SEISMIC RESPONSE SPECTRA FOR EQUIPMENT DESIGN IN NUCLEAR POWER PLANTS

J.M. BIGGS,

Department of Civil Engineering,
Massachusetts Institute of Technology, Cambridge, Massachusetts, U.S.A.

ABSTRACT

Floor response spectra for the seismic analysis of equipment are generated by a very simple, generalized method based on the ground response spectrum and the results of a response spectrum analysis of the supporting structure. In this method the effects of the structure's modes are computed separately and then combined by an empirical procedure. As compared to the alternative time-history approach to the construction of floor response spectra, the proposed method is not only much more simple in application, but is believed to be more reliable than the former when only a few time-histories of ground motion are used. The validity of the method is demonstrated by comparison with results derived from actual recorded ground motions.

INTRODUCTION

Presented in this paper is a method for generating floor response spectra to be used in the analysis and design of equipment or piping mounted in a massive structure. It particularly relates to the problem as encountered in the design of nuclear power plants. The problem is crucial, because in such facilities continued operation of the equipment after an earthquake is essential to safety. The analysis must be done with care, because in certain circumstances the maximum acceleration to which the equipment is subjected may be many times the peak ground acceleration and several times the maximum response acceleration of the supporting structure.

A floor response spectrum, in the present context, is a plot of maximum response acceleration versus period which provides the maximum response of any single-degree system, representing an item of equipment, mounted at the point in the structure for which the response spectrum has been constructed. It may also be applied to multi-degree equipment by utilizing conventional methods of modal analysis. It is not directly applicable to items such as piping which are supported at more than one point in the structure. However, this case may also be handled if one superimposes the effects of the individual support motions.

The method proposed here provides a simple, yet reliable, procedure for generating floor response spectra. It follows, and is based upon the results of, a response spectrum analysis of the structure. The method is general in that it is intended to provide an envelope of the floor response spectra which would be produced by all probable time histories of ground motion. It is limited to the case of uncoupled systems, i.e., cases in which the mass of the equipment is relatively small and does not affect the overall response of the structure. It would not, for example, apply to the reactor vessel in a reactor building because that item has appreciable mass and should be included as part of the dynamic model for analysis of the structure. However, the vast majority of equipment and piping has relatively small mass and may be considered uncoupled. Because of the large number of pieces of equipment in a power plant, it is neither practical nor desirable to include them in the model of the complete building.

A method similar to that presented here was introduced by the author in 1968. [1] The procedures and numerical functions recommended here represent an updating and improvement of the original method based upon additional studies of equipment-structure interaction in response to recorded earthquake ground motion.

To illustrate the nature of the problem and application of the proposed method, consider a typical BWR reactor building. The dynamic model to be used for analysis is shown in Fig. 1. This is a lumped-parameter model with nodes located on the exterior concrete building, the concrete containment or drywell, the sacrificial shield and reactor vessel, and the concrete pedestal supporting the vessel. The exterior building is connected to the interior structures only through the foundation mat, but the drywell, shield and vessel are interconnected by stabilizer springs. To account for soil-structure interaction, the base mat in the model is supported on translational and rocking springs. The parameters of the model, i.e., the mass and stiffness matrices, may be determined by any one of several conventional procedures. The first step in the analysis is to solve the eigenvalue problem, i.e., determine the frequencies and shapes of the normal modes.

Having established the normal modes, the next step in the building analysis is to determine the maximum response due to the seismic input in terms of displacements, accelerations and inertia forces at the nodes of the model. This is normally done by classical modal analysis, but the numerical results can be obtained in one of two ways. (1) A ground motion response spectrum is utilized to produce the maximum modal responses, and the total response is obtained by combining the modal maxima by root-mean-square or other statistical device. (2) A numerical solution of the modal equations of motion is obtained for a postulated time-history of ground motion and the time-history of total responses is obtained by direct superimposing of the modal responses. The first method is now most commonly used for analysis of the building because a ground response spectrum can be predicted with some confidence for a given site, but it is impossible to predict a complete, detailed time-history of ground motion. If time-history inputs are used, either recorded motions from actual earthquakes or simulated motions, it is necessary in design to employ several such inputs to ensure a conservative combination of modes in the multi-degree system. Because of the uncertainties in predicting the detailed ground motion, and the voluminous computation required in time-history analysis, the use of ground response spectra is more realistic for design purposes.

A disadvantage of the response spectrum approach is that it yields only the maximum modal responses at a point in the structure and not the time-history of the motion which is required for the direct generation of the equipment response spectrum for that point in the structure. The purpose of the method described below is to circumvent this difficulty by permitting the construction of equipment response spectra without a time-history analysis of either the building or the equipment.

BASIC CONCEPTS

The maximum acceleration response of the equipment may be considered to be an amplification of either (1) the ground response spectrum or (2) the peak acceleration of the structure at the point where the equipment is attached. These two approaches are complimentary since the first is more accurate for long equipment natural periods and the second is more accurate for short periods. Therefore, the proposed method uses both approaches, each in the range where it is the more accurate. The amplifications factors have been determined empirically. As will be shown below, the factors are essentially a function of only the ratio of equipment to structure periods (T_e/T_s) and the amount of damping in each. This fact makes possible a very simple computational procedure.

The maximum equipment response is determined for each mode of the structure. The total equipment response is then taken to be the root-mean-square of the responses due to the structural modes.

Before the method is described in detail, it will be helpful to identify two limiting cases of equipment response: (1) Very flexible equipment relative to the structure ($T_e/T_s>>1$), and (2) very rigid equipment ($T_e/T_s<<1$). In the first case, the internal distortion of the relatively rigid structure has no effect on the equipment. On the other hand, those frequencies of ground motion to which the equipment is most responsive are passed through the structure without modification. Therefore, the equipment responds as though it were supported directly on the ground.

In the case of rigid equipment, the structure filters out those frequency components of the ground motion to which the equipment would be sensitive. Therefore, the equipment merely "rides along" with the structure and the maximum acceleration of the equipment is equal to that of the structure at the point of attachment.

Considering either of the two limiting cases as a starting point, as the period ratio approaches unity the equipment response is magnified. In the case of flexible equipment the structure serves to amplify the ground motion. In the case of rigid equipment, the equipment itself amplifies the structure's motion since, in effect, it is being subjected to a harmonic support motion. In either case, the amplification factor is very similar to the classical amplification of a damped one-degree system subjected to a harmonic forcing function. This suggests that the amplification factor is a function of only the period ratio and the damping. In fact, this is very nearly the case, as will be shown below.

AMPLIFICATION CURVES

Figures 2 and 3 show amplification curves which were developed empirically and which are used in the proposed method. Fig. 2 provides the ratio of peak equipment acceleration (A_e) to the acceleration which would occur if the equipment were supported on the ground (A_{eg}). Fig. 3 provides the ratio of peak equipment acceleration to the maximum acceleration of the structure at the point of equipment support, (A_{sn}). Amplification curves for other combinations of structural and equipment damping have the same shape but different ordinates.

The amplification curves are based on analyses of the model shown in Fig. 4. This system was subjected to four actual earthquake records, and numerical analyses were made to provide the two amplification factors for a range of period ratio. Although the model is a two-degree system, it should be noted that this does not imply that the structure has only one degree of freedom. Instead, the lower mass and its supporting spring represents any one of the uncoupled normal modes of the structure.

These four particular earthquakes were chosen because they are typical of strong motion records, and also because they have different frequency content, i.e., the maximum responses occur in different frequency ranges.

Since the results are not completely independent of the actual value of the periods, analyses were made for various values of T_s. The points plotted in Figs. 2 and 3 each represent the maximum amplification factor computed for values of T_s ranging from 0.05 to 2.50 secs. However, this does not result in excessive conservatism as may be seen by inspection of Fig. 5, which shows the variation of peak amplification factor (at $T_e/T_s = 1$) with T_s. Each point plotted is the maximum of the responses due to the four earthquake records. The value actually used for the peak amplification (10.4) is only slightly unconservative at certain values of T_s. It is somewhat conservative for $T_s > 1.0$, but such periods do not usually occur in nuclear power plant structures. Plots for other period ratios show similar results and it is concluded that ignoring the effect of T_s does not produce significant error.

The amplification curves adopted (shown in Figs. 2 and 3) are generally upper bounds for the four earthquakes. It may be observed in Fig. 2 that there is little scatter in the points computed for the four earthquakes. However, for small period ratios ($T_e/T_s < 0.7$) the curve becomes irregular, as would be expected because in this range the equipment response is determined by the motion of the structure rather than the ground motion. In Fig. 3 there is little scatter in the lower range of period ratios but considerable scatter at the peak and for higher ratios, as would be expected since the ground motion is more significant in this range. Note that the curve in Fig. 2 approaches unity for large period ratios and that in Fig. 3 approaches unity for small ratios.

Based upon these results, it was decided to use the amplification of the structure's motion (Fig. 3) below $T_e/T_s = 0.5$ and amplification of the ground motion (Fig. 2) for $T_e/T_s > 0.9$. Between these two points an interpolation of the two approaches was adopted. Since for each amplification factor in its applicable range the results are nearly the same for all four earthquakes, it is believed that these amplification curves are generally reasonable regardless of the detailed time-history of the ground motion.

THE PROCEDURE

A floor response spectrum is generated by computing the maximum equipment acceleration for a series of values of equipment period within the range of interest. The structure has been previously analyzed on the basis of a given ground response spectrum, to provide the following data:

T_{sn} = natural period of mode n
Γ_{sn} = participation factor for node n
ϕ_{sn} = eigenvector for mode n at point of equipment support
A_{sn} = maximum acceleration in a mode n of structure at point of equipment support

For each value of equipment period (T_e) the following procedure provides a point on the floor response spectrum:

1. Determine A_{eg}, the equipment response acceleration as if it were supported on the ground. This is obtained by reading the ground response spectrum for the equipment period and damping.
2. For each significant mode of the structure:

   (A) If $T_e/T_{sn} < 0.9$

   Compute $A'_{en} = A_{sn} \left(\frac{A_e}{A_{sn}}\right)$, where the ratio in parenthesis is obtained from Fig. 2.

   (B) If $T_e/T_{sn} > 0.5$

   Compute $A''_{en} = \frac{\Gamma_{sn}\phi_{sn}}{C_{ne}} \cdot A_{eg} \left(\frac{A_e}{A_{eg}}\right)$, where the ratio in parenthesis is given by Fig. 3, and

   $\frac{T_e}{T_s} < 1.25,$

   $$C_{ne} = 1$$

   $1.25 < T_e/T_s < 2.25,$

   $$C_{ne} = 1 + \left(\frac{T_e}{T_{sn}} - 1.25\right) \left[\left(\overset{N}{\Sigma}(\Gamma_{sn}\phi_{sn})^2\right)^{1/2} - 1\right]$$

   $\frac{T_e}{T_s} > 2.25,$

   $$C_{ne} = \left(\overset{N}{\Sigma}(\Gamma_{sn}\phi_{sn})^2\right)^{1/2}$$

   where the summation includes all structural modes being considered.

   (C) If $0.5 < \frac{T_e}{T_s} < 0.9$

   Compute $A_{en} = A'_{en} + (A''_{en} - A'_{en}) \frac{T_e/T_s - 0.5}{0.4}$

   If T_e/T_s is not within this range, A_{en} equals either A'_{en} or A''_{en}.
3. Repeat Step 2 for each significant mode of the structure.
4. Obtain the total equipment response by combining the effects of the structural modes as follows,

   $$A_e = [\overset{N}{\Sigma} A_{en}^2]^{1/2}$$

The interpolation procedure in Step 2(C) is necessary because the two methods in (A) and (B) cannot give identical results. This is true because of the approximation in the amplification curves and also because a smoothed ground response spectrum used for design does not give consistent values of A_{eg} and A_{sn}.

In step 2 (B) the multiplier $\Gamma_{sn}\phi_{sn}$ appears because this is a measure of the effect of mode n on the equipment. For example, if $\Gamma_{sn} = 0$, mode n does not participate in the seismic response. If $\phi_{sn} = 0$, mode n produces no motion at the equipment support. In either case, no equipment acceleration is associated with mode n. C_{ne} is an empirical correction factor which ensures the correct result when T_e is very large. If T_e is much larger than any of the structural periods, $A_e/A_{eg} = 1$ for all modes and A_e must equal A_{eg}. When the modes are combined in Step 4, the construction of C_{ne} ensures this result. The range 1.25 - 2.25 was selected to provide spectra consistent with computed responses to actual earthquake records.

The combination of modal effects by root-mean-square in Step 4 is consistent with the method most commonly used for analysis of structures based on response spectra. Any other method of modal combination could also have been used, but it should be consistent with that used for the structure. Thus, when all T_e/T_{sn} values are small, A_e will be equal to the predicted maximum acceleration of the supporting structure, as it should be.

The computations required by this procedure are extremely simple and can even be executed by hand. When a computer is used the calculations are almost trivial.

VERIFICATION OF METHOD

The proposed method is intended to provide a floor response spectrum which is an envelope of all spectra which would be produced by reasonable time histories of ground motion. Whereas any single time-history would produce a spectrum which is unconservative in some ranges of equipment period, the simplified method produces in one computation a spectrum which is reasonable over the complete period range. In order to verify this statement, comparisons have been made with results obtained by time-history analyses for various earthquake records. Four such comparisons are shown in Figs. 6 through 9.

In these figures the dashed lines are the result of time-history analysis such as is commonly employed for the construction of floor response spectra. This involves first a numerical modal analysis of the supporting structure to procure a time-history of the motion of the structure at the point of equipment support. This time-history is then used as input to a one-degree system in a numerical analysis which provides one point on the floor response spectrum.

The solid curves in Figs. 6-9 have been computed by the simplified method based upon the actual, unsmoothed ground response spectrum for that particular earthquake record. In other words, A_{eg} and A_{sn} have been taken from the unsmoothed spectrum. In this way, the effect of smoothing the ground response spectrum, as is normally done for design, has been eliminated from the comparison.

Figs. 6 and 7 show comparisons for point 46 in the reactor building model shown in Fig.1. The two ground motion records used are 1940 El Centro NS and 1966 Parkfield -5 NW, both normalized to a peak ground acceleration of 0.2g. In both cases the floor response spectrum has two peaks corresponding to the first and second modes of the structure which have periods of 0.80 and 0.29 secs. It will be noted that the small peaks and valleys of the two curves coincide, thus indicating that the simplified method properly reflects the character of the ground motion. In Fig. 6 it may be observed that the El Centro input is unconservative throughout, especially at the first mode peak. In Fig. 7, the response to the Parkfield input is very slightly more conservative on both sides of the second mode peak, but otherwise very similar to that predicted by the proposed method. It should be re-emphasized that agreement between the two curves being compared in each plot is not expected since the proposed general method is intended to be an envelope of all possible seismic inputs.

The Parkfield input is included in Fig. 7 because that record was not one of those used in developing the amplification curves (Figs. 2 and 3). This serves to prove that the proposed amplification curves are indeed general and not dependent on the detailed nature of the seismic motion.

The comparisons in Figs. 8 and 9 are derived from another BWR reactor building which is similar but not identical to that shown in Fig. 1. The Taft and El Centro earthquakes have been normalized to 0.08g. In this case the first four modes of the structure contribute significantly to the floor response spectrum. The periods of these modes are 0.28, 0.19, 0.17 and 0.14 secs. The response in this case is therefore quite complicated, but even so, the general method produces a very reasonable result which is at all points more conservative than the time-history results.

As a result of these and many other such comparisons which have been made, it may be concluded that the proposed method produces conservative, yet reasonable, results throughout the range of equipment period.

APPLICATION

When a smoothed ground response spectrum is used for design, the resulting floor response spectrum is also smooth. Such a spectrum is shown in Fig. 10.

The peaks of floor spectra, which occur at points of resonance with the structural modes, tend to be quite narrow. Since the natural periods of the structure cannot be known precisely, it is prudent to design the equipment for a range of structural periods. This is particularly true of structures on soft foundations represented by soil springs, the constants of which cannot be determined accurately. To account for this uncertainty, the final floor response spectrum should be taken as the envelope of all spectra computed for a probable range of structural periods.

Shown in Fig. 11 is an actual set of floor response spectra for equipment design at a point in the reactor building of Fig. 1. Each of the four curves is for a particular value of equipment damping. The plots are completely computer-produced. To allow for uncertainty in structural periods, each curve is a composite of those computed for assumed upper and lower limits of the periods. As an approximation, the envelope was obtained by constructing straight lines between the peaks associated with the upper and lower limits of each period. The computer cost for producing Fig. 11 was approximately five dollars. Most of this was for the automatic plotting since the computational cost by the simplified method is almost negligible.

SUMMARY

The simplified or generalized procedure presented herein is a convenient, yet reliable, method for the generation of floor response spectra to be used for the seismic design of equipment and piping in nuclear power plants. It eliminates the need for the large number of costly time-history analyses which would otherwise be required. More importantly, it is believed to be more reliable than a time-history approach based on a limited number of ground motion records. This is true whether the motions are actual earthquake records or artificial motions mathematically derived from a ground response spectrum. In either case one cannot be sure that the selected records are conservative for the particular multi-degree structure supporting the equipment. On the other hand the proposed method is intended to be an envelope of all probable seismic inputs.

It is hoped that the method presented provides a more realistic approach to the critical problem of seismic design of equipment in nuclear power plants.

Reference

[1] BIGGS, J.M., ROESSET, J.M., "Seismic Analysis of Equipment Mounted on a Massive Structure," Seismic Design for Nuclear Power Plants, edited by R.J. Hansen, MIT Press, Cambridge, Massachusetts (1970).

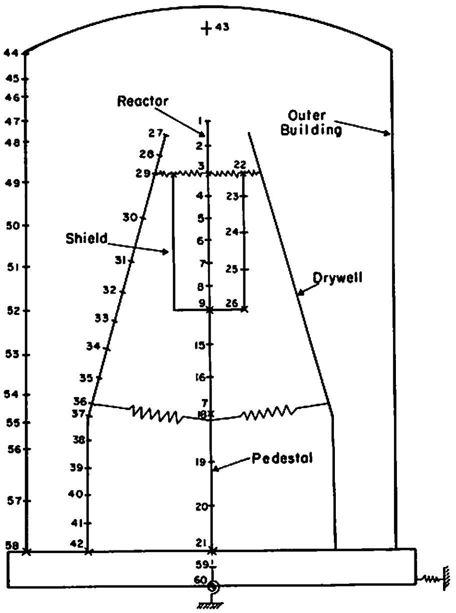

FIGURE 1: DYNAMIC MODEL OF REACTOR BUILDING

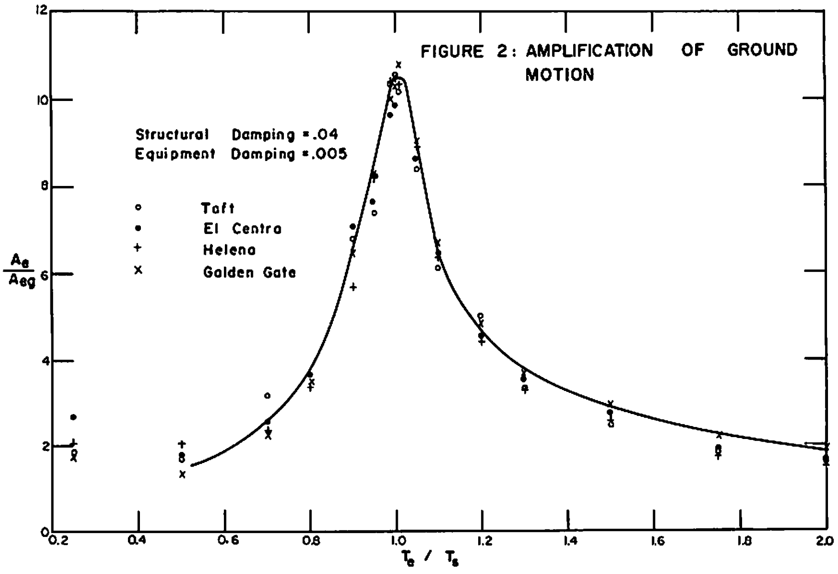
FIGURE 2: AMPLIFICATION OF GROUND MOTION

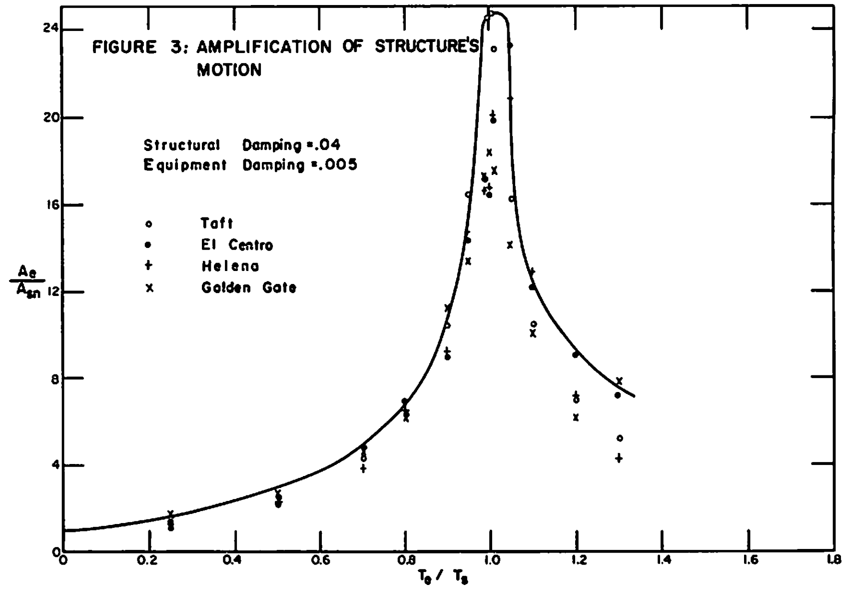

FIGURE 3: AMPLIFICATION OF STRUCTURE'S MOTION

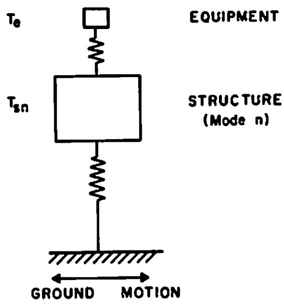

FIGURE 4: MODEL FOR TIME-HISTORY ANALYSIS

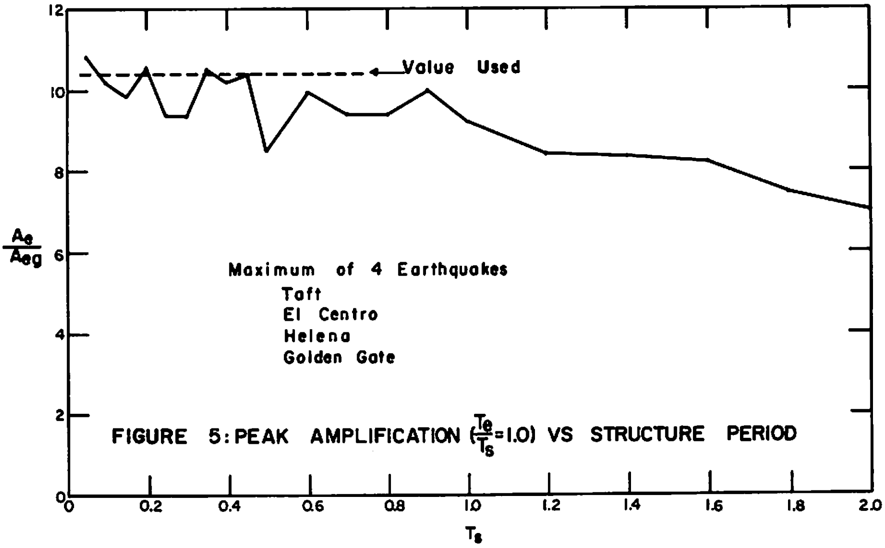

FIGURE 5: PEAK AMPLIFICATION ($\frac{T_e}{T_s}$=1.0) VS STRUCTURE PERIOD

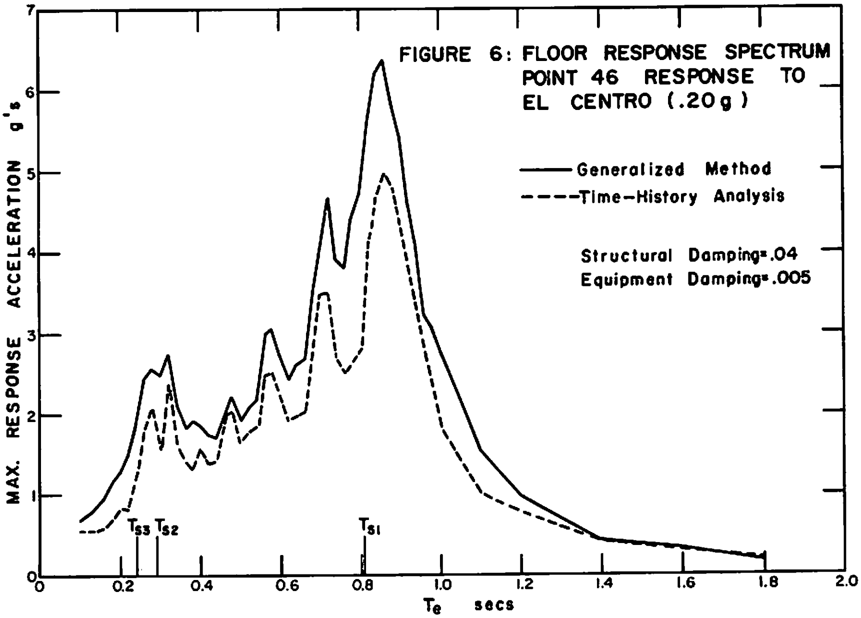

FIGURE 6: FLOOR RESPONSE SPECTRUM POINT 46 RESPONSE TO EL CENTRO (.20g)

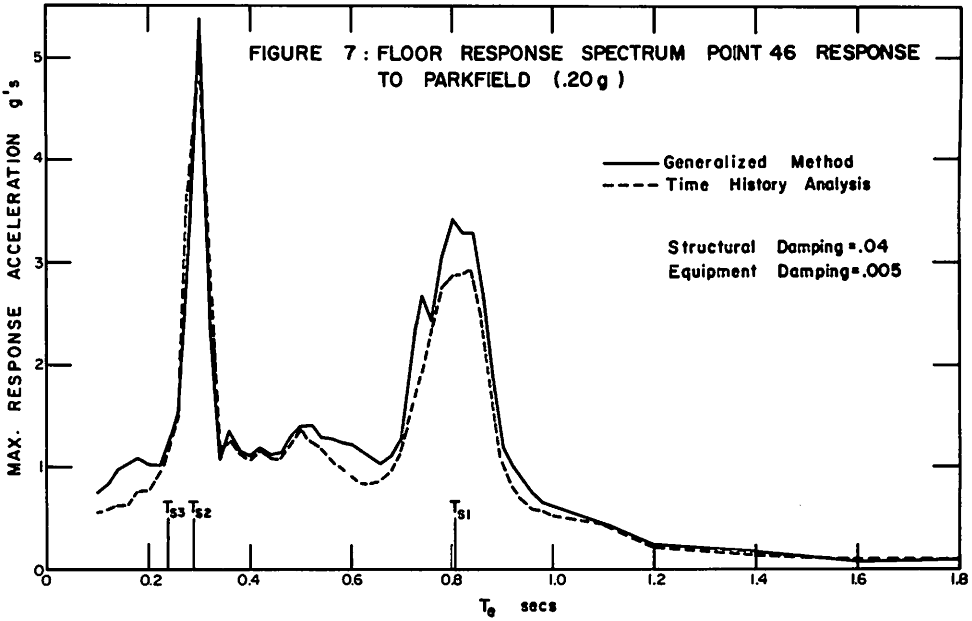

FIGURE 7 : FLOOR RESPONSE SPECTRUM POINT 46 RESPONSE TO PARKFIELD (.20g)

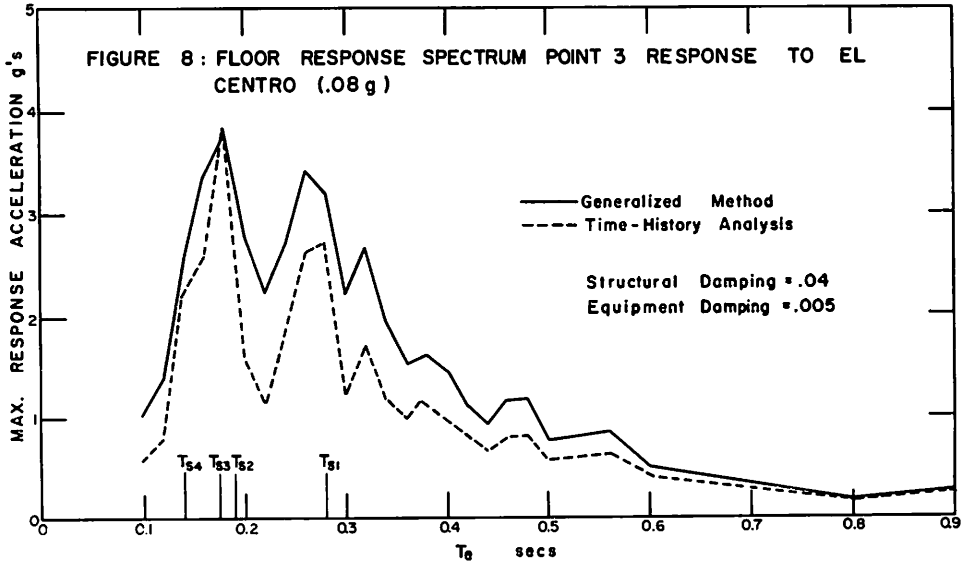

FIGURE 8 : FLOOR RESPONSE SPECTRUM POINT 3 RESPONSE TO EL CENTRO (.08g)

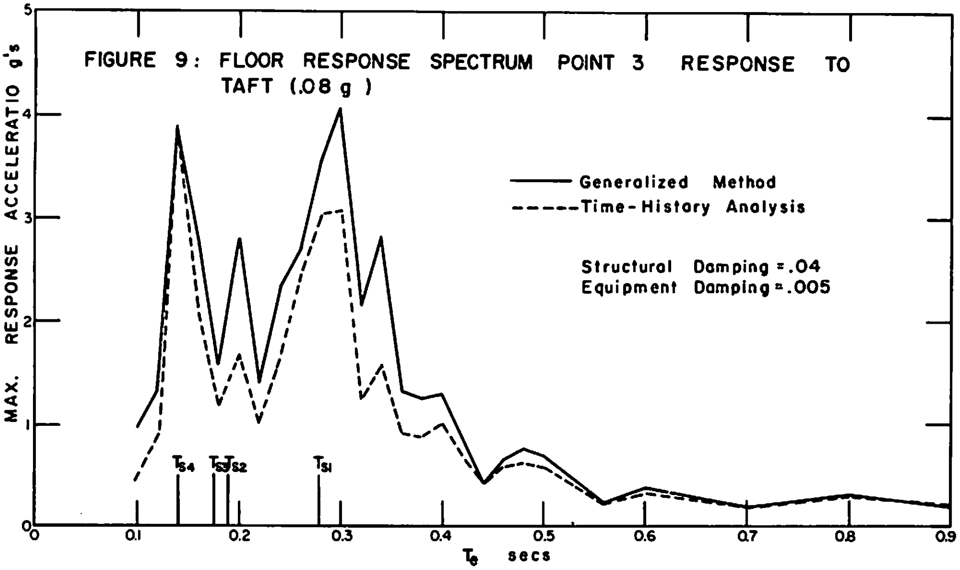

FIGURE 9: FLOOR RESPONSE SPECTRUM POINT 3 RESPONSE TO TAFT (.08 g)

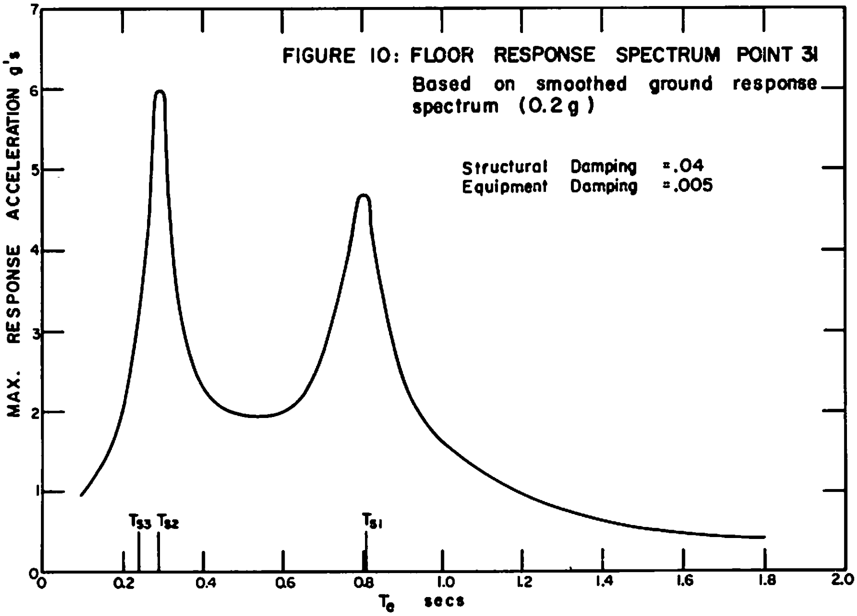

FIGURE 10: FLOOR RESPONSE SPECTRUM POINT 31
Based on smoothed ground response spectrum (0.2 g)

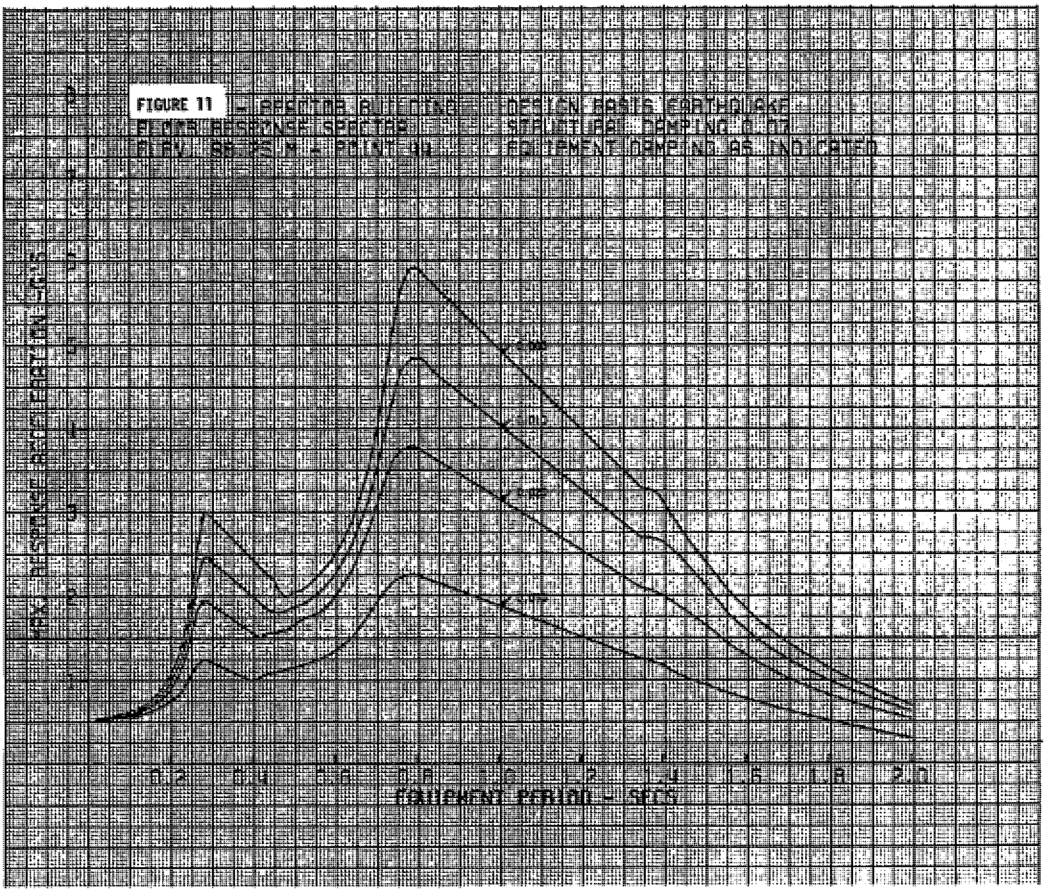

FIGURE 11 - REACTOR BUILDING DESIGN BASIS EARTHQUAKE
FLOOR RESPONSE SPECTRA STRUCTURAL DAMPING 0.07
ELEV. 85.75 M - POINT 44 EQUIPMENT DAMPING AS INDICATED

DISCUSSION

Q

R. J. SCAVUZZO, U. S. A.

In the comparison of the time history analyses with the spectrum analyses, is the same mathematical model used of the power plant ? If the model is the same wouldn't you expect to obtain the agreement shown ?

A

J. M. BIGGS, U. S. A.

The same dynamic model is used in both cases. However, the resulting floor response spectrum would be different for two reasons:

1. the amplification factor might not be correct for that particular earthquake and structural period,and
2. the use of root-mean-square for combination of the modal effects might be in error. Nevertheless, the results indicate that these errors are not serious.

Q

B. NOWOTNY, Germany

Did I correctly understand your method, if I have the following imagination ?: The floor response in the time domain consists of something like decaying vibrations. I think you assume the vibration to be exactly a decaying vibration with the maximum acceleration of the building of this floor and with the damping factor of the building.

A

J. M. BIGGS, U. S. A.

The shape of the amplification curves is very similar to that for the response to a damped harmonic input. However, the actual ordinates shown in the paper have been determined empirically from actual earthquake records.