INVESTIGATION OF THE EFFECT OF KOBE EARTHQUAKE ON A THREE-DIMENSIONAL SOIL-STRUCTURE SYSTEM

Kayoko HASHIMOTO[1] and Nawawi CHOUW[2]

[1] Graduate Student, Graduate School of Natural Science and Technology, Okayama University, Okayama 700-8530, Japan, kayoko@poo.civil.okayama-u.ac.jp
[2] Dr.-Ing., Associate Professor, Dept. of Civil and Resource Engineering, University of Western Australia, on leave from Faculty of Environmental Science and Technology, Okayama University, Okayama 700-8530, Japan, chouw@cc.okayama-u.ac.jp

The study addresses the relationship between the characteristics of near-source earthquakes and the behaviour of the system *frame structure with multiple foundations and subsoil*. The ground excitations are the ground accelerations of the 1995 Kobe earthquake at 22 locations. The investigation reveals that the contributions of the time coincidence of the peak responses due to each ground motion component and the vertical ground motions to the total structural response should be considered. The soil-structure interaction can reduce and also amplify the structural peak responses and the response spectrum values in certain frequency range.

***Key words**: Kobe earthquake, vertical ground motion, SSI, simultaneous excitation*

1. INTRODUCTION

In near-source regions the ground can experience strong movement not only in the horizontal directions but also in the vertical direction. The vertical ground motions can have larger amplitude and higher frequency vibration than the horizontal ones. Far from the source, the vertical ground motions are in general smaller than the horizontal ground motions. Up to now many design regulations are still based on the knowledge of far-source earthquakes, so that the effect of the vertical ground motion may be neglected.

The effect of the vertical ground motions is studied by some researchers (e.g. Kusunoki et al.[1)]). Investigations on the simultaneous ground excitations on the structural responses are often limited to the two-dimensional problems. Nakamura et al.[2)] showed that the vertical ground motion does not have a strong effect on the response. The reason is that the largest vertical and horizontal ground accelerations usually do not occur at the same time due to the difference in the velocities of the compressive and shear waves in the soil. However, Chouw[3)] showed that the time coincidence of the subsequent peaks of the ground motions could strongly amplify the structural responses. Three-dimensional investigations are still very limited. Takabatake and Nonaka[4)] confirmed the significance of a strong vertical ground excitation. Their investigation, however, did not include the influence of the soil. Some researchers study the influence of the vertical ground motion in the shaking table tests, e.g. Kawai and Hirasawa[5)] showed that in the horizontal shaking test the structural damage occurs gradually. However, in horizontal and vertical shaking test it occurs immediately at many locations.

The effect of the soil on the structural responses is often studied as two-dimensional problems. テグー et al.[6)] paid attention to the influence of the natural frequency of the structure including subsoil. Asai et al.[7)] showed the relationship between the first natural periods of the structure and soil. However, they did not indicate the relationship between the characteristic of the ground motions and the structural response. Zheng et al.[8)] showed the effect of the slenderness ratio of the bridge foundation on the structural response. Matsuda et al.[9)] showed the component of the simultaneous ground motion that contributes most to the response of the underground structure. The horizontal ground motions contribute to the shear force and moment, and the vertical ground motion contributes to the axial force. However, these investigations did not consider the relationship between the characteristics of the ground motions, the structures and the soil.

Three-dimensional study with soil-structure interaction (SSI) is often restricted to the foundation-soil systems (e.g. Karabalis and Mohammadi[10)]). Gazetas and Mylonakis[11)] indicated that SSI might not always have benefit to the structures. Nonlinear SSI investigation is very limited. It can be performed directly in the time domain. The disadvantage is a large computational memory, and up to now it is not possible to include the soil material damping. To overcome this difficulty the investigation can be performed subsequently in Fourier/Laplace and time domain, and the material damping can be considered by using complex Young's modulus. This approach has also the advantage that once the dynamic stiffness of one of the subsystems, for example, the soil is defined the response of different structures can be investigated. Only the dynamic stiffness of the actual structure is to be determined (e.g. Chouw[12)]).

In this study the influence of a simultaneous ground excitation, SSI and the epicentral distance on the linear response of a three-dimensional frame structure are considered. The structure is a two-bay six-story frame structure. The relationship between the characteristics of the ground motions and the soil-structure system is considered. The ground excitations are the 1995 Kobe earthquake at 22 stations.

2. 3D SOIL-STRUCTURE SYSTEM

(1) Numerical model

The dynamic behavior of the soil-structure system is described in the Laplace domain. The advantage of this is that the whole system can be dealt with as a composition of subsystems. The structures are described by a finite element method, and the subsoil by a boundary element method. By coupling the two subsystems, the dynamic stiffness [$\tilde{K}$] of the whole system *structure, foundations and subsoil* can be determined. The dynamic stiffness of the structural members can be determined by solving the equation of motions in the Laplace domain analytically. We assume that each structural member has a continuous distribution of mass and stiffness along the member. Compared to the lumped-mass and consistent-mass formulation in the time domain the considered continuous mass and stiffness model can produce more precise structural responses. The dynamic stiffness of the structure with foundations [$\tilde{K}^b$] itself can be obtained by adding the dynamic stiffness of each member by using the direct stiffness method. ($\tilde{}$) indicates a vector or matrix in the Laplace domain. The derivation of the dynamic stiffness of the structural members is given by Kodama et al.[13)]. The dynamic soil stiffness can be determined by transforming the wave equation

$$(c_p^2 - c_s^2)u_{j,ji} + c_s^2 u_{i,jj} + p_i = \ddot{u}_i \qquad (1)$$

into the Laplace domain

$$(c_p^2 - c_s^2)\tilde{u}_{j,ji} + c_s^2 \tilde{u}_{i,jj} + s^2 \tilde{u}_i = -\tilde{p}_i \qquad (2)$$

where c_p and c_s are the compressive and shear wave velocity, respectively. u_i and u_j are the displacement components. p_i is the component of the volume force per unit mass. i and j =1,2,3. By using the full-space fundamental solution, and by assuming the distribution of the displacement u_i and traction t_i along the boundaries, the discretization of the subsystem *soil* leads then to a number of algebraic equations

$$[\tilde{T}]\{\tilde{u}\} = [\tilde{U}]\{\tilde{t}\} \qquad (3)$$

where $\tilde{u}$ and $\tilde{t}$ are the complex frequency dependent displacement and tractions at all nodal location, and $\tilde{U}$ and $\tilde{T}$ are the influence matrices. For given tractions the corresponding displacement can be defined. An assumption that the soil surface is traction free results in the relationship between traction and displacement at the contact area between foundations and soil. An introduction of the area of the boundary elements leads to the dynamic stiffness [$\tilde{K}^s$] of the subsoil.

$$[\tilde{K}^s]\{\tilde{u}^s\} = \{\tilde{P}^s\} \qquad (4)$$

After transforming the degree-of-freedom (DOF) of the soil elements into the contact DOFs we then obtain the transformed soil stiffness [$\tilde{K}^s_{cc}$]. The structural DOFs are devided into the DOFs at the foundation-soil interface and the DOFs of the rest of the structure, and they are indicated in the stiffness matrix by the subscript bb and cc, respectively. The coupling of the two subsystems is achieved by equating the displacements and by equilibrating the forces at the interface between the foundations and the soil.

$$\begin{bmatrix} \tilde{K}^b_{bb} & \tilde{K}^b_{bc} \\ \tilde{K}^b_{cb} & \tilde{K}^b_{cc} + \tilde{K}^s_{cc} \end{bmatrix} \begin{Bmatrix} \tilde{u}^b_b \\ \tilde{u}^b_c \end{Bmatrix} = \begin{Bmatrix} \tilde{P}^b_b \\ \tilde{P}^b_c \end{Bmatrix} \qquad (5)$$

The index b, s, c stand for structure, subsoil, and contact DOFs at the soil-foundation interface, respectively. In the analysis we assume that all structural foundations experience the same ground motions. After transforming the ground excitation into the Laplace domain

$$\{\tilde{P}(s)\} = \int_0^\infty \{P(t)\}\, e^{-st} dt, \tag{6}$$

where $s = \delta + i\,\omega$ is the Laplace parameter and $i = \sqrt{-1}$, we can determine the system response $\{\tilde{u}\}$ from Equation (5). We obtain the time history of the response by transforming the results into the time domain.

$$\{u(t)\} = \frac{1}{2\pi i} \int_{\delta - i\omega}^{\delta + i\omega} \{\tilde{u}(s)\}\, e^{st} ds \tag{7}$$

The material damping is incorporated into the modulus of elasticity in the Laplace domain by using the correspondence principle.

$$\tilde{\sigma} = \tilde{\varepsilon}\,(E^R - i\,E^I) \tag{8}$$

By applying the loss factor $\eta = E^I / E^R$ (Lazan[14]) we can define the equivalent damping ratio

$$\xi \equiv \frac{E^I}{2E^R} \tag{9}$$

The chosen damping model consists of a chain of Kelvin elements with the parameter E_1 and E_n.

$$E^R = \frac{\alpha_0 \alpha_1}{\alpha_1^2 + \alpha_2^2}, \quad E^I = \frac{\alpha_0 \alpha_2}{\alpha_1^2 + \alpha_2^2},$$

$$\alpha_0 = \frac{E}{2} \ln \frac{(E_n - \delta)^2}{(E_1 - \delta)^2},$$

$$\alpha_1 = \frac{1}{2} \ln \frac{(E_n - \delta)^2 + \omega^2}{(E_1 - \delta)^2 + \omega^2}, \tag{10}$$

$$\alpha_0 = \mathrm{arctg} \frac{(E_n - E_1)\,\omega}{(E_n - \delta)(E_1 - \delta) + \omega^2}$$

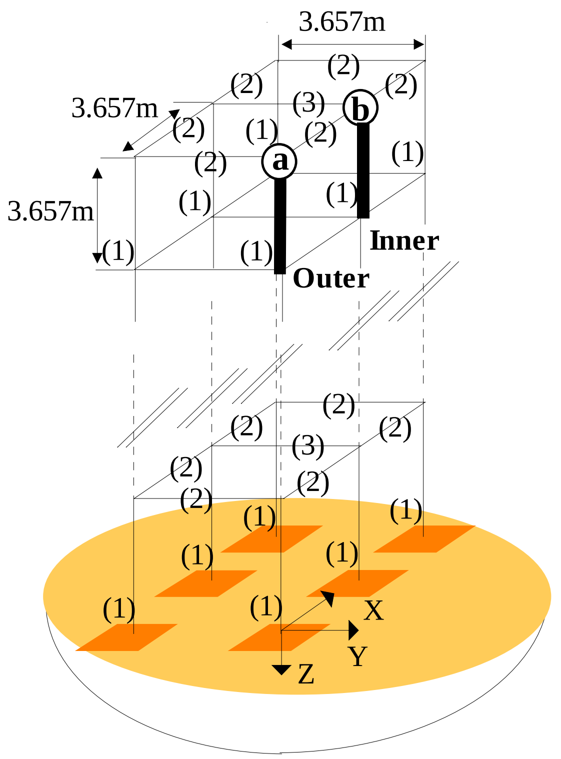

Figure 1. Frame structure with foundations and subsoil

Table 1. Influence of epicentral distance on PGA

Station	PGA [m/s²]			Epicentral distance [km]
	n-s	e-w	Vertical	
PIS	-3.41	2.84	-5.56	17.00
SKH	5.11	-5.84	4.95	24.31
KBU	-2.71	3.05	4.39	25.30
MOT	-4.18	-7.91	-4.61	28.60
TKS	1.78	-1.89	-1.58	28.76
NKP	-1.03	-1.01	1.58	33.99
TDO	-2.90	-1.90	-1.31	36.40
AMA	7.24	-4.01	-3.25	39.00
SKI	-1.49	1.24	-0.97	39.80
SOG	2.99	5.07	-2.05	40.27
WOS	1.13	0.80	-0.82	41.30
FKS	1.80	2.11	-1.93	41.40
MMO	-1.26	0.88	0.96	44.19
ABN	-2.16	2.25	-1.27	44.50
JMO	0.81	0.66	-0.65	46.53
OSA	0.81	-0.59	0.80	46.80
MRG	-2.10	-1.24	-1.58	50.00
YAO	-1.38	1.48	1.00	52.55
YAE	-1.55	1.45	1.27	53.60
SGA	-0.28	-0.25	0.14	56.06
SGV	-0.26	0.20	0.11	56.06
CHY	-0.90	-1.08	-0.72	59.70

(2) Considered system

In the analysis the two-bay six-story frame structure in Figure 1 is considered. Each structural member has the same material and lengths of 3.657m. The mass of the floor is included in the girder mass. Therefore the mass per unit length of the columns (1) is 74.4kg/m. The girders (2) and (3) have the mass of 531.5kg/m and 988.7kg/m, respectively. The flexural stiffness EI_y is 4921.214kNm^2, and EI_z is 34438.95kNm^2. The torsional constant I_p is 7.4e-7m^4. EA is 1991619kN. In the analysis it is assumed that the material damping of the structures is about 1.3% (E_1 = 0.1 and E_n = 10^{28}). The foundations are assumed to be rigid, and have the size of 2.4m x 2.4m. In order to focus on the effect of the soil only it is assumed that the foundations have no mass.

The considered ground excitations are the ground accelerations at 22 stations during the 1995 Kobe earthquake (Table 1). The x-, y- and z-direction correspond to the north-south, east-west and vertical component of the ground accelerations, respectively. The stations are located between 17km and 60km from the epicenter. In some stations the peak ground acceleration in the vertical direction is larger than the peak horizontal ground motions. The ground accelerations depend not only on the epicentral distance, but also on the characteristic of the soil under each station, the direction of the fault and other factors. The response spectra show that at all stations the vertical ground motions have a stronger influence in high frequency range than the horizontal component. (The spectra are not presented here.)

In present study we restrict the investigation to a simple soil. It is assumed that the subsoil is a half-space, and has no material damping, so that only the effect of the radiation damping is considered in the investigation. The propagation velocity of shear waves in the soil is 130m/s. The soil density is 1800kg/m^3, and the Poisson's ratio is 0.33.

3. NUMERICAL RESULTS

(1) Effect of the excitation component on the axial force

In order to clarify the effect of the vertical ground motion we first restrict the investigation to the response of the two-bay six-story structure with an assumed fixed base. Figure 2 shows the contribution of the vertical ground motion to the maximum axial force in the outer and inner columns as indicated in Figure 1. The contribution of the vertical ground motion is defined as a percentage of the response ($NMAX_{xy}$) due to the horizontal ground excitation.

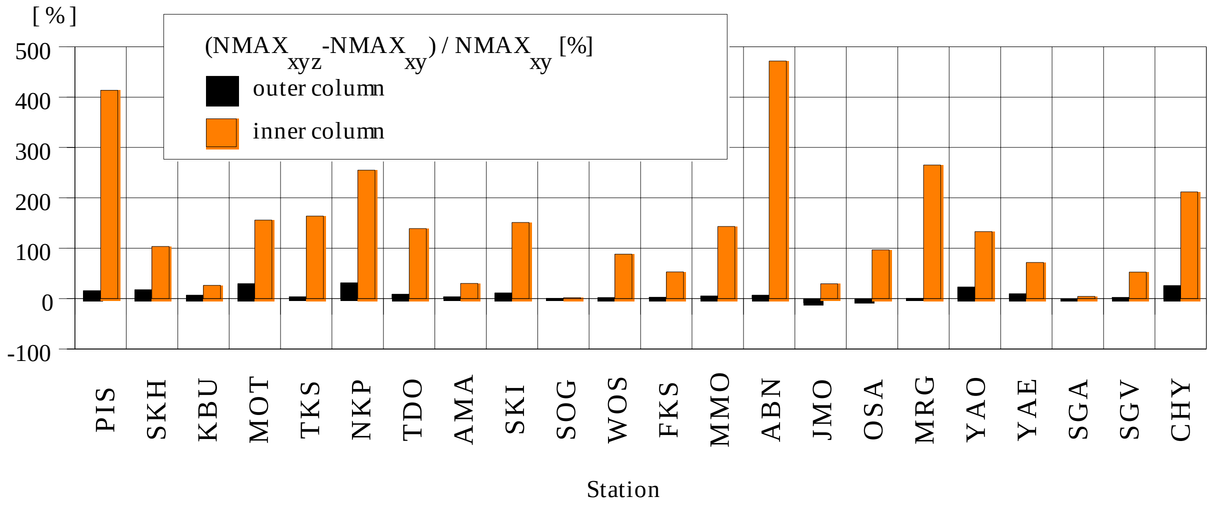

Figure 2. The contribution of the vertical ground motion to the maximum axial force

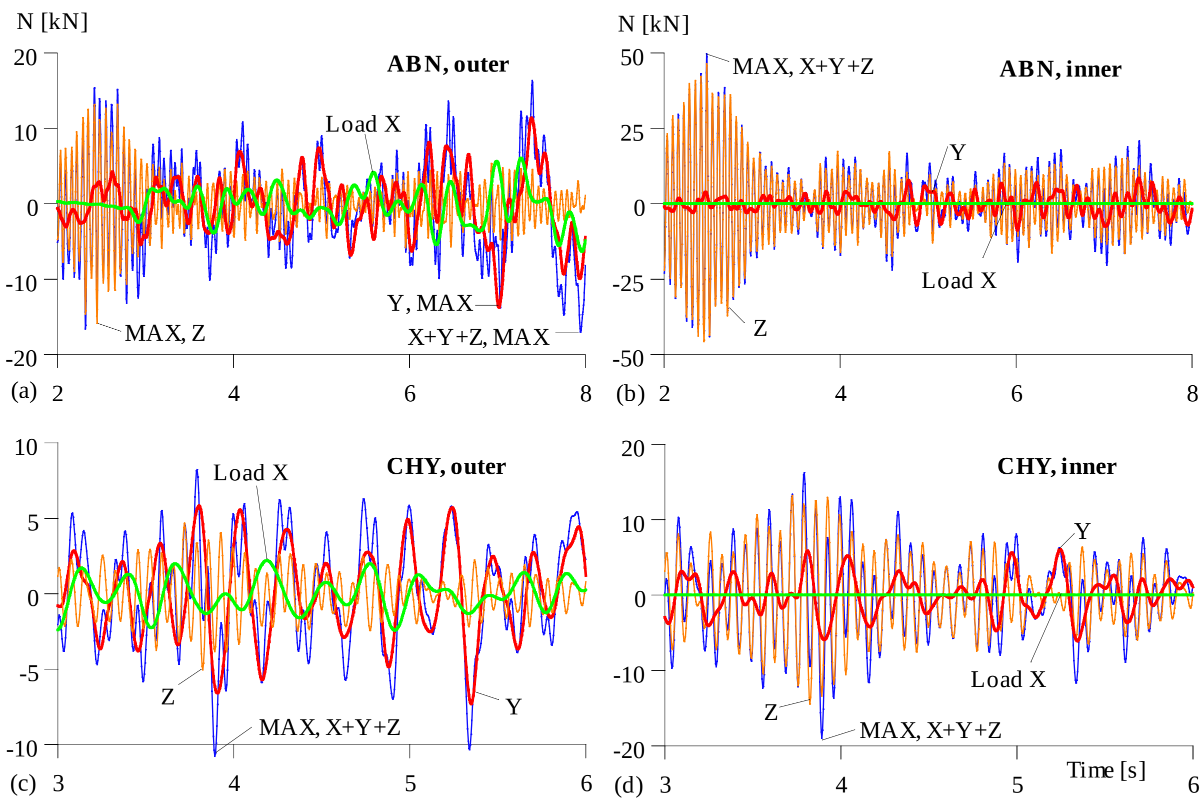

Figure 3(a)-(d). The components of the simultaneous ground motion at ABN and CHY that contribute most to the axial force

The axial force in the inner column has much stronger contribution from the vertical ground motion than the force in the outer column. In the inner column the additional vertical ground motion at Abeno (ABN) causes five times larger axial force than the force due to both horizontal ground motions. Even in the outer column the maximum axial forces are amplified about 30% by the additional vertical ground motions at Motoyama (MOT), Nanko Power Plant (NKP) and Chihaya (CHY). These results show that the consideration of the horizontal ground motions will clearly underestimate the response amplitude.

Figure 2 shows that the vertical ground motion at the Abeno (ABN) has the strongest contribution to the maximum axial force in the inner column, however, it does not have a strong contribution to the response in the outer column. This reason can be seen from Figures 3(a) and (b). Figure 3(a) shows the axial force in the outer column due to the excitation of each ground motion component and a simultaneous ground excitation. The peak axial force due to the vertical ground motion is stronger than the peak response due to the other horizontal ground motions. However, these peaks occur at different times. The maximum axial force due to the simultaneous ground motion depends on the time coincidence of the subsequent peak responses due to each horizontal ground motions. Figure 3(b) displays the axial force in the inner column. The response due to the x-ground motion is negligible small compared to the ones due to the other components of the ground motions. The reason is that the excited horizontal vibration mode in the x-direction produces almost no axial deformation in the inner columns. In contrast, the response due to the vertical ground motion in the inner column is much larger than the one in the outer column. The vertical ground excitation has a very large contribution to the total response in the inner column.

Even though the station CHY is located at a distance of about 60km the vertical ground motion still has strong contribution to the axial force in the inner as well as outer columns. The reason can be seen from Figures 3 (c) and (d). Figure 3(c) displays the axial force in the outer column. The peak axial force due to the vertical ground motion is not large in comparison with the peak response due to the other horizontal ground motions. However, the force due to each component of the ground excitations occurs at same times. Consequently, the vertical ground motion has a strong contribution to the axial force. Figure 3(d) shows the axial force in the inner column. This figure also displays the strong effect of the magnitude of the response due to the vertical ground excitation.

The current study shows that the time coincidence of the responses to each component of the ground motions can have a significant effect on the peak responses due to the simultaneous ground excitation. In the inner columns the amplification due to the vertical ground motion is as expected more pronounced than in the outer column. Consequently, its contribution to the total response is essential. The result shows that the effect of the time coincidence of the subsequent peak responses due to the ground motion components, and the magnitude of the response due to the vertical ground motions should not be neglected.

(2) Effect of the excitation component on induced vibrations

Figures 4(a)-(c) show the characteristic of the induced vibration in each direction due to the simultaneous horizontal and vertical ground excitation at Shin-Kobe Substation (SKH). It is assumed that the structure is fixed at its base.

Figure 4(a) displays the induced vibrations in the x-, y- and z-direction at the top end of the outer column (location **a** in Figure1). The peak-induced vibrations in the horizontal direction are larger than the one in the vertical direction. The structure responds in the vertical direction with high frequen-

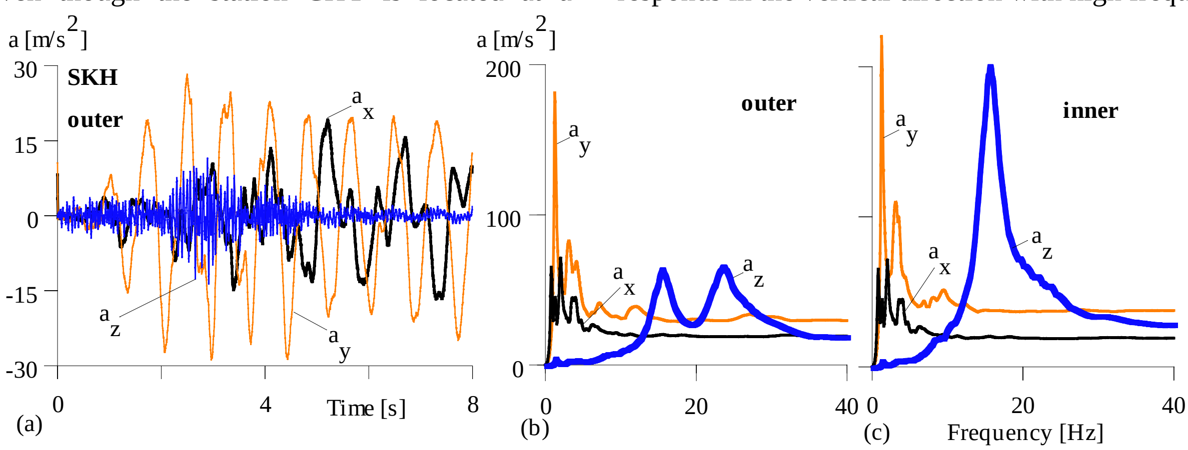

Figure 4(a)-(c). Influence of the direction on the induced vibration due to the simultaneous ground motion at SKH

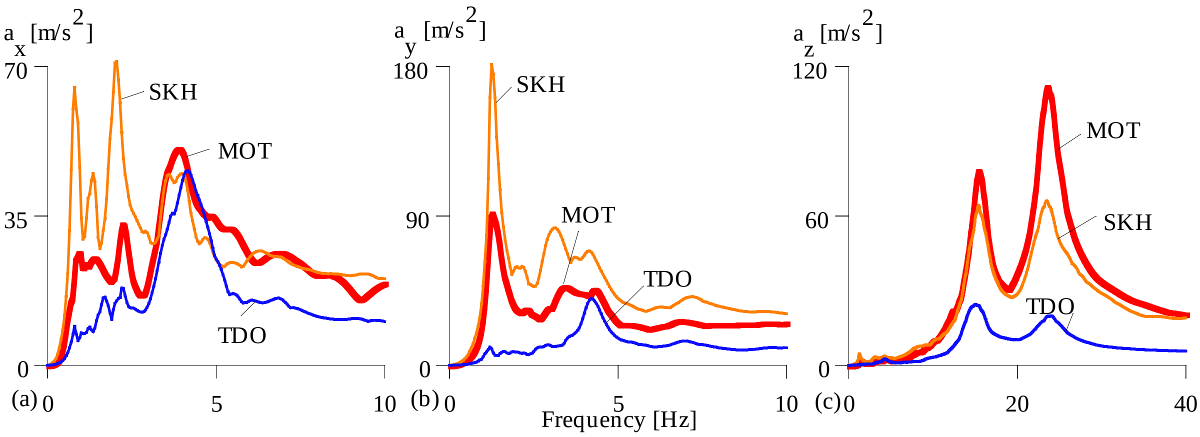

Figure 5(a)-(c). The characteristic of the induced vibration in each direction due to the simultaneous ground motion

cies. These characteristics can be clearly seen also from the response spectra in Figure 4(b). The spectra represent the maximum response of an assumed SDOF secondary structure, which are attached to the members of the main structure. The considered damping ratio in this case as well as in subsequent cases is 5%. The induced vibration in the x-direction has a strong influence on the response of the secondary structures with the same natural frequencies 0.72, 2.1 and 3.5Hz of the main structure vibration in the x-direction. The secondary structure with same natural frequencies 1.2 and 3.7Hz of the main structure in the y-direction also vibrates strongly due to the induced vibration in the y-direction. Since the first two natural frequencies of the main structure in the vertical direction are 14.7 and 22.6Hz, the vertical induced vibration causes therefore in comparison with horizontal induced vibrations stronger response of secondary structures with a natural frequency around 14.7Hz or 22.6Hz. In general secondary structures have higher frequencies than the main structure the vertical induced vibration can therefore have a severe consequence on secondary structures. Figure 4(c) shows the response spectra due to the induced vibration at the top end of the inner column (location **b** in Figure1). The characteristic of the frequency contents of the induced vibrations does not change. However, the vertical induced vibration has much stronger effect on secondary structures with a natural frequency around 14.7Hz than on the structure at the top end of the outer column.

In many design regulations the effect of the vertical ground excitation may be neglected. If it is considered at all, then the excitation has the same frequency content as the horizontal ground

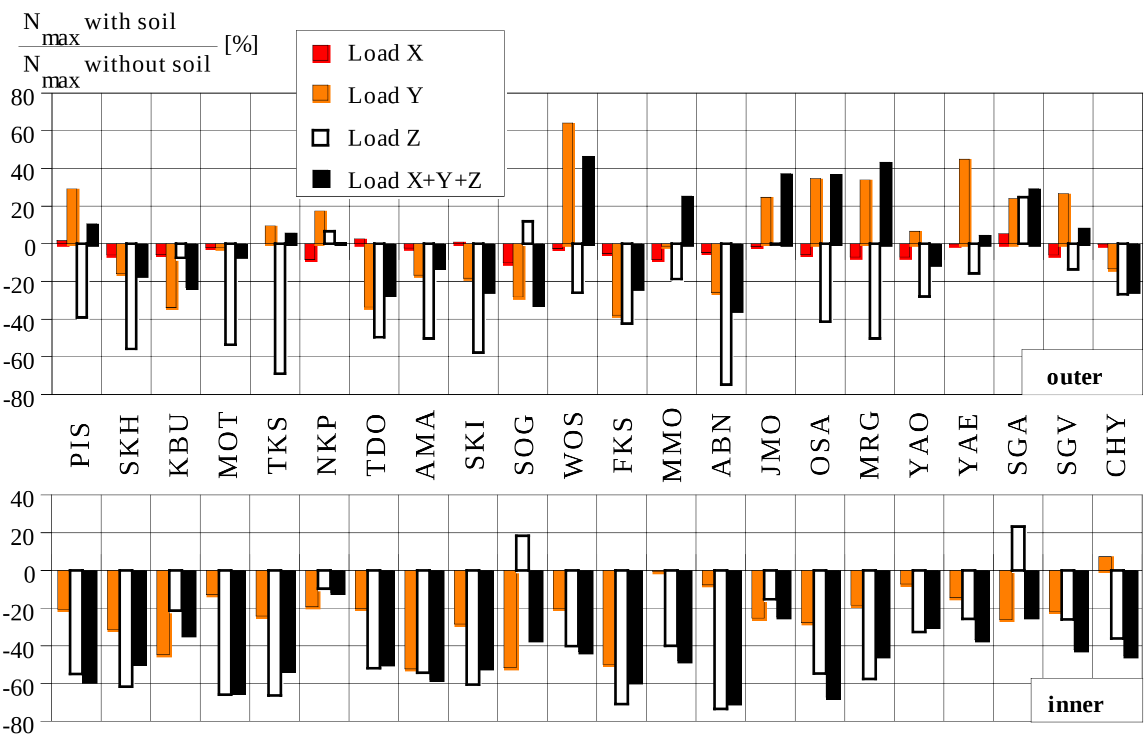

Figure 6. Soil effect on the maximum axial force due to the x-, y- and z-component or a simultaneous ground motion, respectively

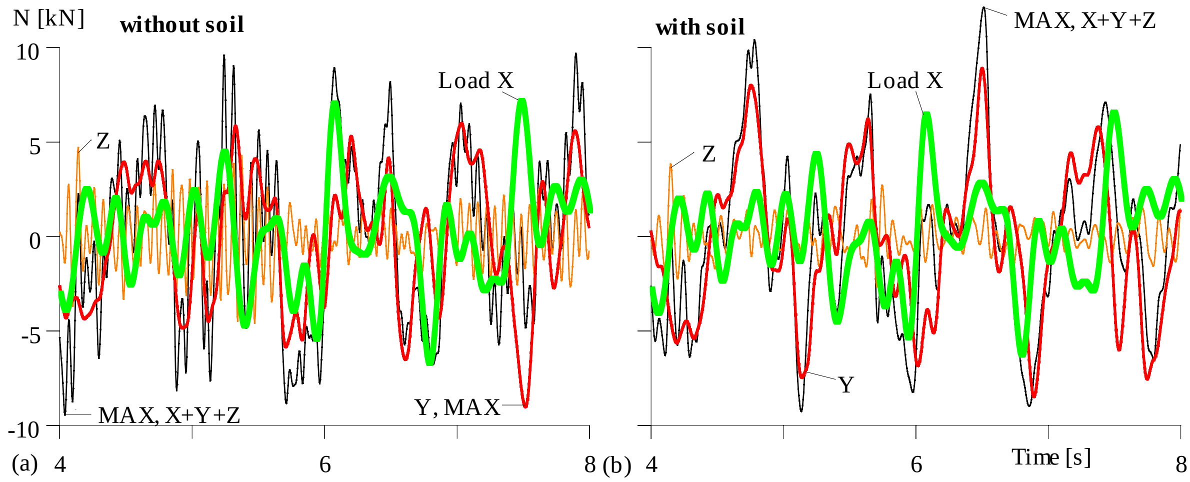

Figure 7(a) and (b). Soil influence on the axial force in the outer column due to the ground motions at MMO

tions. Consequently, in many design regulations the excitation of secondary structures can be significantly underestimated.

Figures 5(a)-(c) show the characteristic of the induced vibration in the x-, y-, z-direction due to the simultaneous ground motion, respectively. The considered ground excitations are the ground motions at Shin-Kobe Substation (SKH), Motoyama (MOT) and Tadaoka (TDO). The induced vibrations have strong effect on the response of the secondary structure with similar natural vibrations as the main structure in the corresponding direction. This influence can also be seen from the induced vibrations due to the simultaneous ground motion at the other station (These figures are not presented). In the design of the secondary structures a consideration of the effect of the natural frequencies of the main structure might be enough even though when the characteristic of the ground motions is unknown.

(3) Influence of SSI on the axial force

Figure 6 shows the influence of SSI on the maximum axial force in the outer and inner columns due to a x-, y-, z-component and due to a simultaneous ground motion. The effect of SSI is displayed as a percentage of the maximum axial force in the structure with an assumed fixed base. The influence of the x-component excitation on the axial force in the inner column can be neglected, and it is therefore not presented. The soil has a different effect on the response in all considered excitation components. In case of the vertical ground motion the soil often has a reduction effect. Since in the inner column the vertical ground motion has strong contribution to the response as indicated in Figure 2, the soil has also in most considered vertical ground excitations a strong influence on the axial force in the inner column.

At Minami-Osaka substation (MMO), however, the reason for the soil effect in the outer column cannot be seen from this picture. The soil has a reduction effect on the maximum response due to each component of the ground motions. However, it has an amplification effect on the response when the simultaneous ground motion is considered. This influence of the soil can be clearly seen from the axial force in the outer column due to a x-, y-, z-component or due to a simultaneous ground motion in Figure 7. In case of the y-component

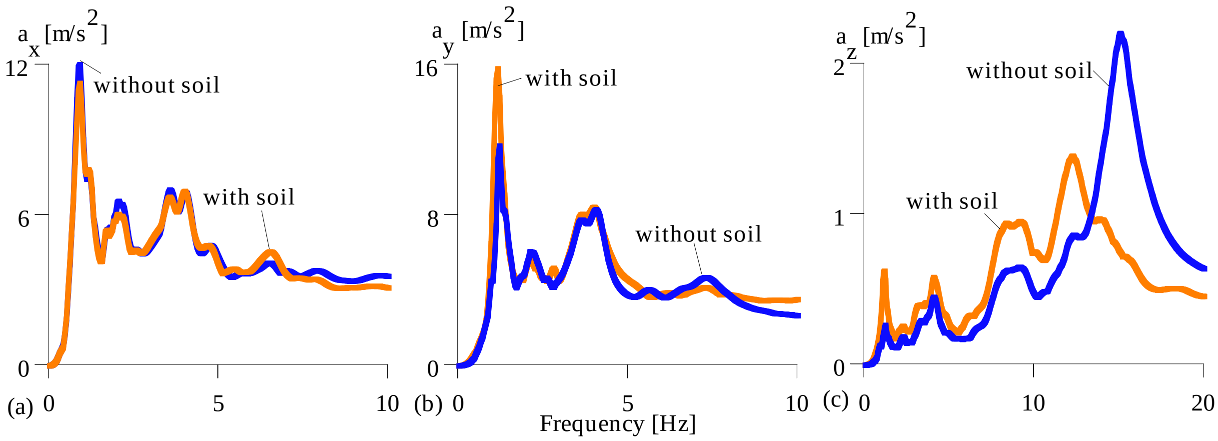

Figure 8(a)-(c). Soil effect on the induced vibration due to the ground motions at JMO ground excitation the soil has a reduction effect on the maximum response, however, an amplification effect on some subsequent peaks of the response. Since the structure with soil has lower natural frequencies than the structure with an assumed fixed base, the maximum and subsequent peaks of the response occur at different times. This time lag affects the time coincidence of the peak responses due to the different component of the ground excitation. The maximum axial force of the structure with soil depends on the amplification effect of the soil in the y-direction that contributes to the time coincidence of the subsequent peaks. Therefore in order to obtain a realistic response the influence of the maximum response itself is not enough. The effect of soil on the time coincidence of the subsequent peaks should also be taken into the consideration.

(4) Effect of SSI on induced vibrations

Figures 8(a)-(c) show the influence of the soil on the induced vibrations in each direction at the top end of the outer column (location **a** in Figure1) due to the simultaneous JMO ground motions. The result indicates that the soil has small effect on the natural frequency of the structure in the horizontal direction, as we can see from Figures 8(a) and (b). The soil can, on the other hand, have an amplification effect on the induced vibration at certain frequency range (Figure 8(b)). In contrast, in the vertical direction the soil has stronger influence on the natural frequencies of the structure. Consequently, different induced vibrations occur.

4. CONCLUSIONS

From the current study the effect of the epicentral distance cannot be seen. However, the vertical ground motions show a strong influence on the structural response, especially in the inner column. In order to have an insight into the influence of the epicentral distance more data should be taken into consideration in coming study.

The investigation reveals:

The maximum axial force depends on the time coincidence of the peaks and the magnitude of the response due to the vertical ground motion.

The vertical induced acceleration has the different frequency contents compared to the ones of the horizontal responses. It may therefore have stronger influence on secondary structures.

Soil can have a different effect not only on the peak responses, but also on their frequency content. Therefore a consideration of the maximum response or the response due to one component of the ground motions can underestimate the effect of the soil.

Further investigations, especially including the nonlinear soil-structure behaviour are necessary.

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