INFLUENCE OF THROUGH-SOIL COUPLING BETWEEN
ADJACENT STRUCTURES ON SEISMIC RESPONSE OF
NUCLEAR REACTORS

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SUMMARY

The theoretical investigations on soil-structure interaction during seismic disturbances in
the past have been confined to single-structure configurations and the coupling through the
soil with other massive structures nearby has not been considered. The increasing popularity
of twin-plant nuclear power installations involving two or more independent containment
structures built on separate base slabs has made it necessary for engineers to assess the
effects of coupling between adjacent structures on the seismic loads in nuclear reactors.

In this paper, the interaction problem is treated by taking into account the influence of
through-soil coupling and the theoretical formulation is based on a dynamic model in which
several three-dimensional flexible structures, symmetric or unsymmetric, are bonded in
close proximity to an elastic half space and simultaneously excited by the surface motion
of the half-space. These structures are simulated by discretized linear systems which are
allowed to be either similar or dissimilar. The superstructures are mounted on separate base
slabs assumed to be rigid and of circular shape. The general equations derived are valid for a
coupled configuration involving an arbitrary number of structures. Example problems
discussed here are for a three-structure complex.

The three-structure model consists of two identical structures simulating the twin reactor
containment buildings and a third structure representing the turbine building, all structures
being multi-mode. Steady-state frequency response was determined for each structure and
the through-soil coupling effects on all modes are displayed. In addition to the response
of the structural masses, the motion of the base slabs is also discussed. The separation
distances between structures were varied so that non-equilateral spacing was included in the
parameter variation studies.

The numerical computations also cover different foundation media and different distribu-
tion of superstructure natural frequencies. Although the spatial variations of the earth-
quake motion is accounted for in the theoretical formulation, they were ignored in the
computer analysis so that all structures are assumed to be subjected to the same disturbance.
The inertia data used for the idealized nuclear power station correspond to those of a large
HTGR. The important findings are that the seismic loads on reactor structures can be
significantly altered by the coupling with adjacent structures when the plants are built on
soil media and that seismic load reduction may be achieved through proper design and layout.
1. Introduction

A theoretical study on soil-structure dynamic interaction of nuclear power plants with the additional consideration of the coupling through the soil with other massive structures nearby has recently been conducted by the present authors [1]. This paper is an extension of that work and presents the results of an investigation on three-structure systems in which the superstructure models are multi-mode. Furthermore, the configuration of the coupled system has been generalized to cases with nonequilateral spacing. The details of the theoretical development of this analysis have been discussed in [1] and will not be reiterated here. In essence, the analysis is based on a three-dimensional model in which an arbitrary number of flexible structures mounted on separate base slabs in close proximity are assumed to be bonded to the surface of an elastic half-space. The mathematical formulation was done by expanding the three-dimensional single-structure solution developed by the present authors in [2] to include the effects of adjacent structures through the use of influence function matrices. The equations of motion involve those governing the dynamic response of three-dimensional linear discretized structural systems as well as those governing the steady-state motion of an elastic half-space both at and away from the region of excitation. The structural portion of the analytical model was formulated by means of Lagrange's equations and the elastic half-space part utilized the method of Bycroft [3-4] in conjunction with the contribution by Richardson [5]. The numerical computations in [1] were made for example problems consisting of up to three structures. In order to provide an insight to the characteristics of the coupled systems, highly idealized models consisting of only single-mass oscillators were used there for the three-structure problem.

The seismic model considered in the present analysis consists of two identical structures simulating the twin reactor containment buildings (RCB) and a third structure representing either the turbine building or the reactor service building. The input data used in the computations were so chosen that the model corresponds to an idealized twin-plant High Temperature Gas-Cooled Reactor (HTGR) nuclear power station of 3000 MW(t) capacity. By changing the separation distances and the structural input data, the third structure was made to represent the turbine building (TB) in one problem and the reactor service building (RSB) in another. The response data were computed mostly for the coupled systems on soft soil since the interaction effects are more pronounced for these cases. Some plots are also displayed here for a case on firm soil in order to provide a comparison. The numerical results are confined to steady-state frequency response. The transient problems, which may be solved by the Fourier synthesis technique as demonstrated in [1], are not treated in this paper.

2. Description of Dynamic Models

Figures 1 and 2 show the two seismic models used in this study. All superstructures are represented by conventional discrete systems mounted on separate base slabs which are assumed to be rigid and of circular shape of radius r_o. For simplicity, the same base radius is assumed for all structures. It has been common practice to generate superstructure modes with the base held fixed (see [6-7], for example). In the present analysis, each superstructure mass is allowed to have 4 degrees of freedom relative to its fixed base. These
include translational degrees of freedom in three orthogonal directions and a torsional degree of freedom. Rocking of the superstructure masses relative to the base is tentatively ignored although rocking of the structure occurs due to base slab rotation. The superstructure in the reactor containment building then has a total of 16 fixed-base modes. To demonstrate the generality of the analysis, the turbine building in Model I (or the reactor service building in Model II) has a dissimilar representation possessing a total of 8 fixed-base modes for its superstructure. The separation distances and natural frequencies used are given in Tables 1 and 2 as follows:

<table>
<thead>
<tr>
<th>Model</th>
<th>$d_1/r_o$</th>
<th>$d_2/r_o$</th>
<th>$d_3/r_o$</th>
<th>$\phi$</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>4.50</td>
<td>3.80</td>
<td>3.80</td>
<td>53.7 deg.</td>
</tr>
<tr>
<td>II</td>
<td>4.50</td>
<td>2.26</td>
<td>2.26</td>
<td>5.4 deg.</td>
</tr>
</tbody>
</table>

($r_o$ = base radius and $\phi$ = angle formed by the two lines $d_2$ and $d_1$, see Figures 1 and 2)

Table 2. Natural Frequencies of Superstructures (Hz)

(a) Items in RCB

<table>
<thead>
<tr>
<th></th>
<th>PCRV</th>
<th>Containment Shell</th>
</tr>
</thead>
<tbody>
<tr>
<td>Horizontal translation in two orthogonal directions</td>
<td>3.08 (1st mode)</td>
<td>2.39</td>
</tr>
<tr>
<td></td>
<td>9.17 (2nd mode)</td>
<td>8.94</td>
</tr>
<tr>
<td>Vertical translation</td>
<td>4.15</td>
<td>5.24</td>
</tr>
<tr>
<td></td>
<td>12.44</td>
<td>16.65</td>
</tr>
<tr>
<td>Torsion</td>
<td>4.67</td>
<td>4.93</td>
</tr>
<tr>
<td></td>
<td>16.71</td>
<td>20.98</td>
</tr>
</tbody>
</table>

(b) Items in TB or RSB

<table>
<thead>
<tr>
<th></th>
<th>Turbine Generator or Fuel Storage Vault</th>
<th>Building Frame (TB or RSB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Horizontal translation in two orthogonal directions</td>
<td>2.30</td>
<td>4.10</td>
</tr>
<tr>
<td>Vertical translation</td>
<td>4.50</td>
<td>5.05</td>
</tr>
<tr>
<td>Torsion</td>
<td>4.20</td>
<td>5.30</td>
</tr>
</tbody>
</table>

It should be pointed out that although the natural frequencies of those items in the third structure have been assumed identical in two different problems, the inertia properties used for the TB items are quite different from those in the RSB. The components in the RSB are relatively lightweight whereas larger values were used for the rotary inertia input of the items in the TB. Furthermore, the natural frequency of the RSB frame structure was subsequently varied to study the effect of such changes on the coupling phenomenon. The inertia values, together with other geometrical input data were separately documented and are not
listed here due to space limitation. These data were chosen such that the seismic response obtained closely approximates that of a large HTGR plant. Although the spacing patterns used here are isosceles triangles, the computer code is applicable for patterns with three unequal sides or with all the base centers lying on a straight line.

3. Seismic Excitation

To obtain the frequency response characteristics of the various components in the coupled system, the earthquake excitation was assumed to be harmonic in time acting in the E-W direction concurrently with a vertical component of ground motion with a magnitude 2/3 that of the horizontal component. In the present analysis, the two excitation components are taken to be in-phase and the spatial variations of the earthquake were neglected so that all three structures are assumed to be subjected to the same disturbance. The free-field ground displacement component in the E-W direction is designated as $u_y$, whose amplitude is taken to be unity in the numerical computation.

4. Results and Discussion

The computer results obtained are presented as frequency response diagrams in Figures 3 through 8. Although each individual structure itself possesses such symmetry that the translational excitations applied will not excite rotational motion when the through-soil coupling is neglected, it is readily seen that in a coupled problem, all structures will in general respond with three-dimensional motion. Figure 3 shows the response of the six displacement components of the containment building base slab in Model I. The uncoupled responses, displayed as dotted curves, correspond to those determined in the single-structure analysis with through-soil coupling ignored. These response results were computed for a soft soil foundation with the shear wave velocity, $V_s$, of the elastic half-space set equal to 1500 ft/sec. Modal damping values of 2% of critical for all horizontal translation modes and 5% for all vertical and torsional modes were assumed throughout the study. The response values obtained in the coupled problem are shown as solid curves. For those displacement components which cannot be excited when through-soil coupling is not considered, the dotted curves do not appear in their response diagrams. Thus, Figures 3c-e show that in the single-structure analysis, the seismic excitations considered here will not excite the N-S translation, N-S rocking and torsional components of the RCB base slabs. These components are, however, excited in the coupled analysis although their response values are approximately one order of magnitude lower than those of the other components. Figures 3a and f show the effects of coupling on the two most important components, the in-plane translation and rocking, which have been studied by many investigators (see [8], for example).

The amplifications of superstructure response for the problem using Model I are given in Figures 4 and 5. On soft soil, the coupling with adjacent structures greatly reduces the response of the superstructure masses in the RCB. It is interesting to note that the response of items in the TB is not appreciably affected by the coupling. The coupled response curves of superstructures exhibit sharp dips in the same manner as previously observed in [1]. In the E-W translation response curves for items in the TB, the dipping was found to occur at the excitation frequencies where the E-W translations of the
items in RCB attain their maxima and vice versa. This phenomenon has been discussed by the present authors in [1].

In the second problem using Model II, the third structure was placed between the two RCBS as shown in Figure 2. The coupling phenomenon reduced the RCB superstructure response by almost the same amount as it did in the first problem but the behavior of the third structure (RSB) in this case was found to be quite different from that of the TB (Fig. 6). The frequency response of the RSB items was significantly altered by the through-soil coupling and, furtheremore, the effects of the adjacent structures reverses its sense at the second peak. The phenomenon of sense reversal, as demonstrated in [1], can occur when the structure is relatively lightweight. The behavior also depends upon the separation distances and the superstructure natural frequency. The curves shown in Figure 6b were plotted with the building frame natural frequency being 4.10 Hz (see Table 2b). The same set of curves was generated again with the natural frequency raised to 5.0 Hz and the new response was displayed in Figure 7. The change in the building natural frequency apparently did not alter the important features of the coupling phenomenon in this case except that the second peak has been slightly shifted to the right as expected.

Figures 8a-d show the superstructure response when the three-structure system is founded on firm soil with $V_S = 3500$ fps. The soil modulus in this case corresponds to an average value of $E = 0.9 \times 10^6$ psi. Comparing these results with those determined previously for the soft soil case leads to the observation that the coupling effects diminish to a relatively unimportant magnitude in the range of $V_S > 4000$ fps.

The influence functions computed by Richardson in [5] are valid in the range of

$$0 \leq \frac{\omega_0}{V_S} \leq 1.0$$

where $\omega$ is the circular frequency of excitation. This restricts the validity of the frequency response curves to approximately 4.0 Hz for $V_S = 1500$ fps and 8.5 Hz for $V_S = 3500$ fps. (Note that in Figure 8d, the upper limit of the excitation frequency is extended to 8.0 Hz.) This restriction prevents one from studying the characteristics of the peaks beyond the above limit. For the same reason, the transient analysis on through-soil coupling effects is accurate for problems in which the complex frequency response functions have a negligible contribution beyond the validity range of the influence functions. Nevertheless, the response of the lower modes within this range normally governs the gross behavior of the system during a seismic disturbance, and this can be adequately investigated.

5. Conclusions

The method of analysis is quite general and while current studies have been limited to three-structure systems, this is not an inherent limitation. The general problem investigated here as well as the three-dimensional single-structure analysis conducted in [2], both using an elastic half-space for ground medium representation, have been found solvable only through the complex frequency response approach adopted by the present authors. The time-following approach as demonstrated by Scavuzzo [6] has not been made tractable for three-dimensional problems. Recently, Bailey, Raftopoulos and Scavuzzo [9] attempted to solve the two-
dimensional interaction problem involving coupled lateral-rocking base motion. They formulated the integral equations based on a time-following method [9]. As reported in that paper, their computer program did not converge and a solution was unobtainable.

Also, the present method of analysis has several desirable features when compared to finite element approaches. Certainly the most obvious is the relative cost, particularly for three-dimensional studies. Problems of quiescent boundaries are avoided, and essentially any number of degrees of freedom in the building structures may be included.

The results presented indicate that for a typical configuration of a large HTGR twin reactor plant founded on a relatively soft foundation medium, the seismic loads experienced in most structures will be less than those predicted from an analysis which neglects the through-soil coupling. On the other hand, the response of some structures may be increased. In either case, the change of the magnitude of the response is sufficient to require consideration in the plant design except for plants founded on competent rock.

A comparison of the results presented here with those obtained for equilateral spacing of the structures (Ref. 1) shows very similar trends for similar $d/r_o$ values and similar mass-frequencies characteristics. For the cases studied to date, therefore, it appears that the modal characteristics and $d/r_o$ ratios are more important than the symmetry or lack thereof of the overall plant layout.

REFERENCES


Figure 1. Three-Structure Model I Containing Two Reactor Containment Buildings and One Turbine Building

Figure 2. Three-Structure Model II Containing Two Reactor Containment Buildings and One Reactor Service Building
Figure 3. Response Amplification of Containment Building Base Slab
Figure 4. Response Amplification of Superstructures in Reactor Containment Building
Figure 1. Response Amplification of Superstructures in Turbine Building

Figure 6. Response Amplification of Superstructure in Reactor Service Building
Figure 7: Response Amplification of Reactor Service Building with Natural Frequency Resonant
Figure 8. Structural Response in Two Different Buildings on Firm Soil