SELECTION OF APPROPRIATE INPUT MOTION FOR FOUNDATION DESIGN IN SEISMIC AREAS

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ABSTRACT :

Engineers often need to use site-specific earthquake ground motions for designing foundations. Seismic design of foundation requires non-linear time history analysis for evaluating soil structure interaction effects. This requires the selection of appropriate time history as input. For the cases where earthquake recorded data is available, manipulation of these records can provide the required site–specific motion to the satisfaction of the all stake holders. However, where these records are unavailable, artificial ground motions need to be generated for analysis and design purposes. Several methods are used in practice for the generation of these artificial ground motions. These approaches include: (a) Direct use of strong motion recorded elsewhere having similar expected earthquake magnitude at the site under consideration; (b) Scaling of strong motion records to the expected P.B.R.A (Peak Bed Rock Acceleration) expected at the location; (c) Code-specified spectrum–compatible ground motion. This paper presents a comparative study on the performance of these three approaches for a typical site where response spectra and the expected peak bed rock acceleration are given. The results indicate that the use of spectrum–compatible ground motion provides least variations in the response parameters. It will be concluded that this third approach provides uniformity amongst the designers and would avoid unnecessary litigations.

KEYWORDS: *RSPMatch*, Ground motion selection, Spectral matching, Kolkata

1. INTRODUCTION

Engineers need to select/develop site-specific ground motions for designing foundations for important structures which require non-linear time history analysis. Numerous design codes and research publications provide guidance for the selection of seismic ground motions for use in this kind of analysis (Bommer and Acevedo, 2004). Mostly these documents are based on the use of a number of real recorded ground motions, scaled by a constant factor over the full duration to be approximately consistent with the expected seismic hazard at the site. Seismological characteristics of the records, such as earthquake magnitude and epicentral distance, are usually considered in the selection of real records, as they are likely to influence the shape of the response spectrum, the energy content and duration of ground shaking, and therefore the expected demand on structures (Grant et al. 2008). This subject has received great deal of attention from structural engineers (as evident from the vast array of publications) but with the emphasis on *Performance Based Design* for geotechnical structures (ISO-23469) it is likely to become equally important for geotechnical engineers. A typical foundation design process in seismic areas is shown in Figure 1.

After identifying the expected seismic hazard at the site, selection of appropriate earthquake records forms an important step in the process. The parts of the design methodology where these records are used are highlighted in the design chart along with the some typical design tools (for example, softwares used within Arup). In selecting these records the only data available to the engineers through their seismologist colleagues comprises of the earthquake source mechanisms in the vicinity of the region (location of the fault and the likely rupture characteristics) and in some cases few recorded data of past earthquakes in that region. For the cases, where some recorded data is available manipulation of these records can generate the required site–specific motion to the satisfaction of the all stake holders.

However, where these records are unavailable, artificial ground motions has to be generated for analysis and design purposes. In these cases, the concerned engineers are left with two pointers to generate an input motion.

1. Country-specific or region-specific code of practice which will provide a response spectrum for different type of soils [typically soft soil, stiff soil and rock];
2. Expected peak bed rock acceleration at the location.

This is indeed the problem with most developing countries which are prone to seismic hazard as sufficient number of recorded motion is not available. India, for example has this problem.

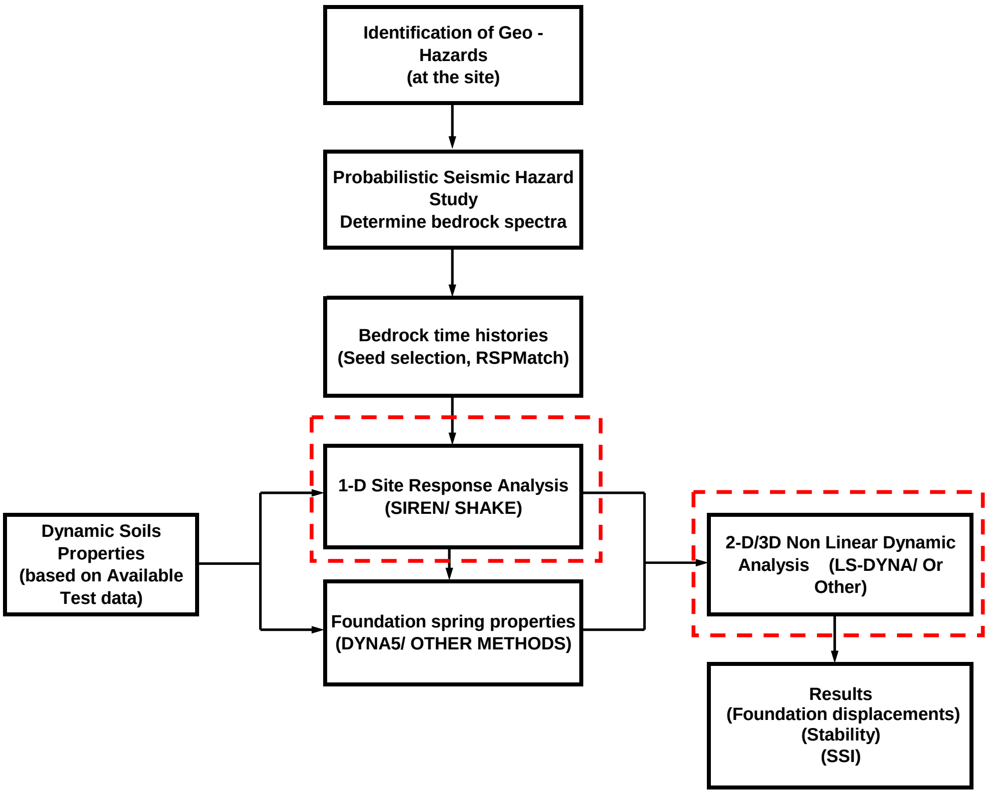

Figure 1: Flowchart showing Seismic Design Methodology for Foundations in seismic areas.

The selected ground motions maybe processed further in different ways depending on final application. Three examples of possible post processing of selected time histories are as follows:

(a) Direct use of strong motion recorded elsewhere having similar expected earthquake magnitude at the site under consideration;
(b) Linear Scaling of strong motion records to the expected P.B.R.A (Peak Bed Rock Acceleration) expected at the location;
(c) Spectral matching using software to design hazard spectra (code based or site specific study).

This paper presents a comparative study on the performance of these three approaches for a typical site where response spectra and the expected peak bed rock acceleration is compared with the code specified values. Acceleration time-series as input motions have been generated by each of the three approaches and equivalent linear analysis has been carried out by performing site response analysis. This analysis specifically evaluates the effects of the local soil deposit to the expected ground motion.

In this paper, a study of the city of Kolkata (earlier known as Calcutta in the eastern part of India) is considered to demonstrate the three approaches. The vital point is lack of recorded earthquake data and the high seismic risk of this city. This study is a part of ongoing efforts to produce microzonation maps for the city. The next section reviews the literature on the selection of earthquake motion where the case of Kolkata city will be referred.

2. USE OF SELECTED EARTHQUAKE RECORDS

Ground motion records to be used in geotechnical analysis should represent the potential earthquake hazards at the site i.e. consideration of magnitude, distance, site conditions, source mechanism, directivity and other effects obtained from seismic hazard analysis. It must be remembered that the objective of the study is to develop a site-specific earthquake motion for analysis where no records are available. Therefore, these records can be either historical which can be algebraically manipulated or artificially generated. In this regard, the appendix of ISO 19901-2 states that a minimum of four records should be used for analysis, and that each record should be selected according to the following criteria:

"*Given the magnitude and distance of events dominating Extreme Level Earthquake (ELE) ground motions, the earthquake records for time history analysis can be selected from a catalogue of historical events. Each earthquake record consists of three sets of tri-axial time histories representing two orthogonal horizontal components and one vertical component of motion. In selecting earthquake records, the tectonic setting (e.g. faulting style) and the site conditions (e.g. hardness of underlying rock) of the historical records should be matched with those of the structure's site*".
As mentioned in the previous section three approaches are often used. All these methods have their advantages and disadvantages and are discussed later in this section.

METHOD -1: Direct use of strong motion record
In this method, a strong motion is chosen to match the seismicity of the place either in terms of Moment Magnitude or expected Peak Bed Rock Acceleration. It may be difficult to find a recorded motion satisfying both the requirements. For example, a site may expect a magnitude 6.0 earthquake and a PBRA of 0.2g. Therefore, a designer has to look for the recorded data matching these characteristics. This method is rarely used in practice as it is quite unlikely that the shape of the spectra will match the expected bedrock spectra at a particular site. This will be illustrated later using an example.

METHOD -2: Scaling of strong motion record to expected peak bedrock acceleration
In this method, an earthquake record is chosen from a database to match the Moment Magnitude and then the maximum amplitude is scaled to match the expected PBRA.

METHOD – 3: Intelligent scaling or Code specified spectrum compatible motion
Traditionally seismic hazard at a site for design purposes has been represented by design spectra. Thus all seismic design codes and guidelines require scaling of selected ground motion time histories so that they match or exceed the controlling design spectrum within a period range of interest. Figure 2 shows the Response Spectra of IS: 1893 (2002) for hard soil or rock. Several methods of scaling time histories have been proposed. In this method an input motion is selected and the motion is manipulated to obtain a motion that matches the design spectra. The manipulation can be carried out in frequency-domain where the frequency content of the recorded ground motions is manipulated in order to obtain a match. Regardless of the method (frequency-domain or time-domain), in virtually all of the existing approaches, the processes of selecting earthquake ground motions and their scaling to match the design spectrum are separate and distinct. In other words, first one or more time histories are selected and then appropriate scaling mechanisms for spectrum matching are applied. The scaling method depends on the end use of the motions and is carried out appropriately so as not to distort the records to the point that they are no longer realistic.
Many programs are available to carry out the spectral matching: WAVEGEN Mukherjee and Gupta (2002), RSPMatch2005. In this paper, the scaling of the time histories to match the target design hazard spectra (hereafter referred to as the target spectrum) was carried out using the software *RSPMatch2005*. This program performs a time domain modification of an acceleration time history to make it compatible with a user specified target spectrum. The methodology is based on that proposed by Lilhanand and Tseng (1987). The modification of the time history can be performed with a variety of different modification models (wavelets). The ease at which the program matches the target spectrum depends on the specific nature of the input time history, typically the initial frequency content and duration. This variability and effort required is reduced through careful seed selection procedure and initial scaling

of the records, particularly over the long period.

2.1 Decisions to be taken by the designers while selecting motion

While the ISO 19901-2 specifies the broad aspects of selection i.e. choosing of 4 records and the importance of site conditions, the information/guidance that is not included in the code requirements are the following:

- Duration of required input records when the intelligent scaling (spectral matching) is used.
- Scaling requirements for separate components (two orthogonal and one vertical) of the ground motion where spectral matching is used.
- Range of acceptable magnitudes and distances for seed (original earthquake record) selection.

Abrahamson (1992), Hancock et al. (2006) presents a set of criteria for selecting seed motions for *RSPMatch05*. The most important consideration is the matching of the initial spectral shape and other ground motion characteristics are used to filter the initial database. Rather than using earthquake magnitude bounds as a proxy for ground motion duration, as recommended by other authors, filtering explicitly on duration of the earthquake motion is suggested by Grant et al (2008). An in house Arup program has been discussed in another paper presented in this conference (Grant et al. 2008) which selects the seed ground motion based on spectral matching to minimize the artificial manipulations to the seed records from the PEER database.

It is true that the use of spectral matching software to a certain extent reduces the reliance on fault type, location of earthquake, magnitude and distance if the spectra are matched. Hence the spectral matching procedure should start with the above criteria as a guide in order to provide the closest matching time histories to the target spectrum. This is so that artificial manipulation of the record is kept to a minimum, providing a final record that is as close to a real earthquake in terms of frequency content and energy as possible. In the next section these selected records will be used for site response analysis

3. A CASE STUDY- Kolkata, India

Kolkata City lies over the Bengal Basin at the boundary of the seismic zones III and IV of the seismic zonation map of India (IS 1893:2002). In the past the city has seen far and near source earthquakes due to associated Himalayan tectonics. The most damaging earthquake so far has been the 1897 earthquake which caused widespread damage in the city of Kolkata. Several faults have been identified in this region out of which many show evidence of movement. There are earthquake fault lines barely 100 km from Kolkata (Murty, 2006). However in the last couple of years the city has seen rapid growth of population as well as construction of major infrastructure projects within the ever expanding city boundaries. Seismic microzonation of fast expanding mega city of Kolkata falling in seismic zone IV and V is essential for retrofitting old and vulnerable buildings and for earthquake resistant design of new constructions and installations. In trying to understand the seismic hazard of the city it is worth remembering that the earthquake database in India is still incomplete, especially with regards to earthquakes prior to the historical period (before 1800 A.D.). According to Global Seismic Hazard Assessment Program (GSHAP) data, the state of West Bengal falls in a region of low seismic hazard in the south-west that rises steadily towards the east and the north of the state. The next section lists the parameters for selecting the earthquake ground input motion.

3.1 Peak ground acceleration (Expected)

The peak ground acceleration can be estimated by using Ground Motion Predictive Equations (GMPE) which has been derived for particular type of earthquake mechanism and tectonic regime. However no such reliable attenuation equation exists for Kolkata. According to seismic hazard map of India, the city of Kolkata lies in moderate seismic zone (Zone III) with a zone factor 0.16. In this area, no seismic recording stations were established and consequently no records of strong ground motion are available. The design ground motion parameter for this study area has been obtained from (GSHAP) map which is based on 10% probability of exceedance in 50 years. Based on the GSHAP map, the corresponding maximum peak ground acceleration (i.e. PBRA) of 1.6 m/s^2 (0.163g) has been selected for Kolkata. However, the authors recently became aware of a Probabilistic Seismic Hazard Study where it is reported that the expected Peak Bedrock Ground Acceleration

(PBRA) for Kolkata City varies from 0.34g to 0.10g (Mohanti & Walling 2008).

3.2 Target Bedrock Spectrum

The target bedrock spectra are obtained from IS 1893 (Part I): 2002 based on the desired PBRA (0.163g) at 5% damping for rock or hard soil. This spectrum is based on the assumption that the bedrock shear wave velocity is at least 760m/s. In absence of any detailed Unified Hazard Response Spectrum calculation, this is a reasonable assumption. This spectrum is shown in Figure 2.

3.3 Selection of earthquake records

This program described in Grant et al. (2008) has been used to select the strong ground motion based on specifying certain filters which are appropriate for Kolkata. This motion is Chi-Chi Taiwan earthquake shown in Table 1. In addition, the Northridge earthquake record is selected which has a magnitude (M) in the range of 6.0 to 6.9 recorded at rock sites (site class 'A' as per USGS classification for which shear wave velocity, $V_s >$ 750 m/s). This is based on matching the PBRA of 0.16g but no spectral matching has been carried out. Figure 2 shows the target spectrum and the matched spectra for the Chi-Chi Taiwan record.

Table 1. Characteristics of selected earthquake records

Earthquake	**Chi Chi Taiwan**	**Northridge**
Date	05/09/1999	17/01/1994
Recording Station (ST)	CWB 99999 CHY088	127 Lake Hughes # 9
Magnitude	M= 6.2	M = 6.7
PeakAcceleration (a_{max})	0.0943g	0.169g
Closet to fault rupture (km)	84.1	26.8
Method of selection	Scaled and matched to spectra shape.	PGA, magnitude, recording station

In the section, site response analysis is carried for a soil profile in Kolkata using the above input motion.

4. SEISMIC SITE RESPONSE ANALYSIS

During an earthquake, stress waves which are generated at some depth are modified as they travel through the various soil layers. The soil acts as a filter, amplifying energy at some frequencies and attenuating energy at others. The effect of this is often calculated by performing a site response analysis. In the present study the parameters of interest in the seismic response analysis involves the fundamental frequency of the soil layers, amplification factor of ground motion parameters and response spectra. The site response analyses undertaken in this project are carried out using the Arup in-house program *Oasys* SIREN. The program operates in the time domain enabling it to model non-linear soil properties with hysteretic damping The inputs to the program are soil unit weight, small strain shear modulus, modulus degradation curves, bedrock properties and input time histories.

4.1 Typical Soil Profile Selected

In the present study, geotechnical bore hole data from more than 100 locations were obtained from various construction organizations and research institutions in and around Kolkata (Govindraju and Bhattacharya 2008). Important locations from where the geotechnical data was collected were categorized as Type 1, Type 2, Type 3 and Type 4. Type 2 is most critical from understanding the seismic soil behavior for new constructions as it covers the reclaimed areas. Figure 3 illustrates typical soil profiles and the corresponding average Standard Penetration (SPT) 'N' values for Type-2 soil profile.

4.2 Calculation of dynamic properties

The input parameter for the model such as shear wave velocity of each soil layer has been obtained from the empirical relation proposed by the Japanese Road Association (Lee, 1992). The relationship between shear modulus and strain amplitude is typically characterised by a normalised modulus reduction curve. To account for soil behaviour under irregular cyclic loading, the dynamic properties of soils such as modulus reduction and damping vs. shear strain curves proposed by Vucetic and Dobry (1991) were used based on plasticity characteristics of respective soil layers.

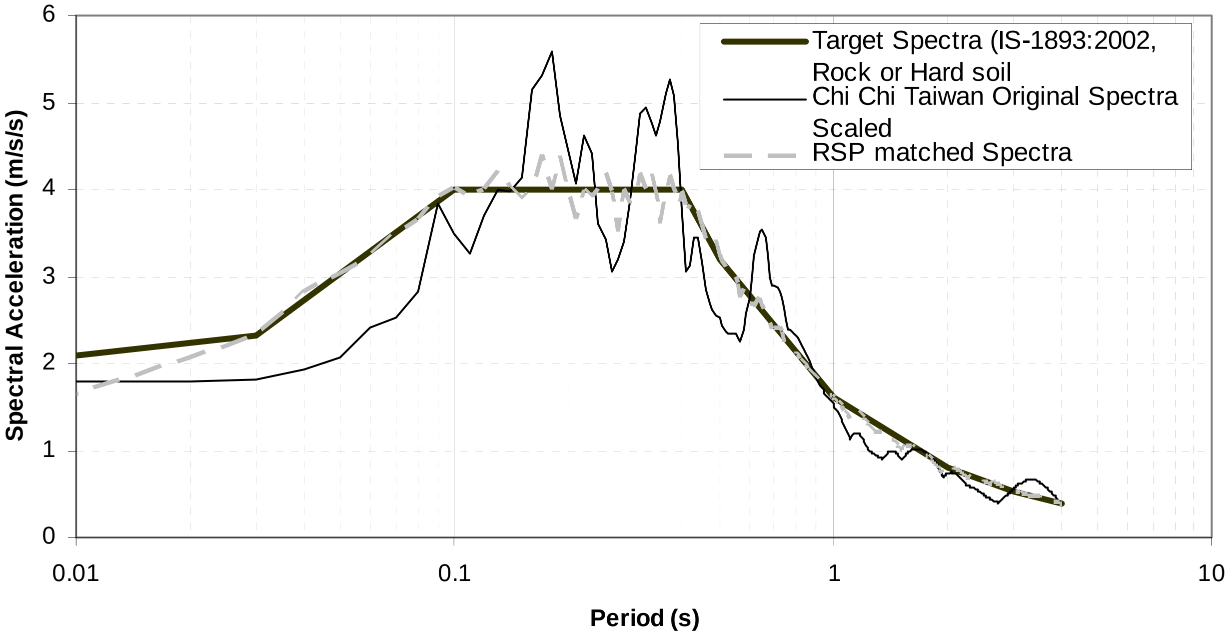

Figure 2. An example of earthquake spectra of selected motion matched to code specified spectra

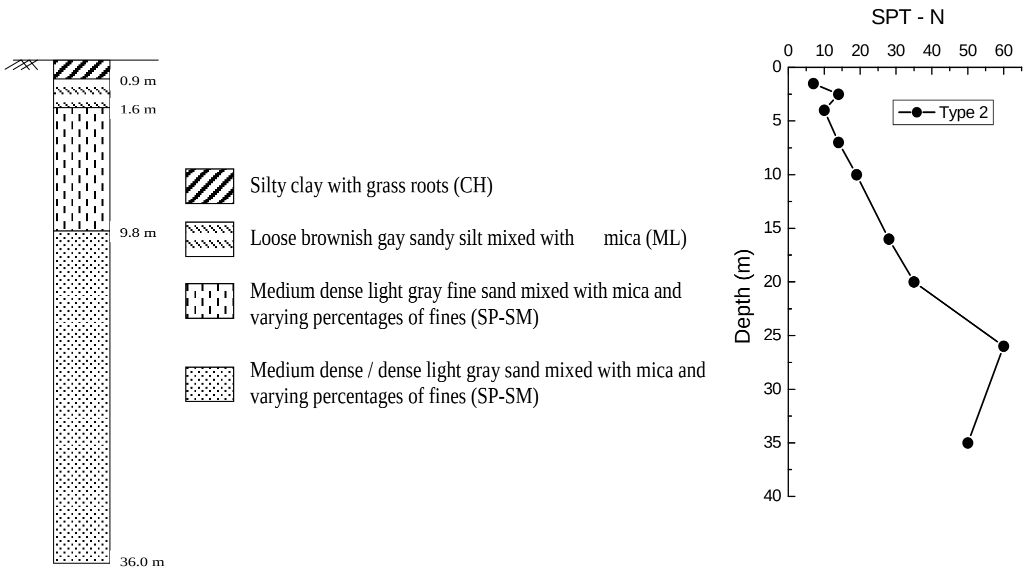

Figure 3. Generalized soil profile and SPT ‘N’ variation for category Type 2(Govindraju et al. 2008)

5. RESULTS AND DISCUSSION

Two earthquake time histories were used in the analyses as shown in Table 1. These were further modified to match the target spectrum. These records were used either scaled or unscaled. Figure 4 shows the surface response spectrum obtained by using an unscaled record and a spectrum compatible time history for Northridge event. The natural frequency of the soil layer is in the range of 0.3-0.4s and peak spectral accelerations are also observed at this period. Spectral accelerations for the unscaled motions are much higher than the spectral accelerations seen for the spectrum compatible motions. The frequency content of the surface response is also different.

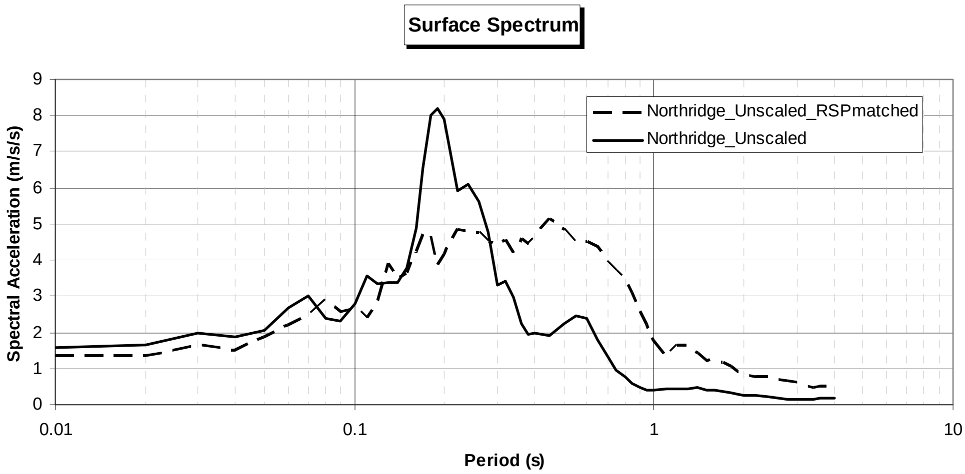

Figure 4. Surface response spectrum input records that were scaled and unscaled

Figure 5 compares the surface spectral accelerations obtained by using two earthquake motions which are spectrum compatible.

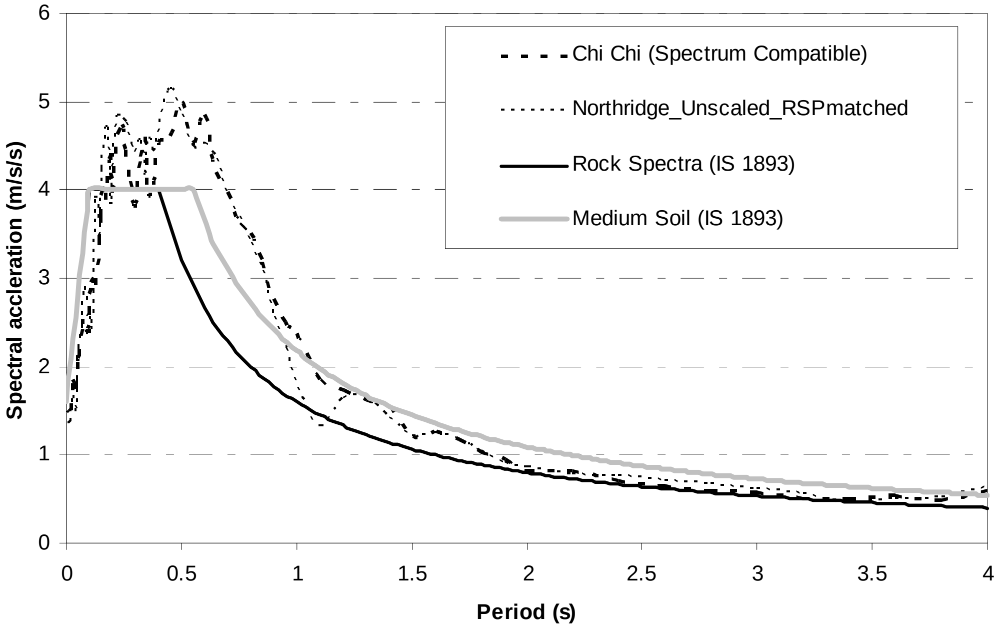

Figure 5. Comparison of surface response spectrum for different types of earthquake input motion.

The Chi Chi earthquake motion has been scaled initially and then matched with the target bedrock spectrum. The Northridge earthquake motion has not been scaled but has been spectrally matched with the target spectrum. Several comments can be made from this figure:

- Scaling does not make a significant difference to the final result if the input motion is spectrally matched to the target spectrum. However the final time history will be significantly affected in the time domain. This is undesirable for non- linear analysis.
- The seed records which may have different frequency content in the recording tend to give the same surface spectral acceleration if they have been matched to the same target spectrum. In this

case it may not be necessary to use three input motion as specified in the codes.

- If the seismic design was done according to IS-1893, the soil would be classified as Medium soil (From N values) and surface spectrum shown in Figure 5 for medium soil would be used. However as the results indicate that the spectral acceleration at low and intermediate periods will be underestimated by approximately 1.5 times. This is also a consequence of not including the S (soil factor) in the design spectrum. This factor is used in most codes (ex EN 1998-1:2004) to account for site response effects.

These results indicate that the use of spectrum–compatible ground motion provides least variations in the response parameters as seen above. However it should also be kept in mind that these spectrum compatible motions can induce additional displacements and the records need to be baseline corrected before they are used for further analysis. The best results – in terms of successful and timely convergence to a solution, and minimal adjustment of the seed record – are obtained when the initial seed has a response spectrum which provides a good initial fit of the target spectrum. It can be concluded that this approach provides uniformity amongst the designers and would avoid unnecessary litigations.

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