ANALYSIS OF THREE DIMENSIONAL EARTHQUAKE RESPONSE OF SOIL-STRUCTURE SYSTEM BY RESPONSE MODE ANALYSIS METHOD

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SUMMARY

This paper presents a new approach to analyze multi-channel simultaneous records on soil-structure system by the Response Mode Analysis Method. The approach separates a soil-structure system to sub-systems; a ground system and a structure system, and evaluate the characteristics of response mode of each sub-system. From the study on the multi-channel simultaneous records at Hachinohe Institute of Technology, the effectiveness of the presented approach will be indicated.

INTRODUCTION

Recently, it has become easy to get multi-channel simultaneous earthquake record by the development of the dense earthquake observation system that arrayed many seismographs on a structure or in the ground. However, the method to evaluate complex three-dimensional behavior of a system by the dense earthquake records has not been established yet. Considering on a multi-channel simultaneous record, it is a collection of information on time and space. Then in order to evaluate the three-dimensional behavior of a system, it will be required to develop any method to evaluate spatial information.

The authors have been developed the Response Mode Analysis Method, that decomposes multi-channel simultaneous records into the mutually orthogonalized components by the eigenvalue analysis of the correlation matrix defined on time domain [Takita et al., 1990-1998]. This method is an extension of a method, that calculates principal axes and their variation of strength by the use of 3 components observed at a point [Kubo, 1978]. From the survey on the related studies, it was found that a similar method named POD Analysis has been developed in the wind engineering [Tamura et al., 1995]. But, as far as we know, the approaches mentioned in the next section has not been introduced to the POD Analysis, and the cases applied to the actual problems are not so much.

The authors have been developed some variations on the calculation of the correlation matrix; the Average Response Mode Analysis, the Time-Segmented Response Mode Analysis, and the Running Response Mode Analysis, and some indices; for example, the participation factor of the response mode, modal orthogonality, and so on. The effectiveness of these methods or the indices was confirmed by the previous study [Takita et al., 1998].

The purpose of this study is to confirm the usefulness of the Response Mode Analysis Method on the analysis of complex three-dimensional behavior of a soil-structure system. In this paper, the Average Response Mode Analysis will be applied to the dense earthquake records of the soil-structure system at Hachinohe Institute of Technology. At first, the characteristics of coupling vibration of the ground and the structure will be confirmed by the ordinal spectrum analyses. To clarify the characteristics of the ground and the structure, the Response Mode Analysis will be applied to each system independently, and the results will be compared with the characteristics of

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the total system.

2. RESPONSE MODE ANALYSIS METHOD

Fig. 1 is a summary of the Response Mode Analysis Method. The first and the second steps are extension of the calculation of principal axes [Kubo, 1978]. From these steps, response modes are calculated by the multi-channel simultaneous earthquake record.

The third step is introduced by the authors. In this step, assuming a record as a linear summation of the response modes and time functions, the time functions are separated from the record. The function $a_i(t)$, call as the variation of amplitude of the ith response mode, contains the information of time variation of the modal amplitude. Then, applying Fourier analysis to $a_i(t)$, the frequency characteristics of the ith response mode will be clarified.

STEP 1: Formulation of Correlation Matrix

Correlation matrix **C** is formulated by
$\mathbf{C}=[c_{ij}]$, $c_{ij}=E[x_i(t)x_j(t)]$, $(i,j=1,2,\ldots,n)$
where n is the number of components of the record, E[] means ensemble average, $x_i(t)$ is the ith component of the record, and the average of $x_i(t)$ must be zero.

⇩

STEP 2: Calculation of Response Modes

Calculates response modes $\mathbf{u}_i$ $(i=1,2,\ldots,n)$ by the solution of eigen problem
$(\mathbf{C}-\lambda)\mathbf{U}=\mathbf{0}$.
Here, $\mathbf{U}=[\mathbf{u}_1\ \mathbf{u}_2\ \ldots\ \mathbf{u}_n]$, and **U** must be normalized as $\mathbf{U}^t\mathbf{U}=\mathbf{I}$. **I** is a unit matrix.

⇩

STEP 3: Modal Decomposition of Record

Assuming as
$x_k(t)=\sum a_i(t)\{\mathbf{u}_{ik}\}$,
where $a_i(t)$ is a time function that gives variation of amplitude of the ith response mode $\mathbf{u}_i$, the function $a_i(t)$ is calculated by
$\{a_1(t)\ a_2(t)\ \ldots\ a_n(t)\}=\mathbf{U}^t\{x_1(t)\ x_2(t)\ \ldots\ x_n(t)\}^t$.

⇩

STEP 4: Fourier Analysis of Modal Amplitude Functions

$a_i(t)$ calculated in the previous step is a time function, then the characteristics of variation of $a_i(t)$ will be analyzed by the ordinal frequency analyses.

Fig. 1: Response Mode Analysis Method

The Average Response Mode Analysis, the Time-Segmented Response Mode Analysis and the Running Response Mode Analysis were derived as the variation formulating correlation matrix. In the Average Response Mode Analysis, the all length of the record is used to formulate correlation matrix, then the obtained response modes give average property during the response. In the Time-Segmented Response Mode Analysis, the correlation matrix is formulated by any segment of the record, then the obtained response modes give response property in the selected time-segment. In the Running Response Mode Analysis, the record is analyzed by moving time-segment; in each step the Time-Segmented Response Mode Analysis is applied, then this method clarifies the variation of the response modes in the record. Furthermore, some indices will be calculated by the variation of amplitude of the response mode; the orthogonality between the response modes, participation factor of the response mode, and so on.

3. RESPONSE CHARCTERISTICS OF GROUND SYSTEM AND STRUCTURE SYSTEM

Fig. 2 shows the dense earthquake observation system at Hachinohe Institute of Technology. This system has 21 accelerometers; the first floor and the roof floor of the building have 6 accelerometers respectively, and Near Field A and Near Field B that are the nearest points to the building and Free Field that is far away from the building has 3 accelerometers respectively. The building is a pile-supported reinforced concrete structure with 3 stories. The information on the site, for example soil profile and so on, was presented in [Takita et al., 1996], then it will be abbreviated.

The study on the general characteristics of the soil-structure system uses 15 records of Table 1. The levels of these records are not so large as the system indicates non-linear response, and the frequency characteristics of them are ordinary as they are not extremely predominant in low or high frequency range.

3.1 Maximum Acceleration Values of Ground and Structure

Studying on the ground points (FF01, NFA01 and NFB01) and the structure points (SW1F and NE1F) by the average values at the bottom of Table 1, the maximum acceleration levels of these points will be estimated as follows. The amplification ratio of EW, NS and UD component at FF01 (G.L.-1m of Free Field) for the input at FF20 (G.L.-20m) is about 4.3, 4.6 and 3.6 respectively. The Free Field point is not affected by the building, then it will be considered that these values of the amplification ratio indicate common characteristics of the ground. On

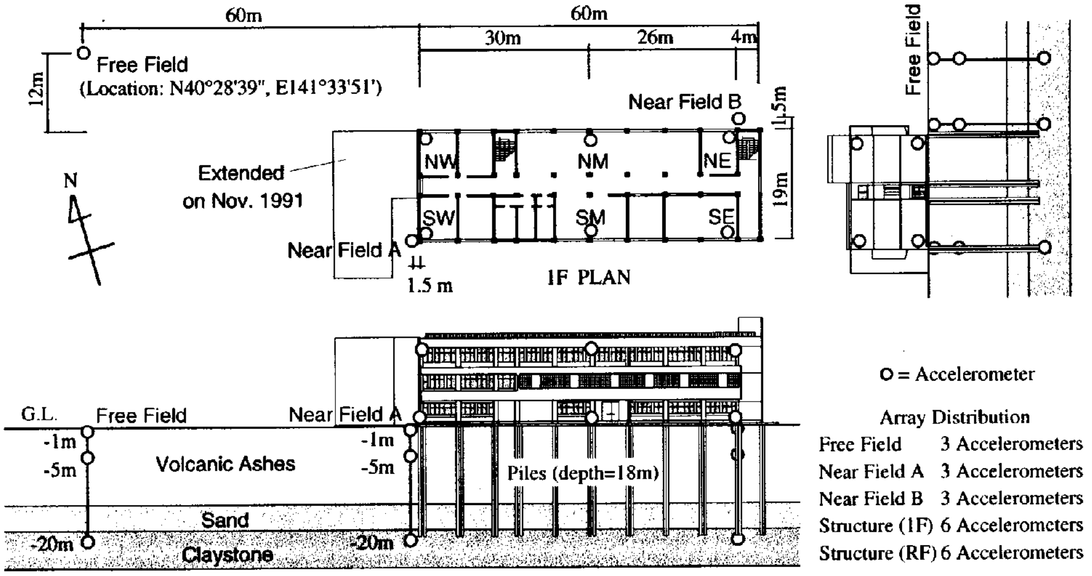

Fig. 2: Dense earthquake oberervation system of Hachinohe Institute of Technology

Table 1: Maximum acceleration values (FF, NFA and NFB are short notation of Free Field, Near Field A and Near Field B in Fig.1, and 20 and 01 after FF, NFA and NFB mean depth of the point from ground level. 1F after SW or NE means floor level of the structure)

No	FF20			FF01			NFA01			NFB01			SW1F			NE1F		
	EW	NS	UD	EW	NS	UD	EW	NS	UD	EW	NS	UD	EW	NS	UD	EW	NS	UD
1	2.1	2.5	2.0	22.4	19.5	6.5	13.8	11.5	5.7	11.2	13.2	9.3	13.1	12.5	6.4	12.7	13.0	6.1
2	3.9	2.8	3.0	17.8	20.9	12.2	16.3	13.3	11.4	18.0	13.8	12.1	12.8	12.4	7.7	12.9	10.3	7.4
3	6.5	5.3	4.2	24.0	20.5	16.8	15.0	21.1	19.1	39.9	30.4	30.2	14.4	10.6	15.2	25.5	21.0	19.3
4	3.5	4.3	2.3	16.8	12.6	12.0	12.7	15.5	10.2	13.2	14.6	11.3	11.9	13.3	8.6	13.5	12.9	7.9
5	1.6	1.2	1.5	8.0	9.6	4.5	8.1	7.0	3.4	7.2	6.6	4.0	7.7	7.3	2.6	7.3	6.9	3.3
6	2.6	3.0	1.6	13.6	14.2	10.6	8.0	13.2	6.9	15.7	12.1	12.7	8.2	11.2	6.4	11.9	12.1	8.0
7	2.6	2.8	3.3	16.9	18.5	15.2	13.9	22.6	10.5	15.5	19.1	17.6	14.1	21.1	9.5	16.0	17.2	8.9
8	9.5	10.8	5.1	25.3	34.7	15.1	15.5	24.5	19.8	18.1	40.0	35.7	15.6	20.7	17.7	20.9	20.3	28.2
9	2.3	2.1	5.0	16.9	17.8	14.0	13.8	16.5	15.1	14.9	15.7	17.6	15.7	20.5	9.1	16.4	12.6	13.7
10	5.2	4.3	3.5	20.1	19.0	12.0	13.2	14.1	12.6	18.6	12.1	14.4	9.9	16.4	9.9	11.8	10.6	9.8
11	3.7	4.1	4.1	14.6	27.5	10.5	15.5	13.3	10.6	17.1	12.1	16.7	16.3	17.6	8.6	18.9	12.4	9.2
12	7.3	7.7	8.2	23.8	32.7	28.5	21.6	34.3	20.0	34.7	39.0	37.2	28.6	32.4	18.1	39.4	29.3	32.6
13	7.2	5.7	5.2	29.3	22.9	19.7	21.0	28.9	23.1	32.3	21.0	25.0	16.0	16.3	12.6	22.9	14.2	15.3
14	9.9	11.3	9.3	40.0	32.0	30.9	30.3	22.6	20.8	42.9	24.9	28.9	29.1	26.3	22.4	31.7	25.2	22.5
15	5.1	5.2	3.7	23.0	33.7	9.1	23.9	21.7	6.1	23.3	25.3	15.9	24.2	22.2	7.0	28.5	23.3	11.8
Min.	1.6	1.2	1.5	8.0	9.6	4.5	8.0	7.0	3.4	7.2	6.6	4.0	7.7	7.3	2.6	7.3	6.9	3.3
Max.	9.9	11.3	9.3	40.0	34.7	30.9	30.3	34.3	23.1	42.9	40.0	37.2	29.1	32.4	22.4	39.4	29.3	32.6
Ave.	4.0	4.1	3.4	17.4	18.7	12.1	13.5	15.6	10.9	17.9	16.7	16.0	13.2	14.5	9.0	16.1	13.4	11.3

the other hand, at NFA01 (G.L.-1m of Near Field A) that is the nearest point to SW1F, the maximum acceleration value is smaller than FF01. At NFB01 (G.L.-1m of Near Field B) that is the nearest point to NE1F, the components of NS and UD tend to be larger than FF01. Studying on the first floor of the structure, SW1F and NE1F are similar to the nearest point NFA01 and NFB01, but the values of the structure points are smaller than the ground points. Then these indicate the input loss of earthquake motion by the restriction of the structure and the foundation.

3.2 Amplification Characteristics of Ground System

Fig. 3 shows the transfer functions of FF01, NFA01 and NFB01 to FF20. These were calculated by ensemble operation of 15 records of Table 1. In Fig. 3 (b) and Fig. 3 (c), the transfer functions of SW1F and NE1F to FF20 were plotted by dashed line. By the previous study [Takita et al., 1996], the lowest 3 natural frequencies of EW component of Free Field point were estimated as 2.8 Hz, 7.7 Hz and 12.0 Hz, and the peaks corresponding to these natural frequencies are found at Near Field A and Near Field B, but the shapes of the transfer functions are different with each point. Namely, at Near Field A, the first peak is clear than Free Field, but the peaks higher than the second are not clear. At Near Field B, the amplification ratio of the first peak is same degree as Free Field, but

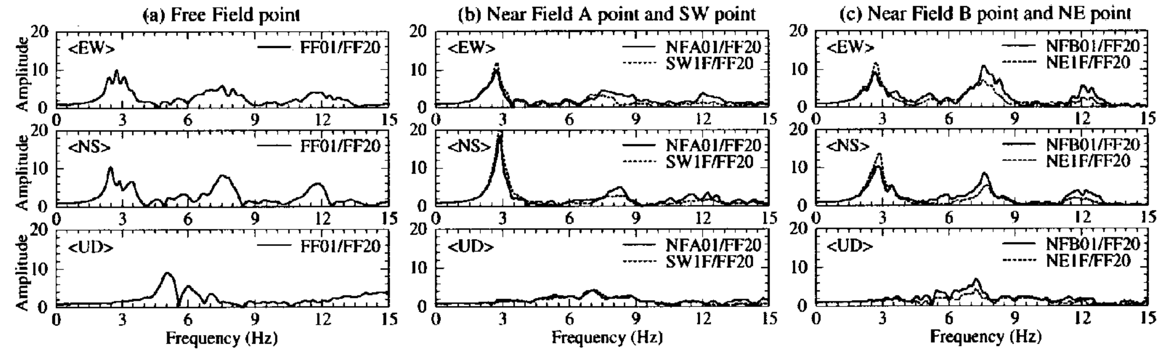

Fig. 3: Transfer function of the ground system (calculated by ensemble operation of 15 records of Table 1).

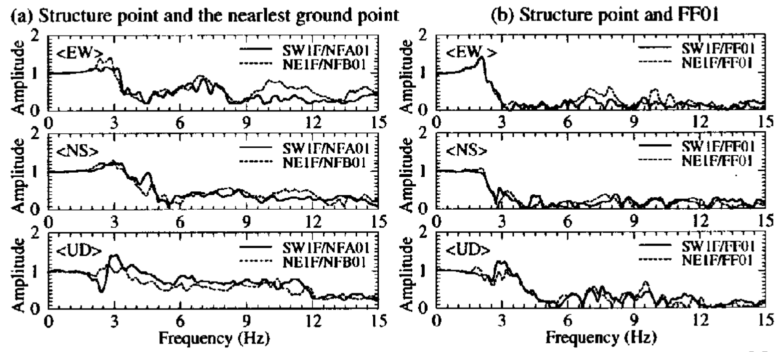

Fig. 4: Transfer function of the structure point to the ground point (calculated by ensemble operation of 15 records of Table 1).

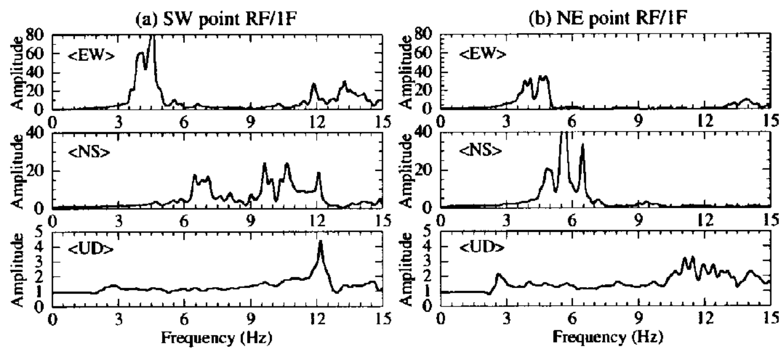

Fig. 5: Fourier spectrum ratio of the structure sub-system (calculated by ensemble operation of 15 records in Table 1).

the second peak of EW component indicates higher amplification ratio than the first peak.

In view of the effects of the restriction by the structure and the foundation, the amplification of Near Field points should be smaller than Free Field point, however, the result of Fig. 3 is not so. This will be understood from the view of the variation of the records, as follows. The records of Near Field A become to have unique property because it is strongly restricted by the structure, so the amplification property of this point becomes clear than the others. On the other hand, in the records of Free Field, the differences of the records were reflected, and the unevenness of the function was appeared where the first peak should be appeared. Furthermore, the restriction of Near Field B is weak than Near Field A, then this point shows the intermediate property between the others.

3.3 Relationship Between Ground System and Structure System

The differences clarified in the previous section means that Near Field points are affected by the structure. Especially at Near Field A, the effect of the point surrounded by the structure appear clearly. Presented in Fig. 3 (b) and Fig. 3 (c) by dashed lines, the structure points (SW1F and NE1F) are different in each other, but each point is fairly well agreement with the nearest point on the ground, then the effects of soil-structure coupling are found.

Table 2: Identified parameters of each point on the structure (the first record of Table 1 was used).

Point	EW direction			NS direction		
	Natural Freq. (Hz)	Damping Const. (%)	Error	Natural Freq. (Hz)	Damping Const. (%)	Error
SW	4.28	5.38	0.082	10.99	26.80	0.019
NW	4.45	14.59	0.117	12.33	25.50	0.018
MS	4.01	6.03	0.123	4.50	17.69	0.238
MN	4.41	9.97	0.139	4.71	18.26	0.221
SE	4.17	10.06	0.151	5.72	9.60	0.108
NE	4.09	8.49	0.177	5.77	9.18	0.099

Fig. 4 shows transfer functions between the first floor of the structure and the ground surface; Fig. 4 (a) is the relation between the corner of the structure and the nearest ground, and Fig. 4 (b) is the relation between the corner of the structure and the ground surface point far away from the structure. In the figures, the input loss of earthquake motion, that the input from the ground to the structure decreases in high frequency range, is appeared clearly. Fig. 4 (a) shows the correlation higher than Fig. 4 (b) in high frequency range, then it will be understood that the ground around the structure behave similarly to the structure. Furthermore, SW point (solid line) and is almost equal to NE point (dashed line), then the difference of inputs between these points is not so much. There is the tendency that the transfer function shows trough around the natural frequency of the structure.

3.4 Charcteristics of Structure System

Fig. 5 shows the amplification properties of SW point and NE point between the first floor and the roof floor. The characteristics of the structure were studied by the transfer functions at first, but the functions distorted around the natural frequencies, because the correlation between the first floor and the roof floor is very small. Then, the amplification property was evaluated by the ratio of Fourier amplitude spectrum. On EW component, peaks are found in the range of 4.0-4.5 Hz commonly at SW point and NE point, but they are split around the natural frequencies. The property of NS component is complex because they are different on the points and unstable; at SW point, it was impossible to confirm which is the true natural frequency, the peak at 7.0 Hz or the peak higher than 10.0 Hz, and at NE point several peaks were found around 6.0 Hz.

Table 2 shows the identified first natural frequencies and damping constants. The identification was done on 6 points of the structure by the acceleration records on the first floor and the roof floor. In the identification, 2 components at a point on the first floor were used as inputs [Tobita, 1996]. The estimated first natural frequencies of EW component are in the range of 4.0-4.5 Hz, and these are common to 6 points. The first natural frequencies of NS component are different with the west points, the center points, and the east points; at the west points they exceed 10.0 Hz, at center points they are about 4.6 Hz, and at the east points they are about 5.7 Hz. It is difficult to decide what caused these results; the extension of the structure, the distribution of the earthquake resisting walls, or the damages by the previous earthquakes, and so on. The estimated natural frequencies of the longitudinal direction are almost equal to the values obtained by the three-dimensional eigenvalue analysis of the structure [Takita, et al., 1988]; the first natural frequency (the first translational mode to the longitudinal direction) is about 4.0 Hz, and the second natural frequency (the first translational mode to the transverse direction) is about 5.4 Hz.

From all the above, the response characteristics of the soil-structure system will be summarized as follows. At the ground points, the peaks correspond to the natural frequencies appear at the common frequency range. However the magnification of amplitude is different with the points. Near Field points, the nearest points to the structure, are affected by the vibration of the structure. On the longitudinal direction the natural frequencies of the structure are almost equal in each point, but on the transverse direction they are different with the west points, the center points and the east points. Then this structure is not so large, but the behavior of the structure is complex.

4. EVALUATION OF CHARACTERISTICS OF SOIL-STRUCTURE SYSTEM BY RESPONSE MODE ANALYSIS METHOD

In this section, the response characteristics of the soil-structure system will be evaluated by the Response Mode Analysis Method. By the analyses of all records of Table 1, it was confirmed that the shapes of the response

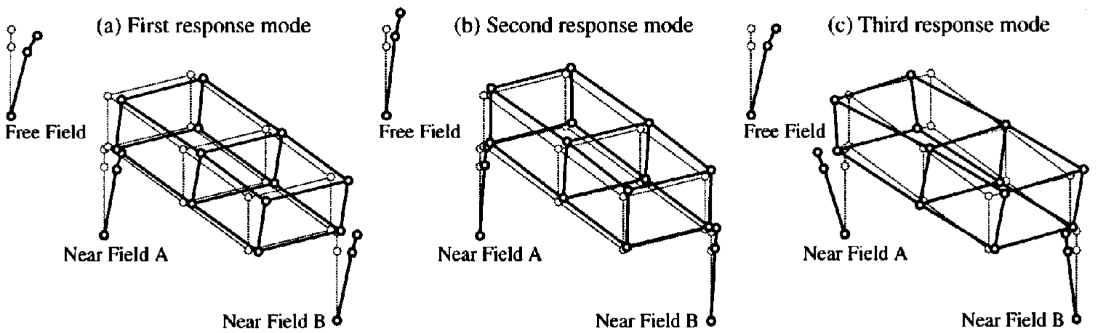

Fig. 6: Average response modes of the ground sub-system and the structure sub-system calculated from the first record of Table 1 (the response modes of the ground sub-system and the structure sub-system were calculated independently in each other).

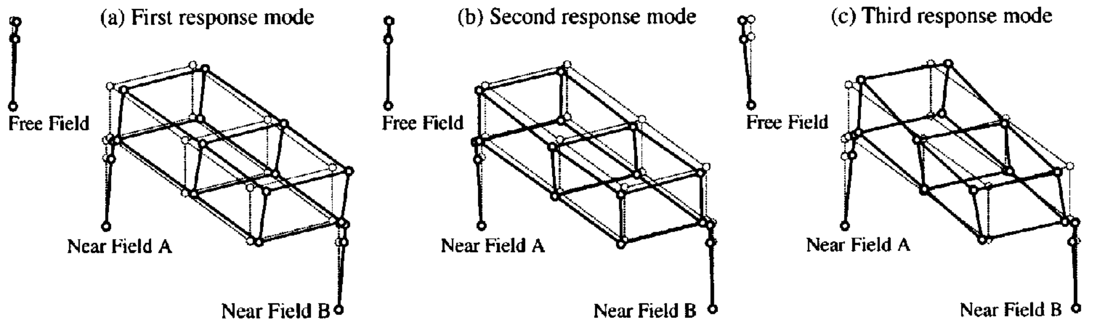

Fig. 7: Average response modes of the soil-structure system calculated from the first record of Table 1.

Table 3: Participation factors of average response mode (the first record of Table 1 was used)

	ground system	structure system	soil-structure system
1st mode	28.3 %	55.0 %	47.0 %
2nd mode	18.9 %	26.6 %	22.8 %
3rd mode	13.9 %	6.5 %	6.0 %

modes, the variation of the participation factors and the variation of modal amplitudes of each record show same tendency in the ground sub-system, the structure sub-system and the soil-structure system. Then, in this section, the results on the first record of Table 1 will be shown. It is a record after the extension of the structure.

4.1 Shapes of Response Mods of Sub-Systems and Total System

Fig. 6 shows the average response modes of the ground system and the structure system; they were calculated independently in each other, and plotted simultaneously. The average response modes are the modes commonly predominated in the all length of a record. The response modes of the ground system were calculated by 27 components of the ground, and the modes of the structure system were calculated by 36 components of the structure. Fig. 7 shows the response modes of the total system (call as total modes), and they were calculated by the 63 components of the soil-structure system.

The first modes of the ground system and the structure system of Fig. 6 (a) are translational modes for EW direction, and the second modes of these systems of Fig. 6 (b) are translational modes for NS direction. These were calculated independently in each other. However the direction of each sub-system shows fairly well agreement. Especially at Near Field A and Near Field B the direction of the modal vectors is almost equal to SW01 point and NE01 point respectively, then these results indicate the coupling vibration of the ground system and the structure system mentioned at section 3.3. Studying on the third modes of Fig. 6 (c), the structure system indicates a torsional mode, and the ground system indicates a component similar to the torsional mode, then it would be found as the modes of these systems indicate well agreement. At Near Field A the direction of the vector is equal to the direction of SW01 point, but at Near Filed B the direction of the vector is opposite to the direction at NE01 point. Then the degrees of the agreement of the third modes are not so well than the lower modes. In Fig. 6 and Fig. 7, it will be found that the UD component is predominated, for example as Free Field of Fig. 6 (b), but the

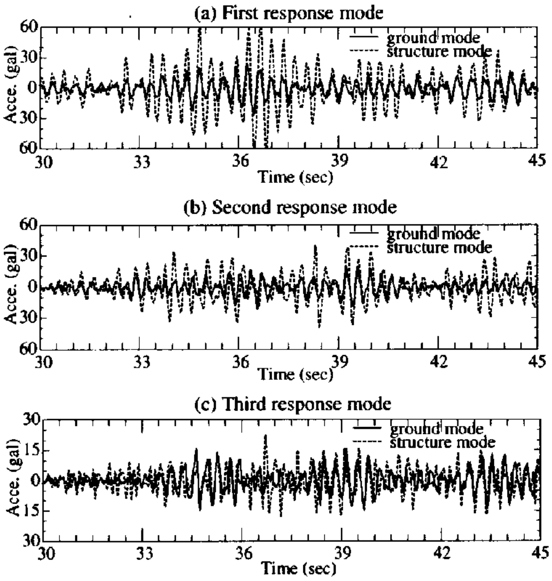

Fig. 8: Variation of amplitude of the response modes of the ground sub-system and the structure sub-system.

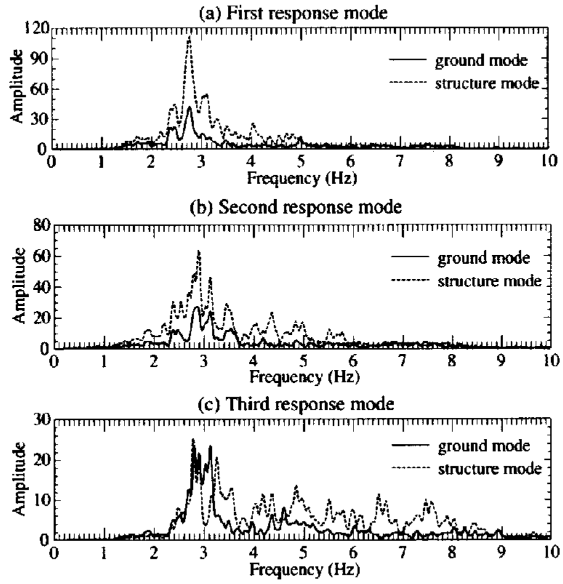

Fig. 9: Fourier spectra of variation of amplitude of the response modes of the ground sub-system and the structure sub-system.

displacement of UD component is extremely small comparing to the horizontal components. Furthermore, in Fig. 6, some of the ground points were shown as moved into the structure, this is the result that the independently calculated response modes were magnified by the same factor. The results presented in Fig. 6 and Fig. 7 show fairly well agreement with the three-dimensional modes of the structure obtained by the modal analysis of the three-dimensional model fixed at the foundation [Takita et al., 1988]; the first mode is a translational mode to the longitudinal direction, the second mode is a translational mode to the transverse direction, and the third mode is a torsional mode.

4.2 Time Variation of Three-Dimensional Vibration of Soil-Structure System

Table 3 shows the participation factors of the response modes of the ground system, the structure system and the total system. The participation factor of a response mode is defined as the quotient of power of the variation divided by the sum of the powers of the variations, where the variation is the time variation of the amplitude of the response mode. Then a participation factor gives degrees of excitation of a response mode in a record. Table 3 shows the tendency of the variation of the participation factors as follows; on the ground system, the participation factors decrease as the order becomes higher, on the structure system, this tendency is equal but the participation factor of the first mode is extremely large, and the total system shows the similar tendency to the structure system.

Fig. 8 shows the variation of amplitude of the response mode. The solid line indicates the ground system, and the dashed line indicates the structure system. In the figure, the variation of the total system was abbreviated, because the amplitudes of the total system become slightly larger than the structure system but the phase is equal to the structure system. On the first mode of Fig. 8 (a), the phase of the variation of modal amplitude of the ground system shows fairly well agreement with the structure system for all range presented in the figure. On the second mode of Fig. 8 (b), the variations of the ground system slightly differ with that of the structure system around 36 s, but they show well agreement with that of the structure system on the other ranges. On the third mode of Fig. 8 (c), the phase of the variation of the ground system become opposite to the phase of the structure system at some points after 32.5 s.

Fig. 8 (a) and Fig. 8 (b) show the change of the response modes. In the range of 36.0-37.5 s, the amplitude of the second mode becomes small as the amplitude of the first mode becomes large, and around 39.0 s the change appears oppositely. These show the change of the response modes during earthquake, and the result indicates that the possibility of the rational evaluation of complex behaviors by the Response Mode Analysis Method.

Fig. 9 shows Fourier spectrum of variation of modal amplitude. Differing on the amplitudes, the peak about 2.8 Hz, that is the natural frequency of the surface ground, appears on the ground system and the structure system, and the total system shows same results. These are the result that the structure system was analyzed including the effect of the ground motion because the absolute acceleration records were used. As the result, on the structure system, the peak corresponding to the natural frequency of the structure system can not be found from the spectrum of the variation of modal amplitude, but considering on the results of Takita et al. (1997), it would be possible to evaluate the natural frequencies of the structure system by the analysis of the relative acceleration record that will be created subtracting the responses of the surface ground from the responses of the structure. On the third mode of Fig. 8, the phases of the variation of modal amplitude are different with the ground and the structure at some segments. This would be the effect of the range where the peaks different with each system shown in Fig. 9, for example the range of 3.0-3.3 Hz or the range higher than 5.5 Hz.

5. CONCLUSIONS

In this paper, the Response Mode Analysis Method was presented as a new approach to analyze multi-channel simultaneous records. In order to confirm the usefulness of the method, it was applied to the dense earthquake records at Hachinohe Institute of Technology.

By the spectrum analysis, it was clarified that the soil-structure system have the following characteristics; (a) at the ground points, the peaks of the natural frequencies are almost equal, but the amplitude is different with the points, (b) the effects of the vibration of structure are found at the ground points nearest to the structure, (c) the natural frequencies of the longitudinal direction of the structure are almost equal on each point, but the natural frequencies of the transverse direction are different with the west points, the center points and the east points, and the structure is not so large but the behavior is complex.

From the analyses of the soil-structure system by the Response Mode Analysis Method based on the results mentioned above, the followings were clarified; (1) the effects of coupling between the structure and the ground around the structure was evaluated, because the direction of response modes of the ground system shows well agreement with the structure system on the first and the second response modes, (2) the shapes of the response modes of the ground system and the structure system that are simply overlapped show well agreement with the modal shapes of the total system in the lowest orders, (3) from the comparison on the modal shapes and the participation factors, it was clarified that the modal shapes of the total system are highly affected by the structure system rather than the ground system.

For a future study, there are some subjects as the difference of the amplitude level of earthquakes or the difference of the frequency characteristics of the earthquakes how affect to the responses of the soil-structure system, and so on.

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