NON-LINER RESPONSE ANALYSIS OF NUCLEAR FACILITIES SUBJECT TO HORIZONTAL AND VERTICAL GROUND MOTIONS

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ABSTRACT :

In this study, non-linear dynamic response analysis was carried out on a full-scale BWR building with the input direction and amplification factor of ground motion as parameters, and the effects of different combination of these parameters on horizontal response of the building were reviewed. As a result, it was found that the input of vertical ground motion had no significant effect when the building was in an elastic region, and that the input of vertical ground motion had effects on the distribution of the maximum horizontal response acceleration and the amplitude of the prevailing periodic band of horizontal floor response spectrum when the building reached a non-linear region.

KEYWORDS: horizontal and vertical ground motions, RC wall, non-linear response analysis

1. INTRODUCTION

In September 2006, “Safety Examination Guideline for Seismic Design of Nuclear Facilities” [1] was revised by Nuclear Safety Commission of Japan. Notable characteristics of the revised guideline are the followings: Introduction of the advanced method for determining design basis ground motion and recognition of the existence of the “Residual Risk”. With the revision of the guideline, a dynamic response analysis for horizontal and vertical ground motions was necessary to evaluate seismic safety of nuclear facilities. In addition, it was also necessary to evaluate the strong non-linear response of nuclear facilities with the consideration of stronger earthquakes and their uncertainty in the evaluation of the “Residual Risk”.

In a past study, the authors developed a non-linear dynamic response analysis code based on a 3D FEM analysis [2]. In this study, we carried out detailed non-linear dynamic response analysis of a reactor building simultaneously subjected to horizontal and vertical ground motion and examined the influence of vertical ground motion input on the horizontal response of the building. First, referring to past shaking table test results of RC wall [3], analysis was carried out with the same conditions to verify the validity of the analysis code used in this examination. Then, sensitivity analysis was carried out on a full-scale BWR building with the input direction and amplification factor of ground motion as parameters, and effects of a combination of these parameters on horizontal response of the building were reviewed.

2. ANALYSIS METHOD

As shown in Figure.1, for detailed evaluation of the 3D non-linear dynamic response of a reactor building subjected to strong ground motion, the input of ground motion must be simultaneous in two horizontal directions and the vertical direction. Various factors have an influence on the non-linear dynamic response of a reactor building, and they include the non-linear characteristics of the RC wall and surface soil, uplift and embedded effect of the building, and interaction between the building and ground. In addition, evaluation of equipments response is necessary to use the building floor response in the place in which the

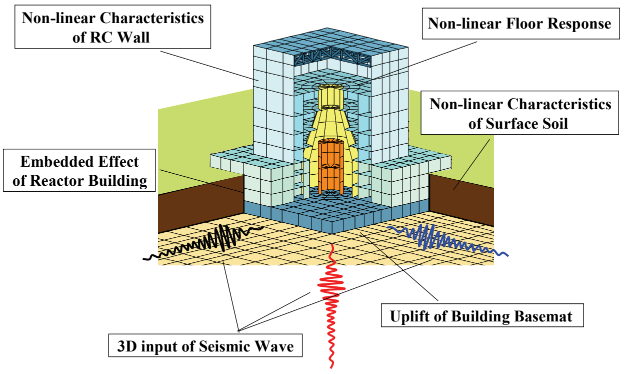


Fig.1 Factors to Affect Non-linear 3D Seismic Response of Reactor Building

equipment installation is reflected.

In a past study, the authors developed a non-linear dynamic response analysis code "SANREF" base on a 3D FEM analysis [2]. In this code multi layer shell elements which can consider the axial force, shear force and flexural moment, and the four-way fixed crack model proposed by Maekawa and Fukuura [4] were introduced to express the non-linear characteristics of the RC wall subject to earthquake. To represent the non-linear characteristics of the surface soil, a material constitutive law, which is the Ramberg-Osgood model and Hardin-Drnevich model extended to three dimensions, was introduced. In addition, to represent the uplift of the building basemat and embedded effect of building, discrete contact surface elements to represent the separation and slip between the building and ground were introduced.

3. VERIFICATION OF VALIDITY OF THE ANALYSIS CODE

3.1 Outline

Nuclear Power Engineering Corporation "NUPEC" published the shaking table test results of test models of RC walls to the International Standard Problem "ISP" hosted by the Nuclear Energy Agency of the Organization for Economic Co-operation and Development "OECD/NEA" [3]. This section aims at verifying the non-linear response evaluation function introduced in SANREF. Thus, an analysis was carried out under the same conditions as ISP and the analysis results were compared to the test results.

3.2 Analysis conditions

3.2.1 Analysis object and analysis model

The test specimen is I-shaped RC wall made of a web wall and flange walls connected to both sides of the web wall. The reinforcement ratio of each part of the RC wall is 1.2% of vertical and horizontal reinforcement in the web wall and 0.92% of vertical reinforcement and 0.36% of horizontal reinforcement in the flange walls. A weight of 93tons is attached to the upper slab, and the basemat is placed directly on the shaking table.

The analysis model is shown in Figure.2. This model is a 1/2-scale model considering the symmetry about the y-axis of the test specimen. The web and flange walls are represented by the multi layer shell elements and the upper slab, the basemat and weight are represented by solid elements. As for the boundary conditions, the bottom face of the basemat was perfectly fixed and the ground motion input was directly introduced to that face along the x axis.

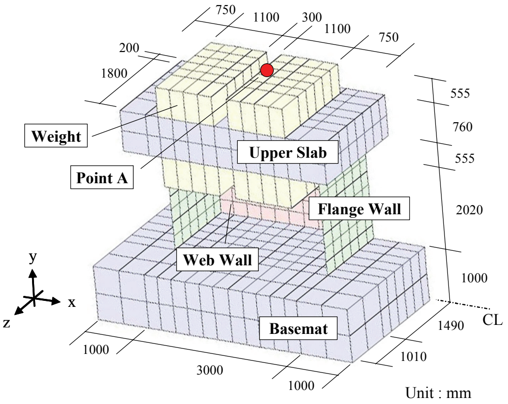


Fig.2 Analysis Model

3.2.2 Material characteristics

Referring to the test results, the RC wall was treated as a RC structure considering the material non-linearity, and the concrete of the upper slab and the basemat, the steel of the weight were treated as elastic bodies. Their material characteristics are shown in Table.1.

Initial stiffness proportional Rayleigh damping was selected for the element damping and the equivalent damping constant of 1.1% measured before the test was set for the damping constant.

Table.1 Material Property

Concrete				Steel		
E_c (N/mm^2)	ν_c	f'_c (N/mm^2)	f_t (N/mm^2)	E_s (N/mm^2)	ν_s	f_y (N/mm^2)
2.27x10^4	0.2	28.6	2.23	1.84x10^5	0.3	383

3.2.3 Input ground motion

The acceleration response spectrum (h=0.05) of input ground motion is shown in Figure.3. For the input ground motion, the acceleration time history measured on the shaking table was adopted.

3.2.4 Analysis cases

The following two cases were selected as the input ground motions: a case in which the maximum response

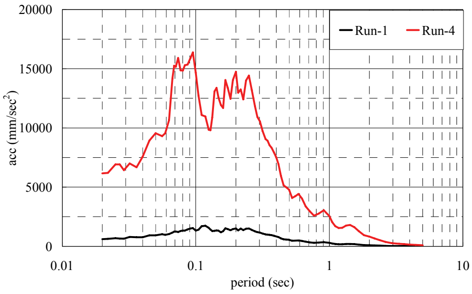


Fig.3 Acceleration Response Spectrum (h=0.05) of Input Ground Motion

stress of the RC wall approaches linear limit of the shear force-shear deformation angle relation of the RC wall (Run-1, PGA=53Gal), a case in which it approaches the ultimate limit (Run-4, PGA=577Gal)

3.3 Analysis results and considerations

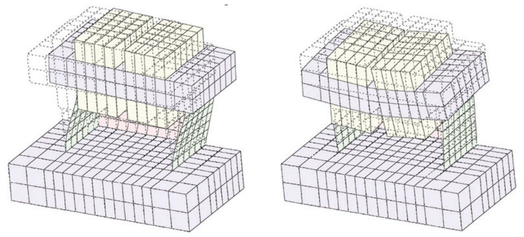
3.3.1 Natural vibration mode

Table.2 shows the eigenvalues obtained from the analysis results and Figure.4 shows representative natural deformation modes.

The 1st and 3rd modes are horizontal vibrations and the 2nd mode is a vertical vibration. For subsequent dynamic response analysis, the concrete initial stiffness of the analysis model was reduced to 85% so that the eigenvalue of the first mode in the analysis results became equal to the test results.

Table.2 Free Vibration Analysis Results

Mode	Period	Participation Factor	
		x (Horizontal)	y (Vertical)
1	0.076	1.080	0.000
2	0.027	0.000	-1.310
3	0.019	-0.175	0.000
4	0.013	0.000	-0.273
5	0.012	0.000	-0.767

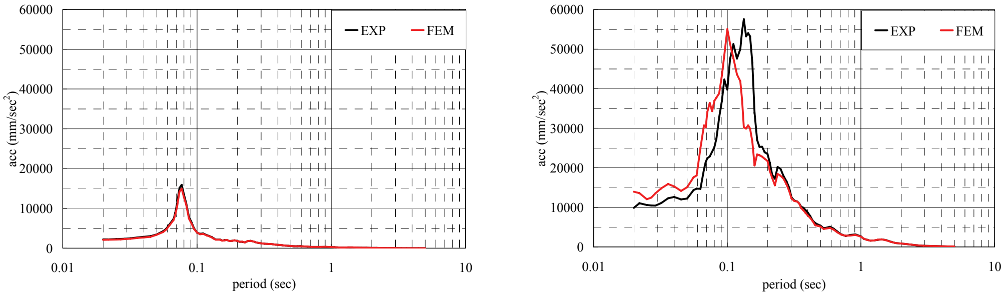


Mode 1 (Horizontal Mode) Mode 2 (Vertical Mode)

Fig.4 Mode Shape

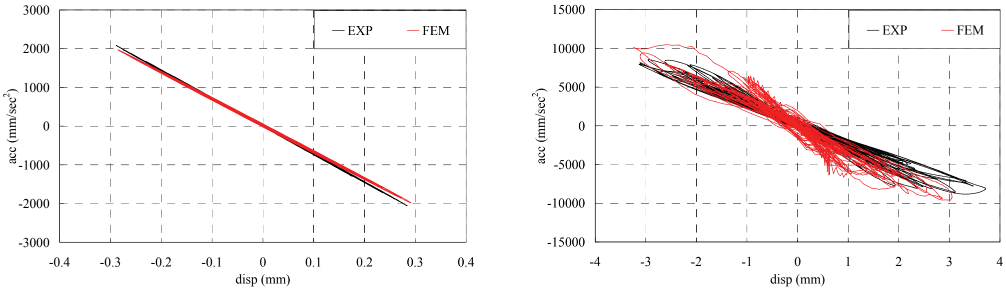
3.3.2 Comparison between analysis and test results

To compare the analysis results to the test results of Run-1 and Run-4, Figure.5 shows the horizontal acceleration response spectrum (h=0.05) at the center of the upper slab (Point A in Figure.2) and Figure.6 shows the horizontal acceleration response-displacement response relation at the same position. And, Figure.7 shows the cracking condition of Run-4.



Run-1 Run-4

Fig.5 Horizontal Acceleration Response Spectrum (h=0.05) at the Center of the Upper Slab



Run-1 Run-4

Fig.6 Horizontal Acceleration Response - Displacement Response Relation at the Center of the Upper Slab

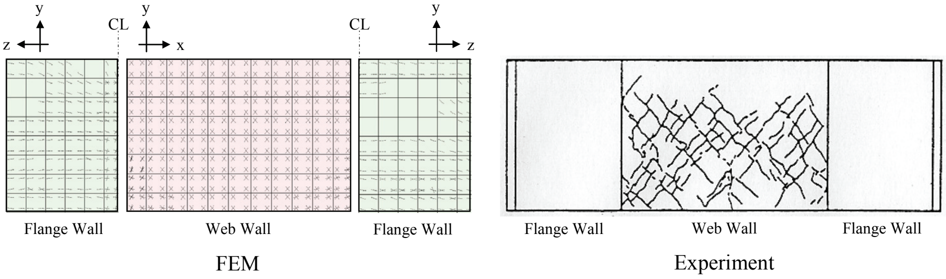


Fig.7 Cracking Condition (Run-4)

The acceleration response spectrum of Run-1 agreed well with the test results. On the other hand, the acceleration response spectrum of Run-4 approximately agreed with the test results; however, the peak period was estimated shorter in comparison with test results and the amplitude was estimated smaller. A conceivable cause for these disagreements is the followings: Occurrence of many cracks in the test specimen due to drying shrinkage. In the test, vertical reinforcement in the RC wall slipped out of the basemat, so a rigid rotational deformation was added to the test results. The test specimen was subjected to excitation forces in Run-1 to Run-3, and cracks have already occurred at the start of Run-4; however, the influence of the cracks was not considered in the analysis.

The response acceleration-response displacement relation of Run-1 showed a linear form in both the analysis and test results and a good agreement between the two. On the other hand, the response acceleration-response displacement relation of Run-4 approximately agreed with the test results in the nonlinear region; however, the initial stiffness was estimated larger in comparison with the test results. The same content as discussed about the acceleration response spectrum above is conceivable as a cause for that.

Regarding cracking in Run-4, horizontal cracks occurred in the flange wall due to bending moments and diagonal cracks occurred in the web wall due to shear forces. The shear cracking condition of the web wall agreed well with the cracking condition in the test results.

From the examination results above, it was confirmed that seismic responses in the strong non-linear reigion of a RC wall can be evaluated properly by using the non-linear response evaluation function introduced in SANREF.

4. NON-LINEAR RESPONSE ANALYSIS OF NUCLEAR BUILDINGS SUBJECT TO HORIZONTAL AND VERTICAL GROUND MOTIONS

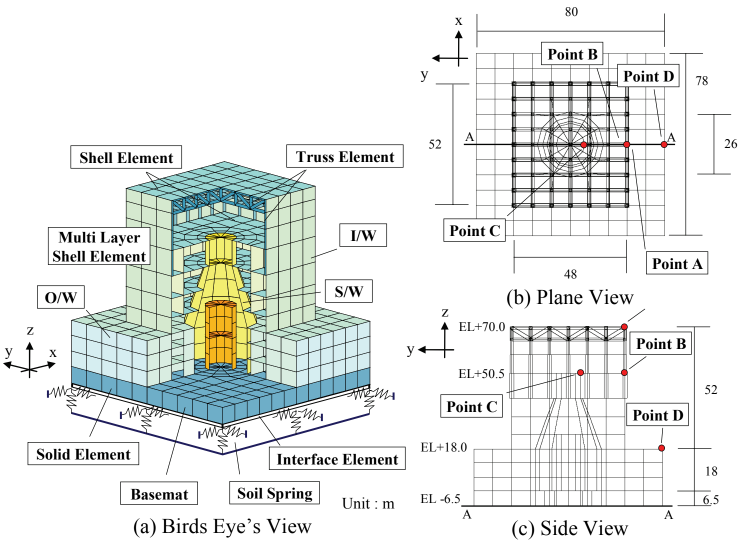
4.1 Outline

In this section, sensitivity analysis was carried out on a full-scale BWR building with the input direction and input amplification factor of ground motion as parameters, and the effects of a combination of these parameters on horizontal response of the building were reviewed.

4.2 Analysis conditions

4.2.1 Analysis object and model

A BWR building created by the Third improvement standardization committee [5] and situated directly on a bedrock site of Vs= 500m/sec was assumed as an analysis object. The building is made up of a basemat, outer box walls (O/W), inner box walls (I/W), and a cylindrical shell walls (S/W) within the boxes.



(a) Birds Eye's View
(b) Plane View
(c) Side View

Fig.8 Analysis Model

Figure.8 shows the analysis model. The analysis model is modeled only with the main quake-resistant RC walls of the building; partition walls are not taken into consideration. The basemat was represented with solid elements, the RC walls (O/W, I/W, and S/W) with multi layer shell elements, the floor with shell elements, and the beams and roof truss with truss elements. The foundation ground was represented with spring elements; discrete contact elements were inserted between the basemat and the ground to represent the uplift of the building.

4.2.2 Material characteristics

The RC walls were regarded as a RC structure in consideration of material non-linearity, and set up with the reinforcing bar arrangement described in JEAG 4601-1987 as a reference [5]. The basemat, floor, beams, roof truss, and ground were regarded as elastic bodies. Table.3 shows these material characteristics. For contact surface elements, the stiffness of the ground was set up at the time of contact, and characteristics without stiffness at the time of non-contact.

Initial stiffness proportional Rayleigh damping was selected for the element damping and the damping constant was set up so that 5.0% of the damping acts on the period of horizontal primary deformation mode of the building model with a thoroughly fixed basemat.

Table.3 Material Property

Concrete				Steel			Rigid of Soil Spring	
E_c (N/mm^2)	ν_c	f'_c (N/mm^2)	f_t (N/mm^2)	E_s (N/mm^2)	ν_s	f_y (N/mm^2)	k_h (N/mm)	k_v (N/mm)
2.25x10^4	0.2	23.5	1.83	2.06x10^5	0.3	343	9.20x10^7	3.16x10^8

4.2.3 Input ground motion and amplification factor

The observation record at Kahoku in the Miyagi-Oki earthquake on August 16, 2005 was normalized so that the maximum acceleration in the direction of NS direction (102.5 Gal) is the maximum horizontal ground motion, and it was used as the input ground motion. Figure.9 shows acceleration response spectrum (h=0.05) of the input ground motions (NS, EW, and UD).

The following three cases were selected as the input amplification factors of the input ground motions: a case in which the maximum response stress of the RC wall approaches linear limit of the shear force-shear deformation angle relation of the RC wall (500 Gal), a case in which it approaches the ultimate limit (1500 Gal), and a case halfway in between the above two cases (1000 Gal).

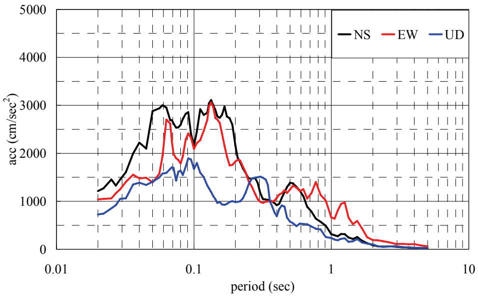


Fig.9 Acceleration Response Spectrum (h=0.05) of Input Ground Motion

Table.4 Analysis Case

Case	Direction and PGA of Input Ground Motion		
	NS (Gal)	EW (Gal)	UD (Gal)
1	500	-	-
2	1000	-	-
3	1500	-	-
4	500	-	320
5	1000	-	640
6	1500	-	960
7	1000	937	640

4.2.4 Analysis case

Table.4 shows a list of dynamic response analysis cases. First, the effects of the non-linearization of the RC wall on the horizontal response of the building could be evaluated by increasing the input amplification factor stepwise in the input of only one of the horizontal ground motion directions (NS, case-1 to case-3). Then, the effects of the input of vertical ground motion and the non-linearization of the RC wall on the horizontal response of the building could be evaluated by increasing the input amplification factor stepwise in the input of two directions, horizontal and vertical ground motions (NS+UD, case-4 to case-6). Furthermore, the effects of the input of two directions of horizontal ground motions on the horizontal response of the building could be evaluated by the input of three directions of two horizontal and vertical ground motions (NS+EW+UD, case-7).

4.3 Analysis results and their review

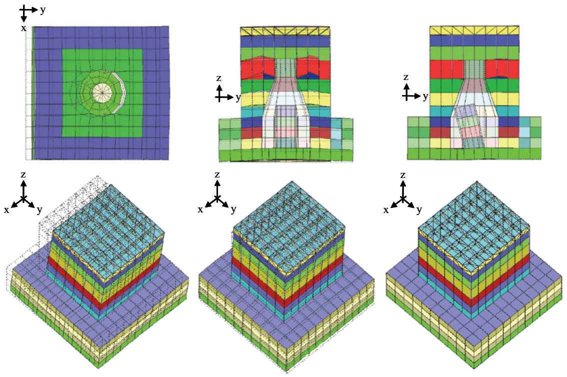
4.3.1 Natural vibration mode

Table.5 shows the eigenvalues obtained from the analysis results, and Figure.10 shows a representative natural deformation mode.

The 1st and 2nd modes correspond to the horizontal primary deformation mode of the building, and the 4th and 5th modes to the horizontal secondary deformation mode. The O/Ws and I/Ws have larger deformation at the center than at the corners with high stiffness. The 6th and 7th modes correspond to the vertical primary and secondary deformation modes of the building, and out-of-plane deformation of the basemat and local deformation of the floor slab are observed. The 3rd mode includes the torsional deformation mode of the building, and the 8th and 9th modes include the deformation mode of reactor pressure vessel pedestal.

Table.5 Free Vibration Analysis Results

Mode	Period	Participation Factor		
		x (NS)	y (EW)	z (UD)
1	0.481	-0.111	1.850	-0.010
2	0.48	1.810	0.109	0.007
3	0.334	0.0	0.001	0.000
4	0.233	-0.172	1.170	0.265
5	0.231	1.060	0.163	-0.206
6	0.227	0.141	-0.116	3.200
7	0.163	0.011	-0.009	1.690
8	0.161	0.107	0.000	0.040
9	0.161	0.001	0.161	-0.127



Mode 1 (Horizontal Mode 1)
Mode 6 (Vertical Mode 1)
Mode 8 (RPV Pedestal)

Fig.10 Mode Shape

4.3.2 Effects of input amplification factor and vertical ground motion input

In order to examine the effects of input amplification factor and the input of vertical ground motion on the horizontal response of the building, Figure.11 shows the maximum horizontal response acceleration distribution of the O/W, I/W, and S/W, and Figure.12 shows horizontal floor response spectrum (h=0.05) at points on the above-mentioned RC wall (Points A, B, C, and D in Figure.9).

The maximum horizontal response acceleration distribution became large to the input amplification factor, irrespective of the input of vertical ground motion. When the building is in the elastic region (cases-1 and 4), the input of vertical ground motion has no effect on the maximum horizontal response acceleration distribution. When the building reached the non-linear region (cases-2, 3, 5, and 6), however, the input of vertical ground motion caused difference in the maximum horizontal response acceleration distribution. When the building reached the strongly non-linear region (cases-3 and 6), in particular, the difference became remarkable; in

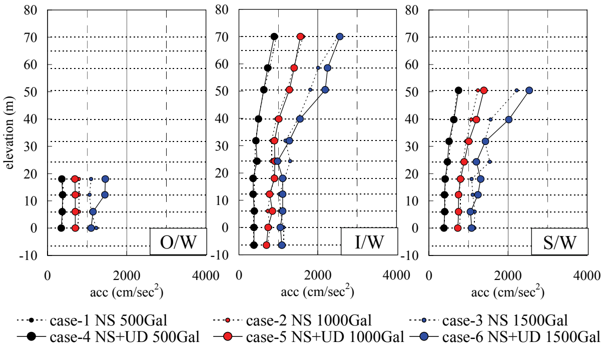
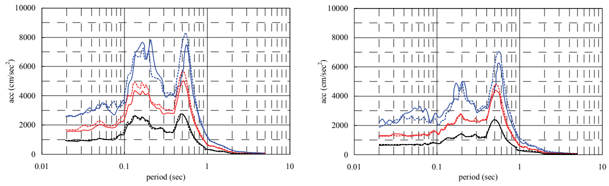
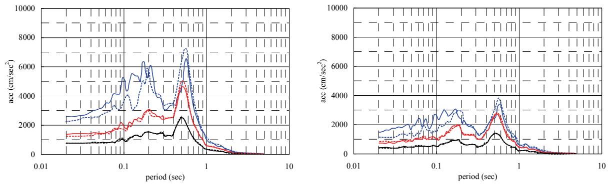


Fig.11 Maximum Horizontal Acceleration Distribution (NS, NS+UD)



Point A (I/W EL+70.0m)
Point B (I/W EL+50.5m)



Point C (S/W EL+50.5m)
Point D (O/W EL+18.0m)

case-1 NS 500Gal
case-4 NS+UD 500Gal
case-2 NS 1000Gal
case-5 NS+UD 1000Gal
case-3 NS 1500Gal
case-6 NS+UD 1500Gal

Fig.12 Horizontal Floor Response Acceleration Spectrum (NS, NS+UD) case-6, a large difference in the distribution was observed locally.

The horizontal floor response spectrum showed a prevailing amplitude profile at the periodic bands of the horizontal primary (0.48 sec) and secondary deformation modes (0.23 sec) of the building. When the building is in an elastic region (cases-1 and 4), the input of vertical ground motion has no effect on the horizontal floor response spectrum. When the building reached the non-linear region (cases-2, 3, 5, and 6), however, the amplitude became smaller at the periodic band of the horizontal primary deformation mode in case of the input of vertical ground motion (cases-5 and 6). This cause of this is thought to be that because the input of vertical ground motion promoted more non-linearization of the RC wall than in a case of no input of vertical ground motion (cases-2 and 3), hysteresis damping increased. Furthermore, when the building reached the strong non-linear region (cases-3 and 6), the amplitude grew at the periodic band of the horizontal secondary deformation mode of the O/W and S/W that cause severe damage to the RC walls. The severely damaged RC wall comes and goes on the load-unload-reload path non-linearized by the input of ground motion; since the non-linear constitutive law of concrete has different stiffness on the load path and unload path, this stiffness difference may have excited the short periodic band of response acceleration.

4.3.3 Effects of a combination of input directions of ground motions

In order to examine the effects of a combination of input directions of ground motions on the horizontal response of the building, Figure.13 shows the maximum horizontal response acceleration distribution of the O/W, I/W, and S/W, and Figure.14 shows horizontal floor response spectrum (h=0.05) at points on the above-mentioned RC wall (Points A, B, C, and D in Figure.9). Figure.15 shows the cracking condition and Figure.16 shows the minimum contact ratio and the state of contact of the basemat.

The maximum horizontal response acceleration distribution showed a larger difference in the I/W in the case of the three directional input (case-7) than in other cases (cases-2 and 5). The cause of this is thought to be that because in case-7 the input of horizontal ground motion in the direction (EW) perpendicular to the observation direction (NS) was added to the input of vertical ground motion, torsional deformation was added to the horizontal deformation of the building at the time of non-linear response, and the RC wall reached the non-linear region at an early stage.

There is no noticeable difference in the horizontal floor response spectrum, irrespective of a combination of input directions of ground motions. This also matches up with the fact that there is no significant difference at the observation points of the horizontal floor response spectrum in the above-mentioned maximum horizontal response acceleration distribution.

As for the state of cracking, there is no significant difference in tendency in cases of the input of one and two directions (case-2 and 5), but there is a certain difference in the state of cracking at the ends of the I/W and O/W. In the case of three directional input (case-7), cracking occurred in the three directions at the ends of the I/W and the O/W.

The minimum contact ratio is affected largely by the combination of input ground motions; the input of vertical

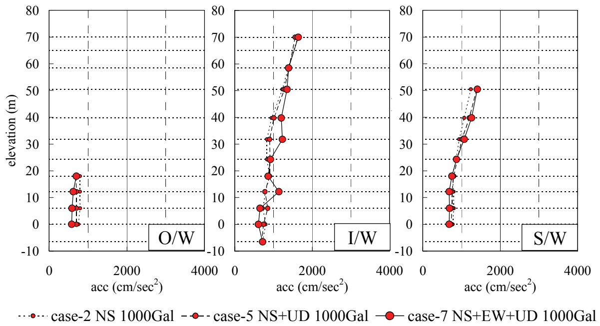
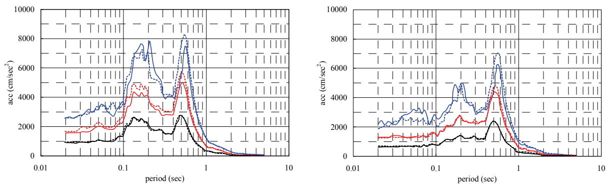
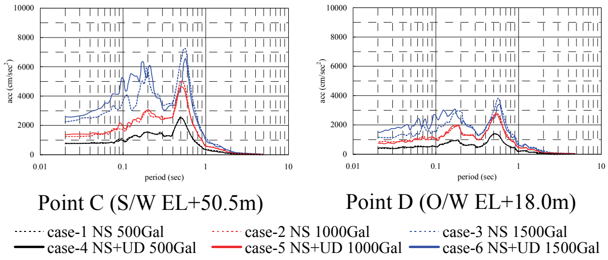


Fig.13 Maximum Horizontal Acceleration Distribution (NS, NS+UD, NS+EW+UD)

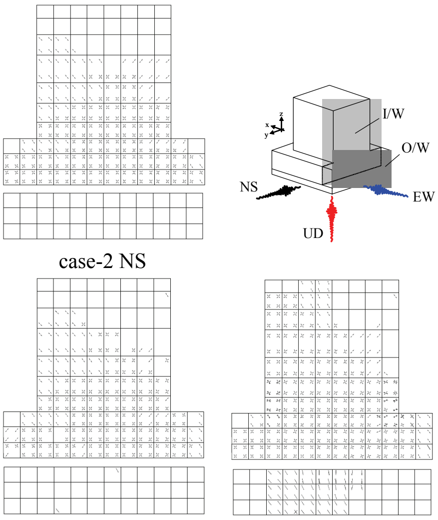


Point A (I/W EL+70.0m) Point B (I/W EL+50.5m)



Point C (S/W EL+50.5m) Point D (O/W EL+18.0m)

Fig.14 Horizontal Floor Response Acceleration Spectrum (NS, NS+UD, NS+EW+UD)

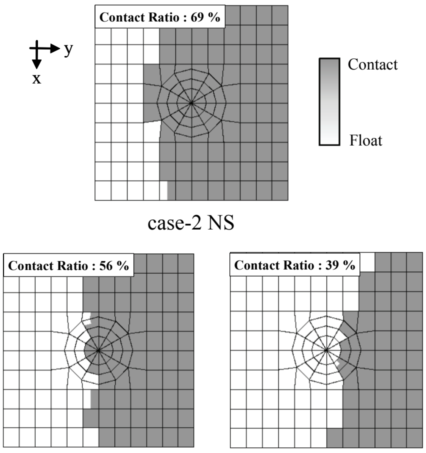


case-2 NS

case-5 NS+UD

case-7 NS+EW+UD

Fig.15 Cracking Condition
(NS, NS+UD, NS+EW+UD)



case-2 NS

case-5 NS+UD

case-7 NS+EW+UD

Fig.16 Minimum Contact Ratio and State of
Contact (NS, NS+UD, NS+EW+UD)

ground motion (case-5) decreases the minimum contact ratio by about 10%, and the input of horizontal ground motion in the direction perpendicular to the observation direction in addition to the input of vertical ground motion (case-7) decreases the ratio by about 20%. In the case of three directional input (case-7), in particular, the addition of uplift by the input of horizontal ground motion in the direction of EW to uplift by the input of horizontal ground motion in the direction of NS decreases the contact ratio significantly.

5. CONCLUSION

In this study, the following conclusions were obtained.

(1) It was confirmed that seismic responses in the strongly non-linear region of a RC wall can be evaluated properly by using the non-linear response evaluation function introduced in SANREF.

(2) It was shown that the input of vertical ground motion had no significant effect when the building was in an elastic region, and that the input of vertical ground motion had effects on the distribution of the maximum horizontal response acceleration and the amplitude of the prevailing periodic band of horizontal floor response spectrum when the building reached a non-linear region.

(3) It was shown that the input of horizontal ground motion in the direction perpendicular to the observation direction in addition to the input of vertical ground motion promotes the non-linearization of a building and has effects on the state of cracking and the minimum contact ratio of the basemat.

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