IN-PLANE DYNAMIC BEHAVIOR OF TWO ADJACENT BUILDINGS
FOCUSED ON DIFFERENT EMBEDMENT DEPTHS
AND FOUNDATION TYPES

基礎種別と根入れ深さに着目した面内方向の隣接建物間動的相互作用

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A parametric study is applied to determine the dynamic cross interaction (DCI) of two closely spaced adjacent buildings focusing on the mean power of superstructures. Analyses are done for mat and pile foundations taking place on layered elastic soil and elastic half-space considering different embedment depths. Adjacent buildings are analyzed by the substructure method consisted of the thin layer method and finite element method in 3 dimensions. Consequently, 3 main factors are found to determine the DCI effect. First one is mass ratio of adjacent buildings that has detrimental consequences on the lighter adjacent building. Second one is rocking restriction that is beneficial effect especially on mat foundations and tall buildings. Third one is horizontal vibration power transfer between foundations having different embedment that induce due to the different horizontal movement of adjacent foundations at the same frequency. This detrimental effect is observed on identical tall adjacent buildings placed on mat foundations. However, this effect cannot be observed on pile foundations. Moreover, more detailed parametric analyses of height and mass of building and soil properties are applied for mat foundation placed on half-space soil.

Keywords : *Dynamic Cross Interaction, Mat Foundation, Pile Foundation, Layered Soil, Natural Period of Buildings, Rocking Motion*

隣接建物動的相互作用, 直接基礎, 杭基礎, 成層地盤, 建物固有周期, 回転運動

1. Introduction

Structures are built closer to each other due to the lack of spaces in big cities in recent decades, as it is declared by Lou *et al.* [1]. Therefore, researches on this topic are necessary for reliable earthquake resistance design to understand the key parameters of adjacency effect on the response of superstructures.

As it is known, the soil-structure interaction (SSI) affects the response of superstructures in some manners by changing its dynamical properties during earthquakes and this phenomenon is deeply researched in 20th century. However, interaction of adjacent structures during earthquakes is given less attention

than SSI. In the pioneering work done by Luco and Contesse [2], this phenomenon is called as the structure-soil-structure interaction (SSSI) and it is asserted that the effect of SSSI is important for low frequency excitations and for excitations nearly equal to fixed base natural frequency of the adjacent structure. In the other pioneering work done by Kobori *et al.* [3], this phenomenon is called as the dynamic cross interaction (DCI) and it is claimed that the effect of DCI on structures built densely on soft soils becomes important and should be considered in earthquake design of such structures. In the research of Kobori and Kusakabe [4], adjacent structures having identical embedded foundations placed on layered soil are analyzed and it

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is asserted that, the effect of DCI diminishes the responses of adjacent identical buildings, but for adjacent structures having different natural periods and masses, responses of buildings may increase due to the DCI effect. Although aforementioned pioneering studies raise awareness on the DCI effect during earthquakes, the mechanism of the problem could not be cleared in detail.

There are more researches about the DCI for nuclear power plants than regular structures [5-12]. Although these are important to make clear the effect of DCI on such structures, results of these studies are hard to generalize for regular structures due to the restricted mechanical parameters of nuclear power plants.

For determining the DCI effect on regular buildings, there are some studies [13-19]. However, it is hard to understand why the DCI effect increases or decreases and which parameters are important on this phenomenon. Moreover, there are also endeavors to create simple models to determine the DCI effect on these structures [20-22]. However, only surface foundations are treated in these researches.

In the all aforementioned researches, there are many studies where soil and foundation types selected as constant. A general comparison for the DCI effect on different foundations, such as different foundation types of buildings (pile and mat foundations) is not applied. Moreover, key parameters of the DCI problem during earthquakes cannot be declared clearly for adjacent buildings having different embedment conditions. Therefore, a parametric analytical study on rocking and horizontal responses of superstructures and their foundations is evaluated considering different kinds of embedment situations and fixed base natural frequencies of two closely spaced adjacent buildings placed on the layered elastic soil and elastic half-space for different kinds of foundation types (mat and pile), shear wave velocity and soil material damping. Moreover, effect of mass and height of the superstructures on the DCI is also investigated.

In this study, mean power ratios (MPRs) and transfer function amplitudes of superstructures and foundations are used to explain the effect of DCI on adjacent buildings supported by mat and pile foundations placed on layered soil. The mean power is the area of the power spectra applied by Alexander *et. al.* [21]. First of all, the effect of different height of identical buildings with the same embedment depth on DCI is shown clearly for these two kinds of foundation by comparing MPRs, transfer function amplitudes, rocking impedances and rocking input motions between adjacent building case and single building case. Next, the effect of different embedment depths of identical buildings on DCI is studied by using the same physical indices as above mentioned. Moreover, a more detailed parametric analysis is applied for mat foundation placed on half-space for different heights and masses of adjacent buildings, shear wave velocity

and material damping of soil by comparing the transfer function amplitudes.

It is surely that nonlinear analyses are important to determine damages induced by large earthquakes. There are some researches considering the nonlinear behavior of soil and structure in the DCI [23-27]. However, they are on early stage to understand nonlinear phenomenon of the DCI. It is asserted by the writers of this paper, it is necessary that the DCI effect for elastic conditions of soil and structure should be addressed first by detailed parametrical analyses before considering the nonlinear behavior of soil and structure, because there are still unclear points on the DCI researches under elastic conditions, such as difference of DCI effect for mat and pile foundations, and the effect of DCI on adjacent buildings having different foundation embedment depths. This research mainly considers the effect of DCI on elastic condition of soils and structures, but nonlinearity of soils is assumed by soil profiles (shear velocities and material damping ratio) according to an equivalent nonlinear approach.

Only the motion of superstructures on the direction of buildings (in-plane SSSI as declared by Trombetta *et al.* [25]) is investigated in this research due to the different nature of the problem on the other direction. It is believed that if the key parameters of the DCI phenomenon is grasped, the importance of the DCI effect on the design of structures can be decided more easily.

2. Analysis Conditions

2.1 System of Superstructures

Fixed base natural periods of superstructures (T_{fx}) are taken as 0.5, 1.0, and 2.0 sec (fixed base natural frequencies 2.0, 1.0 and 0.5 Hz); mass of superstructures (m_s) are taken as 2.5×10^6 kg, 5.0×10^6 kg, and 1.0×10^7 kg respectively. The damping ratio of the superstructures (h_{str}) is taken as 3%.

2.2 Soil and Foundation System

The soil is modeled as layered elastic soil and elastic half-space. For layered soil, the mass density, shear wave velocity and material damping of upper layer of soil (ρ_1 , V_{s1} , and h_{s1}) are selected as 1.7×10^3 kg/m³, 100 m/s and 3% and the mass density, shear wave velocity and material damping of lower part of soil (ρ_2 , V_{s2} and h_{s2}) are selected as 1.8×10^3 kg/m³, 300 m/s, and 3% respectively. The thickness of upper layer of soil (H) is taken as 34m of which predominant frequency coincides with the soil-structure system of $T_{fx}=1.0$ sec on the surface mat foundation. For elastic half-space, the mass density of soil (ρ) is considered as 1.7×10^3 kg/m³, shear wave velocity of soil (V_s) is selected as 100 and 200 m/s and material damping of soil (h_s) is selected as 0%, 3% and 6%. $V_s=100$ m/s and $h_s=6\%$ is also assumed that the soil is degraded under strong ground motions.

Poisson's ratio of soil (ν) is taken as 0.45. Soil conditions can be seen in Figure 1 schematically.

Foundations are supposed as mat and pile foundations. Slabs of foundations are selected as 20x20m square mat foundations having embedment depths 0, 2, 4, and 8m. The mass ratio of foundation to superstructure is selected as 0.2. Slabs of foundations are considered as rigid. It is assumed that there is no separation between the foundation and soil. The properties of adjacent pile foundations can be seen in Figure 2 where S_{pile} is pile interval, E_p is young modulus of piles, ν_p is Poisson's ratio of piles, ρ_p is mass density of piles, and h_p is material damping ratio of piles. Pile diameters (d_{pile}) are selected as 0.75m for $T_{fix}=0.5$ sec buildings, 1.00m for $T_{fix}=1.0$ sec buildings and 1.50m for $T_{fix}=2.0$ sec buildings. The lengths of piles (L_{pile}) are determined considering both 2m anchors to the lower part of soil and embedment depths.

The results for mat and pile foundations placed on the layered soil are considered mainly to determine the DCI effect on the main structures in this study. Moreover, detailed parametric analyses about the DCI effect are applied under the several conditions, which are m_s , height of structure, V_s , and h_s .

2.3 Layout of Adjacent Buildings

To see the effect of DCI for closely built structures, the clearance between foundations is selected as 3m, because this distance value is seen in cities. Moreover, according to Alexander *et al.* [21], the detrimental effect of DCI is only seen in closely spaced buildings. Layout of an adjacent building and a main building can be seen in Figure 3, where D is the clearance between foundations, e_1 is the embedment depth of foundation of the main building, e_2 is the embedment depth of foundation of the adjacent building, U_{si} ($i=1\sim6$) and U_{fi} ($i=1\sim6$) are directions of motions for the structure and its foundation respectively. In this study, T_{fix1} represents the fixed base natural period of the main superstructure and T_{fix2} represents the fixed base natural periods of the adjacent superstructure.

Fig. 1 Selected soil conditions

Fig. 2 Properties of adjacent pile foundations

2.4 Embedment Cases of Adjacent Buildings

To determine the effect of embedment depth of foundations on DCI, 3 different embedment situations are considered as the identical embedment depth of foundation as it is seen in Figure 4(a), the shallower embedment depth for the main building as it is seen in Figure 4(b), and the deeper embedment depth for the main building as it is seen in Figure 4(c).

Fig. 3 Layout of adjacent buildings and motion directions

Fig. 4 Embedment cases for foundations

3. Analysis Method

To determine the key parameters effecting on the DCI phenomenon through responses of superstructures, responses of adjacent buildings are analyzed by the substructure method that consists of the thin layer method (flexible volume method) and the finite element method in 3 dimensions. During these analyses, impedances, input motions and transfer functions are calculated. The soil is modeled by the thin layers with increasing thickness from bottom to top. Moreover, to represent unbounded soil, the paraxial boundary is applied to the bottom of the models. Moreover, a square massless rigid foundation placed on soil is also divided into the 3 dimensional finite elements (Wen [17]), as it is seen in Figure 5. The mass of the foundation is given as a point mass at the connection point of foundation and superstructure. Piles are modeled by beam elements having 1m lengths.

To represent low, medium and high story buildings, 5, 10, and 20 story buildings are assumed. To prevent making the problem more complicated due to considering the modes of superstructures except for the first natural mode, the single degree of freedom (SDOF) systems are selected for effective height (H_{eff}) of 10, 20, and 40m to represent 5, 10, and 20 story buildings respectively. Buildings are modeled by beam elements with infinite bending stiffness.

Fig. 5 Analysis models of soil and mat foundation

To evaluate the effect of DCI, the similar method is applied as Alexander *et al.* [21]. In this method, the ratio of the mean power of the adjacent building case to that of single building case is obtained. This index is called as mean power ratio (MPR). The MPR shows the detrimental or beneficial effect of DCI on the responses of buildings.

In this study, the adjacent building case is called as CaseA and the single building case is called as CaseS. Since there is no effect of the phase and amplitude of the excitation on MPR, ratios of transfer functions are directly calculated. Frequency domain analysis is applied to structure-soil-structure systems. Calculations are done for the frequency from 0.1 Hz to 10.0 Hz. Only results for x direction (in-plane direction) are given in this paper.

4. Analysis Results

4.1 Analysis Results for Layered Soil

4.1.1 Analysis Results for Identical Embedment Depths

(a) The case of mat foundations

The MPRs of superstructures ($T_{fix1} = 0.5, 1.0$ and 2.0 sec, mat foundations, layered soil) for identical embedment depths ($e_1 = e_2$) on x direction are given in Figure 6(a)(1), (b)(1) and (c)(1). Moreover, MPRs of foundation rocking motions for the same parameters are given in Figure 6(a)(2), (b)(2) and (c)(2).

When Figure 6(a)(1), (b)(1) and (c)(1) are examined for different adjacent building height effect on the DCI, it can be said that, as it is seen at the solid curve in Figure 6(a)(1), the highest MPRs are observed for short and light buildings, ($T_{fix1} = 0.5$ sec), adjacent to tall and heavy building ($T_{fix2} = 2.0$ sec). In this figure, mean powers of CaseA increase up to about 20% comparing with CaseS. This conclusion is similar with Alexander *et al.* [21] where it is asserted that the power of earthquake is transferred from tall and heavy structures to short and light structures.

For heavy structures adjacent to light structures, MPRs are not higher than 1 as it can be seen at the solid curve in Figure 6(c)(1). It contradicts with Alexander *et al.* [21] where short and light structures act as passive dampers. One of possible reasons of this situation, a short and light adjacent structure ($T_{fix2} = 0.5$ sec) increases the mean power of foundation rocking motion of the main structure ($T_{fix1} = 2.0$ sec) as it is seen at the solid curve

in Figure 6(c)(2).

If Figure 6(a)(2), (b)(2) and (c)(2) are examined to determine foundation rocking motion effect on adjacent identical buildings for different heights, it can be claimed that there is rocking restriction effect between adjacent identical buildings. This effect depends on embedment depths of foundations and increases with decreasing fixed base natural periods of superstructures as shown at the dashed curves in these figures. However, this effect on the MPR of horizontal motion for $T_{fix1} = T_{fix2} = 0.5$ sec is not found clearly as seen at the dashed curve in Figure 6(a)(1). According to Padron *et al.* [19], when the distance between centers of buildings (D_T) equals to $\lambda/2$, where λ is soil wavelength at the soil-structure fundamental period, the detrimental effect of the wave propagation on the building becomes high. In this study, D_T is 23m and $\lambda/2$ is 31m considering that the soil-structure fundamental period is about 0.62 sec ($T_{fix} = 0.5$ sec). This $\lambda/2$ (31m) is close to D_T (23m). Therefore, MPR of $T_{fix1} = T_{fix2} = 0.5$ sec is increased by this effect although it is decreased by rocking restriction. For other cases of adjacent buildings, this wave-based DCI effect becomes negligible due to the longer λ values.

Fig. 6 MPRs of both superstructure horizontal motions and foundation rocking motions (mat foundation, $e_1 = e_2$, layered soil)

To show the effect of DCI on rocking foundation input motions for mat foundation placed on layered soil, a massless mat foundation model is created for $T_{fix2} = 0.5, 1.0$ and 2.0 sec as it is seen in Figure 7. In Figure 8, transfer function amplitudes of U_{s1} according to ground motion at free surface (U_g) ($|U_{s1}/U_g|$) of

CaseS for embedment depths equal 4m are given. The predominant period of soil layer (T_s) is also depicted in this figure. Amplitudes and phases of the rocking foundation input motion of these models (U_{fs}/U_g) and real part of rocking impedances are given in Figure 9.

Fig. 7 Analysis model for calculate impedances and input motions of massless foundation

Fig. 8 Transfer function amplitudes ($|U_{s1}/U_g|$) of CaseS (mat foundation, $e_1=4m$, layered soil)

Fig. 9 Amplitudes and phases of rocking foundation input motion (U_{fs}/U_g), and real part of rocking impedances of massless foundation for CaseS and CaseA

When Figure 9(b) and (c) are examined, it can be said that relationships of phases and rocking impedances between CaseA and CaseS show difference with the vicinity of the predominant frequency of each adjacent soil-structure system as a boundary. It is found that the massless foundation rocks on reverse direction to the adjacent foundation before this frequency as

shown in Figure 10(a), where T_{input} represents the period of the peak input motion ($T_{input} \geq T_{fix2}$). However, when a main building is also represented in the model, both foundations vibrate with the same phase. Therefore, effect of this reverse phase rocking input motion contributes to rocking restriction effect between adjacent buildings. This rocking restriction effect is defined as input rocking restriction in this study. On the other hand, for frequencies that are higher than the vicinity of the predominant frequency of each the adjacent soil-structure systems ($T_{input} < T_{fix2}$), the same phase rocking motion of foundation of the adjacent building is observed as it is shown in Figure 10(b). However, as it is seen at the Figure 9(c), real parts of impedances of CaseA are higher than those of CaseS. This rocking restriction effect is defined as impedance rocking restriction in this study.

Fig. 10 Rocking modes of massless foundation and adjacent soil-structure system

(b) The case of pile foundations

Next, results for pile foundations are given. The MPRs of superstructures ($T_{fix1} = 0.5, 1.0$ and 2.0 sec, pile foundations, layered soil) for identical embedment depths ($e_1=e_2$) on x direction are shown in Figure 11.

Fig. 11 MPRs of superstructure horizontal motions (pile foundation, $e_1=e_2$, layered soil)

If Figure 11(a), (b), and (c) are compared with Figures 6(a)(1), (b)(1), and (c)(1) to determine pile foundation effects on the DCI, it can be said that almost all MPRs are smaller than those of mat foundations. However for some cases ($T_{fix1}=0.5$ sec – $T_{fix2}=1.0$ and 2.0 sec) as shown at the solid curve in Figure 11(a), MPRs are

higher than those of mat foundations where MPRs increase up to about 30% comparing to CaseS. To understand this phenomenon, transfer function amplitudes of the foundation rocking motion ($|U_5/U_g|$) of CaseS and CaseA ($T_{fix1}=0.5$ sec – $T_{fix2}=1.0$ sec pile and mat foundations) are shown in Figure 12.

Fig. 12 CaseA and CaseS transfer function amplitudes of foundation rocking motion ($|U_5/U_g|$) for x direction ($T_{fix1}=0.5$ sec – $T_{fix2}=1.0$ sec, $e_1=e_2=0$ m, layered soil)

As it is seen in Figure 12(a), the rocking motion amplitude of foundation for CaseA is lower than for CaseS due to the rocking restriction phenomenon as above mentioned. However, if Figure 12(b) is examined, it is found that that the rocking motion amplitude of foundation for CaseA is higher than that for CaseS. It can be said that by the lack of rocking restriction effect on the building ($T_{fix1}=0.5$ sec and pile foundation), MPR of the main building on the pile foundation becomes higher than that on the mat foundation.

Another important point about the effect of pile foundation on the DCI, for identical adjacent buildings $T_{fix1}=T_{fix2}=1.0$ sec, is that the beneficial effect of DCI is observed as it can be seen at the dashed curve in Figure 11(b) comparing to Figure 6(b)(1). Transfer function amplitudes of foundation rocking motion ($|U_5/U_g|$) for CaseS and CaseA are shown in Figure 13. In this figure, the rocking motion diminishes nearly 70% comparing with that of the main building on the mat foundation, but the ratio of CaseA to CaseS does not change so much. It can be considered that the rocking restriction is also effective for the pile foundation like the mat foundation for building having $T_{fix}=1.0$ sec and that phenomenon infuses the beneficial DCI effect on the structures with pile foundations.

Fig. 13 Transfer function amplitudes of foundation rocking motion ($|U_5/U_g|$) of the main superstructures both CaseA and CaseS for x direction ($T_{fix1}=T_{fix2}=1.0$ sec, $e_1=e_2=0$ m, layered soil)

4.1.2 Analysis Results for Different Embedment Depths

(a) The case of mat foundations

The MPRs of superstructures horizontal motions for $e_2=0$ and 8m on x direction are calculated. Since similar results are obtained with identical embedment depths except for adjacent identical superstructures, only the results for such superstructures ($T_{fix1}=T_{fix2}=0.5, 1.0$ and 2.0 sec, mat foundations, layered soil) are given in Figure 14.

If Figure 14 is examined, it can be asserted that the beneficial or detrimental effect of DCI is seen more for the adjacent buildings having different embedment depth of foundation comparing to identical embedment depth cases. Especially, this difference is more distinguished for adjacent identical buildings ($T_{fix1}=T_{fix2}=2.0$ sec), as it is seen at the solid curves in Figure 14. Additionally, it can be figured out that MPRs being higher than 1, in other words detrimental effects of DCI, are only observed for $T_{fix1}=T_{fix2}=2.0$ sec, as it is seen at the solid curve in Figure 14(a) for $e_1>e_2$. The reason of this result is supposed that the horizontal vibration power is transferred from the shallow foundation to the deep foundation. To present the above phenomenon, MPR and transfer function amplitudes ($|U_{s1}/U_g|$) of identical superstructures ($T_{fix1}=T_{fix2}=2.0$ sec, $e_1=4$ m and $e_2=0$ m) for CaseA and CaseS are given in Figure 15.

As it is seen on Figure 15, MPR of the main building is clearly higher than that of the adjacent building. Moreover, it shows the horizontal vibration power transferred between buildings. This phenomenon is explained in detail at Section 4.1.2(c).

Fig. 14 MPRs of superstructure horizontal motions ($T_{fix1}=T_{fix2}$, mat foundation, $e_2=0$ and 8m, layered soil)

Fig. 15 CaseA and CaseS transfer function amplitudes ($|U_{s1}/U_g|$) and MPR of superstructures for x direction ($T_{fix1}=T_{fix2}=2.0$ sec, mat foundation, $e_1=4$ m, $e_2=0$ m, layered soil)

(b) The case of pile foundations

Next, results for pile foundations are given. The MPRs of

superstructures ($T_{fix1}=T_{fix2}=0.5, 1.0$ and 2.0 sec, pile foundations, layered soil) for $e_2=0$ and $8m$ on x direction are given in Figure 16.

When the solid curves are seen in Figures 16, power transfer between adjacent tall buildings, which is mentioned in Section 4.1.2(a) for mat foundations, cannot be determined. To clear this phenomenon, transfer function amplitudes ($|U_{s1}/U_g|$) of CaseA and CaseS and MPRs of identical superstructures ($T_{fix1}=T_{fix2}=2.0$ sec, $e_1=4m$ and $e_2=0m$) are given in Figure 17.

As shown in Figure 17, the difference of MPR between the main building and the adjacent building becomes low comparing to Figure 15. Moreover it is interesting to note that the sum of MPRs of the main and adjacent buildings is lower than for the mat foundations as shown in both Figure 15 and Figure 17.

Additionally, the beneficial effect of DCI is seen more clearly on MPRs for increasing values of embedment depths as it is seen at the solid curves in Figure 16.

Fig. 16 MPRs of superstructure horizontal motions ($T_{fix1}=T_{fix2}$, pile foundation, $e_2=0$ and $8m$, layered soil)

Fig. 17 CaseA and CaseS transfer function amplitudes ($|U_{s1}/U_g|$) and MPR of superstructures for x direction ($T_{fix1}=T_{fix2}=2.0$ sec, pile foundation, $e_1=4m$, $e_2=0m$, layered soil)

(c) Mechanism of horizontal vibration power transfer

As shown in Figure 14(a), the case of $e_1=4m$ and $e_2=0m$ indicates the highest MPR value. Here, the difference of horizontal power transfer mechanism for mat and pile foundations is expressed by using transfer function amplitudes of foundation horizontal motions ($|U_H/U_g|$) of CaseS for different embedment depths as shown in Figure 18. In Table 1, high and low peaks frequencies of Figure 18(c)(1) are given.

If Figure 18 and Table 1 are examined, it can be found only in Figure 18(c)(1) that, high peaks of one soil-structure system and low peaks of another soil-structure system coincide at same frequencies for different embedment depths, especially for

$T_{fix}=2.0$ sec, $e_1=0$ and $4m$, and mat foundation. Therefore, power transfer phenomenon is seen more intensively for $T_{fix1}=T_{fix2}=2.0$ sec than for $T_{fix1}=T_{fix2}=0.5$ and 1.0 sec.

Fig. 18 Transfer function amplitudes of foundation horizontal motion ($|U_H/U_g|$) for CaseS (layered soil)

Table 1 High and low peaks frequencies of Figure 18(c)(1)

Peaks	$e_1=0m$	$e_1=2m$	$e_1=4m$	$e_1=8m$
High	0.33Hz	0.34Hz	0.35Hz	0.38Hz
Low	0.35-0.36Hz	0.36Hz	0.37Hz	0.39-0.40Hz

Moreover, as it is seen transfer function amplitudes for pile foundations ($|U_H/U_g|$) at Figure 18, peaks of frequencies are not affected by embedment depths. For this reason, the interference between high peak of one soil-structure system and the low peak of other soil-structure system do not occur on same frequencies for differently embedded systems. Therefore, the horizontal vibration power cannot be transferred between foundations. It can be asserted that detrimental consequences of power transfer are small for the case of pile foundation.

4.2 Analysis Results for Half-space Soil

The MPRs of superstructures ($T_{fix1}=0.5, 1.0$ and 2.0 sec, mat foundations, half-space soil, $V_s=100m/s$, $h_s=3\%$) for identical embedment depths ($e_1=e_2$) on x direction are given in Figure 19(a), (b) and (c).

If Figure 19 is compared with Figures 6(a)(1), (b)(1), (c)(1) to determine effect of layered soil on the DCI phenomenon for mat foundations, it can be said that MPRs between two soil conditions do not change so much. Moreover, special effect of the predominant frequency of soil on the DCI cannot be observed in this study.

Since the similar relationship of the results is observed between layered soil and half-space soil for different embedment depths, results for half-space soil are not given in this paper. Some results can be seen at Ogut *et al.* [28].

Fig. 19 MPRs of superstructure horizontal motions (mat foundation, $e_1=e_2$, half-space soil, $V_s=100\text{m/s}$, $h_s=3\%$)

4.3 Effect of m_s , H_{eff} , h_s , V_s on Transfer function amplitudes and MPR

In this section, to determine effect of m_s , H_{eff} , h_s , and V_s on the DCI, transfer function amplitudes ($|U_{s1}/U_g|$) and MPRs of horizontal motions of identical superstructures ($T_{fix1}=T_{fix2}=1.0$ and 2.0 sec, $e_1=4\text{m}$ and $e_2=0\text{m}$) on x direction for half-space soil are calculated since high MPR is observed for this analysis case. The half-space soil has the almost same effects on the DCI as the layered soil in this study as it is declared in Section 4.2, so the half-space soil is applied for these parametric studies.

4.3.1 Effect of m_s on DCI

Analyses for doubled mass of superstructures ($m_s=5.0 \times 10^6$ kg and 1.0×10^7 kg, $T_{fix1}=T_{fix2}=1.0$ sec, $H_{eff}=20\text{m}$) are performed to clarify mass of superstructure effect on the DCI. The transfer function amplitudes ($|U_{s1}/U_g|$) and MPRs of horizontal motions of identical superstructures are given in Figure 20. The other analysis parameters are same values as mentioned at Section 2. The rigidity of the superstructure having $m_s=1.0 \times 10^7$ kg is calculated again to obtain the fixed natural period equals to 1.0 sec ($T_{fix}=1.0$ sec).

According to comparison of Figure 20(a) and (b), it can be asserted that effect of mass of superstructure is negligible on the DCI effect.

Fig. 20 CaseA and CaseS transfer function amplitudes ($|U_{s1}/U_g|$) and MPRs of horizontal motions of identical superstructures ($T_{fix1}=T_{fix2}=1.0\text{sec}$, $e_1=4\text{m}$, $e_2=0\text{m}$, $H_{eff}=20\text{m}$, $V_s=100\text{m/s}$, $h_s=3\%$)

4.3.2 Effect of H_{eff} on DCI

Analyses for doubled height of superstructures ($H_{eff}=20\text{m}$ and 40m , $T_{fix1}=T_{fix2}=1.0$ sec) are performed to clarify superstructure height effect on the DCI phenomenon. Transfer function amplitudes ($|U_{s1}/U_g|$) and MPRs of horizontal motions of identical superstructures ($T_{fix1}=T_{fix2}=1.0$ sec, $H_{eff}=20\text{m}$ and 40m) are given in Figure 21. The other analysis parameters are same values as mentioned at Section 2.

According to comparison of Figure 21(a) and (b), it can be claimed that the effect of height of superstructure is clearly higher than that of mass of superstructure on the DCI in this study. For $H_{eff}=40\text{m}$, the period of this soil-structure system elongates due to increasing rotational inertia mass, and the horizontal vibration power transfer phenomenon occurs easily as it is declared at Section 4.1.2(c).

Fig. 21 CaseA and CaseS transfer function amplitudes ($|U_{s1}/U_g|$) and MPRs of horizontal motions of identical superstructures ($T_{fix1}=T_{fix2}=1.0\text{sec}$, $e_1=4\text{m}$, $e_2=0\text{m}$, $m_s=5.0 \times 10^6$ kg, $V_s=100\text{m/s}$, $h_s=3\%$)

4.3.3 Effect of V_s on DCI

Analysis results of different V_s of soil ($V_s=100$ and 200m/s) for $T_{fix1}=T_{fix2}=2.0$ sec are also shown to clarify soil stiffness effect on the DCI. Transfer function amplitudes ($|U_{s1}/U_g|$) and MPRs are given in Figure 22. The other analysis parameters are same values as mentioned at Section 2.

According to comparison of Figure 22(a) and (b), it can be asserted that difference of the amplitude at each peak frequency is not so affected by the shear wave velocity of the soil and effect on MPR becomes nearly half for $V_s=200\text{m/s}$ (where mean power

of CaseA increases 22% for $V_s=100\text{m/s}$, and 12% for $V_s=200\text{m/s}$ comparing to CaseS).

Fig. 22 CaseA and CaseS transfer function amplitudes ($|U_{s1}/U_g|$) and MPR of identical superstructures ($T_{fix1}=T_{fix2}=2.0\text{sec}$, $e_1=4\text{m}$, $e_2=0\text{m}$, $h_s=3\%$)

4.3.4 Effect of h_s on DCI

Analysis results of different h_s of the soil ($h_s=0$ and 6%) for $T_{fix1}=T_{fix2}=2.0\text{sec}$ are also shown to clarify soil material damping effect on the DCI. Transfer function amplitudes ($|U_{s1}/U_g|$) and MPRs are given in Figure 23. The other analysis parameters are same values as mentioned at Section 2. Results for $h_s=3\%$ can be seen in Figure 22(a).

According to comparison of Figure 23(a), (b), and Figure 22(a), it can be mentioned that peaks of transfer function amplitudes ($|U_{s1}/U_g|$) are strongly affected by the soil material damping for $h_s < 3\%$. Moreover, effect on MPR increases nearly 3 times for $h_s=0\%$ than $h_s=3\%$ (where mean power of CaseA increases 60% for $h_s=0\%$, and 22% for $h_s=3\%$ comparing to CaseS), but this parameter becomes insensitive for $h_s > 3\%$. The reason of this phenomenon is considered that for zero damping, restriction effect diminishes and amplitudes of rocking motion of foundations increase. Therefore it can be asserted that the effect of h_s becomes important on the DCI in small strain level, but the effect diminishes rapidly for larger strain level.

Fig. 23 CaseA and CaseS transfer function amplitudes ($|U_{s1}/U_g|$) and MPR of identical superstructures ($T_{fix1}=T_{fix2}=2.0\text{sec}$, $e_1=4\text{m}$, $e_2=0\text{m}$, $V_s=100\text{m/s}$)

5. Conclusions

A parametric study is conducted to determine the DCI effect on two closely spaced adjacent buildings ($D=3\text{m}$). To evaluate this effect, the mean power ratio (MPR) of superstructures is calculated for adjacent building case (CaseA) to single building

case (CaseS). Soil and superstructures are considered as elastic. Different embedment depths of foundations placed on layered soil and homogeneous elastic half-space are assumed. The horizontal responses of superstructures, rocking and horizontal responses of foundations for different type of foundations (mat and pile) are calculated in this study. Moreover rocking foundation input motions and rocking impedances are calculated when there is an adjacent building. The results for mat and pile foundations placed on the layered soil are considered mainly to determine the DCI effect on the main structures in this study. The results of the analyses for identical embedment depths are:

- The DCI effect on short and light main buildings adjacent to tall and heavy buildings with mat foundations increases mean power of main buildings up to about 20% due to the horizontal vibration power transfer in this study.
- For identical adjacent buildings with mat foundations having same embedment depths, horizontal vibration power transfer is not observed and mean power of both buildings diminish due to rocking restriction. As it is defined in Section 4.1.1, input rocking restriction is seen for $T_{input} \geq T_{fix2}$ and impedance rocking restriction is observed for $T_{input} < T_{fix2}$.
- The DCI effect on short and light main buildings adjacent to tall and heavy buildings with pile foundations increases mean power of main buildings up to about 30% in this study. This phenomenon is due to the horizontal vibration power transfer and lack of rocking restriction of soil-structure system for short and light buildings.

Analyses for different embedment depths of adjacent buildings are also performed. Results of these analyses are:

- For identical buildings of mat foundations having different embedment depths, mean power of the superstructure having deeper embedment depth increases and that of the superstructure having shallower embedment depth decreases due to the horizontal vibration power transfer from shallow foundation to deep foundation. This effect is mainly found in the case of the tall adjacent buildings.
- However, for identical adjacent buildings having different embedment depths of pile foundations, the power cannot be transferred since the predominant frequencies of soil-structure systems change very slightly according to the embedment depth.

Moreover, more detailed parametric analyses for m_s , H_{eff} , V_s , and h_s are performed for mat foundation placed on half-space soil. Results of these analyses are:

- Effect of m_s on the DCI is negligible. However, effect of H_{eff} on the DCI becomes important even for same fixed based natural periods of buildings. As the DCI effect, MPRs becomes nearly halves for $V_s=200\text{m/s}$ than $V_s=100\text{m/s}$. Material damping of the soil is effective on the DCI for small damping ratio, which means small strain level.

As a result, the DCI effect on buildings with mat and pile foundations can be considered by three key factors as follows:

- Mass ratio of adjacent buildings: It has detrimental consequences on the lighter adjacent building.
- Rocking restriction: It is a beneficial effect. And this effect is higher for mat foundation and tall buildings. Therefore, special attention should be given for short and light buildings placed on pile foundations due to lack of this effect.
- Horizontal vibration power transfer between different embedment depths: High detrimental effect of the DCI is observed on identical tall adjacent buildings for mat foundation. However, this effect cannot be observed for pile foundation. Therefore, if foundations of adjacent tall buildings are designed by piles, the detrimental consequences of the DCI can be prevented.

As future work, mechanism of DCI should also be studied for y direction which can be named as anti-plane direction.

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和文要約

1. はじめに

本論では、根入れ基礎を有する建物を対象とした隣接建物間動的相互作用に着目し、隣接する各建物の建物高さや固有周期、基礎構造や根入れ深さ等の違いが建物応答に与える影響について検討した。

2. 解析モデル

2.1 上部建物モデル

上部建物としては、階数の異なる3ケース（5階、10階、20階）を想定し、これに応じて建物高さ、及び建物周期（0.5秒、1秒、2秒；いずれも基礎固定時）を設定する。解析にあたっては、上部建物を等価な1質点系せん断型モデル（曲げ剛性は剛とする）に置換し、質量をそれぞれ、 $2.5 \times 10^6 \text{kg}$ 、 $5.0 \times 10^6 \text{kg}$ 、 $1.0 \times 10^7 \text{kg}$ とした。

2.2 基礎と地盤のモデル化

基礎は、20m四方とし、質量は上部建物全質量の2割とした。根入れ深さは0m、2m、4m、8mの4ケースを想定した。基礎構造は直接基礎と杭基礎とした。地盤は成層地盤と半無限一様地盤とした。成層地盤については2層地盤を想定し、下層を $V_s=300\text{m/s}$ 、上層を $V_s=100\text{m/s}$ 、減衰はいずれも $h_s=3\%$ とした。一様地盤では、 $V_s=100\text{m/s}$ 、 200m/s の2ケース、減衰定数は $h_s=0\%$ 、 3% 、 6% の3ケースとした。

2.3 検討で想定した隣接建物の配置

隣接建物が1棟の場合を想定した。建物の基礎間隔は3mとした。検討では、全建物の根入れ深さが等しい場合と隣接建物が深い場合、反対に浅い場合について建物応答への影響を直接基礎と杭基礎の場合について比較している。

3. 解析手法

本論では、サブストラクチャー法に基づき、薄層要素法と有限要素法を考慮した周波数応答解析を実施する。評価指標として、パワースペクトル密度関数の積分値の単独建物の場合と隣接建物がある場合との比(Mean Power Ratio)を用いた。なお、紙面の都合上、本論では、建物が並ぶ方向に加振した場合の結果について示す。

4. 解析結果

4.1 成層地盤に対する解析結果

4.1.1 基礎根入れ深さが同じ場合

(a) 直接基礎の場合

隣接建物が、相対的に規模（高さや質量）が大きい場合には、根入れ深さにかかわらず単独の場合に比べて応答が大きくなること、反対に、隣接建物が、相対的に規模（高さや質量）が小さい場合には単独の場合と大きな差がないことが分かった。また、同規模の建物が隣接している場合には、回転振動に対する拘束効果が現れることにより、単独の場合に比べて応答が低減されることがわかった。この現象は、隣接建物がある場合の回転基礎入力動と回転方向のインピーダンスから説明できる。すなわち、連成系の卓越振動数よりも低振動数側では、回転基礎入力動が上部建物の水平変位に伴う基礎の回転方向と逆位相で作用し、高振動数側では、回転基礎入力動は同位相で作用するものの、隣接建物の存在に伴う回転インピーダンスの増大により、全体として基礎回転動が抑制されると考えられる。

(b) 杭基礎の場合

全体的な傾向としては、回転動の減少により、直接基礎の場合に比べて隣接建物間動的相作用効は小さい。ただし、回転動の減少に伴い、隣接建物の規模（高さや質量）が相対的に大きい場合には、建物応答の増分が直接基礎よりも大きくなることも明らかとなった。

4.1.2 基礎根入れ深さが異なる場合

(a) 直接基礎の場合

全体の傾向としては、根入れ深さが等しい場合と同等である。ただし、一つの建物の連成系の伝達関数における最大ピーク振動数ともう一方の建物の連成系の伝達関数における最小ピーク振動数とが一致する建物同士が隣接する場合には、隣接間動的相互作用効果が顕著に現れる。この場合、根入れ基礎の浅い方から深い方へ水平方向の振動が伝達され、単独建物の場合に比べ、前者の上部建物応答が減少し、後者の上部建物応答は増大することが分かった。

(b) 杭基礎の場合

一方、杭基礎の場合には、同一規模の建物では、上述の現象は認められず、隣接建物の根入れ深さに関わらず、上部建物応答は単独に比べて低減し、対象建物の根入れ深さが深いほどその効果が大きいことが分かった。

4.2 半無限地盤に対する解析結果

半無限地盤 ($V_s=100\text{m/s}$) に対する隣接建物動的相互作用効果について、4.1.1における解析結果と比較した結果、本検討内では、大きな差異は認められなかった。

4.3 建物質量・高さや地盤物性値が建物応答に与える影響

4.3.1 建物質量の影響

両建物固有周期1秒、基礎根入れ深さが、対象建物:4m、隣接建物:0mとし、上部建物質量を $5.0 \times 10^6 \text{kg}$ 、 $1.0 \times 10^7 \text{kg}$ の場合について検討した結果、検討の範囲内では、影響は小さいことが分かった。

4.3.2 建物高さの影響

両建物固有周期を1秒、基礎根入れ深さが、対象建物:4m、隣接建物:0mとし、建物高さを変化させた場合の建物応答を比較したところ、建物高さが高くなると、対象建物の応答が増大し、単独の場合よりも大きくなる可能性があることが明らかとなった。

4.3.3 及び 4.3.4 地盤物性値（せん断波速度、材料減衰）の影響

両建物固有周期2秒、基礎根入れ深さが、対象建物:4m、隣接建物:0mの場合について、地盤のせん断波速度を $V_s=100\text{m/s}$ 、 200m/s 、減衰定数を $h_s=0\%$ 、 3% 、 6% とした場合について応答を評価した。その結果、せん断波速度が小さい、また減衰定数が小さいほど建物応答が増大することが明らかになった。

5. 結論

隣接する各建物の建物高さや固有周期、根入れ深さ、あるいは地盤モデルの違いが建物応答に与える影響について検討を行った。そして、根入れ深さの組合せ等により、設計時に想定する単独建物に比べて応答が増大する場合があることを明らかにするとともに、その要因等について分析した。一連の検討結果を通じて、主として、建物間の質量効果、回転入力動と回転インピーダンスによる回転動拘束効果、個々の建物の連成系伝達関数の関係から、2棟の隣接建物間動的相互作用効果の程度が推定できる可能性があることが分かった。今後は直交方向の検討を行う予定である。

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