ISET GOLDEN JUBILEE SYMPOSIUM
Indian Society of Earthquake Technology
Department of Earthquake Engineering Building
IIT Roorkee, Roorkee

October 20-21, 2012

Paper No. A014

GENERATION OF ACCELERATION RESPONSE SPECTRUM BY USING FUZZY-RANDOM MODELS OF EARTHQUAKE GROUND MOTIONS

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ABSTRACT

The acceleration response spectra are usually used for specifying the seismic ground motions for design. Two of the major factors to be considered while determining the response spectra for a given site are the variability in ground motions expected at the site and the local site conditions. Probabilistic approaches have been used internationally to represent the stochastic variations in ground motion at the site. However, the site conditions are usually defined in a general and qualitative manner in linguistic terms (viz., hard rock, stiff soil). This gives rise to uncertainties, which can best be modelled by using the theory of fuzzy sets. A methodology for generating acceleration response spectrum by using fuzzy-random models of earthquake ground motions is proposed in this paper. The usefulness of the proposed methodology in developing site-specific acceleration response spectra is illustrated through an example problem. From the results obtained, it is noted that proper classification of soil sites is important for design, indicating the need for seismic microzonation.

INTRODUCTION

Ground vibrations during an earthquake can cause severe damage to structures leading to loss of human lives and property. The ground vibrations at a site are influenced by various factors, the most important of which are (Newmark and Rosenblueth, 1971): i) Earthquake mechanism, ii) Properties of the medium of the path of propagation of the seismic waves, and iii) Local site conditions. It has long been realised that the presence of soft soil layers near the earth’s surface causes an increase in the amplitudes of seismic waves. This phenomenon is known as site amplification, and is mainly caused due to the low impedance of soil layers near the earth’s surface (Safak, 2001). The magnitude of site amplification depends upon the depth to the bed rock as well as the type, thickness and properties of the soil layers above the bed rock. Hence, these factors need to be taken into consideration while determining the earthquake ground motions at a given site.

The earthquake excitations are normally characterised using the earthquake response spectrum for the design purposes. The response spectrum used in design should take into account the site geology. This requires a thorough classification of soil sites. It is observed that the soil conditions are specified in a general and qualitative manner using linguistic terms in the codes of practice. Also, there will be variations in soil properties from point to point in a given site. These variations should be taken into account while developing the acceleration response spectrum for a given site. A methodology for determining the acceleration response spectrum for a given site using fuzzy-random models of earthquake excitation is presented in this paper. In the proposed methodology, the uncertainties in the earthquake ground motion expected at a site arising due to the use of linguistic terms for defining site conditions and the stochastic variations in ground motion are taken into consideration by representing the ground motions using a fuzzy-random model. The usefulness of the methodology in developing site-specific acceleration response spectra is illustrated through an example problem.

METHODOLOGY FOR DETERMINING ACCELERATION RESPONSE SPECTRUM USING FUZZY-RANDOM MODELLING

The acceleration response spectra are usually used for specifying the seismic motions for design. One of the major factors to be considered while determining the response spectra for a given site is the variability in ground motions expected at the site. The uncertainties in the earthquake ground motion expected at a site are due to: i) the use of linguistic terms for defining soil conditions, and ii) the stochastic variations in ground motion at the site. The uncertainties associated with the linguistic terms can be handled more rationally by using the theory of fuzzy sets. Hence, a hybrid approach, which can take into account both the probabilistic uncertainties and the fuzzy uncertainties, is required for rationally determining the response spectra.

In the proposed methodology, a fuzzy-random model is used for representing the earthquake ground motions at the site. The severity of ground motion at a site is often represented by PGA. For a given earthquake magnitude, the PGA at a site depends mainly upon the distance of the site from the source, lithological and tectonic features between the source and the site, and the soil conditions at the site (Newmark and Rosenblueth, 1971). Since the soil conditions at a site are normally expressed using linguistic terms (such as soft soil, hard rock), it is more appropriate to represent the PGA with a fuzzy set. Hence, in this study, the PGA at the site has been represented using a fuzzy set. To take into account the stochastic variations in earthquake ground motions, 100 accelerograms for each possible realisation of the PGA has been generated.

Proposed Methodology

For determining the acceleration response spectra for a given site, it is important to classify the soil conditions at the site. The classification given in IBC 2000 (NEHRP soil profiles) is used in the present study (see Table 1). The proposed procedure for determining the acceleration response spectrum is given below (Anoop *et al.*, 2002).

1. Determination of characteristic earthquake magnitude for each seismic zone: The characteristic magnitude of earthquake for the seismic zone under consideration is determined based on the data available on previous earthquakes in that zone using Bootstrap method (Balaji Rao *et al.*, 1999, 2003).
2. Determine the peak ground acceleration (PGA) on rock corresponding to the maximum earthquake magnitude using a suitable attenuation relation. The determined PGA is represented as a random variable and is converted into an equivalent fuzzy variable to represent the uncertainties in its value.
3. Generation of accelerograms: Corresponding to the values at different λ-cut levels of the fuzzy set for PGA, generate different accelerograms (ensemble of 100 accelerograms corresponding to each PGA value of a λ-cut).
4. Generation of fuzzy acceleration response spectrum on rock (Site Class B): Using the 100 simulated accelerograms corresponding to the PGA value of a given λ-cut level, determine the acceleration response spectrum. The outer envelope of the generated acceleration response spectrums is chosen as the acceleration response spectrum corresponding to that particular λ-cut level. In this manner, the fuzzy acceleration response spectrum for a particular site in a particular seismic zone can be formulated.

5. Generation of fuzzy acceleration response spectrum on other soil profiles: Fuzzy acceleration response spectra for other soils are determined by multiplying the response spectrum on rock with the short period (0.1-0.5s) and mid-period (0.5-2.0s) amplification factors given in IBC 2000 (see Tables 2 and 3).

The following assumptions are made.

1. The duration of the earthquake is assumed to be the same for the different λ-cut levels of the fuzzy set for PGA.
2. It is assumed that the short- and mid- period amplification factors given in IBC 2000 are applicable for periods < 0.1s and for periods > 2.0s, respectively.

An example problem is given in the next section to illustrate the proposed methodology.

EXAMPLE

A firm ground at a hypocentral distance of 40 Km from an earthquake source is considered. Using the Bootstrap method for determining the confidence intervals for earthquake magnitude (Balaji Rao *et al.*, 1999, 2003), the characteristic magnitude for a given region is determined as 7 in Richter scale. For a magnitude of 7, the PGA value at the site under consideration (where the near field effects may not be felt (Maniatakis *et al.*, 2008)), using the attenuation relation given in Newmark and Rosenblueth (1971), has been obtained as 0.21g. It is found from literature that to account for the variations in PGA, it is represented by a lognormal distribution with mean as the value obtained from the attenuation relationship and a high value of COV of up to 0.60 (Campbell and Bozorgnia (1994), Deodatis and Shinozuka (1988)]. This probability distribution is converted into an equivalent triangular fuzzy set (Fig. 1) using the method of least squares (Anoop *et al.*, 2006).

Corresponding to the values at different λ-cut levels of the fuzzy set for PGA, an ensemble of 100 non-stationary accelerograms have been generated using the method proposed by Deodatis and Shinozuka (1988). The earthquake type corresponding to 1940 El-Centro earthquake is chosen for generating the accelerograms. A typical realisation of acceleration time history is shown in Fig. 2. Using these accelerograms, the acceleration response spectra on rock (Site Class B) has been determined (Fig. 3). The response spectrums corresponding to other site classes are also determined by multiplying with the response spectrum on rock with short period and mid-period amplification factors given in IBC 2000 (Tables 2 and 3). The defuzzified acceleration response spectra for the different site classes are shown in Fig. 4. The response spectra given in IS 1893-2002 for different site conditions are also shown in Fig. 4. (Since the mean PGA of 0.21g is near to the zero period acceleration value of 0.24g given in IS 1893 for seismic zone IV, the response spectra corresponding to zone IV is used for the comparison).

The design response spectra for a region in seismic zone IV is also determined using the recommendations given in Eurocode 8. This requires the value of design ground acceleration corresponding to a reference return period of 475 years. The design ground acceleration for seismic zone IV is obtained as 0.20g from the seismic hazard map given by Ravi Kumar and Bhatia (1999). The design response spectra thus developed using the recommendations in Eurocode 8 for different site conditions are given in Figs. 5-7. The design response spectra specified in IS 1893-2002 and that obtained using the proposed methodology are for identical site conditions are also given in these figures. (The response spectra obtained using the proposed methodology are converted into the design response spectra by dividing by a factor of 2, as specified in IS 1893-2002).

Discussion of Results

It is noted from Fig. 4 that as the type of soil changes, the period at which the maximum response acceleration occur changes. For soil type A, the peak is around 0.3s, while for soil type C, there are two peaks of almost equal magnitude at 0.3s and 0.65s. For soil type E, while there is a local peak at 0.3s, the maximum peak value occurs at around 0.65s. This is because softer soil sites amplify the spectral acceleration at longer periods. This shows the importance of properly classifying the soil sites.

From Figs. 4-7, it is noted that in the short period regions, the response spectra given in IS 1893 are in agreement with the developed response spectra for similar soil conditions. But, as the period increases, the response spectra given in IS 1893-2002 gives lower values. Also, the individual peaks in the response spectrum developed using the proposed methodology are missing in the response spectrum specified in the codes. This is because the response spectrum in codes of practice is normally developed using a suite of different accelerograms corresponding to different types of earthquakes (ATC, 1996), and averaging the resulting response spectrums. But each individual site has its own characteristic, and will interact with the incoming strong motion in its own way. Averaging the response levels the individual peaks in the response spectrum, which can be unconservative (Seed et *al.*, 2001). It is also noted that the response spectra obtained using Eurocode 8 are more conservative than that obtained using IS 1893. Also, the earthquake time histories that were used for generating the response spectrum given in IS 1893-2002 are not specified. Codes of practice such as ATC 40 (1996) specify the suite of earthquake accelerograms to be considered for developing the response spectra. There is a need to specify such a set of accelerograms for Indian conditions.

SUMMARY AND CONCLUSIONS

While probabilistic approaches have been used internationally in the development of response spectra, the site conditions in the codes of practice are usually defined in a general and qualitative manner using linguistic terms. Thus, both probabilistic and fuzzy uncertainties (arising due to the use of linguistic terms) need to be taken into account while developing the design response spectra. A methodology for generating acceleration response spectrum using fuzzy-random models of earthquake ground motions is proposed in this paper. The proposed methodology takes into account both the random and fuzzy uncertainties in ground motion. The acceleration response spectra for a site in seismic zone IV with different site conditions have been developed using the proposed methodology. The methodology will be useful for developing design response spectrums for the different seismic zones in India for different site conditions.

ACKNOWLEDGEMENT

This paper is being published with the kind permission of the Director, CSIR-Structural Engineering Research Centre, Chennai.

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Table 1 NEHRP Soil Profile Types

Site Class	Description	$\bar{\mathbf{v}}_s$, N or N_{ch}, $\bar{\mathbf{s}}_u$
A	Hard Rock	$\bar{\mathbf{v}}_s > 1500$ m/s
B	Rock	760 m/s < $\bar{\mathbf{v}}_s \le 1500$ m/s
C	Very dense soil and soft rock	360 m/s < $\bar{\mathbf{v}}_s \le 760$ m/s or N > 50 or $\bar{\mathbf{s}}_u > 100$ kpa
D	Stiff soil	180 m/s ≤ $\bar{\mathbf{v}}_s \le 360$ m/s or 15 ≤ N ≤ 50 or 50 kpa ≤ $\bar{\mathbf{s}}_u \le 100$ kpa
E	Soft soil	$\bar{\mathbf{v}}_s < 180$ m/s or with N < 15, $\bar{\mathbf{s}}_u < 50$ kpa or any profile with more than 3 m of soft clay defined as soil with PI > 20, w ≥ 40 %, and $\bar{\mathbf{s}}_u < 25$ kpa
F	Soils requiring site specific evaluation	

NOTE: $\bar{\mathbf{v}}_s$ - average shear wave velocity for the top 30 m of the soil; N, N_{ch} – average standard penetration resistance values for the top 30 m of soil; $\bar{\mathbf{s}}_u$ - average undrained shear strength of soil for the top 30 m; PI – plasticity index; w – moisture content in percent

Table 2 Values of F_a as a function of site class and mapped short-period maximum considered earthquake spectral acceleration

Site Class	Mapped maximum considered earthquake spectral accelerations at short periods				
	$S_S \leq 0.25$	$S_S = 0.50$	$S_S = 0.75$	$S_S = 1.00$	$S_S \geq 1.25$
A	0.8	0.8	0.8	0.8	0.8
B	1.0	1.0	1.0	1.0	1.0
C	1.2	1.2	1.1	1.0	1.0
D	1.6	1.4	1.2	1.1	1.0
E	2.5	1.7	1.2	0.9	a
F	a	a	a	a	a

NOTE: Use straight line interpolation for intermediate values of S_S
a: Site-specific geotechnical investigation and dynamic site response analyses shall be performed

Table 3 Values of F_v as a function of site class and mapped 1 second period maximum considered earthquake spectral acceleration

Site Class	Mapped maximum considered earthquake spectral accelerations at 1 second periods				
	$S_I \leq 0.1$	$S_I = 0.2$	$S_I = 0.3$	$S_I = 0.4$	$S_I \geq 0.5$
A	0.8	0.8	0.8	0.8	0.8
B	1.0	1.0	1.0	1.0	1.0
C	1.7	1.6	1.5	1.4	1.3
D	2.4	2.0	1.8	1.6	1.5
E	3.5	3.2	2.8	2.4	a
F	a	a	a	A	a

NOTE: Use straight line interpolation for intermediate values of S_I
a: Site-specific geotechnical investigation and dynamic site response analyses shall be performed

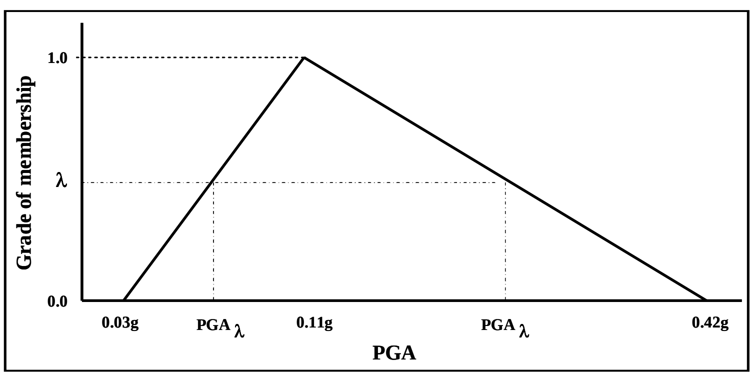

Fig. 1 Fuzzy set for PGA on rock (mean PGA = 0.21g)

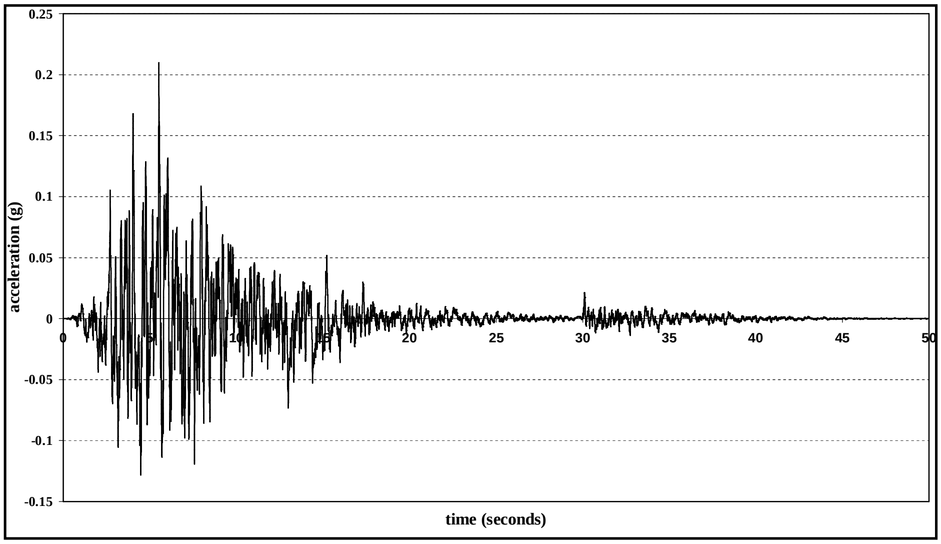

Fig. 2 Typical simulated acceleration time history for the earthquake considered in example problem

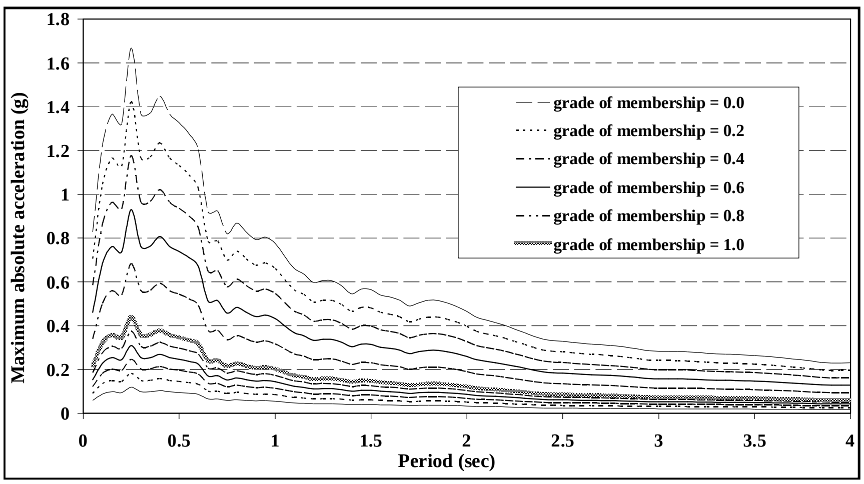

Fig. 3 Acceleration response spectrum on rock in seismic zone IV (damping = 5)

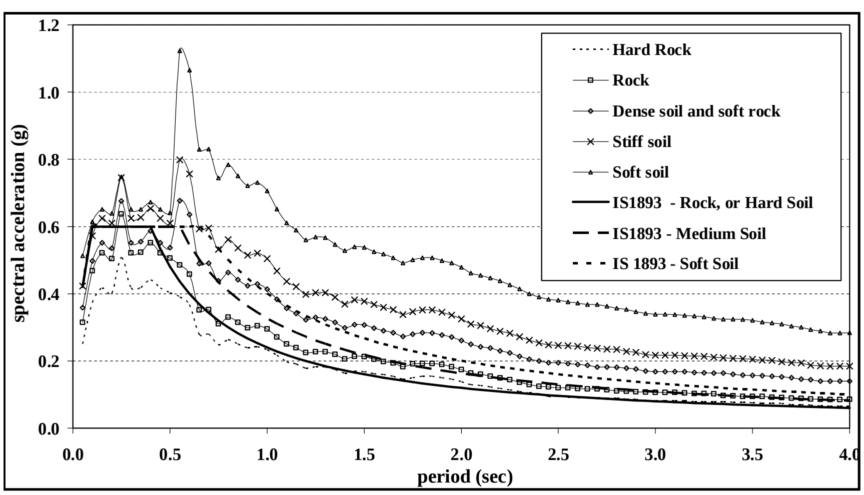

Fig. 4 Defuzzified acceleration response spectra for different soil profiles in zone IV (damping = 5%; Magnitude considered = 7; hypocentral distance = 40 km)

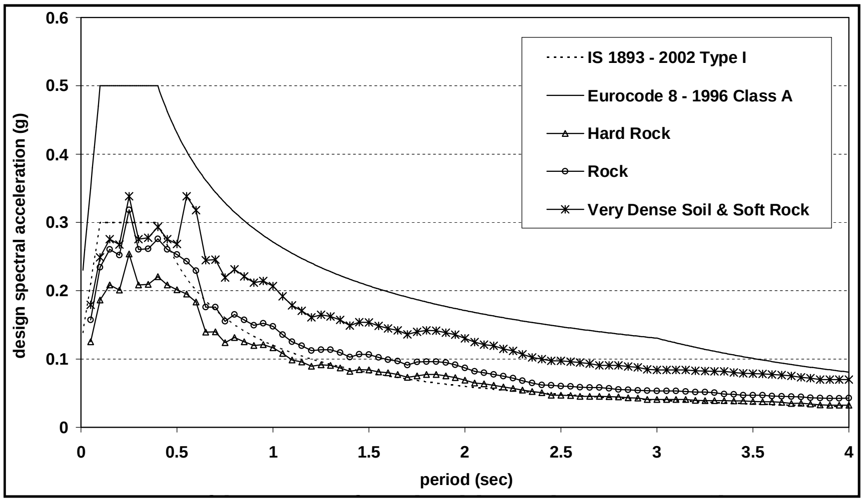

Fig. 5 Comparison of design spectra for rock and dense soil sites in zone IV (damping = 5%; Magnitude considered = 7; hypocentral distance = 40 km)

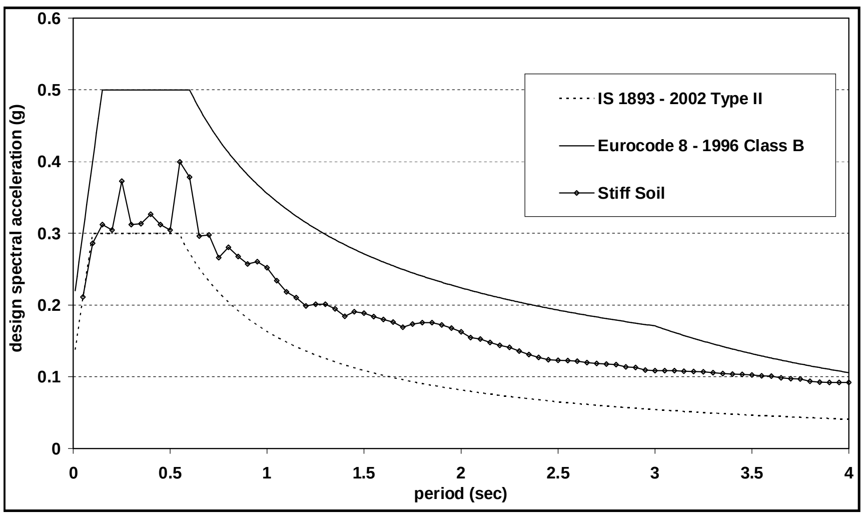

Fig. 6 Comparison of design spectra for stiff soil sites in zone IV (damping = 5%; Magnitude considered = 7; hypocentral distance = 40 km)

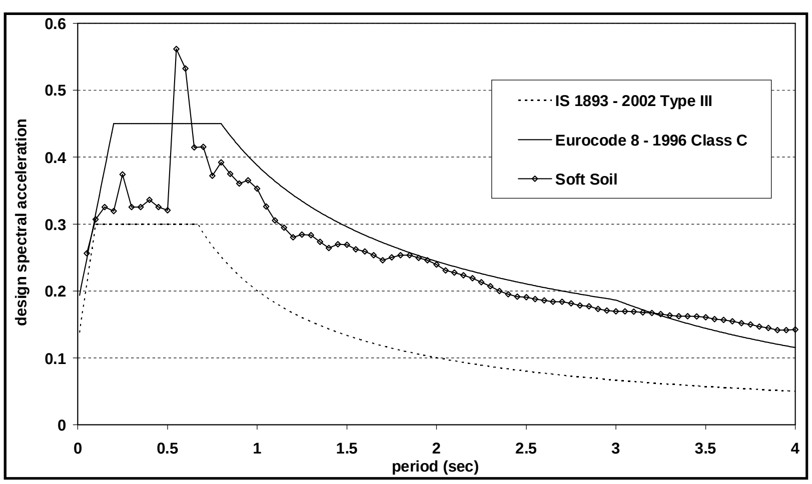

Fig. 7 Comparison of design spectra for soft soil sites in zone IV (damping = 5%; Magnitude considered = 7; hypocentral distance = 40 km)