VERTICAL RESPONSES OF NUCLEAR POWER PLANT STRUCTURES SUBJECT TO SEISMIC GROUND MOTIONS

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SUMMARY

In the seismic analysis of Nuclear Power Plant Structures, it is generally assumed that the floor slab is "rigid" in its own plane. However, the slab may be quite flexible in the direction perpendicular to the plane of the slab. Thus, two pieces of equipment located at different locations of the same floor may be subjected to two different excitations at their supports, due to vertical ground input. If a simplified stick model with one lumped mass at each floor elevation is used, the effect of the flexibility of the floor on the structural dynamic responses is not taken into account.

There are several methods available to treat this problem related to extra amplification due to floor flexibility. The first method is to use the cascade approach. In this approach, the responses obtained from the stick model is used as input motion to each of the separate flexible floor models. This method is straight forward and the amount of work depends on the degree of sophistication of the flexible floor model. The shortcoming of this method is that the energy feedback from the floor to the building is not taken into account and, therefore, the resulting responses may be overestimated.

The second method is to model the flexible floor with plate bending elements and combine them with the rest of the building. This integrated model is then treated as a system and subjected to ground excitation. By doing this, the energy feedback of the floor during vibration is automatically taken into account. Consideration of the interaction between the floor and the rest of the structure, generally yields structural responses lower than those obtained from the cascade approach. However, the computer cost of this analysis is very high especially in generating the floor response spectra for equipment design.

The third alternative as introduced here is to represent the building by a composite lumped model in which the floor is also represented by lumped masses. The stiffness of the interconnecting spring between mass points is computed from the physical properties of the corresponding floor slab. The advantages of this method are that the feedback effect is properly included and the computer cost is significantly reduced.

In this paper, techniques to model the building and the methods used to obtain the spring constants are presented and discussed. The results obtained using the composite lumped mass model approach and those obtained using the finite element method are compared. Various composite lumped mass models and modeling technique are recommended for future engineering applications.

1. Introduction

In the seismic analysis of nuclear power plants, the structures are generally represented by conventional lumped-mass models. In this mathematical model, the mass of half of the walls above and below the floor, the mass of the floor itself, heavy equipment, etc., are concentrated and lumped at each floor elevation. The masses are then interconnected by massless springs whose characteristics are calculated from the arrangement and configurations of the corresponding wall system which the spring represents. The model is then subjected to the excitations specified at the foundation of the structure. The excitation time history could be that specified for the site or that obtained from a separate Soil-Structure Interaction Analysis [1-2]. The structural response and the floor response spectra at selected floor elevations are then obtained using various analysis techniques [3-4]. Because the mass of the entire floor is lumped to one mass point, it is assumed that the floor is rigid in both the in-plane and out-of-plane directions. In general, the floor is quite rigid in its own plane and the assumption of a rigid floor is valid for horizontal response analysis. However, the floor may sometimes be flexible in a direction normal to its plane and thus the above assumption may not always be valid. Therefore, the additional response amplification due to the flexibility of the floor should be taken into account. For the cases investigated, our study shows that the accelerations at locations remote from the supporting walls can be 3 to 5 times higher than those at locations adjacent to the supporting walls for the extreme case. Furthermore, the peak of the floor response curve near the center floor region supported by walls is shifted toward the fundamental frequency of the floor region. Thus neither the magnitude, nor the shape of the floor response spectrum at the center of the floor can be predicted by a simplified lumped mass model with one mass at each floor elevation, unless the fundamental frequency of the floor region is higher than, say, 30 cycles per second. At this frequency the floor is considered rigid and the assumption used in the lumped-mass model is valid. Since safety related equipment and piping could be supported at a point on the floor remote from the supporting wall, additional care must be exercised in generating the floor response spectra for the seismic qualification of this equipment. Analytical methods, which take into account the additional amplification due to the flexibility of the floor, will be presented in this paper and the advantages of each method will be discussed.

2. Analytical Methods

There are several analytical methods available to treat the problem related to the additional amplification due to floor flexibility. The method most suitable to a particular problem depends on the desired degree of accuracy, the cost involved and the intended purpose of the results of analysis. The following three methods will be introduced:

2.1 Cascade Method

In this method, the conventional lumped mass stick model is first constructed and the time histories at selected floor elevations are obtained. These time histories are then input to the detailed finite element model of the floor slab region having long span lengths and the floor response spectra at control points are obtained. These floor response spectra which describe the real equipment response should be used for the qualification of the equipment. Portions of the floor slab with short span length can be eliminated from this detailed analysis by demonstrating that the fundamental frequencies of the particular floor region are higher than the rigid frequence or the frequency beyond which the floor response curve associated with the input time history shows no peaks. Natural frequencies of floor region with various support conditions are given for example by Leissa [5]. In this cascade approach, portions of the floor as shown in Fig. 1 (d) are partitioned as supported subsystems. The interaction between the subsystem and the structural system are neglected. Thus, the energy feedback of the subsystem are not taken into account. This assumption is valid provided the mass and the stiffness of the subsystem are such that they do not signi-ficantly affect the dynamic response of the supporting structure. Alternatively, the mathematical model and stiffness of the structural system can be suitably modified to account for interaction effects at the interface of the subsystem and the supporting structure. The effect of local modifications on the vibration characteristics of linear systems and the effects of the methods of uncoupling on a simple lumped-mass system are discussed by Weissenburger [6] and Pickel [7], respectively. The effect of mass ratio on the mean square response to white noise input are presented in reference [8] by Crandall and Mark.

2.2 Finite Element Approach

A number of control buildings for PWR as well as BWR nuclear power plants have been designed in such a way that the interior steel columns are utilized to support the vertical floor loads and the reinforced exterior concrete walls are utilized to take the tornado and missile impact loads and the horizontal shear force imposed on the wall due to seismic disturbances (see Fig. 2). The advantage of doing this is that concrete of more than one floor can be poured at the same time and the construction period can be greatly reduced. Since the steel columns are longitudinally more flexible than the circumferential concrete walls, the vertical responses at regions near the center of the floor may, in some cases, differ from those around the corners of the floor. For structures of this nature, the finite element method may prove to be very useful in predicting the response of equipment on the floor. As shown in Fig. 2, concrete walls of the structure can be first modeled as a cantilevel beam with lumped masses or consistent masses. The floor slabs are represented separately by finite element models. The floors which are interconnected by steel columns are also connected to the concrete column using springs or rigid links. In doing this, the floor-wall-column interactions are automatically taken into account. The results of a con-trol complex using the above techniques are shown in Fig. 3. It is noted that care must be taken to check the numerical instability problem for the case when the mass ratios are extremely large (or small). In all cases, the mode shapes should be examined for correctness. A set of floor response envelopes for a particular floor generated using this approach is shown in Fig. 5.

2.3 Modified Lumped-mass Method

For the case of thick floor slab supported by exterior walls with large span lengths and few interior supporting walls, the interaction effect between the floor and the structure system may be significant. The method described in 2.1 may not be desirable for this case. The finite element approach as described in 2.2 which is expensive and time-consuming, may not be desirable either. For practical engineering purposes, the Modified lumped-mass model is introduced [9]. In this method, the mass of each floor is divided into two parts: One is the equivalent mass, Me, representing the center region of the floor and the other is the remaining part of the mass, Ms, to be added to the interacting structural system as shown in Fig. 4. The equivalent spring constant ke, as shown in Fig. 4, is obtained approximately from the load and the associated deflection at the center of the floor region. The equivalent mass Me is obtained by equating the fundamental frequency of the floor slab using plate formulas or charts to the simple spring-mass frequency formula, i.e. f = Ke/Me. Having the equivalent mass and rigidity of the floor, the integrated modified lumped-mass model can be constructed. By use of this model in the analysis, the interaction effect between the floor and the structural system, and the amplification due to the flexibility of the floor can be taken into account simultaneously.

3. Discussion and Conclusions

Three methods are proposed here to treat the extra vertical amplification due to the flexibility of the floor slab. Generally speaking, the Cascade method which neglects the floor-structure interaction effect tends to overestimate the responses of the equipment on the floor if the floor is in resonance with the building. The method can be used for equipment with high damping values or for cases when high response can be tolerated. The finite element method is used for unusual problems or when it is intended to reduce or minimize the responses of the floor. The modified lumped-mass approach which is less expensive than the finite element approach, generates more realistic results than the Cascade approach. However, formulas, tables, or charts are needed in computing the equivalent springs and the masses, and some approximation as well as engineering assumptions are generally made. Although this method has some disadvantages, if properly used, it yields reasonably accurate results for engineering purpose.

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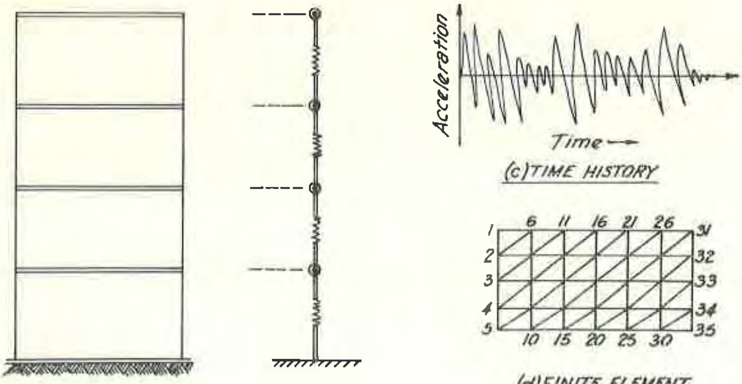

(a) STRUCTURE

(b) LUMPED MASS MODEL

(c) TIME HISTORY

(d) FINITE ELEMENT MODEL

FIG-1 CASCADE METHOD

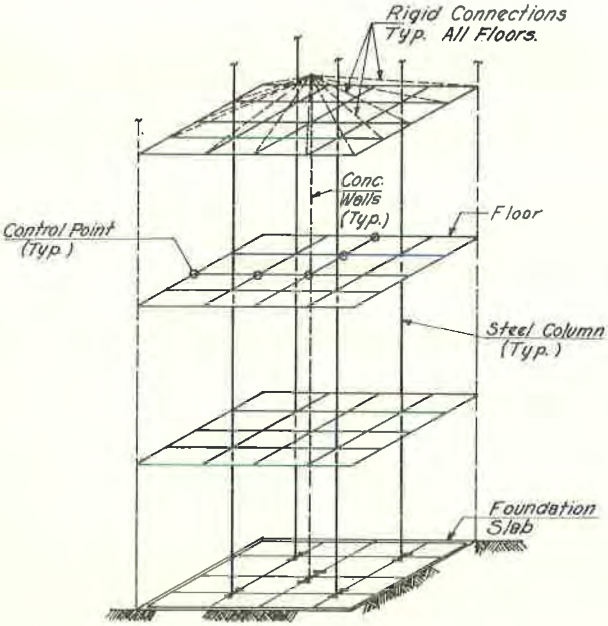

FIG-2 FINITE ELEMENT - MODEL

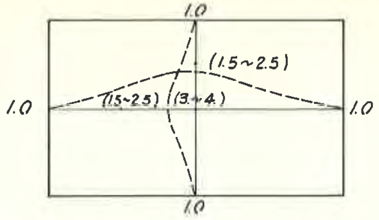

FIG.-3 MAX. ACCELERATION RATIO

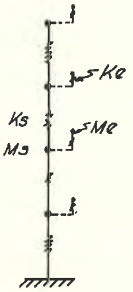

FIG.-4 MODIFIED LUMPED-MASS MODEL

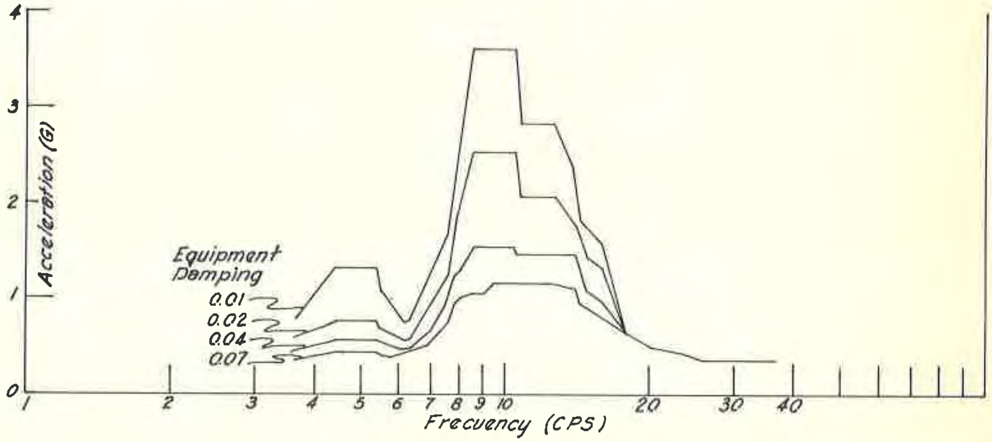

FIG. 5 FLOOR RESPONSE ESPECTRA ENVELOPS