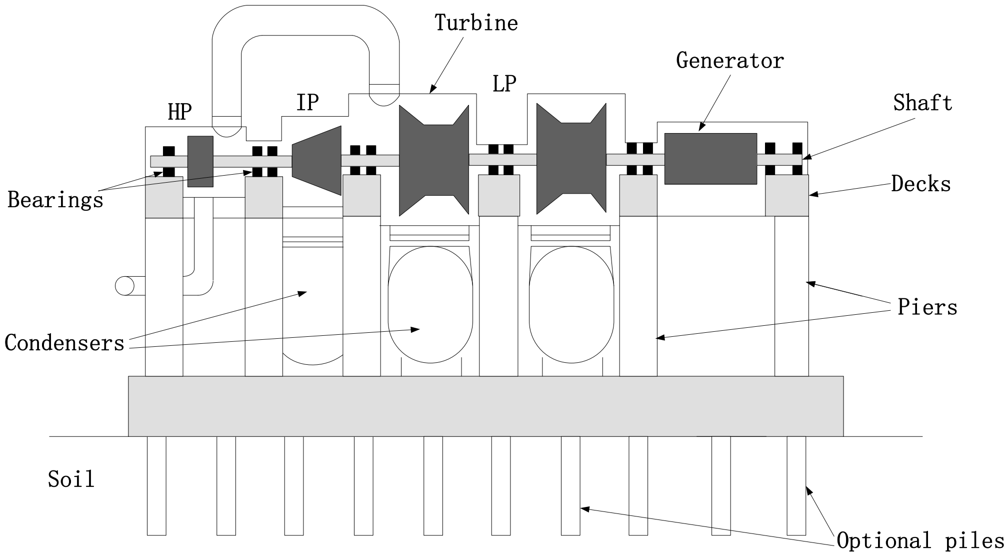
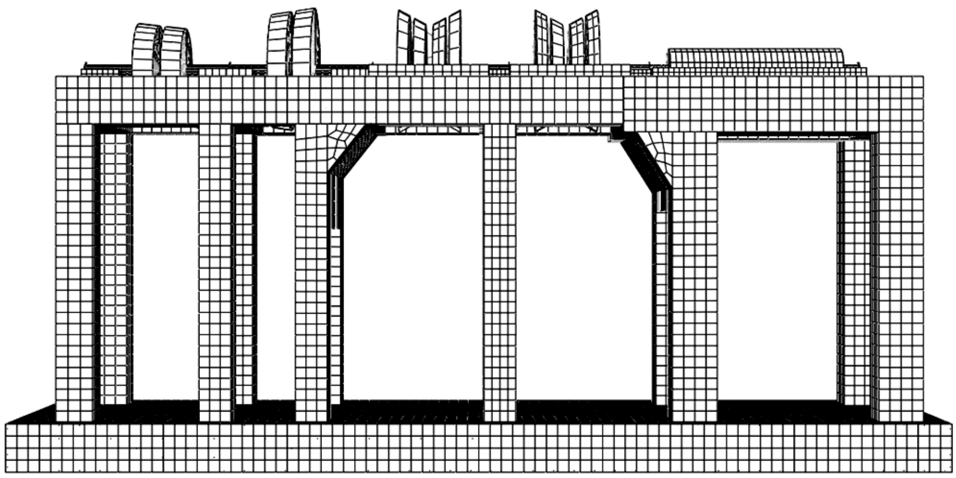


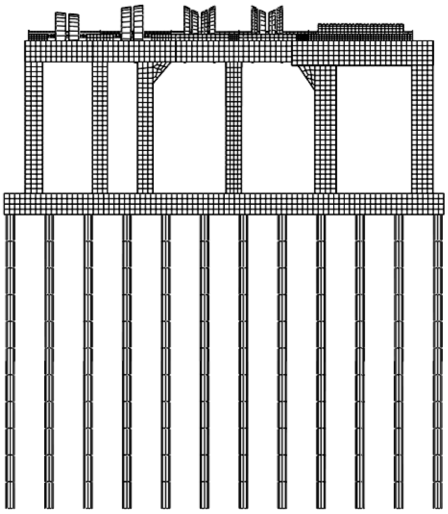
Figure 1. A schematic view of a 1000MW turbine-generator-foundation system

2. THE NUMERICAL MODEL FOR TURBINE-FOUNDATION-SOIL SYSTEMS

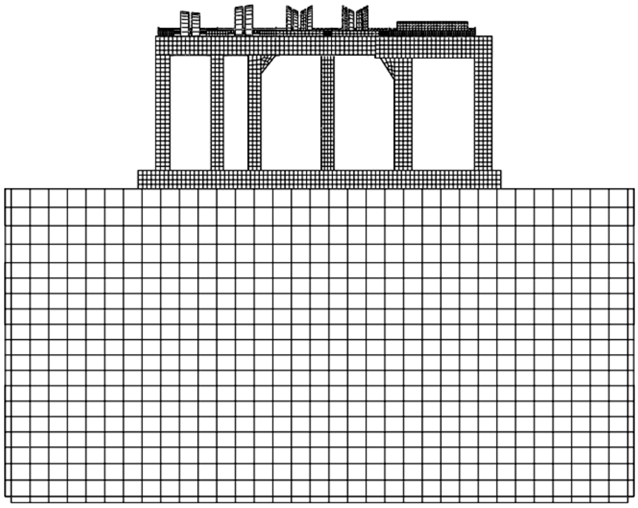
The facility, including shaft, rotors and journal bearings, is considered as rigid body, which has no material definition and is anchored on the deck with rigid connection. The underlying soil is modeled as layered medium, which is surrounded by viscous-spring artificial boundaries. The whole model of the system is illustrated as Figure 2. The turbine has three stages, i.e. HP, IP and LP, with an operating speed of 3000n/s. The rotors are idealized as several rigid disks attached to the shaft, which is supported on six groups of journal bearings. The operating deck and the twelve columns form a spatial frame structure. Both the deck and the mat are rather thick concrete plates. The piles are modeled as three-dimensional solid elements and embedded in the soil medium.



(a) without soil and piles



(b) With piles only



(c) With piles and soil

Figure 2. A schematic view of the 3D finite element model

2.1. The Turbine-Generator System

The turbine-generator system consists of the shaft, the rotors and the journal bearings. The numerical discretization of shaft-rotor is shown in Figure 3.

The shaft, which has the same diameters at each turbine-generator stage, is represented by rigid elements with circular cross-sections. The rotors within several turbine stages and generator are simulated as rigid disks attached along the shaft. The HP rotor is represented as two disks with 12tone mass each. The IP rotor is represented as two disks with masses of 15.5tone each. The LP rotor is represented as four 20tone disks and four 19tone disks. The generator rotor is represented as a long stick with mass of 100tone.

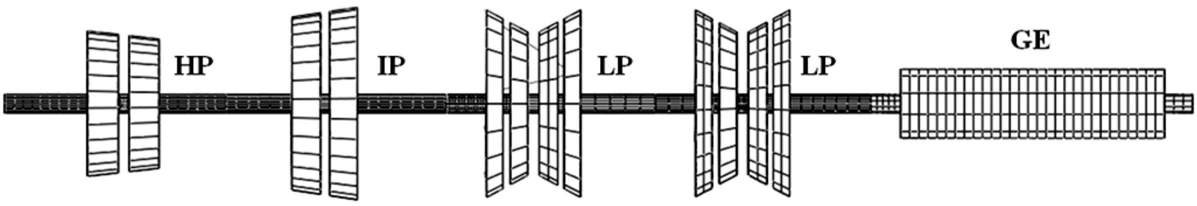


Figure 3. Numerical discretization of the shaft-rotor of a 1000MW turbine-generator set

2.2. The Foundation Superstructure

The turbine machine and the generator are anchored on an operating deck, which is supported by piers. This spatial frame structure, as shown in Figure 2(a) and Figure 4, allows space under the turbine to install other auxiliary facilities such as condensers and piping. The operating deck is made from reinforced concrete with the material parameters listed in table 1. The columns are 18.8m high with the same material as the deck and rectangular cross-section (2.5m×2.5m) on the average. The geometrical dimensions of the mat (with a thickness of 4m) can be shown in Figure 4. The material of the mat is same as that of the deck and columns.

Table 2.1 Material Parameters of The Deck

Material	Young's modulus	Poisson's ratio	Mass density	Damping ratio
Concrete	32.5gpa	0.2	2550kg/m^3	0.05
Rebar	200gpa	0.3	7850kg/m^3	0.05

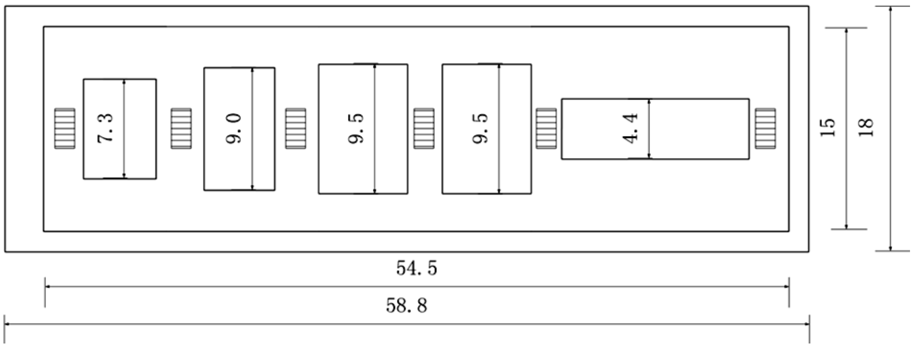
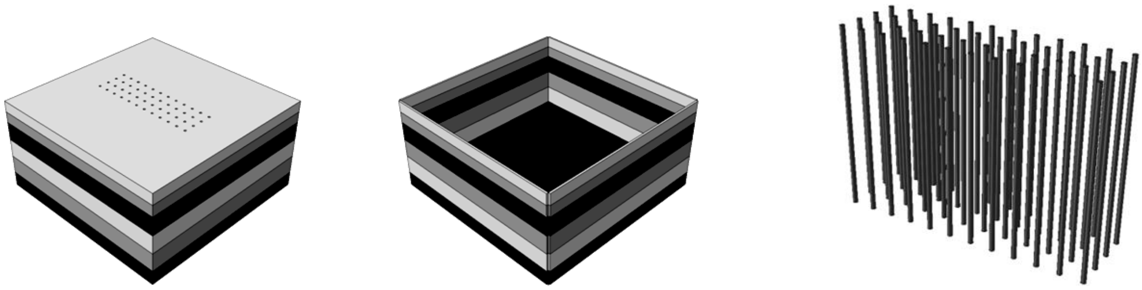


Figure 4. Plan view of the operating deck, columns and the foundation mat (unit:m)

2.3. The Underlying Soil Medium

The underlying soil, which is embedded by 48 piles, is modeled as a three-dimensional medium, as shown in Figure 5. The geometrical size of the soil is 100m×100m×50m and the soil is surrounded by viscous-spring artificial boundaries. The material parameters of the layered soil and boundaries are listed in the Table 2 and Table 3. The plies are also made of reinforced concrete and provided with the same material as deck and columns.



(a) soil medium (b)artificial boundaries (c)piles

Figure 5. Isometric view of the soil medium and piles

Table 2 Material Parameters of The Layered Medium

Layer	Description	Thickness	Young's modulus	Poisson's ratio	Mass density
1	Clay	6m	197mpa	0.3	1930kg/m^3
2	Sand	6m	312mpa	0.3	1920kg/m^3
3	Transition	10m	638mpa	0.35	1940kg/m^3
4	Residual1	10m	1283mpa	0.35	1900kg/m^3
5	Residual2	10m	1872mpa	0.3	2000kg/m^3
6	Weathered rock	8m	3362mpa	0.3	2020kg/m^3

Table 3 Material Parameters of The Artificial Boundaries

Position	Young's modulus	Mass density	Stiffness coefficient
Side 1	6.17mpa	100kg/m^3	0.37
Side 2	9.13mpa	100kg/m^3	0.30
Side 3	17.99mpa	100kg/m^3	0.23
Side 4	33.62mpa	100kg/m^3	0.17
Side 5	46.53mpa	100kg/m^3	0.15
Side 6	76.51mpa	100kg/m^3	0.12
Bottom	86.13mpa	100kg/m^3	0.11

2.4. The Viscous-Spring Artificial Boundary

The purpose of the viscous-spring artificial boundary is to eliminate the reflected wave that occurs at the boundary surface of the soil computational domain by simulating the impact from outside infinite medium to inner area. If the effects of forces between the outside medium and inner domain can be described rationally and precisely by a certain system, the energy transmits from the structure to infinite soil may go though the artificial boundaries without reflection. Such a system always contains components of stiffness, damping and mass, as shown in Figure 6 (a). However, the viscous-spring-mass system is not stable because the damping part and the mass part are in series connection. To guarantee the robustness of the system, the mass cell is removed and left with only stiffness and damping parts, as shown in Figure 6 (b). The parameters of such a system were deduced by Liu Jingbo and he finally proved the accuracy of this method in three-dimensional simulation. The values of the stiffness and damping in this system can be got by following parameters:

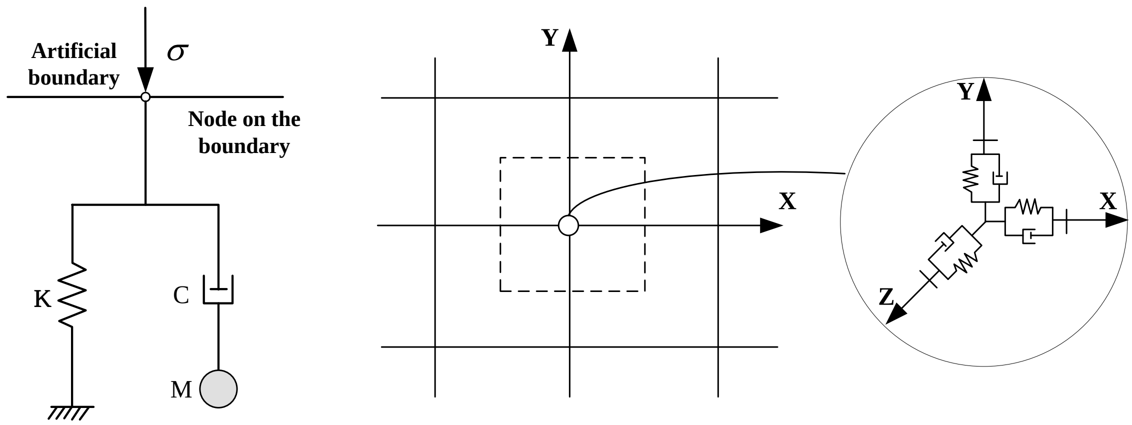
Normal direction: $K = \frac{4G}{R}, C = \rho c_p$; Tangential direction: $K = \frac{2G}{R}, C = \rho c_s$

G is the shear modulus of soil medium

ρ is the mass density of soil medium

R is the nearest distance between the structure base and the boundary surface

c_p and c_s is the wave velocity of P wave and S wave.



(a)Physical system imposed on boundary (b)Three-dimensional viscous-spring boundary

Figure 6. Physical component applied on the normal boundary

However, it causes extreme inconvenience for preprocessor of the numerical simulation to add spring-damping systems to boundary nodes one by one. So an advanced method, i.e. consistent viscous-spring artificial boundary, is raised to reduce the amount of work before numerical analysis and this technology has ample precision to achieve three-dimensional simulation. The consistent viscous-spring artificial boundary employs the boundary elements instead of the damping-spring systems to realize the effects of forces between the outside soil and inner domain, as shown in Figure 5 (b). The viscous-spring elements can produce the equal matrices of stiffness and damping as the damping-spring systems. The special boundary elements, which should be the same types with that of the inner computational domain, are defined by the following parameters:

Young's modulus $\tilde{E} = \alpha_N h \frac{G}{R} \frac{(1+\tilde{\upsilon})(1-2\tilde{\upsilon})}{(1-\tilde{\upsilon})}$; Stiffness coefficient $\tilde{\eta} = \frac{\rho R}{3G}\left(2\frac{c_s}{\alpha_T} + \frac{c_p}{\alpha_N}\right)$

Mass density $\tilde{\rho}$ usually equals a relative low value, such as one-tenth of the medium density ρ .

G is the shear modulus of soil medium

ρ is the mass density of soil medium

R is the nearest distance between the structure base and the boundary surface

h is the thickness of the elements

c_p and c_s are the wave velocity of P wave and S wave.

α_N and α_T are the correction factors; α_N values from 1 to 2 and α_T values from 0.5 to 1.

The parameters of the artificial boundary are listed in Table 3.

3. MODAL ANALYSIS FOR THE FOUNDATION SYSTEMS

The natural frequencies of both the model without soil (fixed-base) and model with soil (flexible-base) are obtained using classic modal analysis. Table 4 shows the first 8 natural frequencies of the systems.

Table 4 Natural Frequencies of The Foundation Systems (Hz)

number	Model without soil	Model with soil and piles
1	2.17	1.76
2	2.59	1.85
3	2.65	2.08
4	7.94	6.04
5	8.93	6.59
6	13.27	6.81
7	14.49	7.62
8	14.92	7.68

The soil-structure interaction provides the rotational freedom of the foundation mat and reduces the natural frequencies of the superstructure without soil. The first order mode shape of the fixed-base system is translation at x direction (the direction along the shaft) with frequency 2.17Hz and the first order mode of flexible-base system has the same shape with frequency 1.76Hz, which is lower than 2.17, because the soil-structure interaction provides freedom of rotation at z direction (the horizontal direction normal to x direction).

The soil-structure interaction provides the rotational freedom of the foundation and decrease the bending stiffness of the mat. That is the reason why when the soil medium is considered the frequencies of the system may be lower.

4. DYNAMIC RESPONSE DUE TO ROTOR UNBANLANCE

The rotor unbalance excitation is defined by an eccentricity e=0.05mm. The applied load is therefore $P = m_i\omega^2 e$ for the *i*th disk, in which ω is the circular frequency, m_i is the mass of the *i*th disk. The rated rotor speed of operation is 3000n/min, i.e. 50Hz, which is employed in the dynamic analysis of this section due to rotor unbalance. These loads are applied at each disk and the rotor unbalance load is intended for investigation of the soil-structure interaction only. The turbine-generator-foundation system is studied under vertical and horizontal rotor unbalance excitation. Two different cases, i.e. fixed-base system and flexible-base system, are considered to explore the effect of soil-structure interaction. The rotor speed increases linearly from 0Hz to 50Hz within 10 seconds and both the displacements of the journal bearings and the internal forces of the columns are given.

4.1. Vertical Excitation

The time history responses of the system due to vertical rotor unbalance excitation, including the vertical displacements of several typical bearings, i.e. the bearings labeled from No.4 to No.6 that are close to the LP and GE parts of the turbine-generator system, and the internal forces in the LP-GE column, are shown in Figure 7. The operating frequency of the rotor increases linearly from 0Hz to 50Hz within 10 seconds, which implies that the time history responses can be interpreted as the frequency results to some extent.

Figure 7 (a) to (c) shows the vertical displacement amplitude vs. time at three bearing locations. It can be observed that the interaction between soil and structure reduces the maximum vibration amplitudes of the picked bearings. For example, the vibration amplitude of the bearing No. 6 decreases from 0.032 to 0.014mm, which is a 56 percent reduction when the soil-structure interaction is considered. This reduction of vibration amplitudes results from the fact that the radiation damping introduced by the soil may alleviate the dynamic response of the structure. At lower frequencies, however, vibration amplitudes may increase due to the SSI effect. For instance, the amplitudes of bearing No. 3 and No. 4 become higher at f =5Hz. The effect of soil-structure interaction diminishes as the frequency increases further to the turbine operating speed. The axial force of picked column is shown in Figure 7 (d). Generally speaking, the amplitude of axial force is influenced by the soil obviously and the values of force increase at higher frequencies when the soil-structure is taken into account.

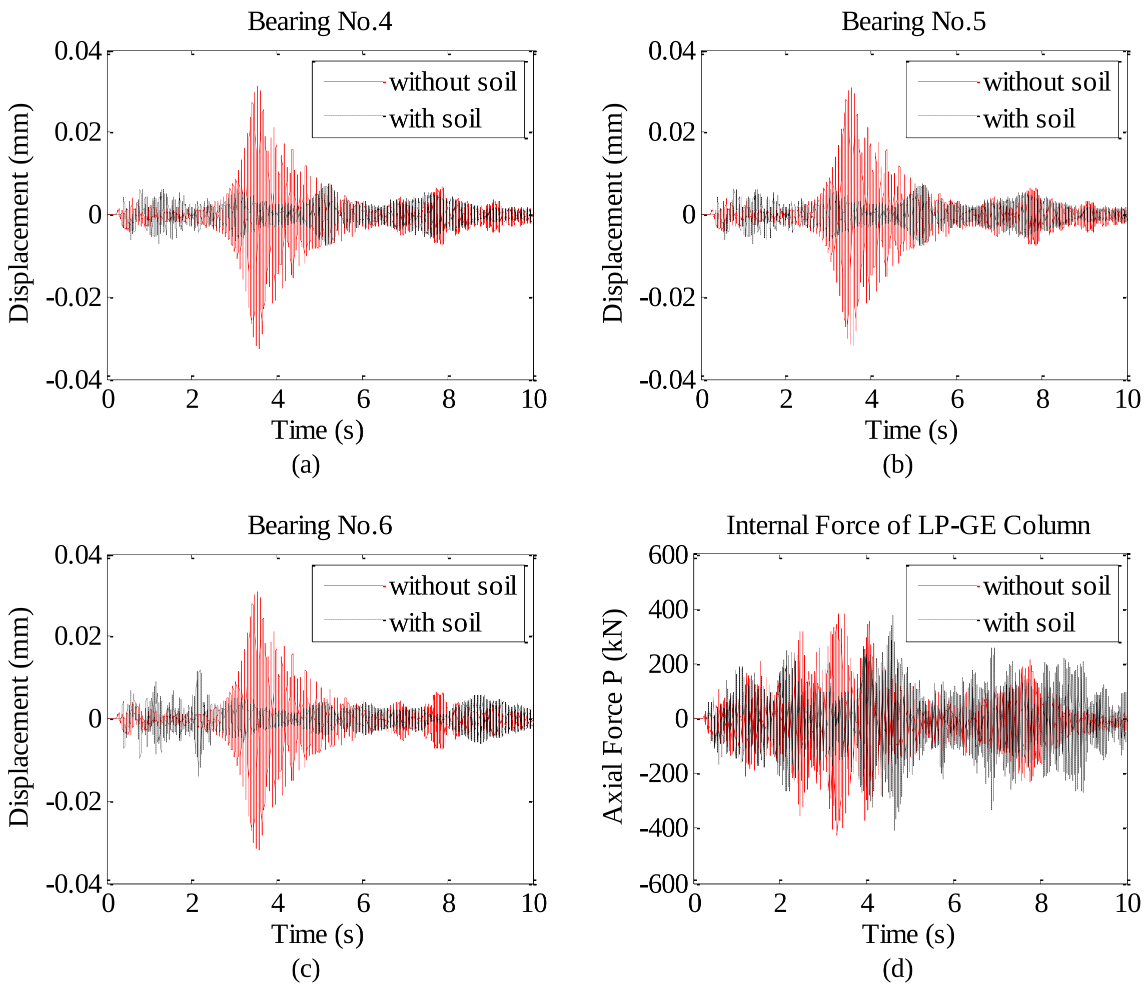


Figure 7. Vertical displacements at bearing locations and axial force of the LP-GE column

4.2. Horizontal Excitation

The time history responses of the system due to horizontal rotor unbalance excitation, including the horizontal displacements of some typical bearings, i.e. the bearings labeled from No.4 to No.6 and the internal forces at the top of LP-GE column, are shown in Figure 8.

Figure 8 (a) to (c) shows the horizontal displacement amplitude vs. time at three bearing locations. It can be found that the interaction between soil and structure reduces the vibration amplitudes of the picked bearings at about all frequencies. For example, the maximum vibration amplitude of the bearing No. 5 decreases from 0.0065 to 0.0044 mm, which is a 32 percent reduction when the interaction of soil-structure is considered. The vibration amplitudes decrease as a result of the fact that the radiation damping introduced by the soil may consume the system's energy and weaken the dynamic responses of the structure.

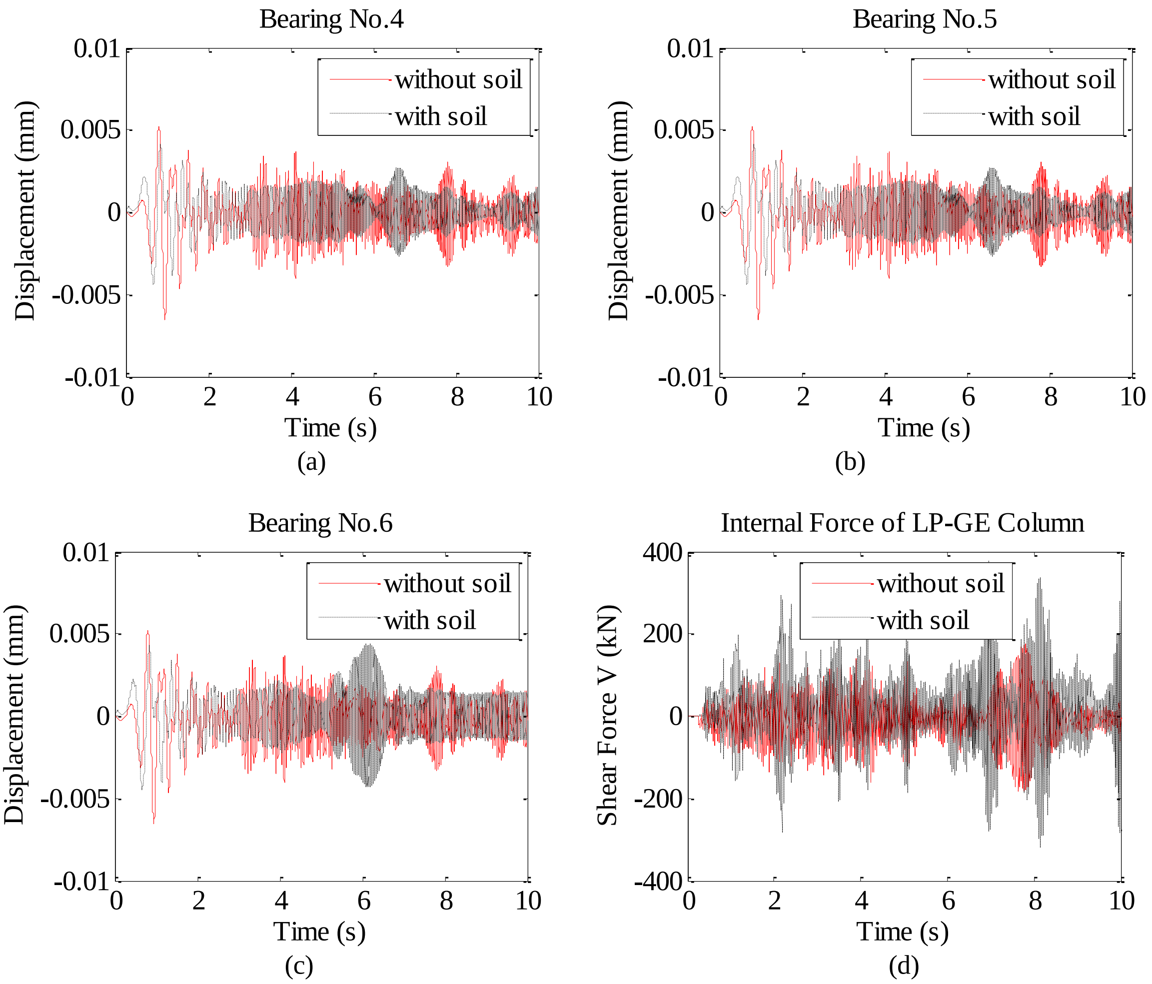


Figure 8. Horizontal displacements at bearing locations and shear force of the LP-GE column

The shear force of picked column is shown in Figure 8 (d). The amplitudes of shear force are influenced by the soil severely and the values of force increase at several certain frequencies such as 11Hz and 21Hz when the soil-structure is taken into account. For example, the amplitude of the shear force increases from 128 to 376 kN when the frequency is about 35Hz.

Generally speaking, the displacement amplitudes due to horizontal rotor unbalance excitation are much lower than those due to vertical rotor excitation, except for very low frequencies. This can be explained by the fact that very strong columns and foundation mat are employed, resulting in high bending stiffness in the horizontal direction. The relatively soft soil medium also contributes to larger vertical displacements.

5. DYNAMIC RESPONSE DUE TO SEISMIC EXCITATION

The seismic excitation is defined by the free-field ground acceleration in the time domain. The time history of Elcentro is picked and the acceleration peak is 0.32g. Figure 9 shows the time history and response spectra of the input ground motion. The uniform ground motion is applied in the transverse direction (perpendicular to the shaft). The models with or without the soil are considered here to incorporate the full soil-structure interaction and the dynamic responses of the journal bearings, such as relative displacement and absolute acceleration at horizontal direction, the base shear of foundation and the internal force of LP-GE column are given.

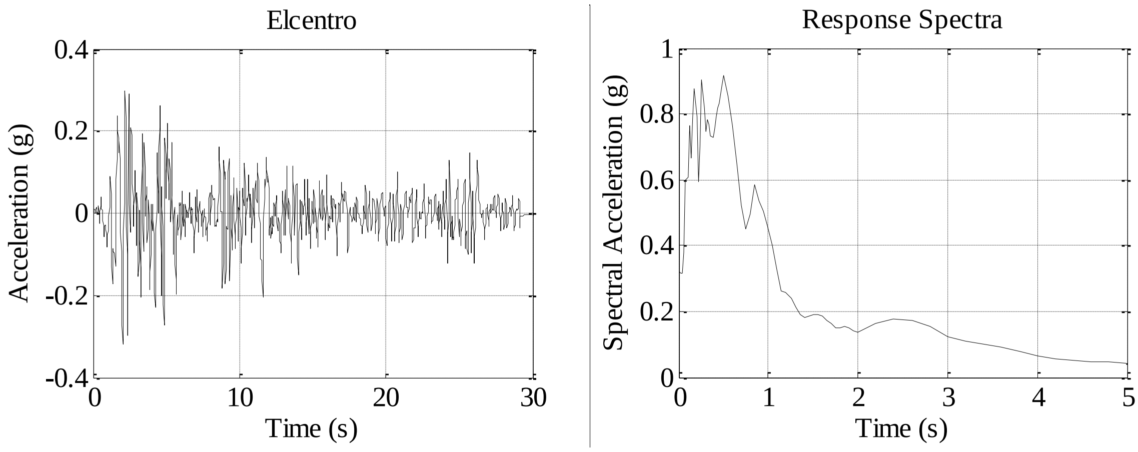


Figure 9. The time history and response spectra of the Elcentro

Figure 10 (a) shows the average displacement of six bearings vs. time at horizontal direction. Apparently, the effect of the soil-structure interaction amplifies the dynamic response through all the seismic excitation time. Concretely, the peak displacement decreases from 19.5 to 51.3mm, which is a 158 percent increase when the SSI effect is considered. This can be explained by that the existence of soil provides the rotation freedom of foundation mat and decreases the bending stiffness of the mat. Therefore it is reasonable for the foundation to deform larger at the horizontal direction when the interaction of soil and structure is taken into account. Figure 10 (b) shows the time history of the absolute acceleration of bearings. It is observed that the amplitude of the acceleration is influenced by the soil-structure interaction slightly. For instance, the peak acceleration at horizontal direction increases from 4969 to 5266mm/s^2, which is a 6 percent enhancement when the soil medium is employed.

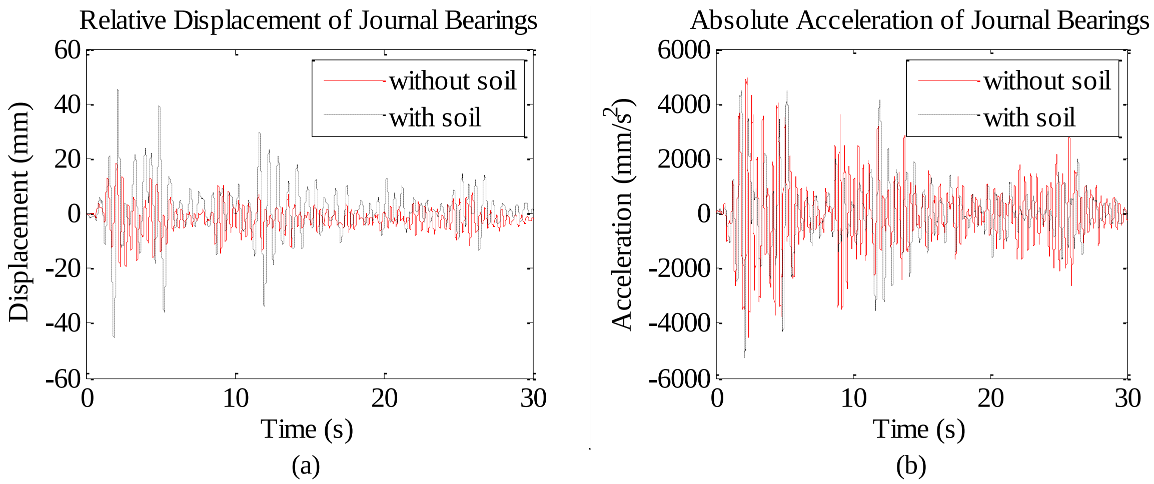


Figure 10. Dynamic response of the journal bearings

Figure 11 (a) shows the base shear amplitude of the foundation mat vs. time at the transverse direction (perpendicular to the shaft). The effect of the SSI play a role in the change of the base shear amplitude, since the peak value decreases from 7130 to 6320kN, which is a 13 percent reduction. Figure 11 (b) shows the shear force of the LP-GE column vs. time at transverse direction. It is observed that the amplitude of shear force is influenced by the soil-structure interaction apparently. For instance, the peak value of force decreases from 3440 to 2682kN, which is a 22 percent reduction when SSI effect is considered.

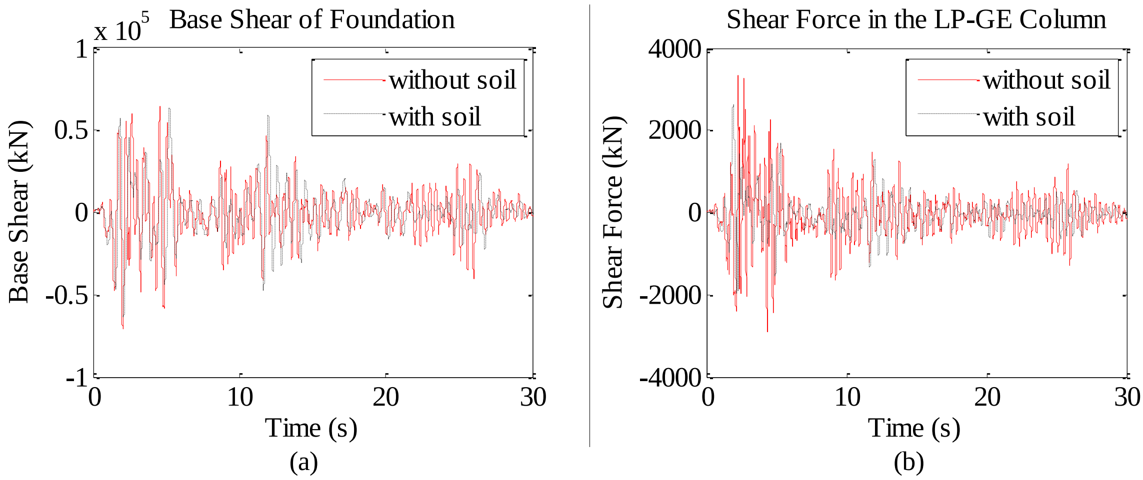


Figure 11. Base shear of the foundation mat and shear force in the LP-GE column

6. CONCLUSIONS

The main findings in this paper are summarized in the following.
Under vertical rotor unbalance excitation, the soil-structure interaction reduces the peak vibration amplitudes of all bearings significantly due to the energy consumption of the soil medium. However, the vibration may increase in the low-frequency range. The axial force is sensitive to the soil-structure interaction only at higher frequencies. Under horizontal rotor unbalance excitation, the effect of SSI decreases the vibration amplitudes of bearings and increases the internal force in the column.
Since the turbine-generator set and the foundation superstructure are relatively rigid compared to the soil medium, the system behaves like a rigid body under seismic excitation. Although the influence of the soil-structure interaction on the relative horizontal displacement of the system is quite significant, it has small impact on the absolute acceleration and the base shear of mat. It should be noted that the dynamic response of the foundation and internal force in the columns are apparently higher than those under rotor unbalance excitation.

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REFERENCES

Weiming Liu and Milos Novak. (1995). Dynamic behaviour of turbine-generator-foundation systems. *Earquake Engineering And Structural Dynamics*. **24**, 339-360.

Eduardo Kausel. (2010). Early history of soil-structure interaction. *Soil Dynamics And Earthquake Enginneering*. **30**, 822-832.

Liu Jingbo, Wang zhenyu, Du Xiuli and Du Yixin . (2005). Three-dimensional visco-elastic artificial boundaries in time domain for wave motion problems. *Engineering Mechanics*. **22:6**, 46-51.

Liu Jingbo, Gu Yin, and Du Yixin . (2006). Consistent viscous-spring artificial boundaries and viscos-spring boundary elements. *Chinese Journal Of Geotechnical Engineering*. **28:9**, 1070-1075.

Liu Jingbo, and Lu Yandong . (1997). A direct method for analysis of dynamic soil-structure interaction based on interface idea. *Dynamic Soil-Structure Interaction Academic Press*, 258-273.