INVESTIGATION OF THE INFLUENCE OF INTERACTION OF TWO ADJACENT STRUCTURES ON THEIR RESPONSES

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SUMMARY

The paper presents a lumped mass/soil spring approach for evaluation of the influence of interaction of two adjacent structures on their responses due to an aircraft impact. The interacting structures were idealized as lumped mass cantilevers supported on independent soil springs and connected by coupling springs. The constants for independent soil springs were developed using a classical half-space approach, taking into account the embedment effects where applicable. The coupling stiffness matrix was derived by computing first the flexibility coefficients based on the geometric relationship of the two footings resting on the surface of a homogeneous, isotropic, linear elastic half-space, and then inverting it. A numerical technique for the computation of the coupling terms of the flexibility matrix was developed.

Two separate analyses were performed for a nuclear power plant; first, to determine the influence of interaction between the Reactor Building and the Auxiliary Building A and, second, to determine the influence of interaction between the Reactor Building and the Auxiliary Building B. Auxiliary buildings A and B differed in their sizes and geometrics, but both were considerably less massive than the Reactor Building. The interaction analyses were carried out for an aircraft impact loading applied at the top of the Reactor Building in the horizontal and vertical directions separately. Floor response spectra at selected elevations of both buildings were evaluated. The results showed that the peak spectral response at several nodes of the Reactor Building was slightly smaller for the coupled case as compared to the uncoupled case. The corresponding response of the Auxiliary Building A was found to be somewhat more significant. Similar results were obtained for interaction between the Reactor Building and Auxiliary Building B.

On the basis of the results of the above analyses, general conclusions are presented regarding the influence of structure-to-structure interaction on the peak values of the structural response and the frequencies at which these peaks occur. The importance of the distance between the two structures and their relative masses on the structural response is also discussed. The paper concludes with recommendations for future work.

1. Introduction

The problem of interaction between structures resulting from the coupling of their foundations through soil has attracted somewhat limited attention in the past, partly because of lack of awareness of its potential importance and partly because of the complexity of the problem itself and the solution techniques required. However, it has been found that the influence of interaction between two adjacent structures on their responses for extreme loadings such as aircraft impact can be significant, depending on the local soil conditions, the relative masses and stiffnesses of the two structures, and the distance between them.

Available analytical procedures for the evaluation of structure-to-structure interaction effects include both the finite element and the lumped mass methods. Although the finite element method is applicable to a wide range of problems, its scope of application is mainly limited to soil-structure systems modeled by using two-dimensional plane strain finite elements owing to the difficulties encountered in the solution of three-dimensional finite element systems and the excessive amount of computer storage and time required. A lumped mass approach was employed for the present investigation to determine the influence of interaction of adjacent structures on their responses.

2. Derivation of Coupling Flexibility Matrix

The interaction model is shown schematically in Figure 1. The interacting structures were idealized as lumped mass cantilevers supported on soil springs and connected by coupling springs. The soil springs for each lumped mass model were developed using a classical half-space approach, taking into account the embedment effects where applicable. The coupling stiffness matrix was derived by computing first the flexibility coefficients based on the geometric relationship of the two footings resting on the surface of a homogeneous, isotropic, linear, elastic half-space, and then inverting it.

The expressions for the displacements of the footings in terms of the corresponding forces may be expressed as:

$$\begin{Bmatrix} d_1 \\ d_2 \end{Bmatrix} = [F] \begin{Bmatrix} f_1 \\ f_2 \end{Bmatrix} \qquad (1)$$

where

$$\begin{Bmatrix} d_1 \\ d_2 \end{Bmatrix}^T = \left\{u_1, v_1, \Theta_1, u_2, v_2, \Theta_2\right\}$$

= Displacements and rotations of the footings

$$\begin{Bmatrix} f_1 \\ f_2 \end{Bmatrix}^T = \left\{fu_1, fv_1, f\Theta_1, fu_2, fv_2, f\Theta_2\right\}$$

= Corresponding forces and moments

and $[F]$ = Flexibility matrix defined by:

$$
\left[\begin{array}{ccc|ccc}
F_{11} & 0 & 0 & F_{14} & 0 & 0 \\
0 & F_{22} & 0 & 0 & F_{25} & F_{26} \\
0 & 0 & F_{33} & 0 & F_{35} & F_{36} \\
\hline
F_{41} & 0 & 0 & F_{44} & 0 & 0 \\
0 & F_{52} & F_{53} & 0 & F_{55} & 0 \\
0 & F_{62} & F_{63} & 0 & 0 & F_{66}
\end{array}\right] \qquad (2)
$$

The terms of the above flexibility matrix are functions of the elastic properties of the isotropic and homogeneous foundation medium (Young's Modulus and Poisson's Ratio), the dimensions of the footings, and the distance, D, between the footings.

The elements in the top left quarter and the bottom right quarter of the flexibility matrix, which correspond to the independent uncoupled footings, may be evaluated either numerically (using the procedure for coupling terms described below) or by using the inverse of the expressions for soil spring stiffness coefficients given in References 1 and 2. The remaining elements of the flexibility matrix which represent the coupling between the two footings were obtained in this investigation by using a numerical procedure described below.

The coupling terms of the flexibility matrix were evaluated by computing the displacements resulting from unit loads applied in the directions corresponding to the degrees of freedom for footings 1 and 2 (Fig. 1). For these unit loads, applied in the horizontal, vertical, and rotational directions for each footing, a pressure distribution suggested in Reference 1 was assumed. Each footing was subdivided into a rectangular grid of elements (Fig. 1). It was further assumed that the pressure distribution under each element was uniform, and the total force at the center of each element was computed by multiplying the area of that element by the pressure at its center. For a concentrated force at the center of each element of one footing, the displacements at the centers of all the elements of the other footing were computed using Boussinesq's solution for loads on the surface of an elastic half-space.

The displacements at the centers of all the elements of the second footing, computed as described above, were then averaged and normalized by the total load applied at the first footing to obtain the corresponding flexibility coefficients. It may be noted that in the flexibility matrix given by Equation 2, the coefficients representing the coupling between the horizontal degrees of freedom at one footing with the vertical and rotational degrees of freedom at the other footing were not considered. These coupling terms were found to be small and were, therefore, neglected.

As mentioned earlier, the diagonal terms of the flexibility matrix in Equation 2 can also be computed using a numerical procedure similar to that described above, where each footing can be assumed to rest independently on the surface of an elastic half-space and divided into a rectangular grid of elements. For a concentrated load applied at the center of each element, the displacements at the centers of all the other elements can be computed, using an assumed pressure distribution. The corresponding flexibility terms for the elements can then be obtained by averaging these displacements and normalizing by the total load.

The coupling flexibility matrix of the soil-structure system so obtained can then be inverted to obtain the coupling stiffness matrix.

3. Example Analysis

3.1 Mathematical Model and Analysis Criteria

Two separate analyses were performed for a Nuclear Power Plant; first, for interaction between the Reactor Building (RB) and the Auxiliary Building A (ABA), and second, for interaction between the Reactor Building and Auxiliary Building B (ABB). Sample results are presented here for the first analysis only. The lumped mass model employed for the analyses of interaction between the Reactor Building and Auxiliary Building A is shown in Figure 2. The analyses for this model were performed for a aircraft crash loadings applied in the X-Y plane for several distances between the buildings (D=0m, D=10m, D=20m and D=∞).

Two different sets of soil spring constants were used in the analyses, one for each building. The theory of a rigid base resting on the surface of an elastic half-space [1] was used for the computation of these soil spring constants. For the Auxiliary Building A, the embedment effects were included. A set of coupling soil spring constants, which represented the interaction between the two buildings through soil, were obtained using the procedure described above. The uncoupled and coupled soil spring constants used in the analyses are presented in Tables 1 and 2 respectively. The complete flexibility matrix so obtained was inverted to obtain the corresponding stiffness matrix.

The modal damping ratios for the complete soil-structure system were computed using a modified weighted strain energy procedure [3]. The coupling matrix representing the interaction effects of the two buildings was modeled by a substructure element connecting the two nodes at the base.

3.2 Analysis Procedure

The dynamic analyses of the soil-structure system were performed using the modal superposition procedure. The aircraft impact loading was applied in the horizontal and vertical directions separately at the top of the Reactor Building. All the modes up to 80 Hz were considered in the analysis for aircraft impact loads. The maximum displacements, maximum accelerations, and floor response spectra for a damping ratio of 2 percent were computed at selected locations of the Reactor Building and Auxiliary Building A.

3.3 Results of the Analyses

The frequencies and mode shapes for the complete soil-structure interaction model were determined for a range of distances (D=0m, D=10m, D=20m, and D=∞) between Reactor Building and Auxiliary Building A basemats. The first five natural frequencies are presented in Table 3. Time histories of displacements and accelerations were obtained at several locations of the model for the two load cases and different distances between the buildings. Acceleration response spectra were obtained from floor acceleration time histories for a damping ratio of 2 percent. Typical plots of floor response spectra are shown in Figures 3. Maximum displacements at several locations of the two buildings are presented in Table 4.

3.4 Discussion of Results

From the results of the analyses described above, it was observed that spectral response at several locations of the Reactor Building was found to be slightly smaller for the coupled case as compared to the uncoupled case. The frequency at which the peak response occurred remained virtually unchanged for the two cases.

For the aircraft impact loading applied in the horizontal and vertical directions at Node 1 of the Reactor Building, the response of the Auxiliary Building A was found to be significant for D=0m. However, for D=20m, this response was significantly smaller. From the plots of floor response spectra, presented in Figure 3, it may also be observed that with an increase in the distance between the two buildings the influence of structure-to-structure interaction on the responses of the two buildings decreased significantly.

4. Conclusions and Recommendations

The following conclusions may be drawn from the results of the analyses described above.

1. The influence of structure-to-structure interaction on the frequencies at which the spectral peaks occur is insignificant.
2. The influence of structure-to-structure interaction on the response of the interacting structures depends on the distance between the two structures and their relative dynamic characteristics (especially their relative masses).
3. By increasing the distance between the interacting structures, the response of the structures for the coupled case approaches that of the case where the two structures are independent.
4. For an interacting system consisting of a massive structure and a light structure, the dynamic effect of the light structure on the massive structure is insignificant; however, the response of the light structure may change due to the presence of the massive structure.

The results of the analyses described in this paper demonstrate that the structure-to-structure interaction effects can be important. The degree of their importance for a given problem, however, depends on the parameters associated with the problem, such as the soil properties, relative dynamic characteristics of the structures (especially their relative masses), and the distances between them.

A considerable amount of research and developmental work is still needed in this area. For lumped mass/soil spring approach, it will be important to investigate the significance of using frequency-dependent coupling springs on the structural response. It will also be of value to examine the effects of variation in damping in the soil-structure system, related to the techniques for the treatment of damping in the different analytical procedures, on the stuctural response.

References

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TABLE 1

UNCOUPLED SOIL SPRING FLEXIBILITY COEFFICIENTS

Flexibility Coefficients	Units	Reactor Building	Auxiliary Building A
F_{11}, F_{44}	m/Mp	$.625 \times 10^{-6}$	$.962 \times 10^{-6}$
F_{22}, F_{55}	m/Mp	$.455 \times 10^{-6}$	$.592 \times 10^{-6}$
F_{33}, F_{66}	Rad/Mp-m	$.556 \times 10^{-6}$	$.483 \times 10^{-8}$

TABLE 2

COUPLED SOIL SPRING FLEXIBILITY COEFFICIENTS

Flexibility Coefficients	Units	D=0m	D=10m	D=20m
$F_{41} = F_{14}$	m/Mp	0.3383×10^{-6}	0.2647×10^{-6}	0.2189×10^{-6}
$F_{52} = F_{25}$	m/Mp	0.2052×10^{-6}	0.1538×10^{-6}	0.1247×10^{-6}
$F_{53} = F_{35}$	m/Mp-m	0.5725×10^{-8}	0.3195×10^{-8}	0.2110×10^{-8}
$F_{62} = F_{26}$	m/Mp-m	0.6962×10^{-8}	0.3576×10^{-8}	0.2282×10^{-8}
$F_{63} = F_{36}$	Rad/Mp-m	0.3790×10^{-9}	0.1445×10^{-9}	0.7559×10^{-9}

TABLE 3

NATURAL FREQUENCIES

Mode	Frequencies (CPS) D=0m	D=10m	D=20m	D=∞
1	1.0643	1.0639	1.0635	1.0609
2	1.9429	1.9467	1.9511	1.9578
3	2.3662	2.3661	2.3661	2.3659
4	2.8955	2.8862	2.8838	2.8759
5	4.0511	4.0514	4.0515	4.0517

TABLE 4

MAXIMUM DISPLACEMENTS

Loading	Model	Building	Node/ Direction	Displacements (mm) D=0m	D=10m	D=20m	D=∞
Aircraft Crash (Horizontal)	1	RB	1-X	9.55	9.58	-	9.58
	1	ABA	51-X	2.09	0.94	-	0.00
Aircraft Crash (Vertical)	1	RB	1-Y	1.71	1.72	-	1.73
	1	ABA	32-Y	0.87	0.67	-	0.00

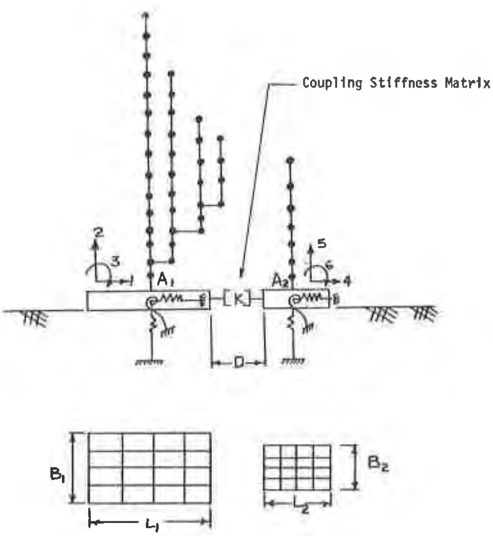

Figure 1 - Schematic Interaction Model

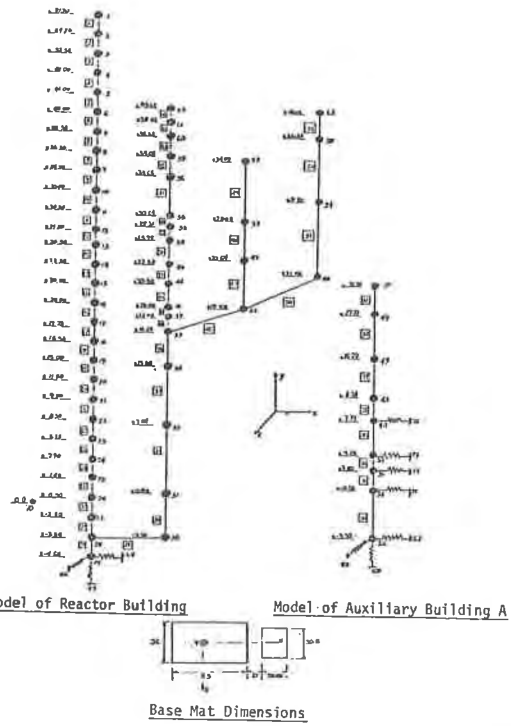

Figure 2 - Interaction Mathematical Model

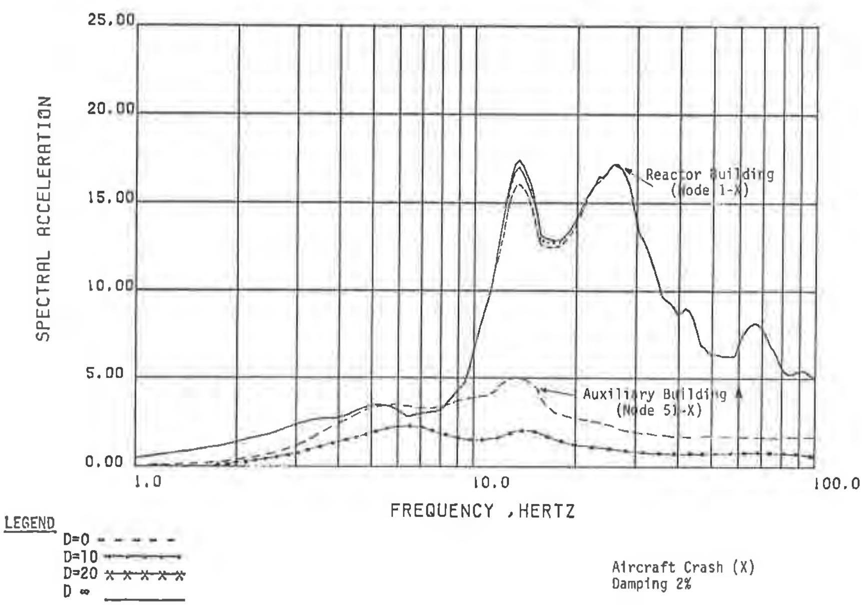

Figure 3 - Floor Response Spectra