SPECTRUM-COMPATIBLE TIME-HISTORIES FOR SEISMIC DESIGN OF NUCLEAR POWER PLANTS

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SYNOPSIS

Current practice for seismic design of Nuclear Power Plants (NPP) structures and components is to utilize a design basis response spectrum which represents an envelope of possible ground motions effects on a series of one degree of freedom oscillators. In order to apply the time-history method of seismic analysis to the design of NPP structures and components, it is often necessary to generate an artificial time-history from a given design response spectrum. The only criteria used currently in the industry which appears to be acceptable to most regulatory authorities is that the generated time-history spectrum must envelope the design response spectrum. When it is required to excite the mathematical models with two-dimensional or three-dimensional seismic motions, an additional criterion has emerged which is the statistical independence between the different motion components. While these criteria have never posed any practical problems, it is believed that very little is known about the different variables and the alternatives associated with the generation process and their impact on the final response of the structure or the equipment housed inside the structure.

In this paper, a state-of-the-art review of the different methods available to develop spectrum-compatible time-histories is presented. Two independent approaches have been utilized to generate two spectrum-compatible time-histories. One approach is deterministic in nature and the other one is based on random vibration theory.

The resulting two time-histories, thus generated, were tested for compatibility and used for the seismic analysis of a typical CANDU 600MWe Reactor Building. Response quantities such as accelerations, displacements, overturning moments and shear forces were computed. Responses were also computed using the conventional response spectrum method. Comparisons of results obtained using the different methods were made and discussed. It is concluded that properly generated time histories yield comparable seismic response in general.

RESUME

Une mise à jour des diverses méthodes de simulation numérique de séries de temps compatibles à un spectre donné est faite. Deux méthodes, une déterministique et l'autre caractérisée par des vibrations aléatoires, sont résumées. L'évaluation du comportement d'une centrale nucléaire de type CANDU avec une puissance de 600 MW est faite. Les accélérations, forces latérales, moments de renversement, etc., sont comparés à ceux obtenus par une analyse conventionnelle, pour conclure que cette simulation est valable si la série est générée avec soins.

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INTRODUCTION

Current practice for seismic design of Nuclear Power Plants (NPP) structures and components is to utilize a design basis response spectrum which represents an envelope of possible ground motions effects on a series of one degree of freedom oscillators (1,2). These design spectra may be completely defined by a peak ground acceleration and are intended to be applicable to all firm ground sites. In order to apply the time-history method of seismic analysis to the design of NPP structures and components, it is often necessary to generate an artificial time-history from a given design response spectrum. The only criteria used currently in the industry which appears to be acceptable to most regulatory authorities is that the generated time-history spectrum must envelope the design response spectrum. When it is required to excite the mathematical models with two-dimensional or three-dimensional seismic motions, an additional criterion has emerged which is the statistical independence between the different motion components. While these criteria have never posed any practical problems, it is believed that very little is known about the different variables and the alternatives associated with the generation process and their impact on the final response of the structure or the equipment housed inside the structure.

In Canada, nuclear power plants have been seismically designed utilizing both spectrum methods as well as time-history methods where real or adjusted earthquake records have been used. These real and adjusted earthquake records are limited in the sense that they are conditional on the occurrence of a set of random parameters (magnitude, focal depth, attenuation, frequency content, duration etc). It is very unlikely that such a set of random parameters will ever be the same for a new site under consideration. Recognizing this difficulty, numerous mathematical models to predict the nature of the ground shaking in the vicinity of the causative fault have been proposed and used. References 3, 4, 5 and 6 give brief histories of these simulation techniques.

The methods currently available for generation of a spectrum compatible motion can be classified into two basic approaches. The first one is the deterministic approach and the second one is the random vibration approach. In the deterministic approach, a time-history of an actual earthquake is modified at selected frequency points to achieve the desired compatibility. In the random approach, waves having random amplitudes and phase angle are generated. In both of these approaches, adjustments are made for the resulting waves.

The number and extent of adjustments that can be used is not unique. Therefore compatible motions can be obtained by widely differing adjustments. This paper attempts to define the criteria for adjustments and discusses the effects of different adjustments on the response.

METHODS AVAILABLE FOR SPECTRUM - COMPATIBLE TIME-HISTORIES

Current available artificial time-history generation techniques whether deterministic or probabilistic in nature involve the following basic steps:

1) Establishing an 'initial guess' time-history. This step may simply involve the specification of a real time-history which is believed to exhibit some unique features to be expected in potential earthquake motions at the site. Alternatively this step may involve the superposition of a large number of random sinusoids as modified by an envelope deterministic function.

2) Manipulation of the 'initial guess' time-history in the time-domain or the frequency-domain, and generation of successive time-histories which have response spectra converging to the target design spectrum.

3) Testing the resulting time-history to establish its adequacy as a representation for the seismic threat at the site as well as its adequacy to meet criteria of the regulatory agencies and industry.

4) When it is required to generate a truly three dimensional seismic environment, the other two components of motion are extracted from the resulting time-history using a set of rules that will be discussed later. Alternatively the whole process may be repeated to generate the other component time-histories. In this case some cross-testing is required among the components as well.

In general the following features of the resulting time-histories should be studied and evaluated for adequacy:

1) The response spectrum of the resulting motion.

2) The resulting ground motion parameters (Acceleration, Velocity, and Displacement).

3) The total duration.

4) The rising characteristics, the duration of the significant shaking, and the decay characteristics of the motion.

5) The Fourier Amplitude and phase spectra

6) The Apparent Frequency

7) The correlation between the different components of motion.

The only two criteria available now to the industry to evaluate these features cover the first and last features only, i.e. the resulting response spectrum is required to envelope closely the design or target response spectrum and the different components of motion are required to be statistically independent with low correlation coefficients (usually less than or equal to 0.16).

The second feature is partially covered as far as the ground acceleration by the closeness of the resulting response spectrum to the design response spectrum at high frequencies (>33Hz). However, the first and second integral of the acceleration time-history (i.e. velocity and displacement) are rarely looked at, although some attempts have been made to subject the resulting time-history to some kind of base-line correction to guarantee that the ground velocity and the ground displacement obtained by integration are reasonable.

The third and the fourth features should be defined based on the seismo-tectonic behaviour governing the site seismicity. Correlating these features to the seismo-tectonic behaviour of a site is a very difficult task considering the fact that the total duration and the duration of significant shaking lack unique and universal definitions. However from the engineering point of view, acceptable and conservative features for these parameters can be defined.

The fifth feature is related somehow to the first one by the well known relationship between the Fourier Amplitude and the zero damping response spectrum as established by Hudson (7). This simply means that the Fourier amplitude spectrum should be reasonable if a close agreement between the resulting response spectrum and the design response spectrum is achieved. Two interesting comments should be pointed out in this regard. The first is that most artificial time-histories for NPP are generated and tested in a certain frequency range (typically from 1 to 33Hz). The frequency content of real earthquakes is not known above 33Hz (actually closer to 25Hz). Thus the resulting time-histories should not contain any frequency component beyond 33Hz. This may be crucial considering the fact that time-histories are sometimes used in analyzing NPP systems and components for nonlinear and impact phenomena where the presence of these fictitious frequencies may result in erroneous response calculations. It has been the authors' practice to use numerical filters (both high-pass and low-pass filters) to remove the unnecessary frequency content before using the resulting time-histories in actual dynamic analyses. The second comment is that most phase spectra of actual earthquakes are random in nature. Thus the resulting time-histories should have random phase spectra. The authors are familiar with at least one method of time-history generation which intentionally does not change the phase spectrum at all (10). Of course there are many other methods which attempt to guarantee the randomness of the phase angles spectra.

The sixth feature which is the apparent frequency of a time-history is an indication of the number of zero crossings which affect the cyclic seismic response of equipment and structures. The number of zero crossings present in a seismic accelerogram has implications on phenomena such as fatigue evaluation and the evaluation of liquification potential.

As for the seventh feature, it is noted that cross-correlation coefficients at zero time delay have been used as a measure of the statistical independence between motion components. Cross-correlation coefficients at zero time delay cannot form a sound basis for determining completely the time phase relationships between the input components. It can be shown that by shifting one input component slightly along the time axis, the cross-correlation coefficients at zero time delay for the shifted and the original components can be very small. Above the zero time delay, however, the correlation coefficients may achieve unity and fluctuate with large values. Consequently, in order that the time-histories will possess the characteristics of real earthquakes, it may be necessary to compare the auto-correlation and cross-correlation coefficient functions for the component motions with real earthquake records.

The following is a brief review of the methods currently available for the generation of spectrum-compatible time-histories.

DETERMINISTIC METHODS

Hadjian (8) has proposed a method to utilize recorded earthquake motions and to perform three types of modifications: Firstly, a linear scaling of the entire motion was used to raise or lower the entire response spectrum, secondly the digitization interval was modified to shift the location of spectral peaks and valleys; and thirdly, a 1-DOF filter was utilized to decrease the power of the motion at desired frequencies. A somewhat similar method using feedback technique is proposed by Duff and Biswas (25).

Similarly, Tsai (11) has proposed a method to start with a motion whose response spectrum resembles the design response spectrum (for some appropriate damping value), and then utilizing 'spectrum suppressing' and 'spectrum raising' techniques. Suppression of the spectrum is achieved by passing the selected motion through a set of frequency suppressing filters which controls the bandwidth of significant suppression (2-DOF mechanical system). Raising the spectrum is achieved by superposing on the selected ground motion sinusoidal components of suitable amplitudes, frequencies, and phase angles.

A frequency domain analogue of the above procedure has been proposed and used by Rizzo, Shaw, and Jasecki (9). A Discrete Fourier Transform (DFT) of a real motion is generated which is then modified in various ways. At the end, an Inverse Fourier Transform (IFT) is computed, i.e. a new time-history is synthesized. Originally Rizzo et al (9) used a multiplicative function when it is necessary to lower the response spectrum while an additive constant is used if the computed response spectrum is to be raised.

Later on Rizzo et al (10) modified their approach and the entire matching process is now accomplished by simply scaling the DFT spectra either up or down depending on whether the calculated spectra fall below or above the smooth design response spectrum. Since they utilize linear scaling of the Fourier amplitude (i.e. both the real and imaginary parts of the DFT are scaled by the same amount), the phase relationships among the elements of the DFT remain constant throughout every iteration. Physically this means that the phasing, as represented by the phase spectrum, of the original starting time history remains unchanged in the final time-history. This feature is different from other time-history generation methods which either filter the original time-history, thereby changing the phasing, or use a random number generator to select the phase of each element of the Fourier Transform at each stage of the iteration process.

While this unique feature may not be important for the generation of a single time-history, it appears to have some advantages by preserving the phasing relationships between various directional components of a seismic event. This retention of the original phasing assures the retention of the same coherence functions. The coherence function is a measure of statistical independence present between two components of the original seismic event. This overcomes the well-known problem that the correlation coefficient suffers from the fact that small correlation is necessary but not a sufficient condition for two stochastic processes to be statistically independent. Therefore, an evaluation of the correlation coefficient associated with two components of a recorded seismic event does not indicate the degree of statistical independence between the components. Thus the preservation of the phase relationships of the initial recorded directional components accelerograms used for the generation of artificial accelerograms constitutes a valid treatment of the degree of correlation between artificial time histories used for multi-directional seismic response analysis.

Scanlan and Sachs (12) first generated an artificial motion by sinusoidal superposition using amplitudes A_i derived from the values of the zero damping target response spectrum, which is known to be related to the Fourier amplitude spectrum of the desired motion (7). Subsequent iterations to provide better spectrum compatibility are used with a correction applied to the sinusoidal amplitude A_i. The number of frequency points is chosen to include all frequencies of interest while the phase angles, ϕ_i, are chosen as a set of N independent random numbers on the interval (0, 2π).

Kost et al (13) have implemented a similar approach to that of Scanlon and Sachs with local manipulations in both the time and frequency domains. Manipulation is done for both the amplitude of the transform as well as the phase angles. If the resulting phase angles are not uniformly distributed, with some frequency ranges having higher density than others, a redistrubution is carried out so that distribution is more uniform for the next iteration steps. Kost el al somewhat suggest that amplitudes should be manipulated if the time-history spectrum exceeds the target spectrum while phase angles may be manipulated if the opposite is true. They suggest using higher frequency components as a useful approach in obtaining a better match between the computed and target spectra. It is noted here that both of these two suggestions may be open to questions.

Levy and Wilkinson (14, 15) presented a method for time-history generation which is similar to that of Scanlan and Sachs (12). Their method is also based on the superposition of sinusoids as modulated by an envelope time function as follows:

$$a(t) = I(t) \sum_{i=1}^{N} (-1)^{i}.A_{i} \, . \, \mathrm{Sin}(2\pi f_{i} t) \qquad (1)$$

where

$a(t)$ = acceleration time-history

$I(t)$ = envelope time function (A function based on El Centro 1940 NS component was used by Levy and Wilkinson)

A_i = i^{th} amplitude to be determined

f_i = i^{th} frequency component assumed in the time-history

They state that the factor $(-1)^i$ improves the solution. While this may be true, it is clear that their phase angles are always zero or 180° degrees depending on whether i is even or odd. Thus it can be argued that their starting assumption is not compatible with the nature of an actual earthquake. In addition to this unique feature in Levy and Wilkinson's work, they implement a modulating function which rises and decays more than once; a feature which has not been used by any others to the authors' knowledge. The richness of the time-history is achieved by choosing a large number of closely spaced frequency points 'f_is' such that their half power points overlap. This approach which is customarily used in the process of generating response spectra leads to:

$$\frac{\Delta fi}{f_i} \leq 2\beta \qquad (2)$$

where

Δf_i = Increment in frequency f_i

β = percentage of critical damping utilized

The amplitudes 'A_i' are determined using an iteration process. Initially the magnitude of the A_i's are taken to be proportional to the corresponding response spectrum <u>g values</u> at frequencies f_i's on the desired response-spectrum curve. Using the initial trial time-history, a response spectrum curve is computed and compared with the desired response spectrum curve. For the second trial time-history, the new magnitudes of the A_i's are obtained by multiplying the initial values of the A_i's by the ratio of the desired response spectrum at frequency f_i to that computed in the first iteration. This iteration process is continued until the computed response spectrum is close enough to the desired one.

Levy and Wilkinson suggested a simple method for generating a second component of a time-history having arrived at the first spectrum compatible time-history. The resulting time-history derived by this method has a response spectrum that approximates, to a satisfactory degree, the original design response spectrum. The approach involves chosing the frequencies and the amplitudes of the second time-history to be mid-way between those of the first time-history. Thus, following a similar terminology to that of equation (1), if the X component of motion is given by:

$$a_x(t)=I(t) \cdot \sum_{i=1}^{N} (-1)^i A_{xi} \bullet \text{Sin}\,(2\pi f_{xi} t) \qquad (3)$$

The Y component can be derived from

$$a_y(t) = I(t) \cdot \sum_{i=1}^{N} (-1)^i A_{yi} \bullet \text{Sin}(2\pi f_{yi} t) \qquad (4)$$

where

$$A_{yi} = \frac{1}{2} (A_{xi} + A_{x(i+1)}) \qquad (5)$$

$$f_{yi} = \frac{1}{2} (f_{xi} + f_{x(i+1)}) \qquad (6)$$

This approach, by intuition, leads to a small correlation coefficient between the components. However it is not clear that the approach represents an adequate simulation of the true correlation between ground motion components. Other approaches of generating dual time-histories have been studied by Levy and Wilkinson as well. The first involves the imposition of a 90° phase shift on all the frequency components. The second is the introduction of a random phase with uniform probability distribution in each frequency component; and the third is the use of a random shift in the frequency f_i with a uniform probability distribution between the adjacent mid frequencies $\frac{1}{2}(f_i-f_{i-1})$ and $\frac{1}{2}(f_{i+1}-f_i)$. Their main conclusion was that the time-histories determined by the mid-frequency shift and the 90° phase shift have correlation coefficients that were very small and were acceptable and preferable in the process of generation of additional time-histories.

RANDOM VIBRATION METHODS

Briefly these methods are based on the concept that an artificial earthquake consists of a random oscillatory function of time multiplied by an 'envelope function' which defines its general or overall character. This envelope function, I(t), is arbitrary but can be chosen, as seen in Fig. 1, to define the overall duration, rise, duration of strong motion, and decay, of many earthquake types. This leads to the following basic equation:

$$a(t) = I(t) \cdot \sum_{i=1}^{N} A_i \cdot \mathrm{Sin}\,(2\pi f_i t + \emptyset_i) \tag{7}$$

The number of frequencies is chosen such that all frequencies of interest are included for the case at hand. The phase angles, $\emptyset_i$, are chosen as a set of N independent random numbers on the interval $(0,2\pi)$. The form of equation (7) for the ground motion has the characteristics that, whatever the choices for A_i and $\emptyset_i$ may be, the earthquake envelope maintains the overall desired general aspects in time.

The results that are presented below are based on the work by Vanmarcke, Cornell, Hou and Gasparini (4,16,17,18,19). Vanmarcke was able to clarify the relationship between the response spectral values for arbitrary damping and the spectral density function (s.d.f) of the ground motion where he assumed the ground motion to be a suddenly applied 'stationary' acceleration with s.d.f. $G(\omega)$ and an equivalent duration S. The pesudo-velocity response spectra $S_v(\omega_n,\beta)$ for a linear one degree system with natural frequency ω_n and damping ratio 'β' (including $\beta=0$) take the following form:

$$S_v\,(\omega_n,\beta) = r.\sigma_v \tag{8}$$

σ_v = pseudo-velocity standard deviation at time S

r = dimensionless peak factor

The standard deviation of relative displacement (σ_d), pseudo-velocity, and pseudo acceleration (σ_a) response are related as follows:

$$\sigma_a = \omega_n\,\sigma_v = \omega_n^2.\sigma_d \tag{9}$$

$$\sigma_v \cong \frac{1}{\omega_n}\left[G(\omega_n).\omega_n.\left[\frac{\pi}{4\beta_s} - 1\right] + \int_0^{\omega_n} G(\omega)d\omega\right]^{\frac{1}{2}} \tag{10}$$

$$\beta_s = \frac{\beta}{1-e^{-2\beta\omega_n S}} \tag{11}$$

Note that $\beta_s \rightarrow \beta$ when $\omega_n S$ is large compared to β^{-1}, i.e. 'Steady State' response has developed, and that $\beta_s \rightarrow (2\omega_n S)^{-1}$ when $\beta \rightarrow 0$ (i.e. the undamped case is included as well).

The peak factor 'r' of equation (8) can be expressed as a function of n; where n is dependent on the average number of cycles of response motion ($S.f_n$), and the desired non-exceedance probability 'p'. For example the (median) peak factor r (p=0.5) may be expressed as a function of $n=1.4(S.f_n)$ for different damping values β. An approximate upper bound value for r (which is approached when the damping is high, say above 10%) is given by the expression $r = \sqrt{2\ln(2n)}$. For more interesting details, the reader is referred to an excellent reference by Vanmarcke (18).

The equations just given define the relationship between the response spectrum (for a specified damping value) and the power spectral density of ground motion. Conversions from S_v to $G(\omega)$ can therefore be made and used for the generation of response spectrum-compatible motions. This would lead to the following relationships:

$$G(\omega_n) \cong \frac{1}{\omega_n\left[\frac{\pi}{4\beta_s} - 1\right]} \left[\frac{\omega_n^2 \left[S_v(\omega_n, \beta) \right]^2}{r^2} - \int_0^{\omega_n} G(\omega)\,d\omega \right] \tag{12}$$

Thus the relationship between S_v and $G(\omega)$ depends on the chosen strong motion duration S and on the damping level β (It may also be made to depend on the non-exceedance probability level p assigned to S_v; a value of p of 0.5 is typically chosen in implementing the process. The solution of the above equation requires a marching scheme; where $G(\omega_{i+1})$ is obtained having determined $G(\omega_i)$.

A_i's are derived from the following relationship, while the phase angles are chosen to be random.

$$G(\omega) \,.\, \Delta\omega = \frac{A_i^2}{2} \tag{13}$$

To smooth the response spectrum and to improve its agreement with the target response spectrum, an iterative procedure is implemented. In each cycle of the iteration, the calculated response is compared with the target at a set of control frequencies. The ratio of the desired response to the computed response is obtained at each control frequency and the corresponding value of the s.d.f. is modified in proportion to the square of this ratio, i.e. at any cycle m;

$$G_{m+1}(\omega) = G_m(\omega) \left[\frac{S_v(\omega)}{S_{v\,m}(\omega)} \right]^2 \tag{14}$$

With the modified s.d.f. (using the original set of random phase angles) a new motion is generated and a new response is calculated.

CRITERIA FOR SPECTRUM COMPATIBILITY

The following represents a set of recommended practical criteria for the acceptability of spectrum-compatible time-histories.

a) The response spectrum of the time-history shall be monitored at a number of closely spaced frequency points. The recommendations in Ref. 2 and 20 may be followed. Alternatively, frequency spacing according to half power method as discussed earlier can be used.

When the frequencies are chosen to be linearly spaced on a logarithmic scale in the range from f_{min} to f_{max} (i.e. $f_{i+1}=\alpha f_i$, where α is a constant greater than 1.0), the number of frequency points 'N' becomes

$$N = \ln\left(\frac{f_{max}}{f_{min}}\right) \Big/ \ln\alpha \qquad (15)$$

To cover the half-band width the maximum value of α is given by:

$$\alpha = 1 + 2\beta \qquad (16)$$

Thus typically for 2% damping, there should be at least 90 separate frequency points within the frequency range from 1 to 33 Hz.

b) The ratio of the computed response spectrum to the design response spectrum should have a mean greater than 1.0 and a coefficient of variation of less than 5%. Statistically this will allow, for the case of a mean of 1.08, that approximately 7% of the points to fall below the design spectrum.

c) Of the points falling below the design response spectrum, none should be less than 90% of the design response spectrum.

The most important point to note is that the smooth design spectrum itself falls below some of the historical data on which it is based. Thus there is no real need for the artificial time-history spectrum to always fall above the design spectrum at all frequencies.

GENERATION OF STATISTICALLY INDEPENDENT TIME-HISTORIES

Sometimes it is required to excite a NPP structural model with simultaneous seismic excitation in two perpendicular horizontal directions and in the vertical direction. This is typically done when a nonlinear analysis is conducted or the method of simultaneous direct integration of the three-dimensional equations of motion is used. In the latter the direct application of the three components of motion simultaneously will lead to a saving of approximately 67% in the computation time. The specified vertical spectrum may differ from the horizontal spectrum, so that the corresponding time-histories differ as well. However, it is desirable in any event to generate two horizontal time-histories, which should be as unrelated as earthquake records themselves are. Statistically, one desires that their correlation coefficients should be low.

The correlation coefficient between two accelerograms $a_x(t)$ and $a_y(t)$ is defined as:

$$\rho_{xy}(\tau) = \frac{1}{T\ \rho_{xx}\rho_{yy}} \int_{\tau}^{T} a_x(t)\ a_y(t-\tau)dt \qquad (17)$$

$$\rho_{xx} = \frac{1}{T} \int_{0}^{T} \left[a_x(t) \right]^2 .dt \qquad (18)$$

$$\rho_{yy} = \frac{1}{T} \int_{0}^{T} \left[a_y(t) \right]^2 .dt \qquad (19)$$

Newmark et al (1) recommend that the three components of motion should be independent. Penzien and Watabe (24) proved mathematically that the three components are statistically uncorrelated provided that they are transformed into the principal coordinates of the ground motions. Their proof is based on the assumption that the three components are a stationary random process modified by the same deterministic intensity function to achieve appropriate non-stationarity.

An interesting study has been made by Chen (21, 22, 23) of the correlation coefficients of strong motion accelerograms recorded at 104 sites. Based on this study Chen recommends that an acceptable level of correlation among any two of the three components can be 0.16 or 0.20 depending on whether the absolute mean or mean plus one standard deviation is used as the criterion.

It is worth mentioning that during the process of generating time-histories, some inevitable correlations are created among the three components of motion. Thus a proper cross-testing has to be conducted to establish that the resulting time-histories are realistic or at least conservative for seismic design. While 'correlation' is currently used as the sole criterion for determining the statistical independence of the artificially generated earthquakes, this approach is a necessary but not a sufficient one for a true representation of the three-dimensional nature of the seismic excitation.

GENERATION OF EXAMPLE TIME-HISTORIES

Two spectrum-compatible motions are generated using two different approaches, namely a deterministic and a random vibration method as discussed earlier. The response spectra of these motions match the spectrum as proposed in Ref. (2). The spectrum curve corresponding to

2% damping is used for the purpose of the matching. These motions are obtained as time-history of accelerations and are normalized to 0.1g with a time interval of 0.01 sec.

TIME-HISTORY USING DETERMINISTIC METHOD

A time-history of acceleration is generated using a deterministic method. The method used is that of spectrum suppressing and spectrum raising techniques at a number of frequency points. This approach is similar to that used previously by Tsai (11) except that both the suppressing and the raising was accomplished by the use of a series of 2 DOF mechanical systems as shown in Fig. 2. The parameters F and ξ determine the extent of raising and suppressing (11). Using this method, an automated computer program COMPT has been developed.

The time-history record of the NS component of El Centro 1940 record is scaled and used as the initial motion. A total of 9 iterations to improve the compatibility were used. The time-history of acceleration of the final motion is shown in Fig. 3. The response spectrum of this motion for a damping value of 2% is overlaid on the design response spectrum and is shown in Fig. 4. In this paper, this time-history will be identified as T.H.-1.

TIME-HISTORY USING RANDOM VIBRATION METHOD

A time-history of acceleration is generated using the random vibration method as presented by Vanmarcke, Cornell, Hou and Gasparini (4, 16, 17, 18, 19). These methods are discussed in detail earlier. An adaptation of the program SIMQKE has been used for that purpose. The time-history of acceleration is ploted in Fig. 5. In this paper, this time-history will be identified as T.H.-2. The response spectrum of this motion for a damping value of 2% is overlaid on the design response spectrum and shown in Fig. 6. From the figure a good compatibility of spectrum in the frequency range of interest is evident.

DYNAMIC ANALYSIS OF REACTOR BUILDING

The two compatible time-histories T.H.-1 and T.H.-2 were used to perform a dynamic analysis of a typical CANDU 600MWe Reactor Building. The objective was to compare the response and the floor response spectra obtained by using two spectrum compatible time-histories arrived at utilizing two independent and different methods. A typical Reactor Building model at a soil site was chosen for that purpose (Fig. 7). Time-history analyses were performed using the computer program STARDYNE. A response spectrum analysis using the design response spectrum was performed as well. The results obtained by using the response spectrum method, time-history analysis using T.H.-1 and T.H.-2 are compared. Accelerations and Displacements along the height of the structure are compared in Fig. 8 and Fig. 9 respectively. The overturning moments and shear forces are compared in Fig. 10 and Fig. 11 respectively. The floor response spectra for 1% damping at node 1 and 4 are computed and compared in Fig. 12 and Fig. 13 respectively. The values of the peaks for other values of damping are compared in Table 1.

DISCUSSION AND CONCLUSIONS

The previous examples indicate that, given a design response spectrum of reasonable shape, an earthquake-like motion can be generated. Theoretically, numerous motions can be generated to match a given design response spectrum. Thus, it is of great interest to study the sensitivity of the structural response and the resulting floor response spectra to individual motions that are compatible with the same design spectrum and have the same general characteristics although may have been developed by different approaches. The objective is to establish confidence in applying synthetic motions to the seismic design of important structures and equipment of NPP. In this paper two independent spectrum-compatible time-histories were developed and the response of a typical CANDU 600MWe Reactor Building for these time-histories was determined.

Based on the comparisons made and the cases studied the following conclusions can be made:

1. The response spectrum method is slightly more conservative than the time-history method. However the degree of conservatism is small and is believed to be within the degree of uncertainty in the overall seismic design process.

2. Spectrum-compatible time-histories which are judicially developed and monitored within an adequate frequency range produce in general comparable results. There is actually no need to use more than a single time-history in most practical applications especially when adequate enveloping and broadening is implemented at the end.

3. An artificially generated time-history rich in all frequencies is not necessarily more severe than a deterministic time-history.

   For the internal structure, T.H.-1 (deterministic time-history) gives higher response than T.H.-2 (probabilistic time-history). For the containment wall however, the opposite is true. The maximum difference of the order of 20% is noted. The same trend is evident in the floor response spectra in Figures 12 and 13 and in Table 1.

4. The common practice of generating a time-history from a single spectrum (or alternatively a spectral density function) is strictly justified if only one earthquake source accounts for nearly all of the total site seismic risk, or if the local geology is principally responsible for shaping of the frequency content of the ground motion. Where this is not the case; the approach, while consistent with the concept of using a broad-band spectrum for design purposes may raise some issues which need considerable further study beyond the current state of the art.

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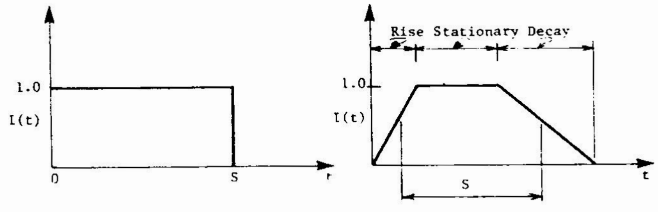
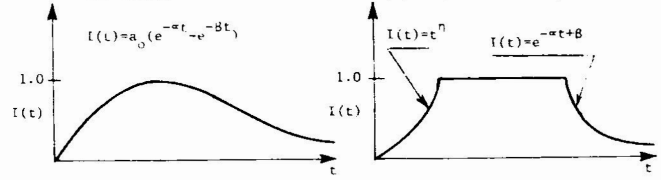
TABLE 1

COMPARISON OF PEAKS OF FLOOR RESPONSE SPECTRA

Location	Damping (%)	Peak Value (g)	
		Using Time-History-1	Using Time-History-2
Node 4 1st Peak	1	3.66	3.35
	2	2.51	2.13
	4	1.54	1.46
Node 4 2nd Peak	1	1.50	1.42
	2	1.23	1.05
	4	.87	.74
Node 4 3rd Peak	1	.82	.65
	2	.65	.60
	4	.51	.41
Node 1 1st Peak	1	1.91	1.67
	2	1.25	1.09
	4	.79	.77
Node 1 2nd Peak	1	.86	.80
	2	.68	.66
	4	.52	.47
Node 1 3rd Peak	1	1.97	1.89
	2	1.44	1.28
	4	1.02	.82



(a) Boxcar (b) Trapezoidal (Hou,1968)



(c) Exponential (Liu,1969) (d) Compound (Jennings ,1968)

FIG. 1 ENVELOPE TIME FUNCTIONS

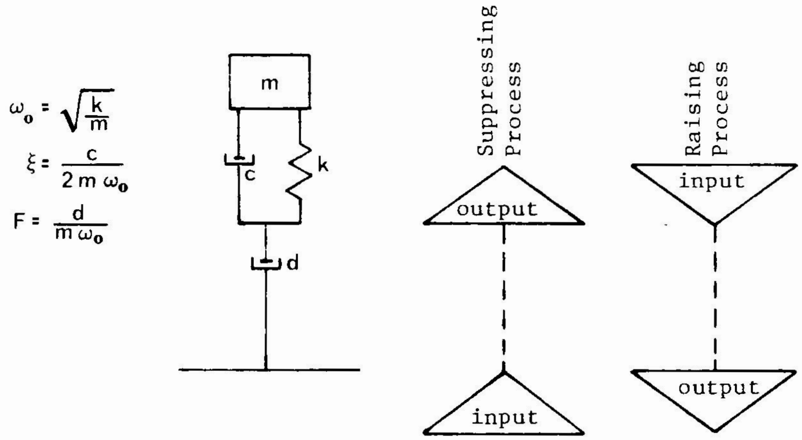


FIG. 2 2-DOF MECHANICAL SYSTEM

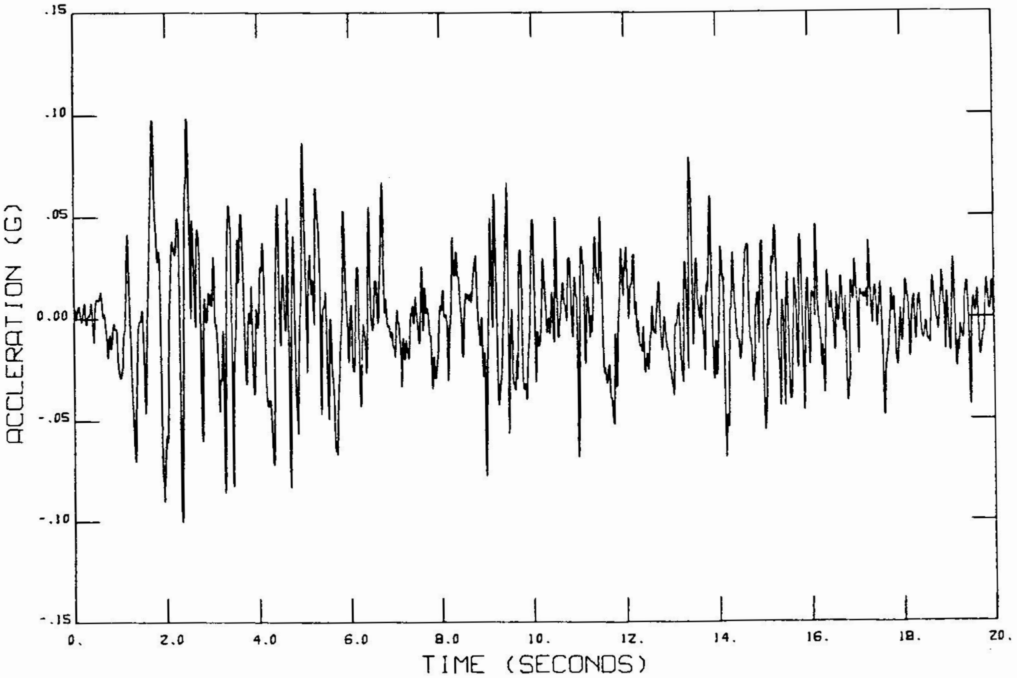


FIG. 3 ACCELERATION TIME HISTORY : DETERMINISTIC APPROACH

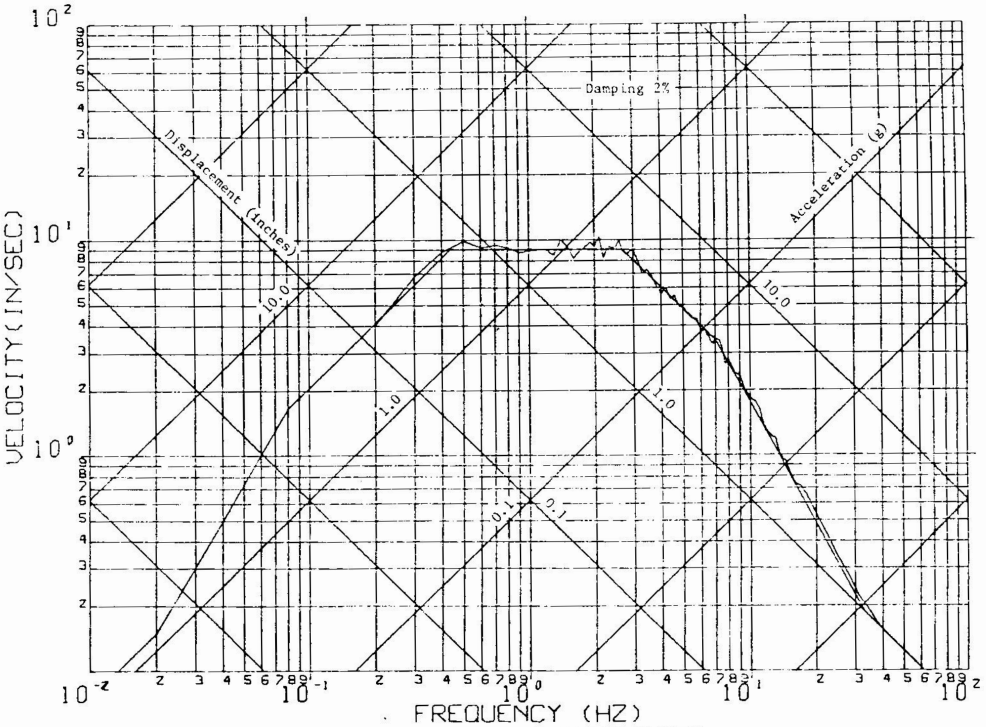


FIG. 4 RESPONSE SPECTRUM : DETERMINISTIC APROACH

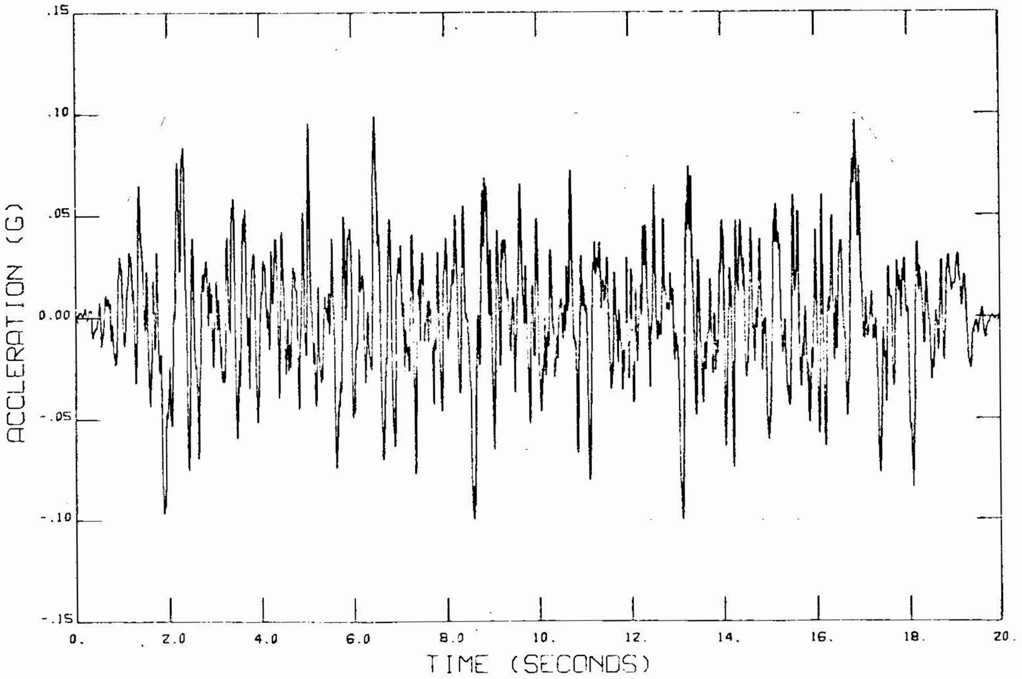


FIG. 5 ACCELERATION TIME HISTORY : RANDOM VIBRATION APPROACH

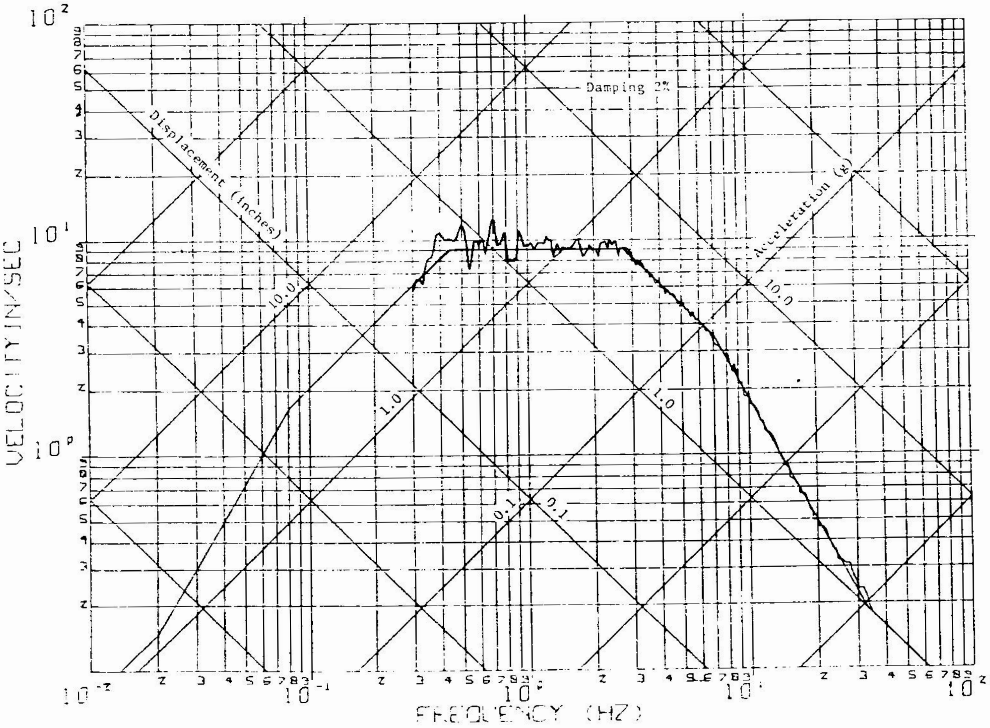


FIG. 6 RESPONSE SPECTRUM : RANDOM VIBRATION APPROACH

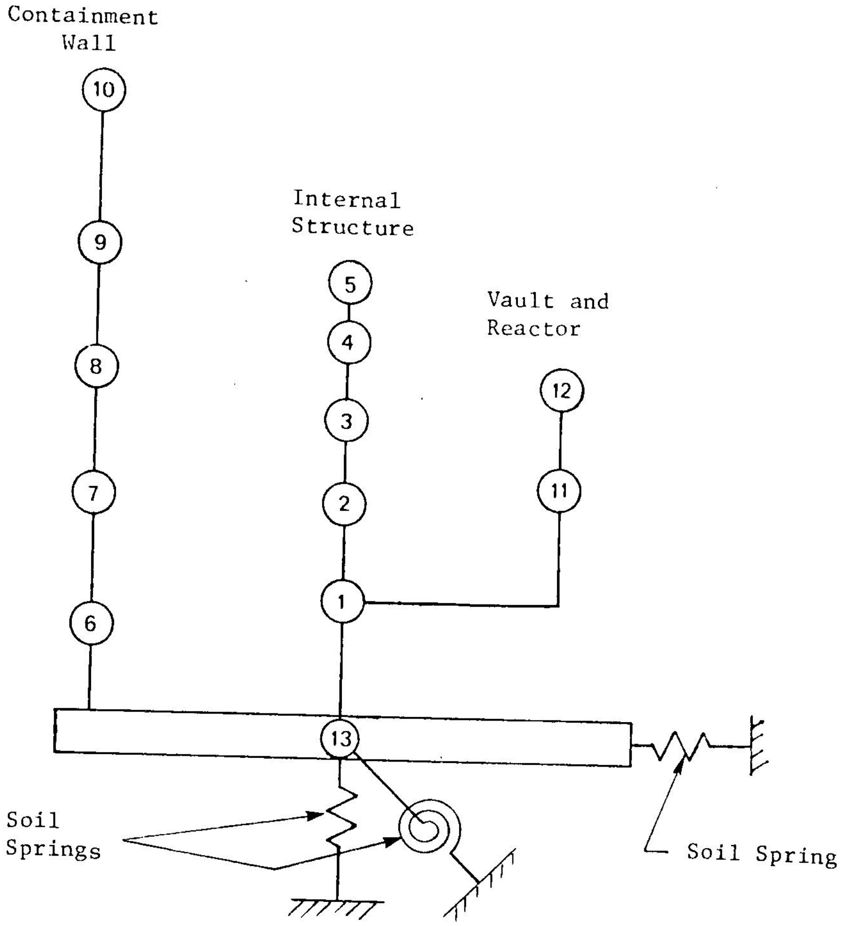


FIG. 7 CANDU REACTOR BUILDING MODEL

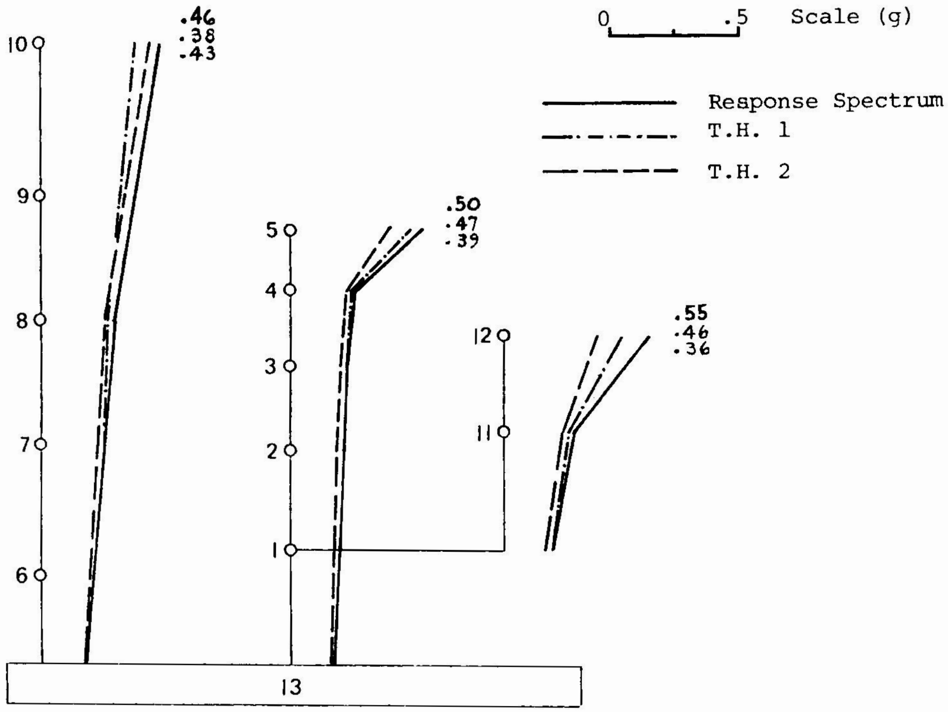


FIG. 8 ACCELERATION COMPARISON

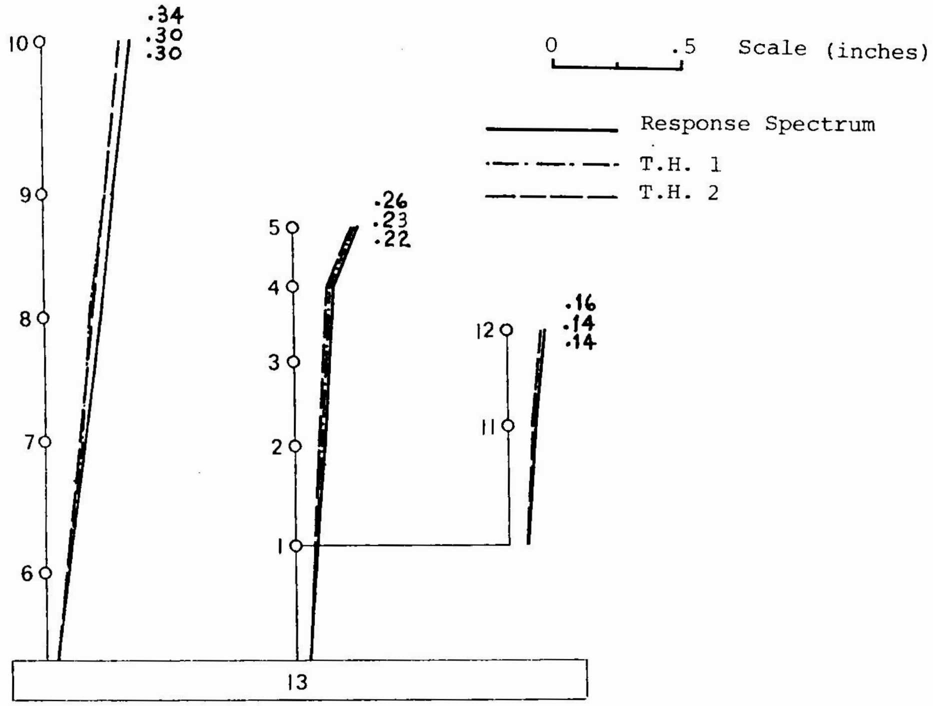


FIG. 9 DISPLACEMENT COMPARISON

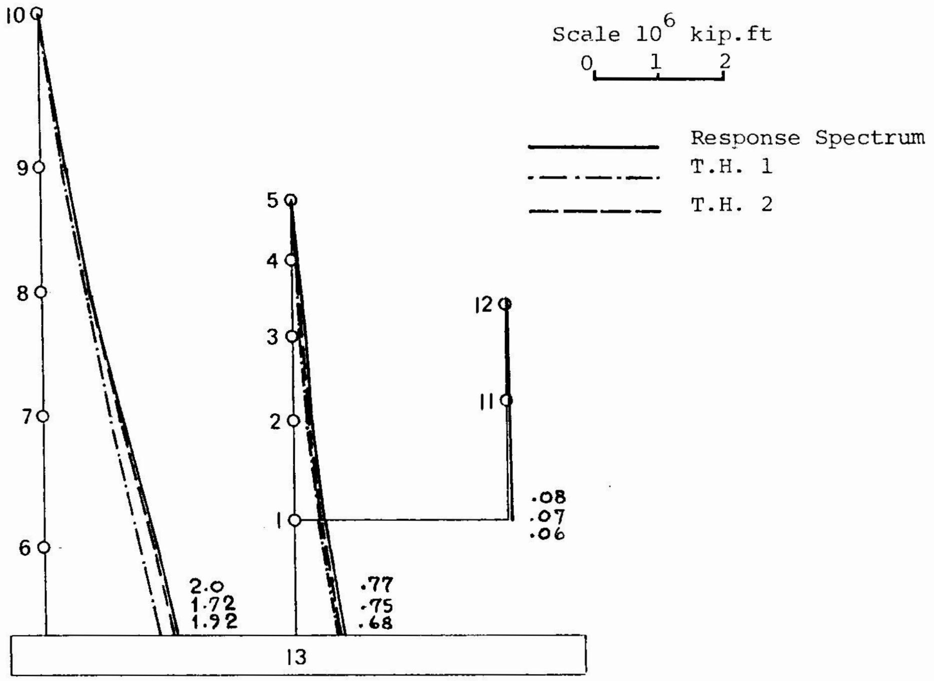


FIG. 10 OVERTURNING MOMENT COMPARISON

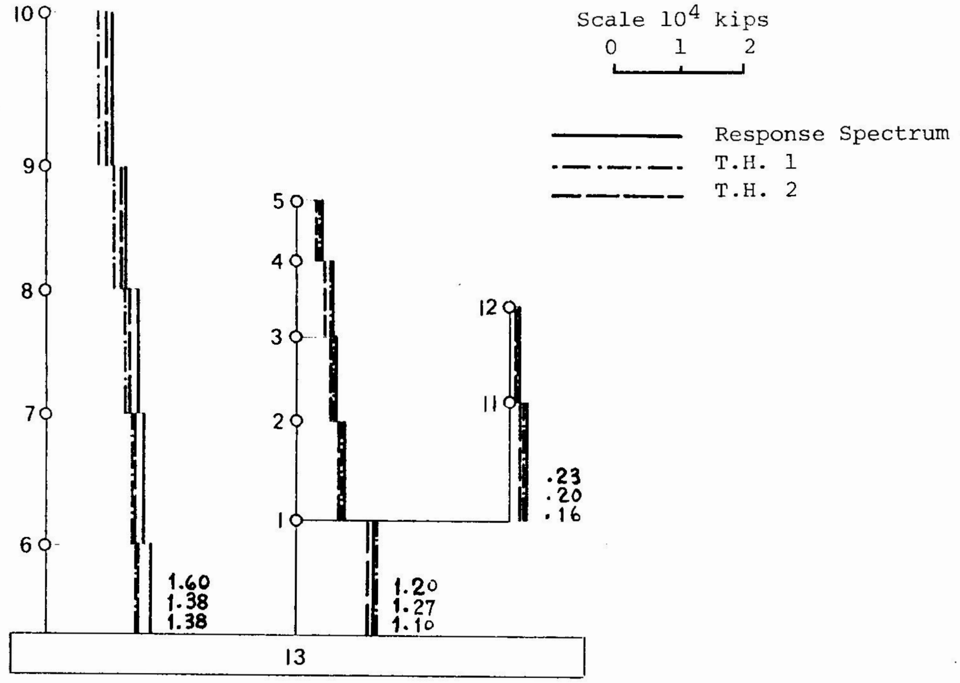
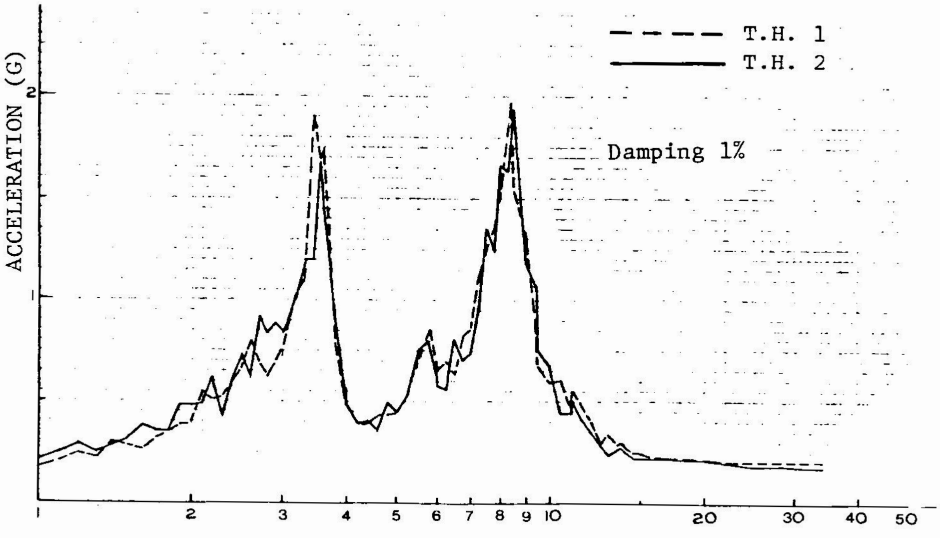
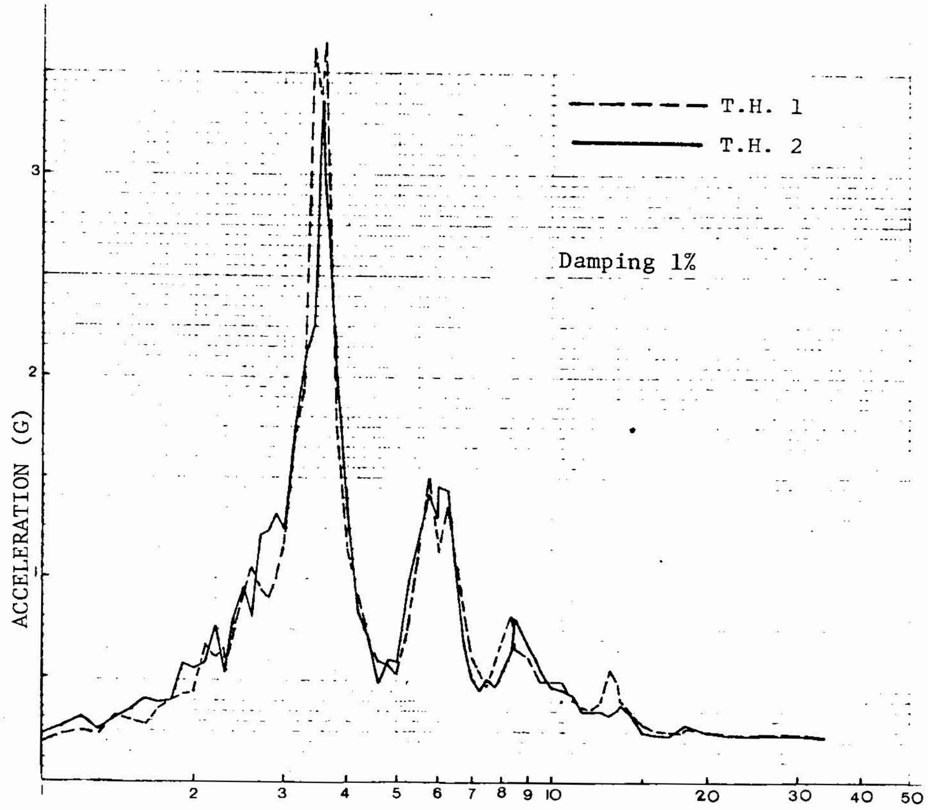


FIG. 11 SHEAR FORCE COMPARISON



FREQUENCY (HZ)

FIG. 12 FLOOR RESPONSE SPECTRUM COMPARISON : NODE 1



FREQUENCY (HZ)

FIG. 13 FLOOR RESPONSE SPECTRUM COMPARISON : NODE 4