8th Canadian Conference on Earthquake Engineering / 8ième Conférence canadienne sur le génie paraséismique
Vancouver - 1999

Relationship between near source earthquakes and structural responses

Chouw, Nawawi

ABSTRACT

Near source earthquakes can be characterized by strong vertical ground motions with broad range of dominant frequencies. Due to the different nature of vertical and horizontal ground motions different forces in the structural members will be activated. The interaction between the excited horizontal and vertical structural natural vibrations may cause an amplification of forces not only in structural members but also in secondary structures. In order to have a proper design of structures in an expected near source region both horizontal and vertical earthquake loads should be taken into account.

INTRODUCTION

In many of current earthquake design codes vertical ground motions may be neglected. Some codes require a consideration of vertical load only for special structures, e. g. structure with columns on cantilevers. The reason for this is the belief that vertical ground motion is smaller than the horizontal one, and structures are over-designed by a large factor of safety to resist gravity loads, hence will be able to resist additional forces from the vertical ground excitation. Far from the source peak vertical ground acceleration PGA_v is indeed in general smaller than the one of horizontal ground acceleration PGA_h. However, near the source PGA_v can be much larger than PGA_h. Most of the current studies on near source earthquakes focus on the effect of surface geology on the strong motions itself. Only limited works have been done on the effect of strong vertical ground motions on structural responses. Some of these works, for example, dealt with Kobe earthquake (Chouw 1996, 1998), Northrigde earthquake (Chouw et. al. 1999), damage of RC structures (Ghobarah et. al. 1998), and behaviour of base isolated buildings (Ikeda et. al. 1998). This study addresses the relationship between strong vertical and horizontal ground motions and the response of frame structures.

CHARACTERISTIC OF NEAR SOURCE EARTHQUAKES

In order to display the significant difference in the nature of horizontal and vertical ground excitations the response of an one-degree system in figure 1 is considered. Since strong motions have limited duration, the ground excitations a_{gh} and a_{gv} are idealized by sinusoidal accelerations and have the duration of only one cycle to four cycles. Figure 1b shows the maximum response of the mass of the system of certain natural frequency to the horizontal and vertical ground motions, respectively. As was to be expected for a system with a natural frequency equal to or near the excitation frequency the response grows with increasing number n of load cycles, since with each cycle additional energy will be induced into the system. Although the responses due to the horizontal and vertical ground motions, respectively, are the same, they have different physical meanings.

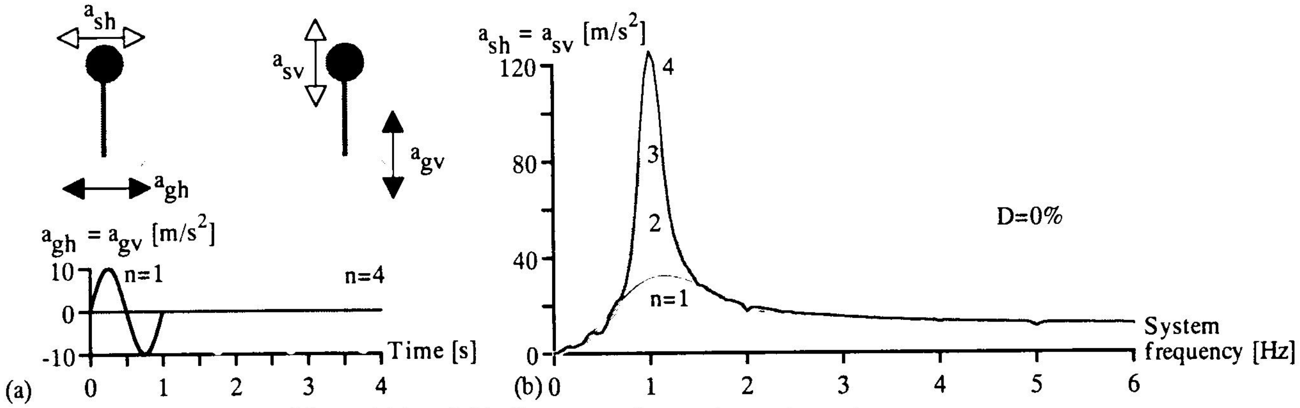


Figure 1(a) and (b). Response of an undamped one-degree system.
(a) System with sinusoidal ground motion, (b) Response spectra.

Assoc. Professor, Dr.-Ing., Dept. of Environmental and Civil Engineering, Okayama University, Tsushima Naka 3-1-1, 700-0082 Okayama shi, Japan, email: chouw@cc.okayama-u.ac.jp

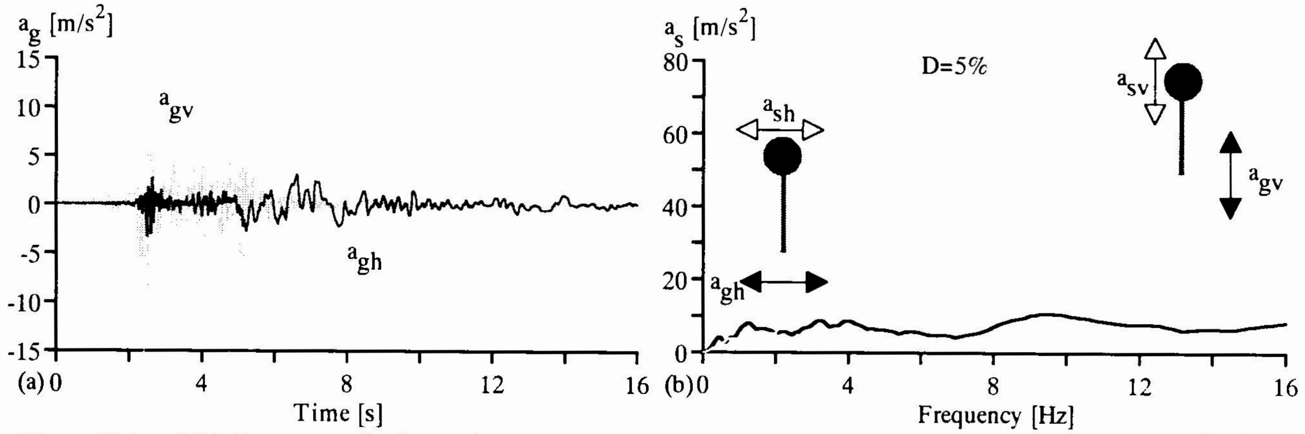
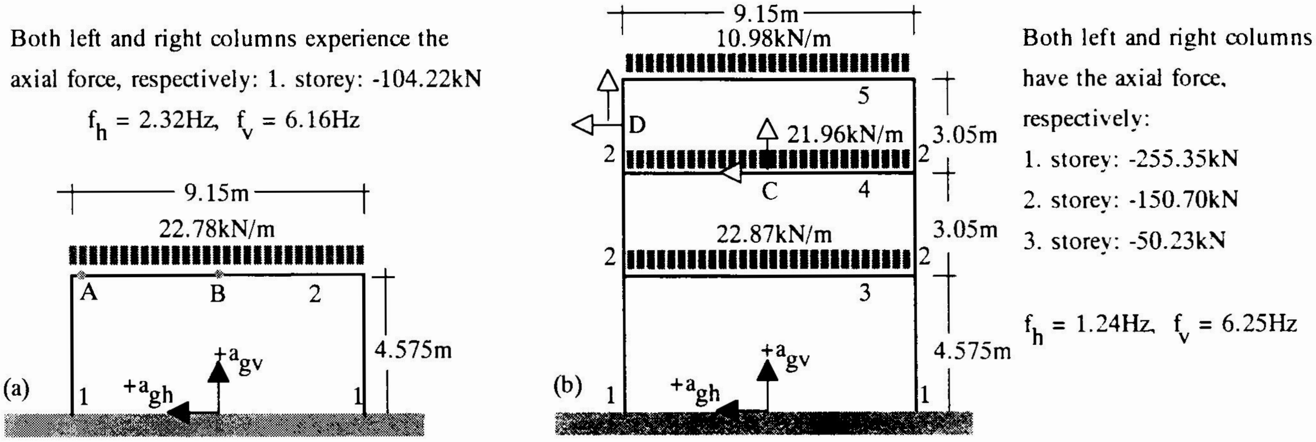


Figure 2(a) and (b). Response of a damped one-degree system to the Imperial Valley earthquake on October 15, 1979. (a) Vertical and horizontal ground accelerations at the epicentral distance of 27.12km, (b) Response spectra.

The maximum accelerations a_{sh} and a_{sv} are the maximum response of the mass in the excited horizontal and vertical directions, respectively. In the case of horizontal ground excitation, the maximum response acceleration corresponds to the maximum shear force at the mass-column interface, and also corresponds with the maximum bending moment at the base. In the case of vertical ground excitation, the maximum response is equivalent to the maximum axial force in the column. With only a consideration of the horizontal ground excitation this difference in the relation of structural responses to the direction of excitations can not be taken into account. An incorporation of vertical earthquake loads in the common design procedure just by scaling the design spectra also ignores the effect of the existing weight. Since the gravity load acts only in the vertical direction, it will affect the vibration of the column differently, if the column vibrates in the transversal direction or if it oscillates in the axial direction. Since surface soil layer generally have higher natural frequencies vertically than horizontally the soil prefers to transmit compressive waves with high frequencies and shear waves with low frequencies. Vertical ground accelerations near the source therefore have higher frequency content than horizontal ground motions. A sinusoidal ground motion with constant amplitude will induce less energy with increasing frequency. However, near source earthquakes can produce PGAs that are much larger in the vertical direction than in the horizontal direction as we can see in the figure 2a. During the Imperial Valley earthquake the PGA_v at 27.12km was about 1.6g. It occurred at 2.42s and was 4.8 times the PGA_h. The higher frequency content of the vertical ground motion can be seen in the response spectra in figure 2b. The system damping is 5%. For the system with a frequency higher than 2Hz the mass will experience a larger response acceleration.

RESPONSE OF STRUCTURAL MEMBERS

In order to analyse the relationship between structural responses and ground excitations two frame structures are considered (figure 3). Their material data are given in table 1. The structural behaviour is described by a continuous mass model. The analysis is performed in the Laplace domain. The mass of the girder given in table 1 includes the corresponding mass of the dead load. The effect of the gravity load, represented by the compressive forces in the columns, is considered.



Both left and right columns experience the axial force, respectively: 1. storey: -104.22kN

f_h = 2.32Hz, f_v = 6.16Hz

Both left and right columns have the axial force, respectively:

1. storey: -255.35kN
2. storey: -150.70kN
3. storey: -50.23kN

f_h = 1.24Hz, f_v = 6.25Hz

Figure 3(a) and (b). Frame structures. (a) One-storey structure, (b) Three-storey structure.

Table 1. Data of the frame structures

	Number of the structural member				
	1	2	3	4	5
mass [kg/m]	67	33	2447	2358	1209
EA [kN]	$1.72*10^{6}$	$8.37*10^{5}$	$3.19*10^{6}$	$3.19*10^{6}$	$2.36*10^{6}$
EI [kNm^2]	$2.10*10^{4}$	$9.80*10^{3}$	$2.00*10^{5}$	$2.00*10^{5}$	$1.00*10^{5}$
Kelvin-chain parameters: E_1=1.0 and E_n=$1.0*10^{29}$					

The material damping is described by a Kelvin chain, so that a causal and almost frequency independent damping exists. For the chosen parameters E_1 and E_n all structural members have a damping of about 1%. While the fundamental horizontal mode of the two structures is charaterized by a horizontal vibration of the whole structure, the fundamental vertical mode of the one-storey structure is defined by a vertical vibration of the girder, and that of the three-storey structure is determined by a vertical vibration of the middle girder.

Relation of structural responses to the direction of ground excitations

The considered ground motion is the Imperial Valley earthquake. The bending moment in figure 4 is induced by the vertical ground excitation or by the horizontal ground excitation. While the bending moment at the location A due to the vertical ground motion is caused by the excited girder vibration, the one due to the horizontal ground motion is determined by the horizontal vibration of the whole structure (figure 4(a)). Corresponding to the ground motion the bending moment due to vertical excitation therefore occurs earlier and has the natural frequency of the girder. Both ground motions produce almost the same maximum bending moment, which is more than four times the static bending moment. Figure 4(b) shows that the horizontal ground motion does not cause any bending moment at the middle of the girder at all. In contrast, the vertical ground motion induces the largest bending moment. It is more than 200% larger than that produced by the dead load. This result shows that the different in the nature of the excitations activates different forces in the structure.

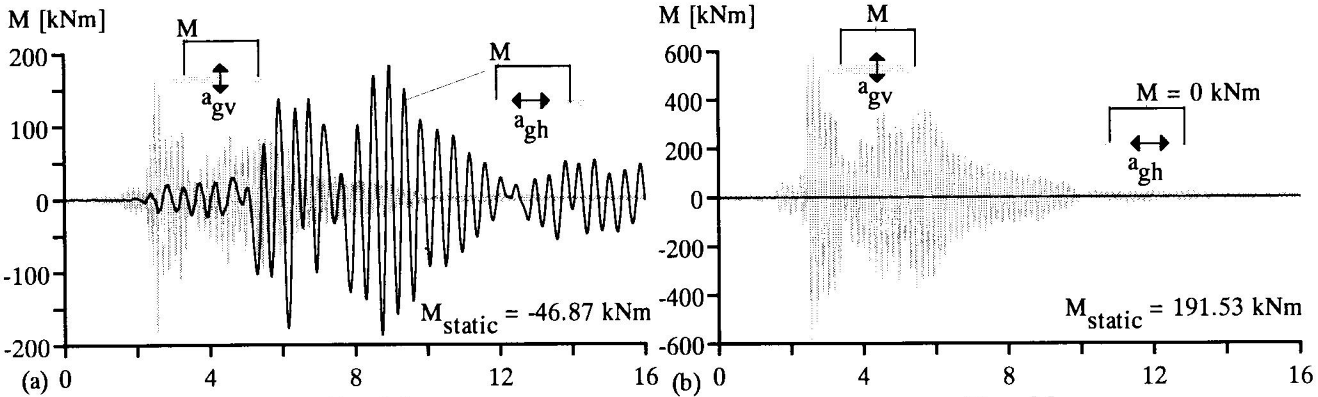


Figure 4(a) and (b). Effect of the excitation directions on the development of the bending moment M.
(a) Bending moment at the location A, (b) Bending moment at the location B.

Relation between vertical and horizontal natural structural vibrations

The development of the axial forces in the left column of the one-storey structure and in the top left column of the three-storey structure due to the Imperial Valley earthquake are considered (figure 5 and 6). Similar relation between responses and excitations can be observed. While the response due to the vertical ground motion is defined by the first vertical natural frequency, the response due to the horizontal ground motion is determined by the horizontal fundamental frequency. The results show that both the maximum tension and the maximum compressive force are produced by the vertical ground excitation. In the case of one-storey structure, a simultaneous excitation (grey line) causes response amplification not only in the phase when the girder vibration is dominant, e.g. at 5.34s, but also in the time when the force development is governed by the horizontal vibration of the whole structure, e.g. at 7.88s, 8.36s and 8.82s. In the case of three-storey structure, significant amplification occurs only in the high frequency period, e.g. at 5.46s. A possible reason is that compared to the natural frequencies of the three-storey structure the frequencies of the one-storey structure are closer to each other.

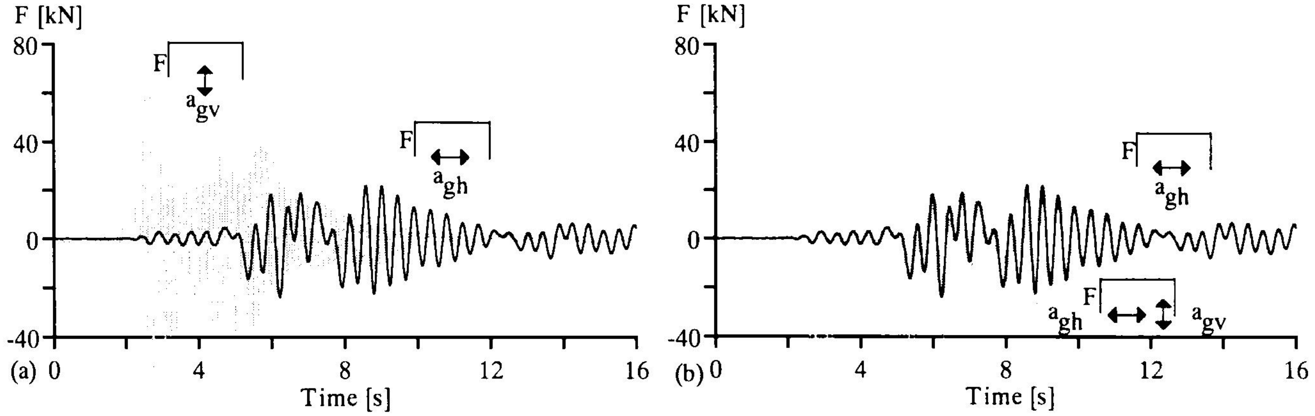


Figure 5(a) and (b). Effect of the excitation directions on the development of the axial force F in the 1-storey structure.

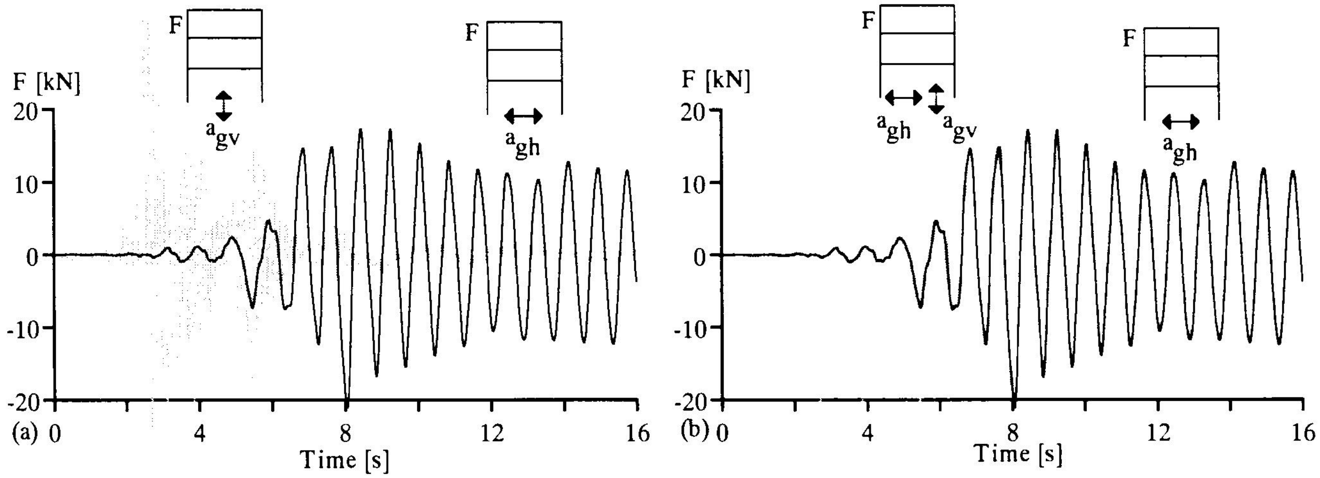


Figure 6(a) and (b). Effect of the excitation directions on the development of the axial force F in the 3-storey structure.

Relation between vertical and horizontal ground motions

The development of the axial forces at the top column of the three-storey structure due to the Imperial Valley earthquake and due to the Kobe earthquake is considered (figure 6 and 7). While the PGA_v and PGA_h of the Imperial Valley earthquake occurred almost at the same time with only 0.075s delay, in the case of Kobe earthquake the PGA_v of $5.56 m/s^2$ at 13.3s arrived 1.92s earlier than the PGA_h. Although the ratio of PGA_v to PGA_h is 1.63, much lower than the ratio in the case of Imperial Valley earthquake, a simultaneous ground excitation causes in both cases almost the same maximum amplification of the axial force. Figure 6 shows that at 5.46s the simultaneous excitation amplifies the compressive force to 25.99kN. It is 1.38 times the force due to the vertical ground motion, and is 3.57 times that produced by the horizontal excitation. In the case of Kobe earthquake several significant amplification occur for example at 6.33s, 7.4s, 9.0s or 9.73s (figure 7(c)). Even though the PGA_v and PGA_h do not coincide in time, the maximum amplification at 10.83s is caused by the time coincidence of the other peak vertical and horizontal ground accelerations (see figure 7(a)). In figure 7(b) and (c) the location is indicated by a vertical line. Since each of the two ground motions alone will already induce tension the simultaneous ground excitation increases the tension to 22.59kN. It is 1.35 times the tension due to vertical ground excitation, and is 3.82 times the force due to the horizontal ground motion. The result shows that the response amplification due to a simultaneous ground excitation depends largely on the peak coincidence of ground motion parts that excite the structural natural vibration modes in the corresponding excitation direction.

RESPONSE OF SECONDARY STRUCTURES

Secondary structures are structures that are attached to structural member, like roof, walls or floors of a building or industrial facility. They normally do not carry load, e.g. architectural components or furniture. A proper design of secondary structures is important, since even if the whole structure does not strongly damage during an earthquake, the failure of secondary structures can bring a building out of function. Falling panels may not only injure people; they may hinder vital rescue works.

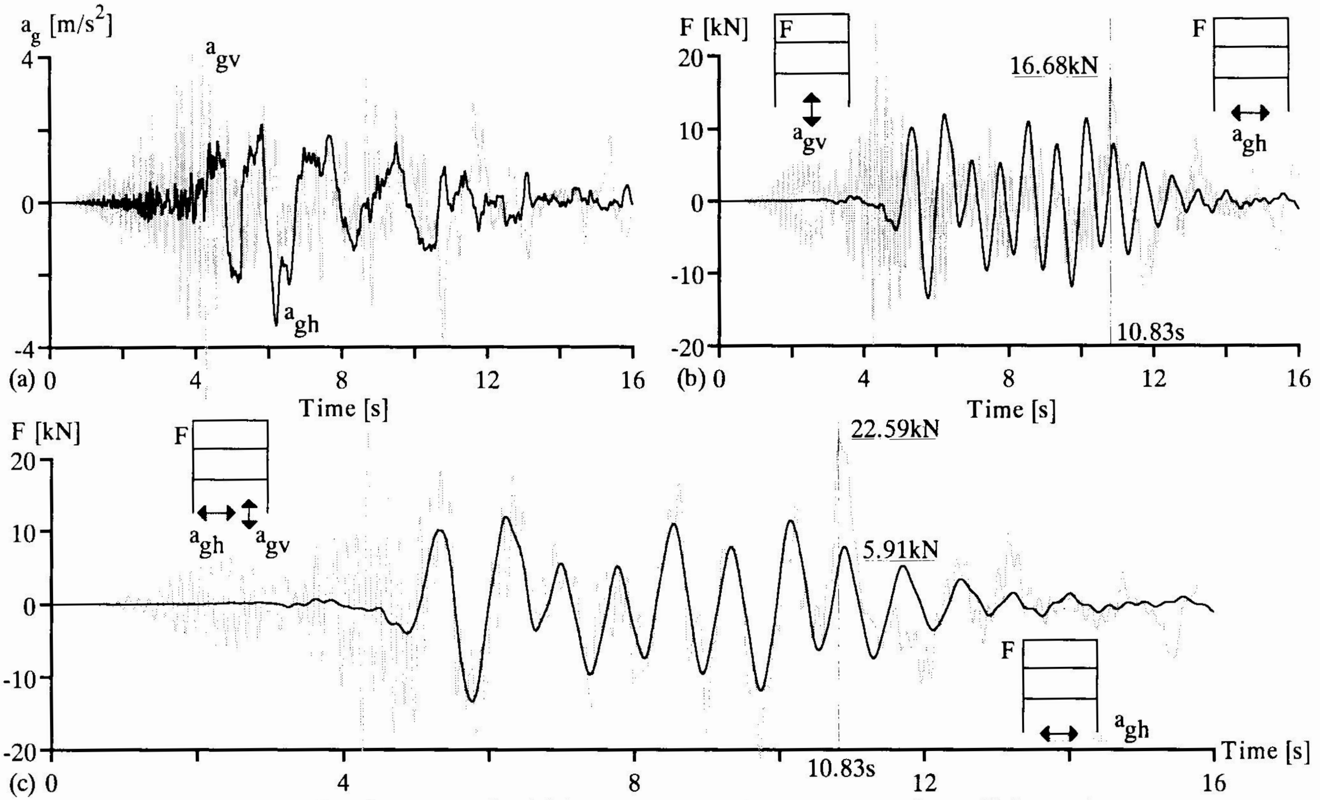


Figure 7(a)-(c). Developments of axial force F in the 3-storey structure due to Kobe earthquake.
(a) Vertical and horizontal ground accelerations at Kobe Port Island, (b) Effect of excitation directions,
(c) Effect of the coincidence of horizontal and vertical peak ground motions.

Figure 8 and 9 show responses of a secondary structure due to the Imperial Valley earthquake. The induced accelerations at the location C indicate the dominant of the excited natural vibrations. Due to the vertical ground motion the induced horizontal acceleration is negligible small. Similar result is obtained, if only the horizontal ground motion is considered, the induced vertical acceleration can be ignored, while the vertical ground motion will produce more than 20g vertical structural acceleration. The secondary structure is described by a one-degree system. Figure 8(c) displays the maximum response of the mass to the induced structural accelerations. If the horizontal earthquake design load is used, the response of a secondary structure with a natural frequency higher than 4Hz will be clearly underestimated. Figure 9 shows the response of a secondary structure attached at the location D. The grey line in figure 9(a) indicates the horizontal response due to the horizontal ground motion, the bold black line due to the vertical ground motion, and the thin black line due to a simultaneous excitation. In the case of a simultaneous ground excitation a system with frequency around the vertical structural natural frequency of 6.25Hz does not experience amplification, since the two horizontal and vertical modes do not strongly interact, as we can see in figure 6(b). In figure 9(b) the grey line indicates the vertical response due to the vertical ground motion and the bold black line shows the response due to the horizontal ground motion. This result shows that the response due to a simultaneous ground excitation (thin line) can not be obtained if only the horizontal ground motion is considered.

CONCLUSIONS

The response of structures depends strongly on the excited natural vibrations. Since horizontal and vertical ground excitations have a different direction, different natural vibration modes will be excited. Consequently, different forces will be activated in the structure. While at some structural locations due to a horizontal ground motion no force will develop, at the same locations the maximum force occurs, if a vertical ground motion is considered. A simultaneous ground excitation should be taken into account, since vertical and horizontal ground motions always occur together, and near source earthquakes can produce ground motions which are much larger in the vertical than in the horizontal direction. Another reason is that a simultaneous ground excitation can cause a larger response, much larger than that produced by the horizontal or vertical ground motion. The response due to a simultaneous excitation depends largely on the relation between the excited vertical and horizontal natural vibration modes and also on the relation between the vertical and horizontal ground motions.

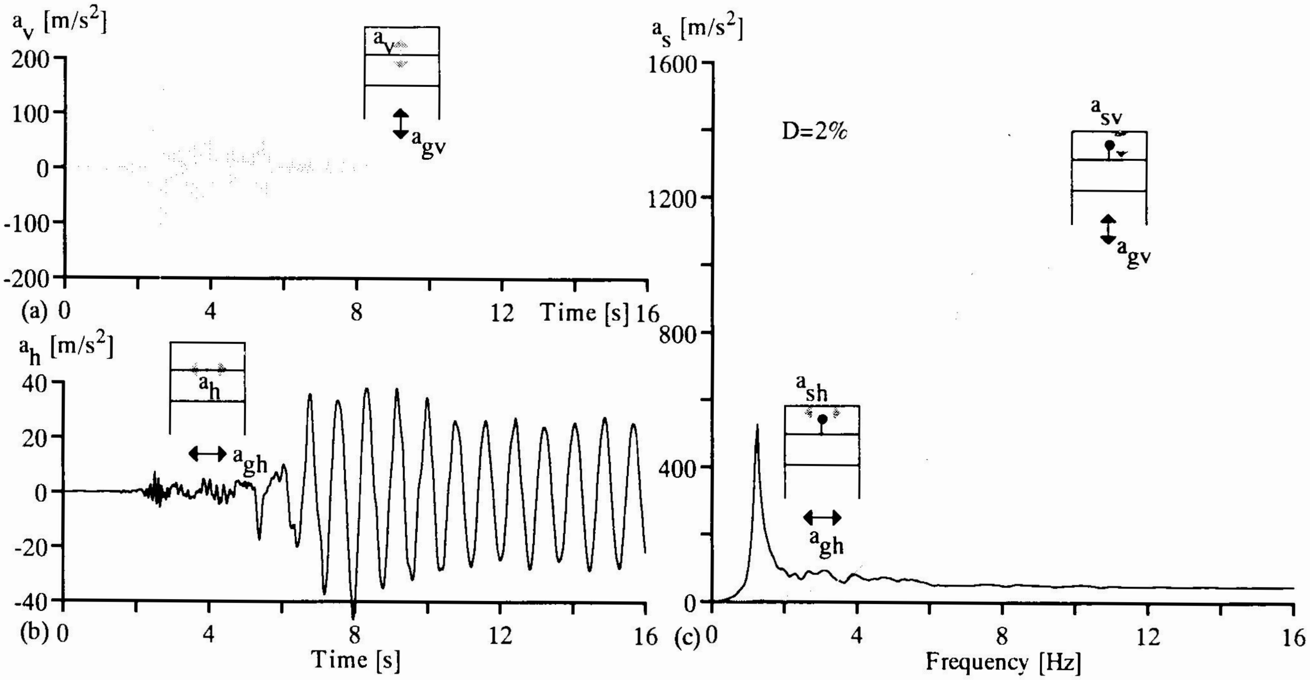


Figure 8(a)-(c). Induced structural accelerations at the location C and response of a secondary structure.
(a) Induced vertical accelerations due to the vertical ground excitations, (b) Induced horizontal accelerations due to horizontal ground excitation, (c) Response of a secondary structure to the induced structural accelerations.

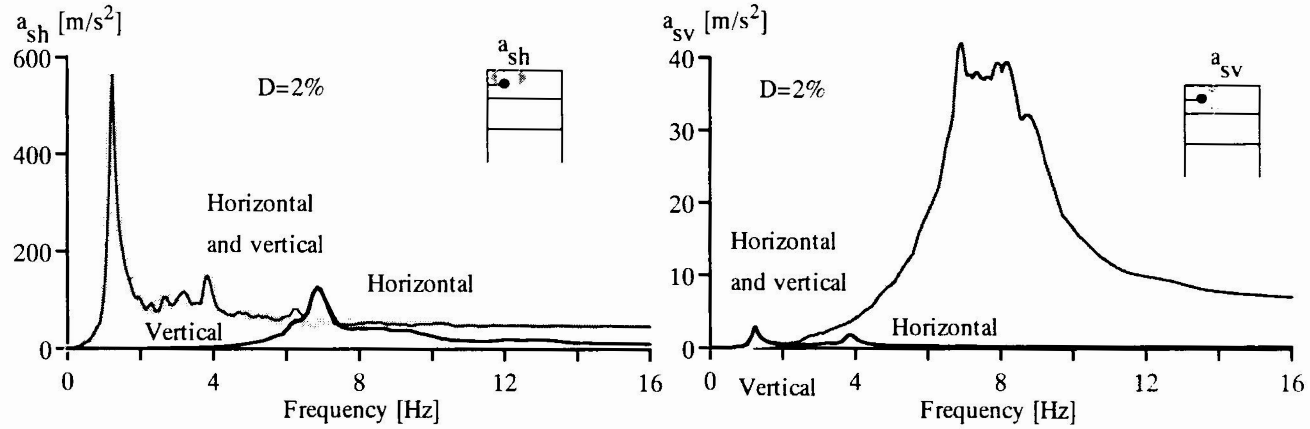


Figure 9(a) and (b). Response of a secondary structure to induced horizontal and vertical structural accelerations at the location D, respectively.

ACKNOWLEDGEMENT

The author would like to thank the Electric Technology Research Foundation of Chugoku, Japan, for the research grant.

REFERENCES

Chouw, N. 1996. Effect of the 17th January 1995 earthquake on Kobe. DACH-Tagung, Graz, pp. 135-169. (In German)

Chouw, N. 1998. Near-source earthquakes and induced structural vibrations. Proc. of 10th Japan symposium on earthquake engineering (10JSEE), Yokohama, pp. 2291-2296.

Chouw, N. and Hirose, S. 1999. Behaviour of a frame structure during near-source earthquakes. Proc. of the 4th European conf. of the European association for structural dynamics, Prague, Balkema. (In press, 6 pp.)

Ghobarah, A. and Elnashai, A. S. 1998. Contribution of vertical ground motion to the damage of RC buildings. Proc. (in CD-ROM) of 11th European conf. on earthquake engineering, Paris, 10pp.

Ikeda, Y. and Nagahashi, S. 1998. Effects of simultaneous action of horizontal and vertical ground motion on pull of multilayered elastomeric isolator of base isolated building. Proc. of 10JSEE, Yokohama, pp. 2765-2770. (In Japanese)