Model Test on Dynamic Cross Interaction of Adjacent Building in Nuclear Power Plants – Overall Evaluation on Field Test

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ABSTRACT

Nuclear Power Engineering Corporation (NUPEC) has conducted the model test on dynamic cross interaction of adjacent buildings in nuclear power plants for 8 years from 1994 till 2001. It is a study about how differently the buildings in nuclear power plants respond to earthquake under the influences of soil-structure interaction (SSI) when they exist in isolation or adjacent to each other and when they are embedded or not embedded. In the last year of the study, we evaluated the results of forced vibration test and earthquake observation by comprehensive analysis to obtain the information about the adjacent effects of the buildings in nuclear power plants as follows:

(1) It was ascertained from qualitative point of view that the adjacent test model tends to show a little lower amplitude at peak dominant frequency concerning SSI than the single test model.
(2) The analytical results showed a certain correspondence with the test results for both peak frequency and amplitude of response spectrum as a result of use of the average values from boring results as to the properties of the soil below the test model foundation and use of the property values measured by means of a buried accelerometer as the backfilling soil properties as well as provision of a loose stratum directly beneath the foundation on the basis of the results of soil surface elastic wave exploration.
(3) We compared the seismic response between non-embedded single-building model and two-identical building models as well as between embedded single-building model and two-identical building models, respectively, on an analytical model. When not embedded, the both models showed almost the same results regardless of parallel or perpendicular to the row of buildings. When embedded, the two-identical-buildings model less responded than the single-building model by about 20 percent when parallel to the row of buildings. In the case of perpendicular to the row of buildings, the both models showed almost the same response.

KEY WORDS: a single building, adjacent buildings, nuclear power plant, dynamic cross interaction, soil-structure interaction (SSI), forced vibration test, earthquake observation, loose stratum, soil surface elastic wave exploration, dynamic soil spring, foundation input motions, boring tests, rigid foundation, flexible volume method, S-R model, green function, three-dimensional thin-layered element method, two-dimensional FEM

1. Introduction

The paper of SMiRT17[1] reports the entire results of the “Tests on Adjacent Effects for Reactor Buildings” over eight years, summing up the field test and the laboratory test. This paper describes especially into details of the analytical comprehensive evaluation of the results of field tests.

The field tests served for observation of adjacent effects by forced vibration test and earthquake observation with three types of test models, namely single-building model, two-identical-buildings model and two-different-buildings model in both non-embedded and embedded cases, respectively. No observation records of the same earthquake for both embedded and non-embedded cases were, however, available for every model on the same site. Furthermore, it is influenced by a subtle soil difference depending on the position within the same site. For these reasons, it is essential for evaluation of the adjacent effects to make judgment not only directly from the observation records, but also from combined analytical evaluations. In this study, we undertook simulation analysis of the results of forced vibration test and earthquake observation, verified adequacy of the analytical models and methods, and finally evaluated the adjacent effects on the basis of the analytical models.
Out of the above-mentioned results, this paper analyzes those of simulation analysis and the adjacent effects on the basis of discussion with single-building model and two-identical-buildings model.

2. Test Models

Figure 1 shows the conditions of installation and dimension of the test models of single building and two identical buildings without embedment. All test models AA, BAs and BAn were of RC structure with a total weight of 6440kN, having the same shape or 8×8 m in plan and 10.5 m high. Each test model was tested with and without embedment whose depth amounted to 5 m. In case of two-identical-buildings model, the buildings were made with a distance of 60 cm to each other, which was filled back in case of embedment.

3. Analytical Method

We analyzed the dynamic soil spring and the foundation input motion of 1 or 2 units of embedded rigid foundation by substructure method based on flexible volume method and integrated them into S-R model to simulate forced vibration test and earthquake observation. For volumetric method, we used the green function obtained by three-dimensional thin-layered element method.

The equation of motion for the single-building model is as follows:

\[
\begin{bmatrix}
K_{BB} & K_{BF} \\
K_{BF}^T & K_{FF} + S^{(s)}
\end{bmatrix}
\begin{bmatrix}
u_B \\
u_F
\end{bmatrix} = \begin{bmatrix}
0 \\
S^{(s)} \Lambda^{(s)}
\end{bmatrix}
\]

where \(u_B\) and \(u_F\) are the displacement vectors in superstructure (B) and foundation (F), respectively; \(K_{BB}, K_{BF}\) and \(K_{FF}\) are the dynamic stiffness matrices of the superstructure-foundation system; and \(S^{(s)}\) and \(\Lambda^{(s)}\) are dynamic soil spring and foundation input motions, respectively.

The equation of motion for the earthquake where Building 1 and Building 2 adjoin each other is as follows.
where subscripts 1 and 2 indicate Building 1 and Building 2, respectively. $S_{11}^{(C)}$, $S_{12}^{(C)}$ and $S_{22}^{(C)}$ are the dynamic soil spring $S^{(C)}$ containing adjacent effects, while $\Delta_{1}^{(C)}$ and $\Delta_{2}^{(C)}$ are the foundation input motions $\Delta^{(C)}$ containing adjacent effects.

4. Procedure of Simulation Analysis

Simulation analysis was performed in the following procedure:

1) Simulation analysis was made for forced vibration test with embedded single-building and two-identical-buildings models to set the soil constants of soil and embedment directly beneath the test model.

2) Simulation analysis was made for earthquake observation with embedded and non-embedded single-building and two-identical-buildings models by means of the soil constants set in 1) above to verify adequacy of the analytical method and model.

3) The adjacent effects were examined analytically by means of the analytical model according to 2) above.

This paper describes the results of examination according to 2) and 3) above. As for 1) above, the results of forced vibration test and the analytical results showed a good coincidence by setting the soil constants according to the following procedure.

a) Simple average values of the results of several boring tests were used as the property values of the soil on the test model bottom.

b) A loose stratum was provided directly beneath the test model foundation. The property values of the loose stratum were set from the results of surface elastic wave exploration.

c) The property values measured by means of a buried accelerometer were used for the embedment properties.

5. Analytical Results of Seismic Response

Simulation analysis was performed for the results of earthquake observation for single building and two identical buildings.

(1) Conditions for test model installation and seismic wave input

The analytical cases are given in figure. 2. A case was analyzed in which embedded and non-embedded single building and two identical buildings are installed on a soil with the properties set from simulation analysis of forced vibration test.

Figure.2 Analysis cases
The soil property values are given in Table 1. The time history wave form of acceleration and the acceleration response spectrum of input seismic waves No. 157 and No. 172 are shown in figure 3 at GL-47.75. Seismic wave No.157 was observed when test models were installed without embedment, whose maximum acceleration value was 30Gal at the ground surface, and seismic wave No.172 was observed when test models were installed with embedment, whose maximum acceleration value was 14Gal at the ground surface.

Table.1 Soil property values under foundations

<table>
<thead>
<tr>
<th>Layer</th>
<th>depth(m)</th>
<th>thickness(m)</th>
<th>Vs(m/sec)</th>
<th>Vp(m/sec)</th>
<th>ν</th>
<th>ρ (g/cm³)</th>
<th>damping (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>①</td>
<td>-6.0~0</td>
<td>0.5</td>
<td>150</td>
<td>328</td>
<td>0.120</td>
<td>1.94</td>
<td>5</td>
</tr>
<tr>
<td>②</td>
<td>-6.0~0</td>
<td>2.5</td>
<td>340</td>
<td>750</td>
<td>0.371</td>
<td>1.94</td>
<td>5</td>
</tr>
<tr>
<td>③</td>
<td>-8.0~11.0</td>
<td>3.0</td>
<td>430</td>
<td>1190</td>
<td>0.415</td>
<td>1.94</td>
<td>2</td>
</tr>
<tr>
<td>④</td>
<td>-11.0~25.0</td>
<td>14.0</td>
<td>1390</td>
<td>5990</td>
<td>0.386</td>
<td>2.21</td>
<td>2</td>
</tr>
<tr>
<td>⑤</td>
<td>-25.0~62.75</td>
<td>27.75</td>
<td>1590</td>
<td>3250</td>
<td>0.345</td>
<td>2.21</td>
<td>2</td>
</tr>
</tbody>
</table>

The soil property of backfill: V_s = 155-235m/sec

\[ v = \frac{V_p/V_s^2 - 2}{2[V_p/V_s^2 - 1]} \]

Figure.3 Time history wave form of acceleration and the acceleration response spectrum (h=5%)

(2) Analysis results

The results of simulation analysis of earthquake observation are shown in figure 4.

i) Results of simulation analysis for non-embedded single building and two identical buildings:
   The peak frequency of acceleration response spectrum showed a good correspondence with the observation results for both single building and adjacent buildings. Approximate correspondence was observed also for the amplitude at peak frequency. It is difficult to distinguish the response of single building and from that of adjacent buildings on the basis of observation results.

ii) Results of simulation analysis for embedded single-building model and two-identical-buildings model:
   As for the acceleration response of embedded two-identical-buildings model, there was a good coincidence between the analytical results and the observation results. On the other side, the observation results did not coincide with the analytical results for embedded single-building model. Although the observation results indicate that the response of
embedded two-identical-buildings model is smaller than that of embedded single-building model, it is not possible to make judgment on any difference in response between single building and adjacent buildings. For the purpose of verifying adequacy of the analytical method, the seismic response of embedded single building was examined in detail.

6. Analysis of Seismic Response of Embedded Single-Building Model

We analyzed the seismic response of embedded single-building model by assuming two variations of soil model as follows. For reason that the three-dimensional thin-layered element method deems soil as a horizontally layered soil model, we used two-dimensional FEM which allows for inhomogeneity of soil and makes it possible to model the embedment separately from its periphery.

1) There is a filled soil of about 5 m on one side of the single-building model. Its possible influences were ascertained by analysis with models having several heights of filled soil. (Analysis model and figures of result are omitted.)

2) Shear wave velocity Vs of stratum No. 2 was estimated to be 430 m/sec because stratum No. 3 is going to ride on it as shown in Table 1 as a result of irregularity of the soil directly beneath the single-building model. On the other hand, Vs = 150 m/sec, the smallest measured value, was used for the embedment, evaluating its rigidity separately. This is owing to estimation from the results of simulation by thin-layered element method that the rigidity of the embedment had been overvalued. The model chart and the analytical results are as shown in figures 5 and 6.

It can be gathered from 1) and 2) above that the single-building model is hardly affected by the fill, but is sensitive to the rigidity of the soil on its bottom and to that of the embedment. Judging from this, therefore, the discrepancy

Figure 4 Results of simulation analysis of earthquake observation
(Respond spectrum of acceleration at roof of models)
between the analytical results of seismic response and the observed values for the embedded single-building model as stated in Section 5 is attributable to the fact that it has soil conditions which cannot easily be modeled in thin-layered element method.

### 7. Analytical Comparison of Seismic Response between Single Building and Adjacent Buildings

A comparison between the analytical results with each other seems to be meaningful based on the judgment according to Section 6. Figure 7 compares the spectrum of acceleration response of single building with that of adjacent buildings in the following cases:
(i) Not embedded:
In NS and EW directions, the single-building model and the two-identical-buildings model showed the same amplitude or the latter showed a tendency a little smaller amplitude than the former one at the peak frequency.

(ii) Embedded:
In NS direction or parallel to the row of buildings, the two-identical-buildings model showed an amplitude by approx. 20% lower than the single-building model. In EW direction, the two-identical-buildings model indicated a little lower amplitude near the peak frequency than the single-building model.

8. Examination of Foundation Input Motion

Figure.8 shows the foundation input motion obtained by means of the analytical model for embedded single-building model and adjacent models.

Both the single test model and the adjacent test models showed almost the same foundation input motion in horizontal direction. Difference in the foundation input motion between directions NS and EW was also small. As far as rotation is concerned, the single test model and the adjacent test models indicated a remarkable difference in NS direction (parallel to the row of buildings): the latter showed a much smaller value. The rotation component in EW direction was almost the same for the both models. In other words, the tendency that larger adjacent effects appear parallel to the row of buildings can be confirmed also in the foundation input motion which was smaller with the adjacent test model than the single test model. In addition, the adjacent effects are influenced largely by rocking.
9. Conclusion

1) Simulation analysis achieved satisfactory results for both forced vibration test and seismic response by using the average values of boring data together with introduction of a loose stratum to the layer directly under the test model foundation.

2) The seismic response of the single-building model and the two-identical-building models, when not embedded, was equal both in the direction of parallel to the row of buildings and perpendicular to it.

3) As to the seismic response in the direction of parallel to the row of buildings under embedded conditions, the amplitude at predominant frequency of the adjacent test model was lower by 20% than that of the single test model. The response in the direction of perpendicular to the row of buildings did not show difference between the single test model and the adjacent test model.

4) The tendency that larger adjacent effects appear in the direction of parallel to the row of buildings can be confirmed also in the foundation input motion which was smaller with the adjacent test model than the single test model. Further, large influence of rocking upon the adjacent effects can be explained by the foundation input motion.

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