Study on horizontal - vertical interactive SR model for basement uplift (Part 2: Non-linear response analysis and validation)

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ABSTRACT: Non-linear earthquake response analyses of a BWR MARK-II type nuclear reactor building are conducted by using a Sway Rocking model (SR model) proposed in Part 1 (Tanaka 1995) considering the interaction between horizontal and vertical motion. The results are compared with those of accurate mathematical model using the Green Function method.

Horizontal response of the SR model agrees very well with that of the Green Function model. The floor response spectra of induced vertical motions by both methods are also corresponding well in periodic characteristics as well as peak-levels. From these results, it is confirmed that the horizontal-vertical interactive SR model is applicable to non-linear response analyses considering basement uplift.

Based on the comparison of the induced vertical motions due to basement uplift by both methods, an application limit of the horizontal-vertical interactive SR model is set up at the ground contact ratio of about 50%.

1 INTRODUCTION

In Part 1, the SR model for the horizontal-vertical interactive motion, is proposed as a convenient analytical model enabling the evaluation of induced vertical motion due to basement uplift (hereinafter referred to as an interactive SR model). The non-linear characteristics of the rigidity and the damping of the soil springs for the interactive SR model are evaluated as a function of the ground contact ratio.

In Part 2, in order to examine the adequacy of the evaluation method of the soil spring and its applicability to the earthquake response analyses, the building response analyses by the interactive SR model and the accurate mathematical model using the time domain Green Function method are conducted. The Green Function method is capable for evaluating the geometrical non-linearity by the basement uplift and the soil-structure interaction simultaneously.

The analyses are conducted with the parameters of the physical property of the rock foundation and the input acceleration level.

2 CONDITIONS

A BWR MARK-II type nuclear reactor building with a basement of 80 m square weighing about 320,000 t is analyzed. The analytical model of the building is shown in Fig. 1. Two types of rock foundation are considered in the analyses as shown in Table 1.
Table 1 Physical property of rock foundation

<table>
<thead>
<tr>
<th></th>
<th>Secondary wave velocity</th>
<th>Primary wave velocity</th>
<th>Density $\rho$ (t/f$^{3}$)</th>
<th>Poisson ratio $\nu$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rock-1</td>
<td>Vs(m/s) 1500</td>
<td>Vp(m/s) 3410</td>
<td>2.3</td>
<td>0.38</td>
</tr>
<tr>
<td>Rock-2</td>
<td>500</td>
<td>1346</td>
<td>1.7</td>
<td>0.42</td>
</tr>
</tbody>
</table>

A distribution of the basemat ground reaction force is assumed to be that of a rigid basemat. Therefore the values of the parameters $\alpha$ and $\beta$ are 4.7 and 0.46, respectively.

The input earthquake motion is the first 15 seconds of the artificial earthquake motion as shown in Fig. 2, which is prepared by the Improvement and Standardization Committee of Light Water Reactor in Japan. Although this earthquake motion is set up with maximum acceleration of 286.14 cm/s$^{2}$, in order to realize the low ground contact ratio of about 50%, the amplitude of the earthquake motion is proportionally adjusted ranging 400 ~ 600 cm/s$^{2}$ for the Rock-1 and 800 ~ 1200 cm/s$^{2}$ for the Rock-2.

3 METHODS

The soil springs of the interactive SR model are shown in Fig. 3(a) as stiffness matrix relating to each displacement of horizontal-, vertical- and rotational-motion at the center of a basemat. The rigidity and the damping in linear domain of each spring are calculated by the three dimensional wave propagation theory. After occurrence of basemat uplift, assuming that the reaction force of the vertical spring acts to the center of the contact zone between the basemat and ground, the rigidity and the damping of each spring are deemed to change in accordance with function of the ground contact ratio as described in Part 1.

As the accurate mathematical model to be compared with the interactive SR model, the time domain non-linear response analyses under use of ground surface response displacement (so-called Green Function) obtained by applying force to the surface of elastic half space has been adopted. This model, the Green Function model (shown in Fig. 3(b)), enables the strict and analytical consideration of the geometric non-linearity being accompanied with the basemat uplift and the soil-structure interaction. Therefore, in this investigation, it is defined as an accurate solution for the distribution of ground reaction force for the rigid basemat.

In these analyses, the analytical model of the reactor building itself is to be in common.

4 RESULTS

4.1 Horizontal motion

The maximum horizontal response accelerations and the floor response acceleration spectra of the reactor building for the Rock-1 and the Rock-2 are shown in Fig. 4 and Fig. 5, respectively.

For two different types of rock properties, these horizontal responses by the interactive SR model and the Green Function model agree very well each other. Hysteresis loops of the moment(M) - rotational displacement($\theta$) relation are shown in Fig. 6. The hysteresis shapes by the interactive SR model and the Green Function model are similar to each other including the partial swelling in case of the basemat uplift. (Hangai 1988 and Maeda 1992)
The minimum ground contact ratio ($\eta_{\text{min}}$) in Fig. 4 ~ Fig. 6 is a little less than 50%.

4.2 Vertical motion

The comparison of the floor response acceleration spectra of the induced vertical motion of the reactor building by both models are shown in Fig. 7. For both models, the periodic characteristics of spectra and the peak values agree well. It should be noted that there is the primary peak (Hangai 1989) corresponding to half-period of the rocking vibration period (approximately 0.26 seconds for the Rock-1, 0.44 seconds for the Rock-2). The primary peaks of the interactive SR model show equivalent or bigger values than those of the Green Function model. Figure 8 shows the maximum acceleration ratio of induced vertical motion ($\frac{\alpha_{\text{Green Function model}}}{\alpha_{\text{SR model}}}$) at four floor levels with variation of the minimum ground contact ratio. It can be seen that the induced vertical motion by the Green Function model becomes greater than that of the interactive SR model at smaller ground contact ratio, but the maximum acceleration ratio remains less than 1.2 with $\eta_{\text{min}}$ up to 50%.

Then, it can be said that the interactive SR model is applicable to the non-linear response analysis considering the basemat uplift within the range of the minimum ground contact ratio ($\eta_{\text{min}}$) greater than 50%.

5 CONCLUSION

The results of the investigation concerning the applicability of the interactive SR model to the earthquake response analyses with the induced vertical motion can be summarized as follows:

1) The horizontal response characteristics (the maximum acceleration and the floor response spectra) by the interactive SR model agree very well with those of the Green Function model with various foundation rock properties and input levels.

2) The vertical response characteristics by the interactive SR model also agree well with those by the Green Function model.

3) The non-linear response analyses of the basemat uplift can be efficiently conducted by using the interactive SR model within the range of the ground contact ratio greater than 50%.

REFERENCES

Fig. 1 Analytical model of reactor building

Fig. 2 Input earthquake motion

(a) SR model for horizontal - vertical interaction

(b) Green Function model

Fig. 3 Analytical models considering nonlinearity due to basement uplift

Fig. 4 Maximum response acceleration of reactor building (horizontal motion)
(a) Rock-1 : Input accel. = 600 cm/s²
(b) Rock-2 : Input accel. = 1200 cm/s²

Fig. 5 Comparison of horizontal response spectra

(a) Rock-1 : Input accel. = 600 cm/s²
(b) Rock-2 : Input accel. = 1200 cm/s²

Fig. 6 Hysteresis loop of moment (M) - rotational displacement (θ) relation
(a) Rock-1: Input accel. $\approx 600 \text{ cm/s}^2$

$\eta_{\min.} = 43\%$

(b) Rock-2: Input accel. $\approx 1200 \text{ cm/s}^2$

$\eta_{\min.} = 48\%$

Fig. 7 Comparison of vertical response spectra

Fig. 8 Max. acceleration ratio of induced vertical motion by basemat uplift