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Division V

A STUDY ON INFLUENCE OF GROUND CONDITION AND SURROUNDING BUILDING FOR SEISMIC RESPONSE OF NUCLEAR POWER PLANT BUILDING

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ABSTRACT

In the seismic design of nuclear power plants, it is considered that the influence of the irregular ground condition and surrounding buildings is relatively small. Therefore, current seismic response analysis models are used without estimating these conditions. However, for some nuclear power plant buildings, the ground condition is complex and surrounding buildings are close, but their influence is not clearly understood. In this study, in order to understand this influence, seismic response analyses were carried out using a nonlinear three-dimensional FEM, which expresses these conditions well. It was shown that the input motion to the building and the maximum response of the building were affected by these conditions at some level. Especially, the influence of the irregular ground condition was significant.

1. INTRODUCTION

In the seismic design of nuclear power plants, the influence of both the ground condition and surrounding buildings is considered to be relatively small. As a result, seismic response models are only developed for the plant building. In the past, there have been reports regarding the influence of surrounding buildings (Kitada et al (1998), Endo et al (2005)) and the shape of the ground on foundation input motion (Kowada et al (1993), Kurita et al (2003)). However, in actual nuclear power plants, the ground shape is complex, surrounding buildings are close by, and their influence on foundation input motion and building response is not clearly understood.

To improve earthquake safety, we developed a detailed ground-coupled nonlinear three-dimensional FEM model as a future seismic design model. In a previous study, using this model and considering foundation lift behaviour, we conducted seismic response analysis in which horizontal and vertical seismic motions were input simultaneously (Nakamura et al (2008)). Furthermore, we doubled the coefficient factor and attempted to evaluate the behaviour of the building under the ultimate condition and the building fragility during major earthquakes (Nakamura et al (2010)).

In this study, to thoroughly investigate the influence of ground shape and adjacent buildings on the building response, we conducted seismic response analysis, using a detailed three-dimensional building-ground coupled FEM model that includes a building (Shown in Figure 1).

2. MODELING AND ANALYSIS CONDITIONS

In this study, we employed a three-dimensional building-ground coupled FEM model. The model and analysis conditions are described in the following subsections.

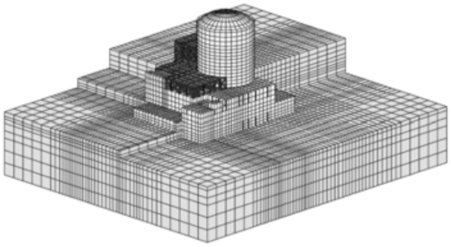


Figure 1. Three-dimensional nonlinear FEM building model considering soil-structure interaction

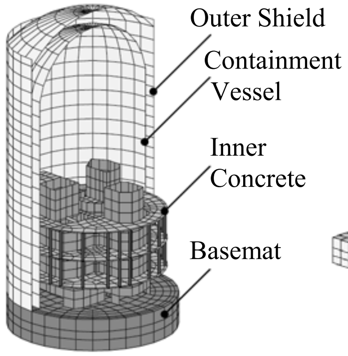


Figure 2. Model geometry of the R/B

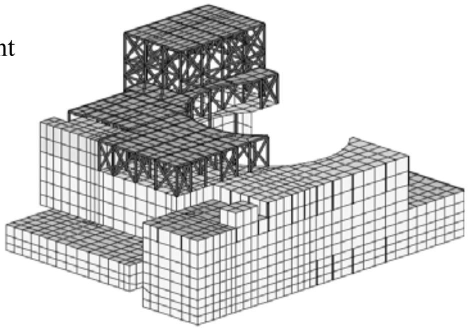


Figure 3. Model geometry of the A/B

2.1. Modeling of the building

The subject of the response evaluation is a reactor building (R/B). The influence of adjacent buildings is studied with respect to the auxiliary building (A/B) located closest to the R/B.

2.1.1. Reactor Building

The R/B is cylindrical with an outside diameter of approximately 44 m and a height of 86 m when measured from the bottom of the basemat. The total weight of the R/B is 83000 tons. The model geometry is shown in Figure 2. The model consists of an outer shielding wall (O/S), a containment vessel (C/V), and inner concrete (I/C). The reactor building O/S is modeled with layered shell elements that can account for nonlinearity. Furthermore, C/V and I/C are linear models. In this paper, the responsive conditions of the building are evaluated for the O/S.

To consider the foundation lift, joint elements are modeled between the basemat and ground. The basemat is embedded 3 m below the ground surface (EL+4 m). Only rigidity in the normal direction is considered at the sides of the basemat. The adhesive force between the basemat and ground is also neglected. Moreover, apart from the embedded section of the basemat, the building is not in contact with the ground.

2.1.2. Reactor auxiliary building

The model geometry of the A/B used for investigating the influence of adjacent buildings is shown in Figure 3. The total weight of the A/B is approximately 70000 tons. Similar to the reactor building O/S, the A/B bearing wall is modeled with layered shell elements that can account for nonlinearity. The slab and roofing material are modeled with linear shell elements, and the steel frame is modeled with linear beam and truss elements.

Furthermore, the shape of the bottom of the A/B foundation is extremely complex and there are many points regarding the lift of such complex foundation shapes that have not been clarified yet. Therefore, we did not consider the foundation lift of the A/B. The modeling of the R/B and A/B components is summarized in Table 1.

2.1.3. Nonlinear model

Layered shell elements are used for the reactor building O/S and A/B bearing wall to account for nonlinearity. Using the layered shell elements, as shown in Figure 4, the reinforced concrete plates are replaced by layers of concrete and reinforcement steel to enable a response to perpendicular material nonlinearity through plate bending of the shell. In this study, the shell elements are modeled with five layers of concrete and four layers of reinforcement steel (double reinforcement inside and outside).

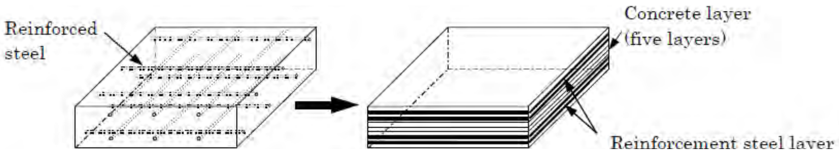
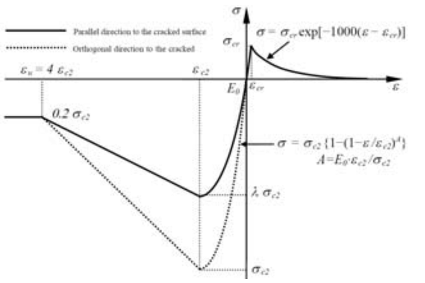


Figure 4. Layered shell elements



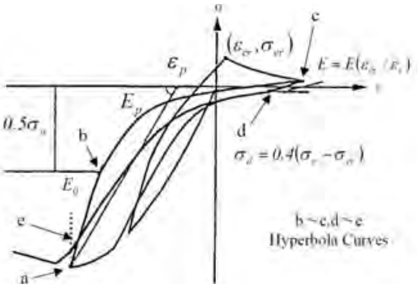


Figure 5. Relationship between the uniaxial stress and strain of concrete after cracking

Figure 6. Hysteresis characteristics of the cracked surface

The nonlinear characteristics for each layer of concrete and reinforcement steel are shown below. The main physical properties of the building are listed in Table 2.

- A trilinear elasto-plastic constitutive relationship is used for concrete that has not yet cracked.
- The yield surface is used for the cracking and compression-side yield conditions.
- The relationship between stress and strain after cracking is evaluated as two axial springs, one in the direction of the crack and one parallel to the crack direction (see Figure 5).
- On the crack surface, shear is transferred by the engagement of the friction force between the concrete and aggregate and the reinforcement dowel effect. This shear transfer force is evaluated as a decreasing function of the strain orthogonal to the crack.
- After cracking, concrete has the hysteresis characteristics represented by the hyperbolic curves shown in Figure 6.
- The relationship between reinforced steel stress and strain exhibits bilinear hysteresis characteristics.

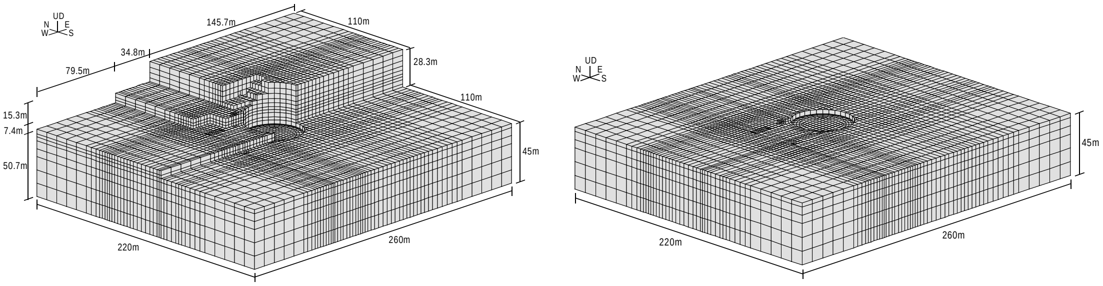
Table 2: Main material properties of the buildings

	Specification	Code	Reactor building O/S quake-resistant wall	Reactor auxiliary building quake-resistant wall
Concrete	Elastic modulus (N/mm^2)	Ec	2.15E4	2.05E4
	Poisson ratio	ν	0.20	0.20
	Compressive strength (N/mm^2)	σ_c	20.6	17.7
	Tensile strength (N/mm^2)	σ_t	1.42	1.32
	Compression side first yield point stress	σ_{c1}	$\sigma_c/2$	$\sigma_c/2$
	Distortion at maximum stress	ε_0	2.5E-3	2.5E-3
	Compression-side ultimate strain	ε_u	0.01	0.01
Reinforced steel	Elastic modulus (N/mm^2)	Es	2.05E5	2.05E5
	Poisson ratio	ν	0.30	0.30
	Yield strength (N/mm^2)	f_S	324.5	324.5
	Second gradient	E'	1/1000Es	1/1000Es

*The damping of the FEM model is equal to Rayleigh damping and is set to h = 3%(Nakamura et al (2007))

2.2. Modeling of the ground

The geometry of the ground FEM model used in this study is shown in Figures 7. The ground is modeled using solid elements. The physical properties of the ground are listed in Table 3. The ground is hard rock with uniform physical properties and is composed of linear materials, which remain in the elastic state against the assumed seismic motion.



(a) Irregular ground (b) Flat ground

Figure 7. Three-dimensional ground model

Table 3: Main material properties of the buildings

Shear wave velocity(m/s)	Poisson ratio	Damping constant(%)	Unit weight(t/m^3)
1650	0.40	3.0	2.6

The horizontal size of the ground model is approximately six times the outside diameter of R/B (approximately 44 m) in the East–West (EW) direction and approximately five times the outside diameter in the North–South (NS) direction, i.e., 260 m (EW) × 220 m (NS). Moreover, the center of the basemat of R/B, which is the subject of this study, is located at the center of the ground model. The depth of the ground model from the ground level (EL+4.0m) is the same as that of the R/B outside diameter of 45.0 m, and the height of the ground base reaches up to EL−41.0 m.

Regarding boundary conditions at the ground surface, the base and sides are characterized by conditions that are viscous. However, in the case of irregular ground, the rectangular field cannot be easily modeled on all four surfaces because the ground sides have a step-like shape. Therefore, as shown in Figure 8, the field that corresponds to the side geometry is modeled as a system of multiple particle uniaxial models, which are connected to the ground sides by side viscous dampers. At this point, a decrease in accuracy is possible near the free-field steps. In this study, we reduce the effect of this decrease in accuracy by increasing the size of the ground model, as mentioned earlier. The number of total nodes and elements of the FEM model used in this study are shown in Table 4.

Table 4: The number of total nodes and elements

	Nodes	Elements
Ground (Irregular ground)	26874	23011
Building(R/B & A/B)	8335	9398

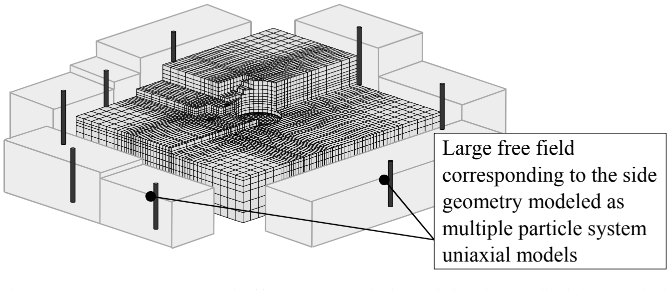
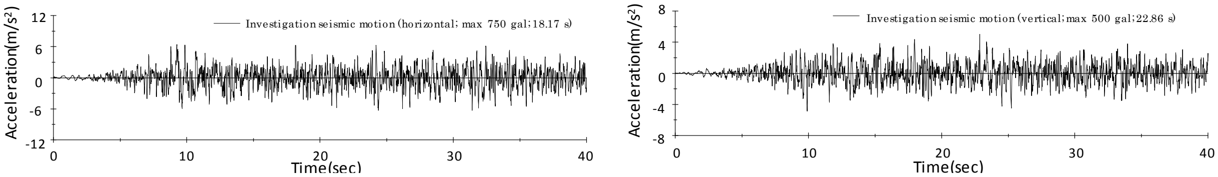


Figure 8. Conceptual diagram of the side free-field model

2.3. Seismic motion and analysis conditions

The seismic motion used in this investigation has a maximum horizontal acceleration wave of 750 gal and a maximum vertical acceleration wave of 500 gal, and is defined at the R/B basemat location of EL+1.0m (Figure 9). In contrast, the input seismic motion for the building-ground coupled FEM model is defined at the ground model base. Therefore, a ground model with a ground level of EL+1.0m is developed. Moreover, the basemat response induces an offset motion that is equivalent to the seismic tremor used in this investigation and is the input seismic motion.

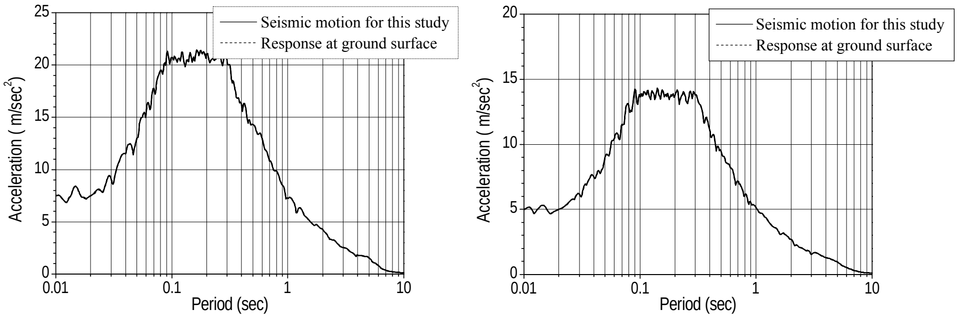


(a) Horizontal (b) Vertical

Figure 9. Seismic motion used in this study

A comparison of the acceleration response spectrum for the original seismic motion and the acceleration response spectrum for the basemat output wave when an offset motion is input is shown in Figure 10. Both spectra are almost identical. The time history waveforms are also nearly identical.

The Newmark β method (β = 0.25) is used in the analysis and the modified Newton–Raphson method is used in the convergent calculation. The seismic motion duration is 40 sec and the analysis time is 0.002 sec.



(a) Horizontal (b) Vertical

Figure 10. Comparison of the acceleration response spectra (h = 5%)

3. EVALUATION OF FOUNDATION INPUT MOTION

3.1. Investigation overview and analysis cases

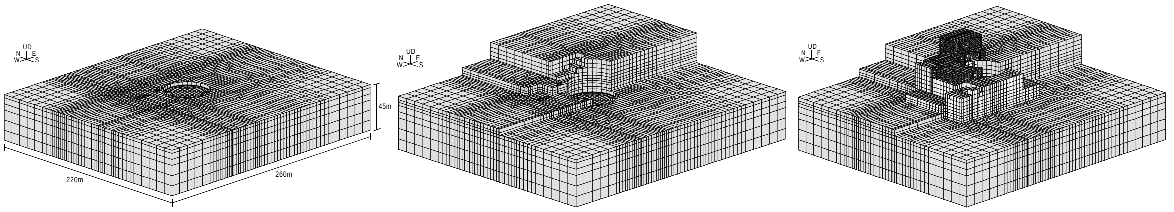
Here, we evaluated foundation input motion caused by the seismic motion used in this investigation. The offset motion described in section 2.3 is input at the base of the ground models shown in Figure 11, and the responses of the rigid basemat at the base of the R/B for the analysis cases shown in Table 5 are compared. We used two types of seismic motion inputs: the horizontal input alone and simultaneous horizontal and vertical input. The influence of irregular ground on foundation input motion is investigated by comparing Cases 1 and 2, and the influence of adjacent buildings on foundation input motion is investigated by comparing Cases 2 and 3.

3.2. Response results for the ground input motion

3.2.1. Influence of irregular ground

We compared the results of Case 1 and Case 2 to verify the influence of irregular ground. The maximum response acceleration for the rigid basemat is shown in Table 6. A comparison of the horizontal acceleration response spectra of Case1-H, -HV and Case2-H, -HV is shown in Figure 12(a).

Some difference is observed between the result of Case1 and Case2. The ground input motion in Case2 is smaller than that in Case1. This difference is caused by influence of irregular ground. On the other hand, A significant difference is not observed between the results of the individual horizontal input and the horizontal and vertical simultaneous input. In Figure 12(a), the spectra for Case1-H and Case1-HV almost overlap. Similarly, Case2-H and Case2-HV almost overlap, too.



(a) Case1 (Flat ground) (b) Case2 (Irregular ground) (c) Case3(Irregular ground and A/B)

Figure 11. Geometry of the model for each case

Table 5: Analysis Cases (evaluation of foundation input motion)

Case Name	Ground irregularity	Adjacent building effect	Input motion*
Case1-H	ignore	ignore	H
Case1-HV			H+V
Case2-H	consider	ignore	H
Case2-HV			H+V
Case3-H	consider	consider	H
Case3-HV			H+V

*H: Horizontal individual input, H+V: Simultaneous horizontal and vertical input.

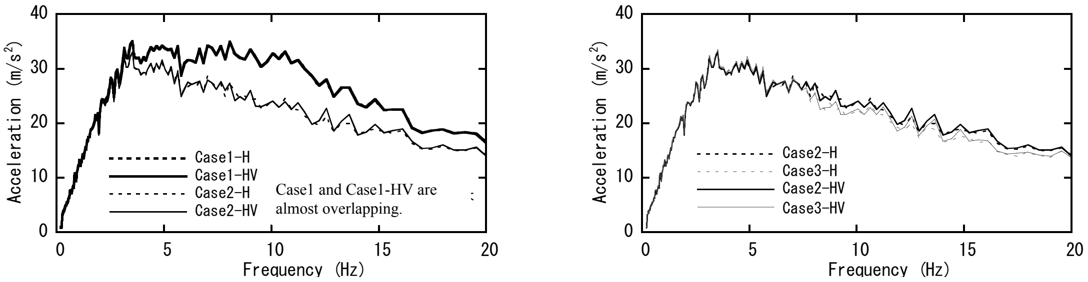
Table 6: Maximum Response Acceleration (gal)

	Case1-H	Case1-HV	Case2-H	Case2-HV	Case3-H	Case3-HV
Horizontal	728	729	609	621	601	618
Vertical	-	491	-	454	-	448

3.2.2. Influence of adjacent buildings

We investigated the influence of adjacent buildings on foundation input motion by comparing Cases 2 and 3. A comparison of the maximum response acceleration is shown in Table 6, and a comparison of the acceleration response spectra is shown in Figure 12(b).

Similarly, in the case of horizontal acceleration, there is no obvious significant difference between the results of the individual horizontal input and those of the simultaneous horizontal and vertical input. The spectra of Case3-H and Case3-HV in Figure 12(b) also overlap similar to Case 1 and Case 2. In the case of vertical response, the difference between Case 2 and Case 3 was also small. Therefore, we conclude that adjacent buildings slightly influence foundation input motion.



(a) Case1 and Case2 (b) Case2 and Caes3

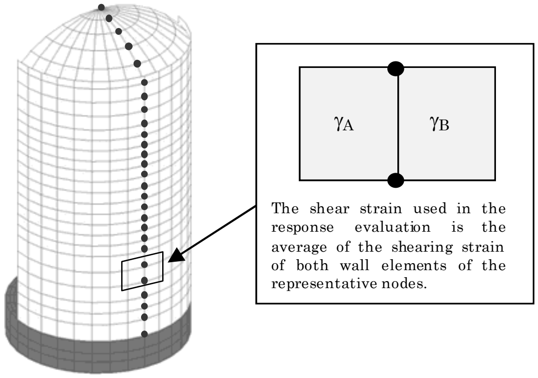
Figure 12. Comparison of the horizontal acceleration response spectra (h = 1%)

4. EVALUATION OF THE BUILDING RESPONSE

4.1. Investigation overview and analysis cases

In this section, we evaluate the O/S response of the R/B, which is the object of this investigation. The O/S response evaluation nodes and elements are shown in Figure 13. The response displacement is equivalent to the displacement from the nodes, which are located at the top of the basemat (EL+9.6m), and the bearing wall shear strain is the average shear strain of the layered shell elements located at both ends of the nodes that are being evaluated.

The analysis cases are the same shown in Table 5 and the geometry of the analysis models used in Case 1–Case 3 are shown in Figure 14. As in the evaluation of foundation input motion described in section 3, the influence of the irregular ground is verified by comparing Case 1 and Case 2, and the influence of adjacent buildings is verified by comparing Case 2 and Case 3.



The shear strain used in the response evaluation is the average of the shearing strain of both wall elements of the representative nodes.

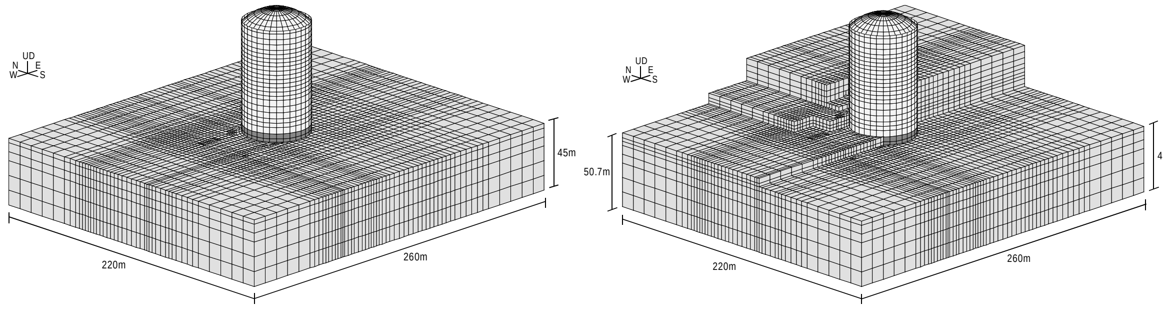
Figure 13. Location of the nodes for the O/S response evaluation (●) and elements

4.2. Response evaluation results of the building FEM model

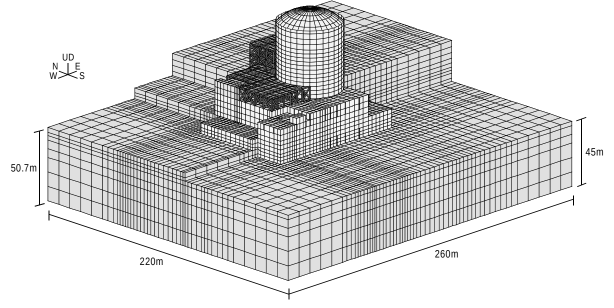
4.2.1. Influence of the individual horizontal input and simultaneous horizontal and vertical input

Comparison of the height directional distribution of the maximum response values in each case is shown in Figure 15. A significant difference is not apparent between the individual horizontal input and the simultaneous horizontal and vertical input in terms of response acceleration, response displacement, and shear strain, regardless of the ground shape and adjacent buildings. Moreover, in each case, a discontinuous disturbance in response acceleration is apparent at EL+20–40m. This is caused by the peak values that occur instantaneously. These values are thought to occur in accordance with the nonlinearity of the layered shell elements. However, this disturbance is energetically small, and therefore, it has almost no effect on the building behaviour.

Consequently, we can infer that vertical motion has little influence on the horizontal response. We conduct a comparative investigation using the response results of the simultaneous horizontal and vertical input cases in this study hereafter.

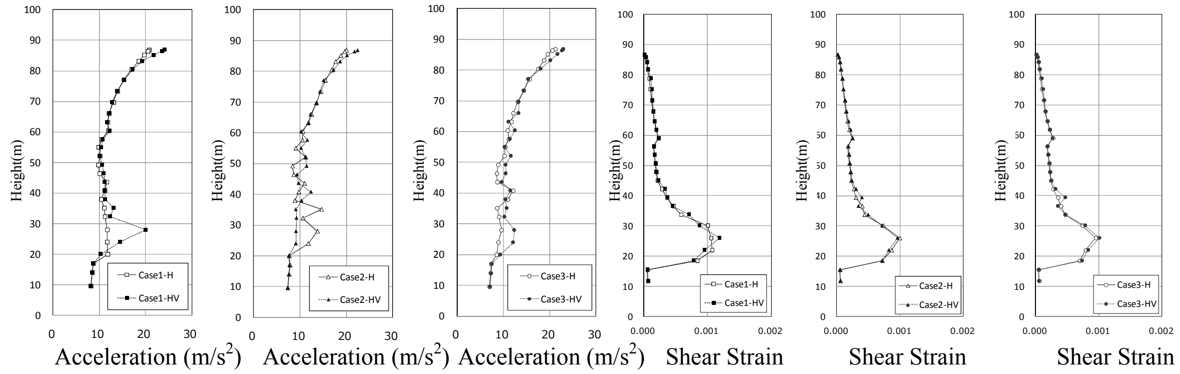


(a) Case1(R/B at Flat ground) (b) Case2(R/B at Irregular ground)



(c) Case3(R/B +A/B at Irregular ground)

Figure 14. Shapes of the analysis model for each case



i) Case1 ii) Case2 iii) Case3 i) Case1 ii) Case2 iii) Case3

(a) Acceleration (b) Shear strain

Figure 15. Height directional distribution of the maximum response values

4.2.2. Influence of irregular ground

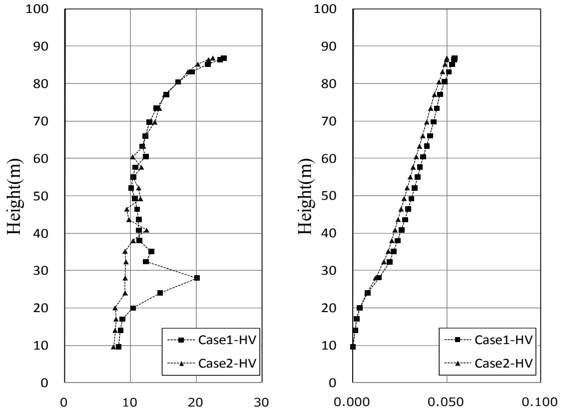
Here, we compare the building responses of Case 1-HV and Case 2-HV to examine the influence of irregular ground on the building response. Height directional distributions for acceleration, displacement, shear strain, and the plastic strain energy absorbed by the RC bearing wall (hereafter referred to as strain energy) are shown in Figure 16.

The diagrams indicate a slight variation in acceleration, but the overall response in Case 2, which considers ground irregularity, is comparatively smaller than that in Case 1. A difference is particularly apparent in the shear strain and strain energy. This difference may correspond to the influence of the irregular ground on foundation input motion.

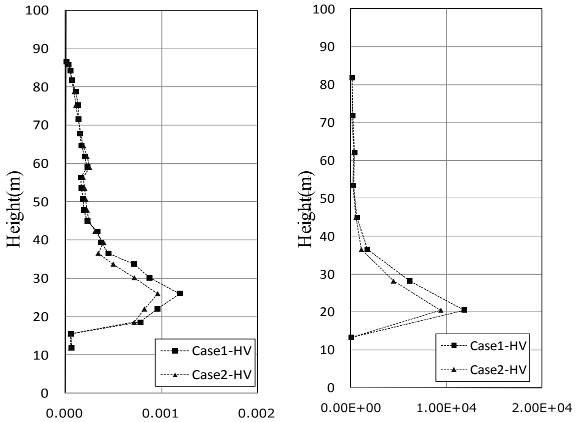
4.2.3. Influence of adjacent buildings

Next, we investigate the influence of adjacent buildings on building response by comparing Case 2-HV and Case 3-HV. The height directional distributions for acceleration, displacement, shear strain, and strain energy are shown in Figure 17.

From Figure 17, it is apparent that there are no significant differences between Case 2-HV and Case 3-HV. These results correspond to the results of foundation input motion. Therefore, adjacent buildings are considered to have little influence on building response.

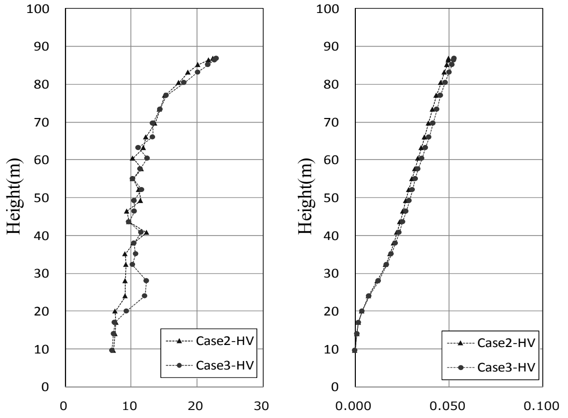


(a)Acceleration(m/s^2) (b)Displacement(m)

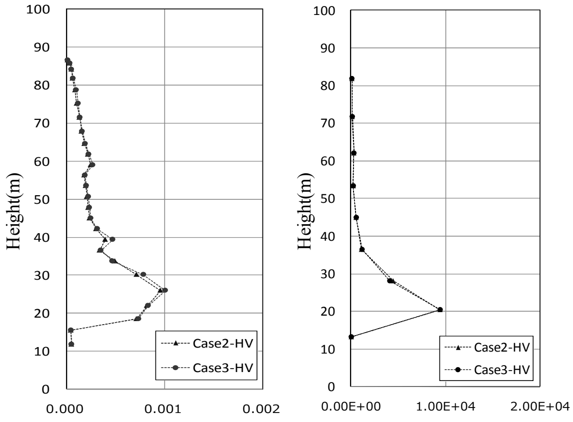


(c)Shear strain (d)Strain energy(kJ)

Figure 16. Height directional distribution of the maximum response values (Comparison between Case1 and Case2)



(a)Acceleration(m/s^2) (b)Displacement(m)



(c)Shear strain (d)Strain energy(kJ)

Figure 17. Height directional distribution of the maximum response values (Comparison between Case2 and Case3)

5. CONCLUSIONS

In this study, we conducted seismic response analysis using a nonlinear three-dimensional response model and investigated the influence of irregular ground and adjacent buildings on building response. As a result, we obtained the following findings:

1) The influence on foundation input motion was apparent when irregular ground and adjacent buildings were considered. Moreover, this difference was mainly attributed to the influence of irregular ground.
2) Comparison of the response results of the individual horizontal input and simultaneous horizontal and vertical input revealed that the vertical motion did not significantly influence horizontal acceleration, displacement, and shear strain.
3) In contrast to the cases of flat ground, a reduction in the building response was apparent in the cases of irregular ground. Moreover, the influence of adjacent buildings on building response was small. It was found that the results of all cases supported that the building response decreases because of the influence of ground irregularity.

The following are future areas of investigation:

1) The investigation in this study was conducted under extremely limited analysis conditions. To obtain more general conclusions, it is necessary to investigate changes in the analysis conditions, such as excitation direction, and use other input seismic motions and building models.
2) To understand the building behavior in more detail, it is necessary to investigate the influence of lift on the building response and the rotational and twisting motions of the building generated by ground irregularity.

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