A study on seismic behavior of nuclear power building in strong nonlinear area and fragility evaluation using 3 dimensional FEM
Part-1 Ultimate seismic condition of building

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1 ABSTRACT

The evaluation based on probabilistic safety assessment (PSA) is expected for nuclear power buildings because the risk of the occurrence of the seismic ground motions beyond the design assumption cannot be denied. For the assessment, seismic ultimate analyses of the building are necessary.

In this paper, the seismic ultimate behavior was evaluated using an accurate three-dimensional nonlinear FEM model. In the model, the basemat and the soil were modeled by solid elements, and shear walls of the building were modeled by nonlinear layered-shell elements. The uplift behavior was estimated using joint elements between the basemat and the soil. The response analyses considering the maximum horizontal acceleration up to 3500Gal was done. Then, the influence on the response given by the vertical ground motion and the basemat uplift was evaluated. Moreover, the response was compared with that of the lumped-mass model, which is generally used for current seismic design.

2 INTRODUCTION

The September 2006 revision of the Regulatory Guide for Reviewing Seismic Design of Nuclear Power Reactor Facilities Nuclear Safety Commission of Japan, (2006) noted the existence of risk (residual risk) arising from the seismic ground motion exceeding the design basis ground motion. This has created demand for the proactive introduction of evaluation methods for quantitatively evaluating this risk based on the most up-to-date techniques, such as probabilistic safety analysis (PSA), and aggressive efforts for establishing these methods.

For the purpose, it is important to analyze the seismic ultimate behavior of the buildings accurately. In the seismic design of Japanese nuclear power plants, a lumped mass sway-rocking (hereafter, SR) model (for example, Figure 1(a)) is generally used. In terms of real buildings, since the building shapes are often three-dimensionally complex, dynamic nonlinear analyses using three-dimensional (hereafter referred to as 3D) models (refer to Figure 1(b)) have been used in order to accurately evaluate the behavior (in particular, localized behavior) during a large earthquake.

Kasuga et al. (2000) have created a detailed 3D FEM model for PWR 3LOOP type nuclear reactor buildings, and have conducted dynamic nonlinear analysis for horizontal seismic motion. Furthermore, the characteristics of the progression of building destruction were found by inputting enlarged design level seismic motion, and the characteristics were compared to the lumped mass model, which is the common type of design model. In particular, in the lumped mass model, when restorative force characteristics are considered based on a peak-oriented hysteresis model Japan Electric Association (1991) configured based on experiments of reinforced concrete shear walls, if the damping coefficient in the elastic regime is taken to be
the same as the FEM model, the hysteretic energy absorption exhibits a tendency of being underestimated in strongly nonlinear regions Kasuga et al. (2003).

Nakamura et al. (2007a) created a 3D FEM model of soil using linear solid elements, and evaluated the uplift behavior of the lumped mass building model by appropriately configuring a joint element between the soil and the basemat. The results were that the ground contact ratio and induced vertical motion (vertical motion that occurs accompanying basemat uplift) from this analytical model, virtually matched the results of the theoretical solution by the Green’s function method, confirming good accuracy.

Furthermore, Nakamura et al. (2008) have investigated the effect of vertical seismic motion on building horizontal response and basemat uplift behavior by conducting analysis where both horizontal and vertical seismic motion are input simultaneously. The analysis is done by incorporating a joint element, which expresses the basemat uplift behavior as described above in the soil FEM model and non-linear 3D FEM building model.

In this study, the seismic ultimate behavior of the nuclear power building is investigated using a nonlinear 3D FEM model. This, therefore, requires response analysis of input levels greatly exceeding the design basis ground motion. Response analyses are conducted by increasing the input ground motion in steps of multiples of the design levels (maximum acceleration: horizontal: 500 Gal, vertical: 300 Gal) up to a maximum of seven times (horizontal: 3500 Gal, vertical: 2100 Gal).

At each input level, analyses are conducted for the three cases of horizontal input only, vertical input only, and simultaneous horizontal and vertical input. Among these cases, the case of simultaneous horizontal and vertical input is considered as the base case closest to the actual phenomena, and other cases are compared to this case.

In the analysis, the basemat uplift is taken into account using a joint element. The effect of the basemat uplift on the building response is also evaluated by conducting analysis of the case where the bottom of the basemat is in contact with the soil preventing uplifting. The following points were investigated:

1. Response characteristics of the base case: The response characteristics of the building were investigated for the case of seven-times input levels for simultaneous horizontal and vertical input.

2. Comparison of response characteristics to horizontal input only and vertical input only: In the seismic design of nuclear power buildings, evaluation is generally made based on results of analysis for horizontal input only or vertical input only. The results of (1) were, therefore, compared to the response characteristics for horizontal input only and the response characteristics for vertical input only.

3. Comparison of response to the case where basemat uplift is not considered: The response characteristics when basemat uplift is not considered were compared to the response results of (1), and the effect of basemat uplift on the building response was evaluated.

4. Comparison with lumped mass SR model: Analysis was conducted for horizontal input only using the generic lumped mass SR model that is commonly used in the seismic design of nuclear power, and the response characteristics were compared to (1).

![Shaking direction](image)

(a) Lumped mass model  (b) 3 dimensional FEM model

**Figure 1.** Analysis models
3 ANALYTICAL MODEL AND ANALYSIS CONDITIONS

Figure 1 shows the 3D FEM model and the lumped mass model that was used in the investigation. Basemat uplift and soil-structure interaction effect were taken into account in both models.

The building is a PWR type reactor building (R/B). This building is a compound building consisting of an outer shield (O/S), inner concrete (I/C), fuel handling building (FH/B), enclosure building (E/B), and a containment vessel (C/V). Figure 2 shows the locations of each building and Table 1 shows the abbreviations and materials of these buildings.

![Image of buildings and models](image)

**Figure 2.** Position of each building consists of the reactor building

**Table 1.** Abbreviations and materials

<table>
<thead>
<tr>
<th>Building</th>
<th>Abbreviation</th>
<th>Material</th>
</tr>
</thead>
<tbody>
<tr>
<td>Outer Shield</td>
<td>O/S</td>
<td>RC</td>
</tr>
<tr>
<td>Inner Concrete</td>
<td>I/C</td>
<td>RC</td>
</tr>
<tr>
<td>Fuel Handling</td>
<td>Upper</td>
<td>FH/B</td>
</tr>
<tr>
<td></td>
<td>Lower</td>
<td>FH/B</td>
</tr>
<tr>
<td>Enclosure Building</td>
<td>E/B</td>
<td>RC</td>
</tr>
<tr>
<td>Containment Vessel</td>
<td>C/V</td>
<td>Steel</td>
</tr>
</tbody>
</table>

### 3.1 Lumped Mass Model

The lumped mass model was modeled using the bending-shear building elements and the sway-rocking soil springs shown in Figure 1(a). In the reinforced concrete areas of the O/S, E/B, and FH/B, the restoring force characteristics from Japan Electric Association (1991a) were taken into account in the bending component and the shear component. The sway and rocking soil springs were calculated using vibration admittance theory Tajimi (1959). Nonlinear basemat uplift from Japan Electric Association (1991b) was taken into account in the rocking soil spring. The strain proportional damping model was used, and the damping coefficients for each material shown in Table 2 were used.

**Table 2.** Main material properties

<table>
<thead>
<tr>
<th>Soil</th>
<th>Shear wave velocity</th>
<th>Poisson’s ratio</th>
<th>Density</th>
<th>Maximum strain</th>
</tr>
</thead>
<tbody>
<tr>
<td>2200(m/s)</td>
<td>0.33</td>
<td>2.7(t/m³)</td>
<td>--</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Concrete</th>
<th>Young’s modulus</th>
<th>Poisson’s ratio</th>
<th>Density</th>
<th>Maximum strain</th>
</tr>
</thead>
<tbody>
<tr>
<td>22.8(kN/mm²)</td>
<td>0.2</td>
<td>2.35 (t/m³)</td>
<td>t₀=2.5/1000</td>
<td></td>
</tr>
<tr>
<td>Compressive strength</td>
<td>Tensile strength</td>
<td>1° compressive turning point</td>
<td>Compressive ultimate strain</td>
<td></td>
</tr>
<tr>
<td>24.5 (N/mm²)</td>
<td>1.58(N/mm²)</td>
<td></td>
<td>α₀=0.5</td>
<td>τ₀=10/1000</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Re-bar &amp; Steel</th>
<th>Young modulus</th>
<th>Poisson’s ratio</th>
<th>Density</th>
<th>Yield strength</th>
</tr>
</thead>
<tbody>
<tr>
<td>205.8(kN/mm²)</td>
<td>0.3</td>
<td>8.0 (t/m³)</td>
<td>343.2(N/mm²)</td>
<td></td>
</tr>
</tbody>
</table>

| Damping ratio | Soil | RC | Steel | FEM:3%, SR:4.9% | C/V: 1% | FH/B(Upper) : 2% |
3.2 3D FEM Model

The 3D FEM model is shown in Figure 1(b). Because the buildings have a virtually symmetric shape around the central plane along the horizontal shaking direction, a half model with the symmetry plane is used. The walls and floor materials of the building are modeled using shell elements. The beams, pillars, and brace materials are modeled using beam elements. The basemat and soil are modeled using solid elements. Joint elements are located between the basemat bottom surface and soil to evaluate basemat uplift. Details of the models of each part are shown below.

3.2.1 Building Model

While the base sections of the O/S, C/V, I/C, and E/B are made up of the same basemat, because the shear walls are separated by expansions joints, etc., the nodes of these sections were treated as double nodes and separated between each of the buildings.

Due to the 9-meter thickness of the basemat, it was taken to be a linear solid element divided into four pieces in the direction of thickness. For the O/S and basemat, the shell element of the O/S was embedded into half of the thickness of the basemat to give continuity of rotational transformations between the shell element and the solid element.

In consideration of the nonlinear characteristics of the shear walls, the reinforced concrete sections of the O/S, E/B, and FH/B were modeled by layered shell elements where the reinforcing steel and concrete were replaced by layers. An outline of the method for modeling the concrete and reinforcing steel of the shear walls is given below. Refer to Nakamura et al. (2008) for details.

This non-linear analytical model of reinforced concrete shear walls has been analyzed by a variety of simulations, including cyclic load experiments Ohmiya et al. (1995), Nakamura et al. (2003) and dynamic vibration experiments Ueda et al. (1997), Nakamura et al. (2007b), and has been demonstrated to be able to evaluate response with high precision.

In this study, the non-linear element described above was employed for the reinforced concrete shear walls in the O/S, E/B, and the lower parts of FH/B. The basemat, I/C, steel C/V, and steel frame of the upper part of the FH/B are treated as linear materials.

The Rayleigh’s damping model was employed using the damping coefficients shown in Table 2 at the horizontal and the vertical primary eigen-frequency of the O/S.

3.2.2 Soil Model

The soil section of the 3D FEM model is considered to have a joint element where the vertical degree of freedom has extremely high compressive stiffness and zero tensile stiffness added to the soil FEM model created using a solid element in order to represent the uplift behavior of the building basemat. This solid model is the same as the one used in the previous study Nakamura et al. (2008).

The nonlinear characteristics of the joint element and the boundary conditions of the soil model are shown in Figure 3 and Figure 4, respectively. Side planes are treated as viscous boundaries, and are connected to free soil with the same physical properties as that of the side of the model. The lower base of the model is also treated as a viscous boundary.

In the previous study Nakamura et al. (2008), the validity of the soil model was confirmed by evaluating the correspondence with the theoretical solution of the soil impedance (vibration admittance theory), evaluating the response of the lumped mass building model of the basemat block placed on top of the soil model, and evaluating the state of uplift from the moment–rotation angle (M–θ) relationship of the massless rigid basemat placed on top of the soil model. Refer to the paper for details.
3.3 Material properties

The physical values of the materials used in the response analysis use realistic physical median values (refer to Table 2) selected by considering variations in concrete strength, concrete damping coefficient, soil shear wave velocity, and reinforcing steel yield strength based on previous examples of PSA investigations (Okazaki, et al., 1994).

The damping coefficients for reinforced concrete were chosen as follows based on Nakamura et al. (2007b). In the lumped mass SR model, a median value of 4.9% (average value of 5%) was taken by considering the small hysteretic absorption energy in the nonlinear regime. In the 3D FEM model, a value of 3% was taken based on the state of actual buildings in the elastic condition.

3.4 Input Seismic Motion

In this study, the input ground motion used in the investigation is the same as the input motion of Nakamura et al. (2008). Where the maximum horizontal acceleration is 500 Gal, the maximum vertical acceleration is 300 Gal, the duration period is 80.0 s, and the time step is 0.01 s. The waves were used after multiplication by a coefficient. Figure 5 shows the horizontal and vertical acceleration time history waves and the acceleration response spectra (h = 5%).

Although this ground motion is defined at the ground surface position of the soil model, when the soil-structure interaction model from this study is used, the seismic motion is specified at the position.
Analysis of both the lumped mass model and 3D FEM model used the Newmark-\(\beta\) method (\(\beta = 1/4\)) for the time integral calculation and the modified Newton–Raphson method for the convergence calculation. The analysis time step \(\Delta t\) was taken to be 0.002 s, and analysis was performed over the first 40 seconds of input seismic motion. Within the analysis, a compressive force was applied to the joint elements by the static gravity analysis first, and the seismic motion was then input.

4 BUILDING RESPONSE CHARACTERISTICS FOR LARGE INPUT

In this study, the ultimate building responses were evaluated for seven-times inputs (maximum acceleration: 3500 Gal horizontally, 2100 Gal vertically) as ultimate stage input. Figure 6 shows the position where the maximum response value was evaluated. In Nakamura et al. (2008), response was evaluated at the locations indicated by open circles in the figure as representative points for the building.

In this study, evaluating the average response at the same level of height was considered to be more important than at local positions within the building, and for each level of height, the responses at the positions indicated by filled circles in the figure were averaged at each time step, and the maximum response value was selected from all time steps.

![Figure 6. Estimation positions for maximum response values](image)

4.1 Response Characteristics in the Basic Case

First, the case that is considered the closest to reality in which simultaneous horizontal and vertical input is used and uplift is taken into account was studied as the basic case. Figure 7 shows the maximum horizontal and the maximum vertical acceleration response for the basic case when using seven-times input. In general, it is common for the building acceleration response to become larger toward the upper part of the building. However, in the results in Figure 7 the response was about the same from the top to the bottom of the building. This may be because the building was made largely nonlinear.

Furthermore, the result was obtained that the response values at the positions of the representative points shown by open circles in Figure 6 were virtually the same as the response values averaged over the positions of the closed circles at the same level. In subsequent investigations, evaluations were, therefore, made using the average values at the same level, which reflect the overall characteristics of the shear walls.

![Figure 8. Diagram of the concrete cracking](image)

The compressive stress in each flange region is shown in (b). When compared to the median strength value of 33.7 N/mm\(^2\), the average value of each flange region is less than half of this value, even for the maximum of 15 N/mm\(^2\). This tendency was virtually the same in the other cases (such as the cases of...
horizontal input only or vertical input only, or the case where uplift is ignored), giving the result that the occurrence probability of compressive crash is extremely small. Because of this result, in subsequent studies, examining the shear strain of web regions is considered to provide an evaluation of the damage.

**Figure 7.** Response behaviors for large input motion (simultaneous input, considering uplift, 7 times input)

![Figure 7](image)

(a) O/S (web parts and flange parts)  (b) E/B (web parts and flange parts)

**Figure 8.** Cracking condition for large input motion (simultaneous input, considering uplift, 7 times input)

![Figure 8](image)

**Figure 9.** Damage condition for large input motion (simultaneous input, considering uplift, 7 times input)

4.2 Comparison with Horizontal Input Only and Vertical Input Only

Figure 10 shows a comparison of the basic case results with the horizontal input only and vertical input only results. The maximum horizontal acceleration in (a) and the maximum shear strain in (c) were compared to the results for horizontal input only, and exhibited a good match. The maximum vertical acceleration in (b) was compared to the results for vertical input only, and exhibited a similar good match.
4.3 Comparison with Cases Where Uplift was Ignored

Figure 11 shows a comparison of the basic case results with the case results where basemat uplift was ignored. The results for both the maximum horizontal acceleration in (a) and the maximum shear strain in (c) exhibited a good match. For the maximum vertical acceleration in (b), however, there is a fairly large difference when the results for the basic case are compared to the results where uplift is ignored. It is considered that the difference was caused by the induced vertical motion accompanying basemat uplift.

4.4 Comparison of Ground Contact Ratio

Figure 12 shows a comparison of the ground contact ratios in each case. In the basic case (simultaneous horizontal and vertical input), although the ratio was 75% for one-time input, the ratio decreased to 27% for two-times input and to below 5% for three-times and higher inputs. By comparison, although the horizontal input only case results were virtually the same for one-time and three-times or higher input, for the two times input the result of 52% differed greatly from the basic case.

In previous studies, it has been noted that the effect of vertical motion input on ground contact ratio is small when the ground contact ratio for horizontal input only is 50% or more. In contrast, a large difference occurred in the results for two-times input in this study. The reasons for this may be as follows.

In previous studies, it was common for the vertical motion to have an amplitude of 50 to 60% of the horizontal motion, giving 300 Gal or less. In this study, however, the vertical motion was set to 600 Gal (approx. 60% of the gravitational acceleration), and the amplitude of the vertical motion could be much larger than in previous studies.

In this study, the case of vertical input only was also analyzed. For inputs of four-times or more, the ground contact ratio became 0. The validity of the analysis results was confirmed even when all of the joint elements released compression and entered the tensile condition due to the large input vertical acceleration beyond the gravity and the building jumps from the soil.
CONCLUSION

In this study, a nonlinear 3D FEM model was used to conduct seismic response analysis of large inputs to a nuclear power plant building and estimated the seismic ultimate behavior. First, response analysis was conducted by increasing the maximum horizontal acceleration up to 3500 Gal, and the effects of vertical input motion and basemat uplift on the response characteristics were evaluated. A comparison was also made with SR model response results.

From this study, the following results were obtained.

1) The building reached the ultimate condition at 7 times of the design basis ground motion input. Shear failure was occurred 3500 Gal input. Shear failure laws observed in O/S leading to compressive failure.

2) The horizontal response of the structure for simultaneous horizontal and vertical input was almost the same as for horizontal only input, thus the effect of vertical input was relatively small. The vertical response of the structure for simultaneous input agreed well for vertical only input.

3) The effect of basemat uplift on the horizontal response was relatively small. However, the effect on the vertical acceleration was not small. The difference was considered as the vertical induced motion.

4) The shear strain of the lumped mass SR model exhibited almost the same level as the FEM model in O/S. However in E/B, the SR model overestimated damage compared to the FEM model.
REFERENCES


