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RESPONSE SPECTRA FROM REAL EARTHQUAKES AND ITS APPLICATION

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ABSTRACT: In this paper, efforts have been made to formulate response spectra based on real earthquake ground motion. Performance of the proposed spectra has been tested against Uniform Building Code (1994) spectra by analyzing various structures. In order to evaluate the performance of the developed spectra, on building structures subjected to seismic forces, a typical beam column frame structure has been selected. Base shear of the building, which has been calculated for different time periods using a general-purpose finite element package STRAND6, has been selected as the criterion for comparison. Natural frequencies of buildings have been calculated considering short direction, long direction and the building as a whole. The dynamic analysis procedure uses a response spectrum representation of the seismic input motions. Since maximum modal responses will not occur at the same time during the earthquake ground motion, it is necessary to use approximate procedure to estimate the maximum composite response of the structure. It has been observed that base shear coefficient for developed spectra is greater than the base shear coefficient produced by Uniform Building Code (1994) at lower time period.

KEYWORDS: Earthquake response spectra, base shear, dynamic analysis

1 INTRODUCTION

Many building codes stipulate either a design acceleration spectrum or a base shear coefficient as a function of natural period. These coefficients are essentially ordinates of acceleration spectra divided by the acceleration of gravity; the relationship holds exactly in single-degree systems. Several widely differing methods [1] exist for specifying the design earthquake. Some of these methods are equivalent-static loading in codes, response spectra, and records of real earthquakes and theoretical simulation. In this study, real earthquake spectra has been compared with the corresponding spectra proposed by Uniform Building Code (UBC, 1994). Efforts have also been made to propose a design response spectra for dynamic structural analysis. A coefficient to be used in equivalent static load method to cater for various soil types and varying building time periods have been derived.

Efforts have been geared towards arriving at an all encompassing response spectra which may either be readily used in dynamic analysis or may be conveniently adopted in static analysis by deriving a suitable numerical co-efficient from it. During the course of the study a wide range of real earthquake data have been collected. The design aids have been compared with Uniform Building Code [1] provisions by analyzing various moderately high tall buildings.

2 BUILDING ANALYSIS USING PROPOSED AND UBC SPECTRA

In order to evaluate the performance of the developed spectra, using real earthquakes, on building structures subjected to seismic forces, a typical beam column frame has been selected. The developed

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spectra have been compared with the existing Uniform Building Code [2] spectra. Base shear of the building which has been calculated for different time periods using the software STRAND6 [3] has been selected as the criterion for comparison. For the purpose of spectral analysis, base acceleration has been applied to the direction parallel to the short planar dimension of the building. Natural frequencies of buildings have been calculated considering short direction, long direction and the building as a whole. When short or long direction analyses were performed, degrees of freedom of other directions were kept restrained. This has been done to minimize the computer running time. Short direction of the building has been used for further analyses. The importance factor (*I*) and the zone factor (*Z*) have been taken equal to 1.0 and 4.0, respectively, for the purpose of response spectrum analysis. The value of $R_w = 12$ has been used in the analysis. Square-root-sum-of-the-squares (SRSS) and Complete Quadratic Combination (CQC) [4, 5, 6] methods are generally used for combination of modes to get the maximum spectral ordinate. In the present study CQC method with 5 percent of critical damping has been considered for modal combination. Two different spectra have been chosen for the purpose of response spectrum analysis. The chosen spectra were (a) UBC [2] spectra and (b) Spectra developed using recent real earthquakes.

3 DESCRIPTION OF MODEL BUILDING

The floor plan and geometry of the building have been adopted from Ghosh and Domel [7]. The columns, beams and slabs have constant cross section throughout the height of the building. Although the uniformity and symmetry used in this example have been adopted primarily for simplicity, these are generally considered to be sound engineering design concept, which should be utilized wherever practicable for seismic design. Although the member dimensions used in the example are within the practical range, the structure itself is a hypothetical one and has been chosen mainly for research purpose. Superimposed dead load has been taken equal to 42.5 psf (2.06 kN/m^2). Weight and ultimate crushing strength of concrete has been take as 150 pcf (23.56 kN/m^3) and 4000 psi (27576 kN/m^2),respectively. The member dimensions selected for this design were, beams 24 in. (60.96 cm) wide x 26 in. (66.04 cm) deep in transverse direction, beams 24 in. (60.96 cm) wide x 20 in. (50.8 cm) deep in longitudinal direction, columns-24 in (60.96 cm) and slabs-7 in. (17.78 cm) thick.

It should be noted that the building has the same lateral load resisting system in both the principal directions. Thus, the lateral seismic forces will be the same in both the longitudinal and the transverse directions of the building. However, since the building is rectangular rather than square in plan, the lateral shears produced by torsion will most likely not be equal in the two directions. The weight of a typical floor includes that of all the elements located between two imaginary parallel planes passing through the mid height of the columns above and below the floor considered.

4 RESPONSE SPECTRUM ANALYSIS

The dynamic analysis procedure used in this study uses a response spectrum representation of the seismic input motions. The procedure is applicable to linear elastic building models developed in accordance with the requirements of Section 106.3 of Uniform Building Code [2].

4.1 COMBINING MODES

The response spectrum analysis procedure provides the maximum responses of the structure when it is vibrating in each of its significant normal nodes. However, because these maximum modal responses will not occur at the same time during the earthquake ground motion, it is necessary to use approximate procedures to estimate the maximum composite response of the structure. Such procedures are typically based on an appropriate combination of the maximum individual modal responses, and should account for possible interaction between any closely spaced modal responses that may exist.

A simple and accurate modal combination approach that satisfies this requirement is the Complete

Quadratic Combination (CQC) method. This approach is based on random vibration concepts and assumes that: the duration of the earthquake shaking is long when compared to the fundamental period of the structure; and the design response spectrum exhibits slowly varying amplitudes over a wide range of periods that include the dominant modes of the structure. On this basis, the CQC method leads to the following expression for the structure's maximum composite response, u_k, at its k_{th} degree of freedom:

$$u_k = \left[\sum_{i=1}^{N} \sum_{j=1}^{N} u_{ki} \rho_{ij} u_{kj} \right]^{1/2} \tag{1}$$

Where u_{ki} and u_{kj} correspond to the structure's maximum modal response in its k^{th} degree of freedom when it is vibrating it in its i^{th} and j^{th} mode respectively, and ρ_{ij} is the cross-modal coefficient. It is noted that here, u_k, u_{ki}, u_{kj} are general symbols and may correspond to total acceleration, relative (to base) displacement, inter story drift, base shear, overturning moment, or any other structural response quantity. Furthermore, when computing u_k in accordance with the above expression, the signs of u_{ki} and u_{kj} should be preserved.

The cross-modal coefficient ρ_{ij} as denoted above is dependent on the damping ratios and the natural periods of the i^{th} and j^{th} mode. When the modes have identical damping ratios ξ, ρ_{ij} is expressed as :

$$\rho_{ij} = \frac{8\xi^2(1+r)r^{3/2}}{(1-r^2)^2+4\xi^2 r(1+r)^2} = \rho_{ji} \tag{2}$$

where r is the ratio of the natural period of the j^{th} mode, T_j, to the natural period of the i^{th} mode, T_i (that is, $r = T_j/T_i$).

It can be shown that: a) $\rho_{ij} = 1$ when $r = 1$; and b) ρ_{ij} decreases with decreasing r in a manner that is dependant on the modal damping ratio ξ. Furthermore, when the modal periods are well spaced such that:

$$r = \frac{T_j}{T_i} \leq \frac{0.1}{0.1+\xi} \, (T_i > T_j) \tag{3}$$

then: $\rho_{ij} \approx 0 \, (i = j)$ and the CQC expression for computing the maximum composite response given in Eqn. 1 becomes:

$$u_k = \left[\sum_{i=1}^{N} u_{ki}^2 \right]^{1/2} \tag{4}$$

That corresponds to the square-root-sum-of-the-squares (SRSS) modal combination approach. This shows that the SRSS approach is a special case of the more general CQC method, and can be applied when the modal periods are sufficiently well spaced in accordance with Eqn. 3. Furthermore, the quantities ρ_{ij} for $i \neq j$ can be visualized as corrections to the SRSS approach in order to incorporate effects of coupling between closely spaces modes. These coupling effects become more important as the modal damping ratio increases. Also, these effects are typically important for three-dimensional structural systems, which often have closely space frequencies.

In Section 106.2.2 of Uniform Building Code [2], the largest damping ratio that can be considered when developing site-specific spectra is specified to be 0.05. Furthermore, ρ_{ij} can be assumed to be negligible when

$$r = \frac{T_j}{T_i} \le 0.67 \tag{5}$$

5 ANALYSIS SCHEME

For spectral analysis purposes, using different acceleration spectra, only one direction, that is, short direction of the building have been selected. This directional analysis has been performed by locking the global degrees of freedom of other direction. Two analyses have been performed taking 16 and 10 storey special moment resisting concrete frames keeping all the degrees of freedoms unlocked. It is clearly observed that modes perpendicular to the direction of analysis and torsional modes have no participation to final result. Taking this fact into account and to minimize the time of computer run, short direction analysis scheme have been adopted for further analyses, which is expected to produce equally good accuracy of the analytical analysis. Comparing the total mass participation factors as reported, it can be said that total mass participation factor actually increases when the unnecessary modes which have no contribution to the final result, are excluded.

6 COMPARISON OF TIME PERIOD

In this section equations prescribed by different seismic Codes of practice have been compared with more refined methods of calculating time period. STRAND6 [3] has been used to calculate the relatively refined time period of building. STRAND6 [3] used the following Eqn. 6 to get eigenvalues, which eventually gave the natural frequency of the building.

$$[K]\{x\} = \chi[M\{x\}] \tag{6}$$

Here, $[K]$ is the banded stiffness matrix, $\{x\}$ is the eigenvector, χ is the eigenvalues and $[M]$ is mass matrix (Consistent and lumped). The building frame used has two predominant directions - short and long. Natural time period for both the directions and considering the whole building has been calculated and plotted in Fig. 1. It is observed from the Fig. 1 that for moment resisting concrete frame these time periods were independent of building direction.

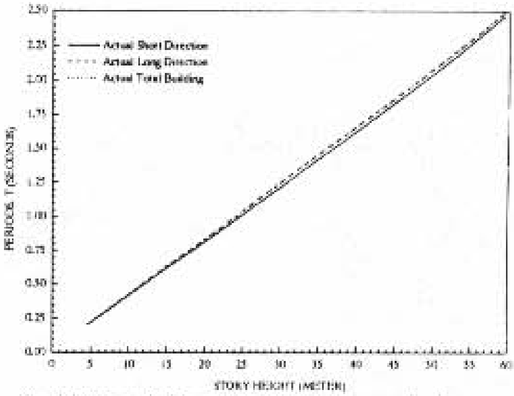

Fig. 1 Time period for moment resisting concrete frame considering short, long and total building direction.

7 COMPARISON OF BASE SHEAR

Efforts have been made to compare the base shear calculated using the Code specified response spectra and response spectra developed in this study using a good number of (recent) real earthquakes. Response spectrum analysis, which has been discussed in detail here, has been used to calculate the base shear of the moment resisting concrete frame. STRAND6 [3] has been extensively used, once again, to perform these computations.

To calculate the base shear for different time periods, height of the moment resisting concrete frames have been varied from storey one to storey sixteen. Spectral analysis has been done for soil types II (hard soil) and IV (soft soil). Other soil types have not been considered to limit the number of computer runs, since spectral solution requires greater time effort than normal static solution. Ninety computer runs were required to get twelve spectral shapes as plotted in Fig. 2. Base shear for a particular building has been found by summing all the horizontal forces of each of the column base for a particular direction. It is observed from Fig. 2 that base shear coefficient for developed spectra is greater than the base shear coefficient produced by Uniform Building Code [2] at lower time period and decreased faster in higher time periods. Same trend is observed for both the soil types. It can be said by observing Fig. 2 that serious thought should be given during future updating of the spectral shapes. Whereas the higher values of spectral ordinates at lower time periods might be left unchanged (as they would lead to more conservative (that is, safer)) design, faster attenuation at higher time periods, as observed here, may be modified to keep it tune with the conservative nature of existing spectra.

8 COMPARISON OF BASE SHEAR DISTRIBUTION

Base shear distribution has been compared with the corresponding shear distribution proposed by Uniform Building Code [2]. For the purpose of comparison, 16 and 10 storey special moment resisting concrete frames have been selected. In Fig. 3 normalized storey shear, for 10 storey building, has been plotted against percent height using UBC [2] acceleration spectra, proposed free field acceleration spectra for soil types II and IV. Normalized storey shear distribution proposed by UBC [2] has also been in these figures for comparison purpose. It is observed from these figures that storey shear distribution for different spectral analysis has very little difference. The static storey shear distribution of UBC [2] adopt linear formula which is absent in spectral solutions. It can be said that, further improvement of storey shear distribution can be done for future adoption in seismic Codes.

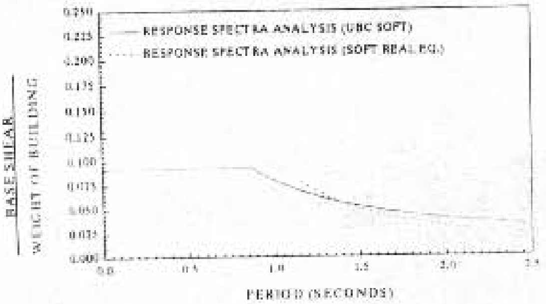

Fig. 2 Comparison of base shear coefficient of developed spectra with UBC [2] for soil type IV.

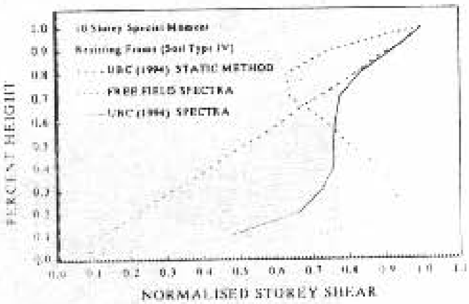

Fig. 3 Base shear distribution of 10-storey moment resisting frame for soil type II

9 PROPOSED DESIGN SPECTRA

In this study response spectra for real earthquakes have been developed. Further these spectra have been modified and compared with UBC [2] and has been found to be quite consistent. Efforts have been here to propose a design response spectra based present study, for 5 percent damping.

Table 1 list the time period for maximum spectra, maximum spectral ordinate and coefficients *a*, *b* of the equation $S = aT^{b}$ which has been used to modify response spectra for real earthquakes. It is observed from the Table 1 that the coefficient *b* which represents the rate of attenuation is always near or greater than 1, as such the value of *b* has been fixed to 1. This has been done to remain conservative in higher time period. Higher values at lower time period have been retained as it has found. The final design spectra after this modification for both real earthquakes is shown in Fig. 4. The static equivalent equations have been listed in Table 2 for different soil types derived using free field earthquakes.

Table 1 Value of maximum spectral ordinate and coefficient a, b for modified real response spectra for different site category.

Site Category	Time Period	Maximum Value of Spectral Ordinate	Coefficient a	Coefficient b
I	0.28 sec.	3.69	0.34	-1.83
II	0.43 sec.	3.42	0.83	-1.68
III	0.80 sec.	2.88	2.07	-1.48
IV	1.00 sec.	2.80	2.86	-1.75

Table 2 Site coefficient derived from free field earthquake for different site category.

Site Category	Site Coefficient
I	S = 1.03/T
II	S = 1.47/T
III	S = 2.30/T
IV	S = 2.80/T

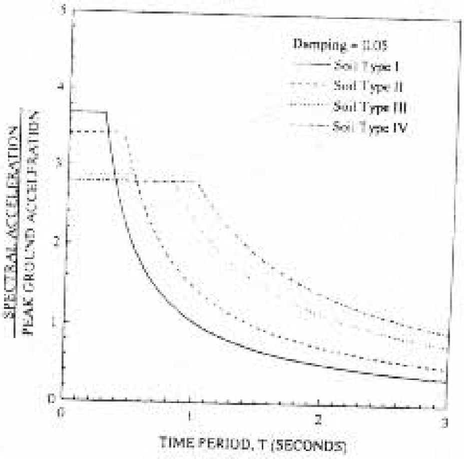

Fig. 4 Design spectra based on recent free field earthquake for different soil types.

10 CONCLUDING REMARKS

It has been observed from above discussion that, for directional analysis in three-dimensional analysis any mode shapes transverse to the direction and torsional modes shapes have no participation to the final result of the structure. It is also observed that ordinate of response spectra, for real earthquake, is greater that UBC [2] spectra at lower time period and decrease faster in higher time periods. It has been proposed in this study to keep unchanged the higher spectral value at lower time period. Faster attenuation has been modified and attenuation rate has been suggested which is inversely proportional to time period.

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