THE EFFECT OF VERTICAL EXCITATION ON STRUCTURAL RESPONSE SEISMIC CHARACTERISTICS

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ABSTRACT

Under an earthquake, structures might vibrate not only horizontally but also vertically due to a vertical excitation. Now the effect of the vertical excitation, however is not considered directly or with scientific Justification. The effect of vertical excitation must be studied to improve the seismic capacity of structures under real earthquakes. In this paper, the characteristics of vertical excitations are discussed comparing with horizontal excitations using 12 ground acceleration records including 1995 Hyogoken-nambu Earthquake records as the first step. As the results, these can be said that the maximum vertical ground acceleration is generally smaller than the horizontal, the vertical input energy due to earthquake is less than the horizontal, but the vertical response acceleration is larger than the horizontal, and the simultaneity of the horizontal and vertical response should be considered as the horizontal and vertical maximum response acceleration should occur at the same time.

1. INTRODUCTION

The earth would quake not only horizontally but also vertically under earthquake. Recently vertically high ground accelerations were recorded especially at sites close to the epicenter. For example, the horizontal and vertical maximum ground acceleration at the Northridge/San Fernando Valley Earthquake of January 17, 1994[1)] are shown in Table 1. A Vertical maximum ground acceleration is almost the same or bigger than the horizontal at some sites. Structures would vibrate vertically by this large vertical excitation, and additional varying axial force might act at columns due to the vertical vibration. So the restoring moment force of column would varies caused by this additional varying axial force.

TABLE 1. MAXIMUM GROUND ACCELERATION AT EACH SITES AT THE NORTHRIDGE/SAN FERNANDO VALLEY EARTHQUAKE OF JANUARY 17, 1994[1]

Place	Maximum Acceleration (G)	
	Horizontal	Vertical
Tarzanna Codar Hill Nursery	1.82	1.18
Arleta Nordhoff Ave. Fire Station	0.35	0.59
Pacoima Kagel Canyon Fire Sta.	0.44	0.19
Sylmar 6-story County Hospital	0.91	0.60
Century City LACC North	0.27	0.15
Los Angels Hollywood StrangeBldg. Free Field	0.41	0.19
Los Angels Hollywood StrangeBldg.	0.41	0.19
Santa Monica City Hall Ground	0.93	0.25
LA-Baldwin Hilla	0.24	0.10
Los Angels Pico and Sentous	0.19	0.07
Los Angels Temple and hope	0.19	0.10

In Japan, the effect of the vertical excitation is considered in "Technical Guideline for a seismic design of nuclear power plant JEAG 4601"[2] or "Technical Guideline for Generation of Design Basis Earthquake"[3]. In reference 2, the effect of the vertical excitation is considered as the static force of which intensity is a half of the horizontal depends on the importance of structures. But it does not has so scientific justification; why the vertical intensity is a half of the horizontal. And in reference 3, this is not for the static design but to make a artificial ground motion record to analysis. So the vertical response acceleration spectrum is proposed in this guideline of which natural period is 0.0~10.0. Since in a structure, the vertical natural period is generally very small, the vertical response spectrum of which natural period is small, is need to be used at the structural design. And also it must be under considering the relationships between horizontal and vertical response characteristics of structures.

And the other guidelines or standards do not consider the effect of the vertical excitation directly. It is not considered also in "Japanese Standard for Structural Calculation of Reinforced Concrete Structures"[4]. One of the reasons why the effect of the vertical excitation is not considered in this standard is that redundant force caused using allowable unit stress for long sustained loading would include the effect of vertical excitation if assumptions that the maximum vertical ground acceleration is a half of the horizontal and vertical response magnification ratio is less than horizontal are true.

Also in "Design Guidelines for Earthquake Resistant Reinforced Concrete Buildings Based on Ultimate Strength Concept"[5] replacing the Japanese standard as the new structural design method, the effect of the vertical excitation is not under consideration. Especially in this guideline of which concept is yield mechanism shall be the beam-yielding type, column can yield based on the axial force-moment curve of a section because of the additional axial load by the vertical excitation. The reason why is that usually the dimension and bar arrangement of a member section are decided based on the ultimate strength concept so that the axial force-moment curve of the restoring force would comprehend the maximum stress when the collapse mechanism is formed. If the varying axial force due to the vertical excitation would act at the column, it depends on the redundant force of the column but there is a possibility of yielding as shown in Figure 1.

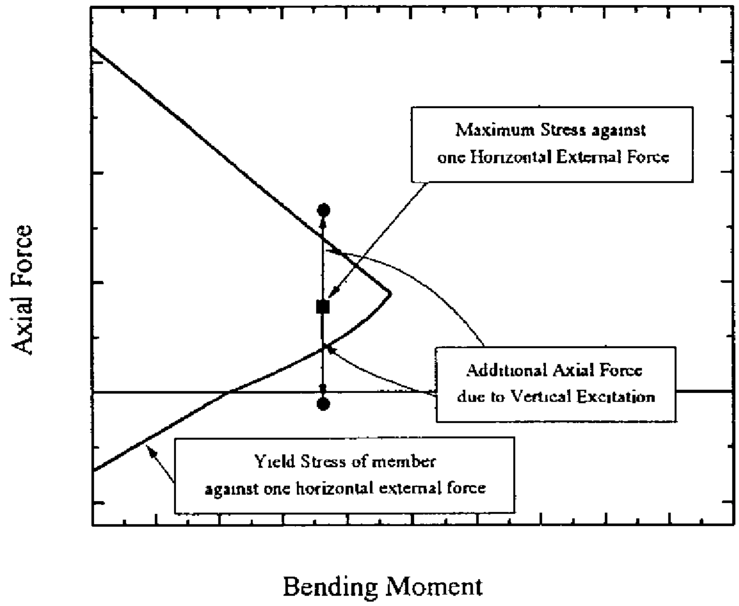

Figure 1. The effect of additional varying axial force by vertical excitation on axial force-moment curve

So it must be studied as follows to improve the seismic capacity of buildings against the earthquake real ground motion in reference 5.

1. Comparison the characteristics of the vertical ground motion with the horizontal.
2. Comparison the vertical response characteristics of structures with the horizontal.
3. Elasto-plastic Dynamic analysis of a frame structure under the bi-axial ground motion to study the effect of the vertical excitation especially on the response of a column.

And then, it must be done to establish the design method based on the ultimate strength concept considering the vertical excitation from results of above three subjects. In this paper, the first subject, comparison the characteristics of the vertical ground motion with the horizontal one, is discussed.

2. COMPARISON THE CHARACTERISTICS OF VERTICAL GROUND MOTION WITH HORIZONTAL

(1) Maximum ground acceleration

To compare the characteristics of the vertical ground motion with the horizontal, 12 earthquake records as follows are studied. These maximum ground acceleration of each direction and maximum ground acceleration ratio (vertical/horizontal) are shown in Table 2. Chiba was recorded at 1987 Chibaken-Toho-Oki Earthquake in Chiba Experiment Station of Institute of

Industrial Science[6]. El Centro was recorded at 1940 Imperial Valley Earthquake, Hachinohe was recorded at 1968 Tokachi-Oki Earthquake and Taft was recorded at 1952 Kern County Earthquake. These records are usually used for the structural design. And Kobe1~Kobe7 were recorded at 1995 Hyogoken-nambu Earthquake in JMA sites[7] and KPI was also recorded at 1995 Hyogoken-nambu Earthquake in Kobe Port Island (artificial land)[8]. City names, latitude north and longitude east of each JMA sites are shown in Table 3. There were two records for the horizontal ground motion (EW, NS). In Table 2, the underlined ratios are calculated with horizontal record of which maximum ground acceleration was larger than the other.

TABLE 2. MAXIMUM GROUND ACCELERATION AND RATIO OF EACH RECORDS

Record	Max. Acceleration			Ratio	
	EW	NS	UD	UD/EW	UD/NS
Chiba	222.7	401.4	118.2	0.53	<u>0.29</u>
El Centro	210.1	341.7	206.3	0.98	<u>0.60</u>
Hachinohe	182.9	225.0	114.3	0.62	<u>0.51</u>
Kobel	41.5	33.0	10.1	<u>0.24</u>	0.31
Kobe2	146.9	136.7	39.1	<u>0.27</u>	0.29
Kobe3	617.1	817.8	332.2	0.54	<u>0.41</u>
Kobe4	52.2	66.9	39.4	0.76	<u>0.59</u>
Kobe5	59.1	77.3	35.9	0.61	<u>0.46</u>
Kobe6	65.9	80.8	64.5	0.98	<u>0.80</u>
Kobe7	74.2	76.7	14.7	0.20	<u>0.19</u>
KPI	284.3	341.2	555.9	2.00	<u>1.63</u>
Taft	175.9	152.7	102.9	<u>0.58</u>	0.67

TABLE 3. JMA RECORDS AT 1995 HYOGOKEN-NAMBU EARTHQUAKE[7]

Record	Longitude East	Latitude North	Location	Trigger Time
Kobe1	136'14"	36'03"	JMA Fukui	05:46:54
Kobe2	136'15"	35'16"	JMA Hikone	05:46:46
Kobe3	135'11"	34'41"	JMA Kobe	05:46:27
Kobe4	135'19"	35'27"	JMA Maizuru	05:46:40
Kobe5	135'55"	34'39"	JMA Okayama	05:46:40
Kobe6	135'31"	34'41"	JMA Osaka	05:46:31
Kobe7	134'14"	35'29"	JMA Tottori	05:46:43

From Table 2, in KPI records, the maximum vertical ground acceleration was larger than the horizontal because of the liquefaction, but it can be said generally that the maximum vertical ground acceleration is usually less than the horizontal. Generally, the maximum vertical ground acceleration ratio against the horizontal depends on the following three factors [9].

1.Soil Condition
2.Distance between site and epicenter
3.Earthquake intensity

Since these factors are correlated each other and only 12 records are studied in this paper, so not general characteristics of vertical excitation using statistical inference but comprehensive characteristics of these records are proposed.

(2) Response acceleration spectra

At first the period T_{max} of each records when the response acceleration is maximum as shown in Figure 2 is calculated to compare the frequency characteristics. From this result, it can be said that the superior period of the vertical excitation is smaller than that of the horizontal one.

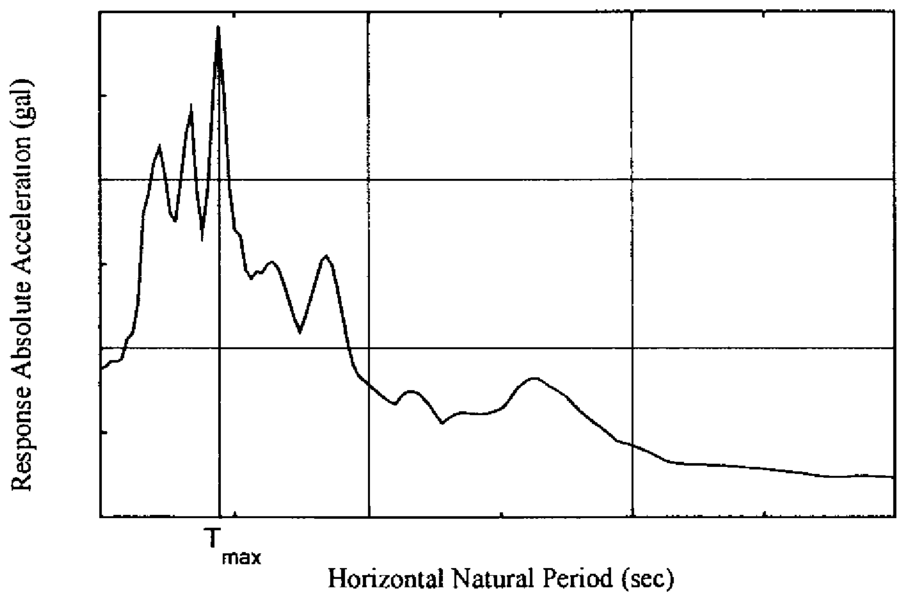

Figure 2. The Period Tmax when the response acceleration is maximum

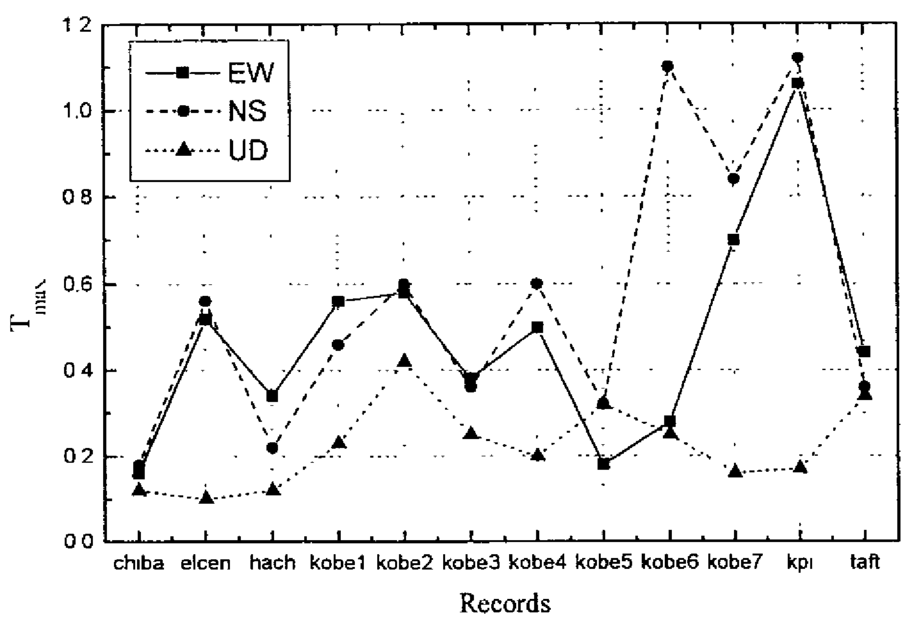

Figure 3. T_{max} of each records

For the effect of the vertical excitation on the response characteristics of structures, the difference between the vertical and horizontal natural periods of structures must be considered. The horizontal natural period ratio against the vertical is calculated easily the length by the depth of column, as H/D (Equation 2), considering following six assumptions.

ASSUMPTION

1.horizontal and vertical stiffness have no correlation each other
2.floors are rigid
3.dimensions of all members are the same
4.moment distribution of column is antimetric
5.shear deformation of member does not occur
6.sections of column are rectangular

The ration H/D is calculated in the way as follows. The horizontal restoring force vs. horizontal displacement stiffness K_H and the axial restoring force vs. axial displacement stiffness K_V of one column are calculated as Equation 1.

$$\begin{cases} K_H = \dfrac{12EI}{H^3} \\ K_V = \dfrac{EA}{H} \end{cases} \tag{1}$$

Horizontal and vertical eigen-value equations can be calculated independently as follows. In these equations, ω_H and ω_V are the horizontal and vertical natural angular frequency, [M] is mass matrix. and $\{U_H\}$ and $\{U_V\}$ are horizontal and vertical eigen-vector.

$$\begin{cases} \left(-\omega_H^2[M]+[K_H]\right)\{u_H\} = 0 \\ \left(-\omega_V^2[M]+[K_V]\right)\{u_V\} = 0 \end{cases}$$

Then, these two stiffness matrix $[K_H]$ and $[K_V]$ have the relationship as $[K_V]=a \bullet [K_H]$ based on Equation 1 and assumptions. So the relationship between ω_H and ω_V is derived as follows from the vertical eigen-value equation.

$$\therefore \omega_V = \sqrt{a}\,\omega_H$$

So the horizontal natural period ratio against vertical can be calculated as Equation 2.

$$\frac{T_H}{T_V} = \frac{1}{\sqrt{a}} = \sqrt{\frac{K_V}{K_H}} = \sqrt{\frac{\dfrac{EA}{H}}{\dfrac{12EI}{H^3}}} = \sqrt{\frac{AH^2}{12I}} = \sqrt{\frac{bDH^2}{12\dfrac{bD^3}{12}}} = \frac{H}{D} \tag{2}$$

The ratio of vertical maximum response acceleration against the horizontal is studied based on Equation 2 to consider the response of structures. The ratio of the vertical maximum response acceleration against the horizontal (Response Acceleration Ratio) of each records are shown in Figure 4 at H/D=6.0. Since two directional accelerations (EW and NS) are recorded as horizontal ground motion, the record of the direction of which maximum ground acceleration is larger than the other is used as horizontal record as before. The value of Response Acceleration Ratio is above 1.0 at the wide range of the natural period except extremely small period, so generally it can be said that the vertical response acceleration is bigger than the horizontal in a structure.

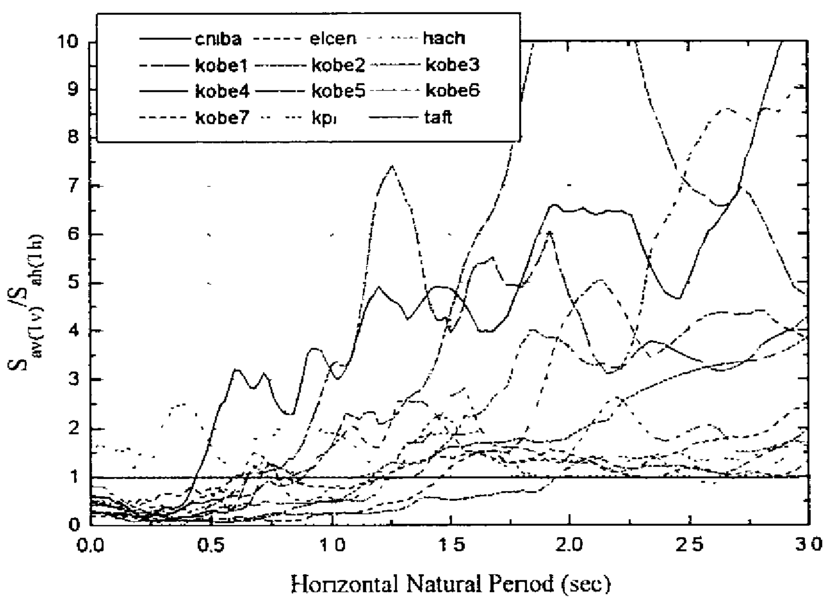

Figure 4. The ratio of vertical maximum response acceleration against horizontal of each records

(3) Response velocity spectra

On the other hand, Response Velocity Ratio was studied on the same way as Response Acceleration Ratio. The Response Velocity Ratio is shown in Figure 5. The ratio is under 1.0, so the vertical response velocity is generally less than the horizontal in structures. It can be said that the vertical input energy due to earthquake is generally less than the horizontal because the response velocity is correspondent to input energy due to earthquakes.

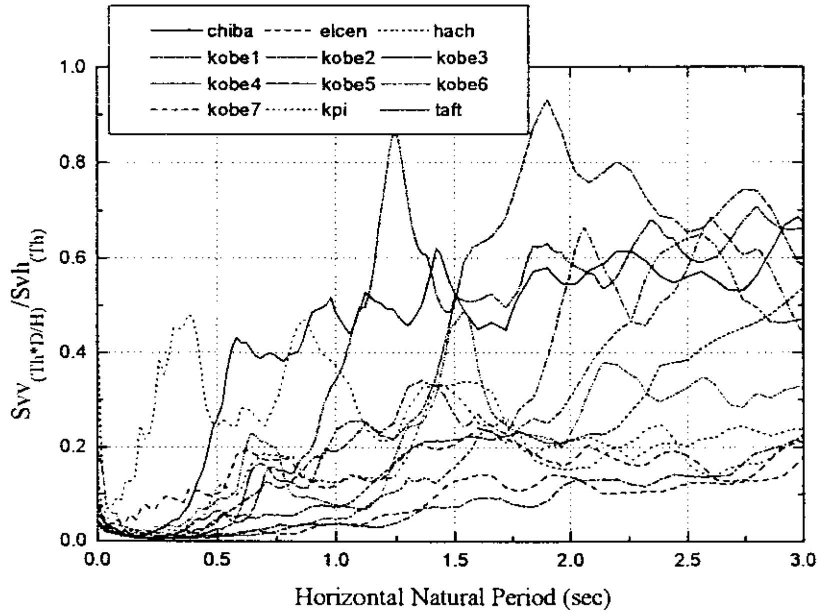

Figure 5. Maximum Response Velocity Ratio

(4) Simultaneity of horizontal and vertical response

The other important factor to discuss about the effect of vertical excitation on the response characteristics of structures is simultaneity of the horizontal and vertical response. To study the simultaneity of the horizontal and vertical elastic response, one mass and two degree-of-freedom (horizontal and vertical) model is used as a structure (Figure 6). The way how to study the simultaneity is indicated as follows. At first the horizontal natural period T_H is varied from 0.0 to 2.0 sec, and the time history of horizontal response absolute acceleration is calculated at each horizontal natural period T_H with each earthquake horizontal record. And second, the time history of vertical response absolute acceleration is calculated at each vertical natural period T_V with each earthquake vertical record. At this time, T_V can be calculated as $T_H \cdot D/H$ based on the natural period ratio as before. 6.0 is used as H/D in this study. Then $R_{(t)} = 0.5\left(\left|\frac{A_{h(t)}}{A_{h\max}}\right| + \frac{A_{V(t)}}{|A_{V\max}|}\right)$ is used as an index of the simultaneity depends on time using the horizontal and vertical maximum response absolute acceleration A_{hMAX}, A_{VMAX} and the horizontal and vertical response absolute acceleration $A_{h(t)}$, $A_{V(t)}$. In this equation, the absolute value is not used as $A_{V(t)}$ because of the assumption that only additional tensile axial force due to vertical excitation would decrease the seismic capacity of structures in this study. R(t) would vary from 0.0 to 1.0 depending on time, so the maximum of R(t) is used as an index of the response simultaneity.

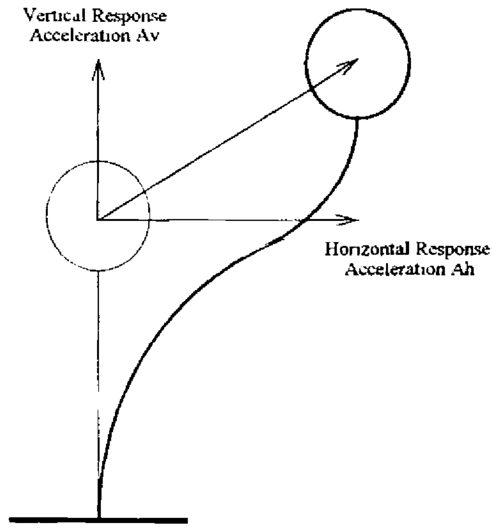

Figure 6. Model to study simultaneity

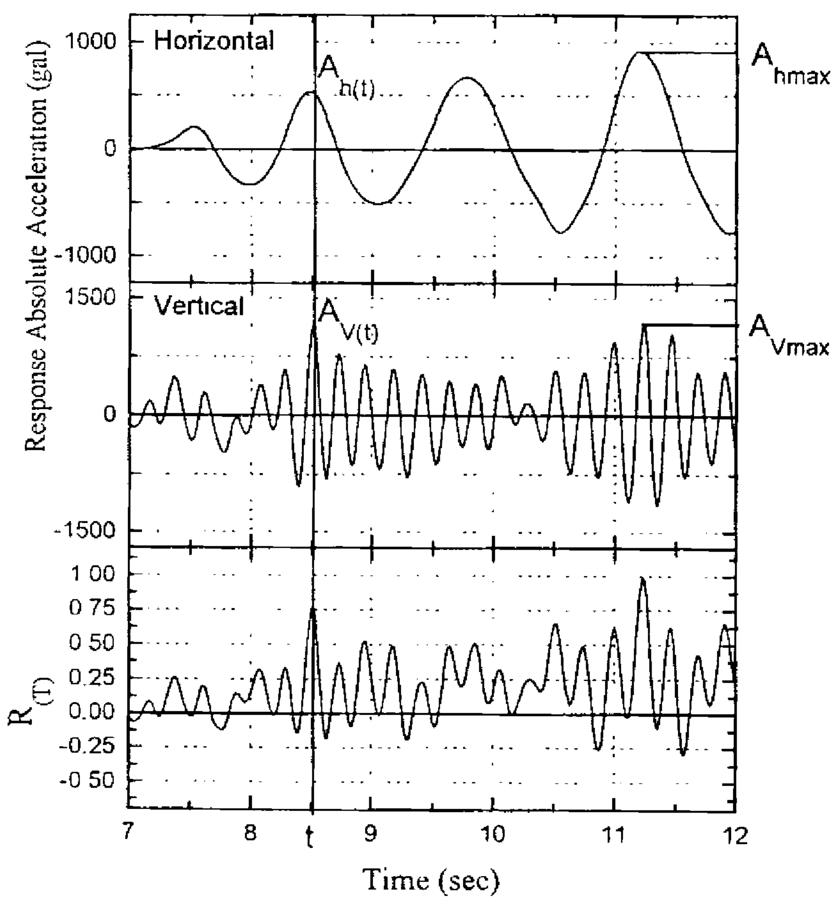

Figure 7. Index of response simultaneity

The results of the response simultaneity of El Centro, Kobe1(JMA Fukui) and Kobe3(JMA Kobe) are shown in Figure 8, Figure 9 and Figure 10. From these figures, the response simultaneity of each wave records are grouped into three classes as follows.

1. The simultaneity is not so high at all natural period of structure.
2. The simultaneity is high only at the particular natural period of structure.
3. The simultaneity is high at the wide natural period region.

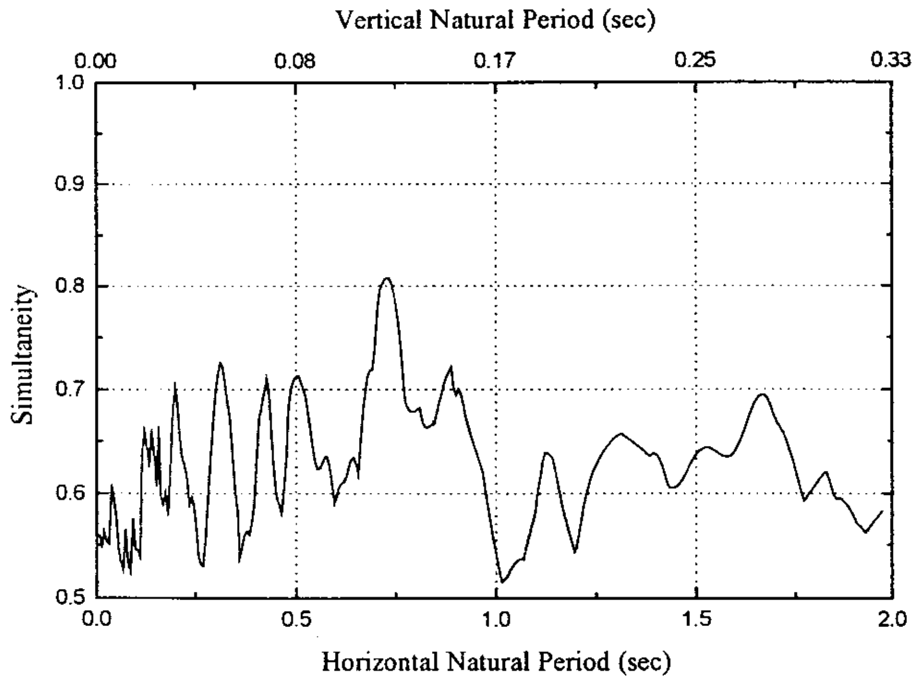

Figure 8. Simultaneity of El Centro

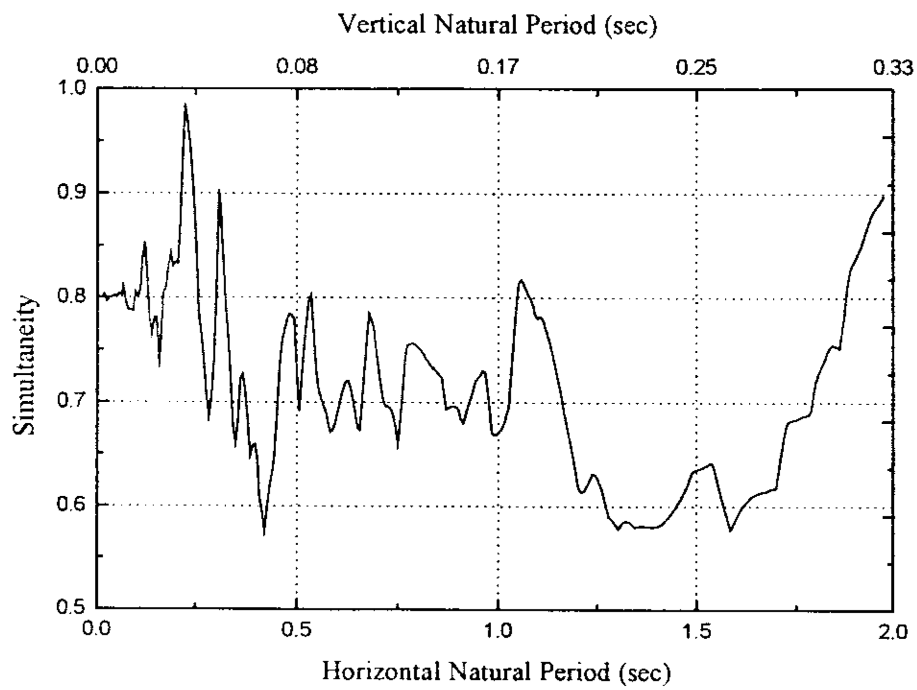

Figure 9. Simultaneity of Kobe 1 (JMA Fukui)

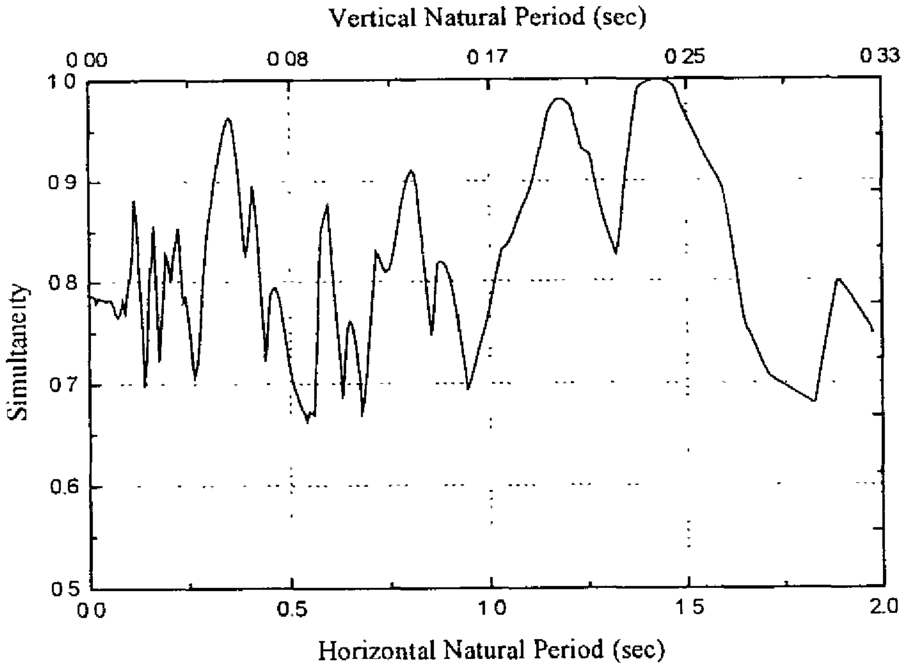

Figure 10. Simultaneity of Kobe 3 (JMA Kobe)

The classifications of each wave are shown in Table 4. Especially in JMA Kobe3 record, the simultaneity is so high at the region where T_H =1.0~1.5 sec. But it is difficult to get some information about the general tendency of the simultaneity because it depends on the wave records and natural period ratio. So it is safe to use R as 1.0 so that the maximum horizontal and vertical response acceleration would occur at the same time.

TABLE 4. RESULT OF SIMULTANEITY OF RESPONSE

simultaneity	Records
I.	El Centro, Hachinohe
II.	Kobe1, Kobe2, Kobe4, Kobe5, Kobe6, Kobe7, KPI
III	Chiba, Kobe3, Taft

3. CONCLUDING REMARKS

To compare the characteristics of the vertical excitation with the horizontal, 12 earthquake ground motion records were studied. The following main conclusions can be drawn for the emphasis.

1. It can be said generally that the maximum vertical ground acceleration is less than the horizontal
2. The vertical response due to the vertical ground acceleration is superior in smaller natural period than the horizontal.
3. In a structure, the vertical response acceleration is superior to the horizontal in wide natural period range.
4. The vertical input energy due to earthquakes is generally inferior to the horizontal.

5. There are some records that the simultaneity of the horizontal and vertical response is high. But it is difficult to get some information about the general tendency of the simultaneity because it depends on the wave records and natural period ratio. So it is safe to use R as 1.0 so that the maximum horizontal and vertical response acceleration would occur at the same time.

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