STUDY ON VERTICAL SEISMIC RESPONSE MODEL OF BWR-TYPE REACTOR BUILDING

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1. INTRODUCTION
A study on advanced seismic design for LWR has been carried out by the Nuclear Power Engineering Corporation (NUPEC), under the sponsorship of the Ministry of International Trade and Industry (MITI) of Japan.

As a part of the study, it has been investigated to construct an accurate analytical model of reactor buildings for a seismic response analysis, which can reasonably represent dynamic characteristics of the building.

In Japan, vibration models of reactor buildings for horizontal ground motion have been studied and examined through many simulation analyses for forced vibration tests and earthquake observations of actual buildings. And now it is possible to establish a reliable horizontal vibration model on the basis of multi-lumped mass and spring model. However, vertical vibration models have not been so much studied as horizontal models, due to less observed data for vertical motions.

In this paper, the vertical seismic response models of a BWR-type reactor building including soil-structure interaction effect are numerically studied, by comparing the dynamic characteristics of (1) three dimensional finite element model, (2) multi-stick lumped mass model with a flexible base-mat, (3) multi-stick lumped mass model with a rigid base-mat and (4) single-stick lumped mass model. In particular, the BWR-type reactor building has the long span truss roof which is considered to be one of the critical members to vertical excitation. The modelings of the roof trusses are also studied here.

2. ANALYTICAL MODELS AND CONDITIONS
2.1 Outline of Reactor Building
A typical BWR Mark-II type reactor building is selected for study, as shown in Fig.1. The building is mainly made of reinforced concrete and its dimensions are 75.5m high and 78.6m x 78.6m rectangle at the basemat. The total weight of the building is about 293,000ton. The main seismic structural members of the building are the circular shield wall (SW), the inner box wall (IW) and the outer box wall (OW). The thicknesses of the walls and the slabs are also shown in Fig. 1. The roof trusses at the top of the building are made of steel. Main-trusses and sub-trusses are orthogonally arranged in horizontal plane.

The building is assumed to be built on a surface of rock outcrop.

2.2 Analytical Models
The following four vertical seismic response models are surveyed here, as shown in Fig.2.

(1) Three Dimensional Finite Element Model (3-D FEM)
The structural members of seismic walls, basemat, floor-slabs and roof-slabs
of the building are modeled by finite shell elements. And beams, columns and
roof trusses are modeled by beam elements, which have bending, shear and axial
stiffness. The soil under the basemat is represented by interactive complex soil
springs connected with every nodal points of the basemat. The soil springs are
estimated by the theory of elastic half-space wave propagation theory (Tajimi's
vibration admittance method). In this case, the 1/4 model of the building may be
adequate for response analysis, because the building is almost symmetry in two
horizontal directions. This model is regarded as a reference model.

(2) Multi-Stick Lumped Mass Model (MSM) with Flexible Basemat

The building is represented by a three stick model with lumped masses and
springs, which is horizontally divided to three main seismic walls (SW, IW and
OW) as shown in Fig.3. Each seismic wall is modeled by axial springs and
masses concentrated in every floor levels. Some walls (such as pool girders)
connected horizontally between seismic walls are modeled by shear springs.
Considering the flexibility of the basemat, the interactive complex soil springs
are attached to the bottoms of the three sticks. These springs are obtained by the
reduction of the above complex soil springs used in the FEM model, applying a
multi-point constraint technique.

Using this model, the modelings of roof trusses are studied, as shown in
Fig.2. The first model is a grid-shaped lumped mass model connected at the top
of the building and the main and sub trusses are modeled by beam elements. The
second model is the same roof model but separated from the building model
which has a concentrated roof mass at top of the building. Response acceleration
time history at the top of the building is input to this roof model. The Third
model is one beam lumped mass model connected at the top of the building,
which represents the main-trusses.

(3) Multi-Stick Lumped Mass Model (MSM) with Rigid Basemat

The building model is the same with (2), but the basemat is assumed to be
rigid. The soil stiffness, therefore, is represented by a single frequency dependent
complex spring which is easy to be computed. The roof truss is modeled in the
one beam type.

(4) Single-Stick Lumped Mass Model (SSM)

The building is represented by a single-stick model of which masses and
springs are evaluated as summing up the above multi-stick model horizontally in
each floor level. The basemat is also assumed to be rigid and the roof truss is
modeled in the one beam type.

2.3 Analytical Conditions

(1) Material Properties of Building

The material properties of concrete and steel used are shown in Table 1.

(2) Material Properties of Soil

Two kinds of soil conditions are considered as shown in Table 2. One is
shear wave velocity $V_s=500\text{m/s}$ for a soft rock site and the other is $V_s=1000\text{m/s}$
for a hard rock site.

(3) Input Ground Motion

The input vertical ground motion is an artificial wave fitting to a smoothed
acceleration response spectrum, of which the input acceleration time history
(maximum acceleration:143 Gal) and its acceleration response spectrum are shown
in Fig.4.

3. ANALYTICAL RESULTS

Free vibration analyses (using the static soil stiffness), frequency response
analyses and seismic response analyses are conducted for the above models. The
tendencies of the analytical results among the models are almost same in each
case of two soil conditions. The results for the soil condition of $V_s=500\text{m/s}$ are
mainly mentioned hereafter. Typical results are compared as follows;

(1) Fundamental Natural Period
Fundamental natural periods of roof truss and soil-structure interaction mode are compared in Table 3. The fundamental periods of the roof truss are almost same in the 3-D FEM and the grid lumped mass model, however, the one beam lumped mass models are slightly different from the above two models. The fundamental periods of the soil-structure interaction mode are almost same between all the models.

(2) Maximum Response Acceleration

Maximum response accelerations (Max. Acc) of four models are compared in Fig.5. The Max. Acc of the building show good agreement between the 3-D FEM model and the other lumped mass models. The Max. Acc of multi-stick lumped mass models show nearly equal to or a little greater than those of 3-D FEM model. The Max. Acc of the single-stick lumped mass model nearly correspond to average values of the three walls at each floor level.

(3) Maximum Response Axial Force Factor

The factor that a axial force divided by the total weight of upper part of the stick is denoted by “axial force factor” here. Maximum response axial force factors of three models are compared in Fig.7. The maximum axial force factors of the multi-stick model with rigid basemat show a little greater than the values of the multi-stick model with flexible basemat. The maximum axial force factors of the single-stick lumped mass model approximately correspond to average values of three sticks at each floor level.

(4) Floor Response spectrum

Acceleration floor response spectra (FRS) at EL50.5m (operating floor) of the inner box wall are compared in Fig.6. The FRS of the multi-stick models are in good agreement with the FRS of FEM model. The FRS of the single-stick model is a little different from the other models at the peak of about 0.1 second.

(5) Roof Truss Model

Maximum response shear force and bending moment of the main trusses are compared among the grid model connected to the building, the grid model separated from the building and one beam model connected to the building in Fig.8. The one beam model can represent the maximum response forces of the main trusses. And the roof truss can also be analyzed by the separated model.

FRS at typical part of roof trusses are compared in Fig.9. The FRS of the 3-D FEM and the grid models are in good agreement each other, but the one beam model give different responses from the other three models at the peak about 0.2 second.

4. CONCLUSION

Various vertical seismic response models of a BWR reactor building were numerically studied by comparing dynamic characteristics of lumped mass models to that of a 3-D FEM model. And the conclusions are summarized as follows;

(1) The multi-stick lumped mass models with flexible or rigid basemat can reasonably represent the dynamic characteristics of the building. However, the case of the rigid basemat tends to give a little greater values than the others.

(2) The single-stick lumped mass model can represent the maximum responses, nearly corresponding to the average responses of the seismic walls. Therefore, this simple model is considered to be useful model for primary design purposes.

(3) Regarding the roof model, the one beam lumped mass model is adequate to estimate the maximum response stresses of the main truss. However, the frequency dependent characteristics are estimated better by the grid lumped mass model. And the roof responses can be analyzed by the roof model separated from the building model.

Acknowledgment

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Table 1 Material Properties of Building

<table>
<thead>
<tr>
<th>Material</th>
<th>Concrete</th>
<th>Steel</th>
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<tr>
<td>Strength</td>
<td>300 kg/cm²</td>
<td>-</td>
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<tr>
<td>Young's Modulus</td>
<td>257 t/cm²</td>
<td>2100 t/cm²</td>
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<tr>
<td>Poison's Ratio</td>
<td>0.167</td>
<td>0.33</td>
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<td>Unit Weight</td>
<td>2.3 t/m³</td>
<td>7.85 t/m³</td>
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<td>Damping Factor</td>
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<td>0.02</td>
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Table 2 Material Properties of Soil

<table>
<thead>
<tr>
<th>Shear Wave Velocity</th>
<th>500m/s</th>
<th>1000m/s</th>
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<tr>
<td>Young's Modulus</td>
<td>12.4 t/cm²</td>
<td>57.1 t/cm²</td>
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<td>Poison's Ratio</td>
<td>0.42</td>
<td>0.40</td>
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<tr>
<td>Unit Weight</td>
<td>1.7 t/m³</td>
<td>2.0 t/m³</td>
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Fig. 1 Reactor Building (BWR Mark-II)  
Fig. 2 Vertical Analysis Models  
Fig. 3 Multi-Stick Model (MSM)
Table 3  Fundamental Natural Period (sec)

<table>
<thead>
<tr>
<th>Vs</th>
<th>Mode</th>
<th>3D-FEM</th>
<th>MSM (Flex. Base)</th>
<th>MSM (Rigid)</th>
<th>SSM</th>
<th>One B.</th>
<th>SSM</th>
<th>One B.</th>
<th>Roof Model</th>
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<tbody>
<tr>
<td>500m/s</td>
<td>Roof</td>
<td>0.392</td>
<td>0.393</td>
<td>0.390</td>
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<td>0.438</td>
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<tr>
<td></td>
<td>Soil-Structure</td>
<td>0.313</td>
<td>0.309</td>
<td>0.311</td>
<td>0.310</td>
<td>0.310</td>
<td>0.310</td>
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</tr>
<tr>
<td>1000m/s</td>
<td>Roof</td>
<td>0.390</td>
<td>0.391</td>
<td>0.390</td>
<td>0.437</td>
<td>0.437</td>
<td>0.437</td>
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<tr>
<td></td>
<td>Soil-Structure</td>
<td>0.171</td>
<td>0.165</td>
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<td>0.165</td>
<td>0.162</td>
<td>0.158</td>
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MSM: multi-stick model, SSM: single-stick model, S.Grid: separated grid model, One B.: one beam model

3-D FEM  Multi-Stick M. (Flex. Base)  Multi-Stick M. (Rigid Base)  Single-Stick M.
Fig. 5 Maximum Response Acceleration (Vs=500m/s)

Fig. 6 Acceleration Response Spectrum (EL 50.5m-IW, Vs=500m/s)
Fig. 7 Maximum Response Axial Force Factor (Vs=500 m/s)

Multi-Stick M. (Flex. Base)  Multi-Stick M. (Rigid Base)  Single-Stick Model

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Fig. 8 Maximum Response Stresses of Main Truss (Vs=500 m/s)

Shear Force  Bending Moment
Grid Model vs. One Beam Model  Separated Grid Model vs. One Beam Model

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Fig. 9 Acceleration Response Spectrum (Roof, Vs=500 m/s)