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SITE SPECIFIC GROUND RESPONSE ANALYSES AT DELHI, INDIA

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ABSTRACT

Any meaningful site specific ground response analysis requires a ground motion either recorded or artificially generated, measured shear wave velocity profile, shear modulus and damping ratio variation with strain of local soils. Due to the absence of recorded strong ground motions at Delhi, India, three local sources at distances of 25, 50 and 100 *km* for a moment magnitude of 6.5 and another source from central seismic gap with a moment magnitude of 8.5 is considered for generating strong ground motion on the rock outcrop using Specific Barrier model and Finite Source model. Spectral Analysis of Surface Waves (*SASW*) method is used for measuring the shear wave velocity in the field close to borehole locations where *N*–Values are measured. Correlation between measured shear wave velocity and N value is presented for routine engineering use. Strain controlled cyclic triaxial tests are conducted on remolded samples of 70 *mm* diameter and 140 *mm* height as per *ASTM D3999* for evaluating the modulus reduction and damping curves of local Yamuna sand. All these tests were conducted on saturated samples (B>0.98) at 1 *Hz* frequency of sinusoidal loading at different shear strains. Tests were conducted at void ratio of 0.75 (D_r of 55%) at 100 *kPa* of confining pressure. Equivalent linear ground response analysis is carried out using *SHAKE* for developing the site specific response spectra and soil amplification based on measured shear wave velocities and conclusions of practical significance are drawn.

Keywords: Ground response analysis, stochastic models, shear wave velocity, cyclic triaxial testing.

INTRODUCTION

The loss of life and extensive damage caused by the recent earthquakes of Uttarkashi, (1991, M_w 7.0), Jabalpur (1997, M_w 5.8), Chamoli (1999, M_w 6.5), and Bhuj (2001, M_w 7.6) demonstrated the seismic hazard being faced by mega cities in India, such as Delhi. Delhi and its environs are seismically active and are shaken by earthquakes of local origin as well as those of Himalayan origin. Delhi lies in Seismic Zone IV as per the seismic hazard map of India (IS 1893 - 2002) with an expected *ZPA* of 0.24 *g*. The local soils have a profound influence on the ground response during earthquakes. It is possible to reduce loss of life and property damage by conducting detailed dynamic response of local soil deposits as well as of structures.

For regions where strong motion data is abundant, such as California, empirical relationships for strong ground motion parameters have been developed and successfully used in seismic hazard analysis. However, for regions where recorded strong ground motion data is totally absent or scanty, such as Delhi, it becomes imperative to use physical models to represent the ground motion generation and propagation.

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In this paper, results of ground response analyses at Delhi due to earthquakes from long distance as well as local sources is presented in the form of free field acceleration histories as well as response spectra. The necessary inputs for carrying out the ground response analyses are measured either in the laboratory or in the field and an attempt have been made to represent the field conditions as closely as possible.

STRONG GROUND MOTION

As very scanty recorded strong ground motion data is available for Delhi, stochastic models were used to generate the acceleration time histories at rock outcrop level. These rock outcrop motions are subsequently used to excite the soil column and to calculate ground motions at ground level (free field motion). Based on the previous studies (Khattri 1999; Singh *et al., 2002;* Sharma *et al*., 2003; Iyenger and Ghosh, 2004; Parvez *et al*., 2004) and considering seismic tectonic features around Delhi two seismic source zones, namely: central seismic gap (inter plate and long distance) from Himalayan Arc and local sources (Intra plate) are considered in generating strong ground motion on a rock outcrop**.**

Stochastic Simulation of Strong Ground Motion

A simple and powerful method for simulating ground motions is to combine parametric or functional descriptions of the ground motion amplitude spectrum with a random phase spectrum modified such that the motion is distributed over a duration related to the earthquake magnitude and to the distance from the source. This method of simulating ground motions often goes by the name "stochastic method". It is widely used to predict ground motions for regions of the world in which recordings of motion from potentially damaging earthquakes are not available. One of the essential characteristics of the method is that it distills what is known about the various factors affecting ground motions (source, path, and site) into simple functional forms. At shorter periods, ground motions are complex due to the loss of phase coherence and geologic heterogeneity and are more adequately modeled by stochastic methods than traditional deterministic or empirical approaches (Hanks and McGuire, 1981).

Himalayan Source (Long Distance)

Himalayan seismogenic zone is the most seismically active zone posing a threat to Delhi region (Khattri 1999; Singh *et al., 2002;* Sharma *et al*., 2003). During the last episode of strain release, a 750 *km* long segment, lying between the eastern edge of 1905 rupture zone and western edge of 1934 earthquake, remained unbroken. This segment, known as the "*Central Seismic Gap*" continues to be under high strain. There have been 10 earthquakes with magnitude greater than 6.0 and more than 100 with magnitude less than 6.0 is observed in this region after 1720 (Singh *et al*., 2002). The large earthquakes occurred in this seismic gap in between 1803 and 1833 were magnitudes less than 8.0, and hence, they are not gap filling events (Khattri, 1999). Based on these observations and a shortening rate of 20 mm per year across the Himalayas (Bilham *et al*., 1998), Khattri (1999) has estimated the probability of occurrence of 8.5 magnitude earthquake from this gap in next 100 years to be 0.59. Since the damage from such a large earthquake would be considerable, acceleration – time histories have been generated for this event.

To generate strong ground motion from an event with a moment magnitude of 8.5 at a distance of about 250 km, since the rupture area is large in comparison with the distance, the point source approximation will not be valid (Beresnev and Atkinson, 1998). In addition, since specific barrier model was also not calibrated for such high magnitudes of inter plate earthquakes (Halldosson and Papageorgiou, 2005), Finite source model was used for generating the acceleration time histories. The seismological parameters used for finite source model are given in Table 1. The acceleration time histories were generated for 10 rupture scenarios and a typical acceleration time history generated for one rupture scenario is shown in Figure 6.

Table 1. Input Parameters Used for Finite Source Model (*FINSIM*) for Himalayan Source (After Singh *et al.*, 2002)

Input Parameter	Value Adopted
Strike	300^0
Dip	7^0
Depth to the Upper Edge of Fault	16 *km*
Source Latitude	30.8 *N*
Source Longitude	78.3 *E*
Destination Latitude	28.7 *N*
Destination Longitude	77.2 *E*
Fault Length (Strike)	240 *km*
Fault Width (Dip)	80 *km*
Number of Subfaults (strike)	16
Number of Subfaults (dip)	5
Crustal Shear Wave Velocity, β	3.6 *km/sec*
Crustal Density, ρ	2.85 gm/cm^3
Moment Magnitude, M_W	8.5
S – factor	1.4
Stress Drop, $\Delta\sigma$	50 *bar*
f_{max}	15 *Hz*
Q – factor	$508\ f^{\,0.48}$
Geometric Attenuation	Bilinear = 1/r for r$\leq$100 *km* = $(100r)^{-1/2}$ for r.100 *km*

Local Sources
Regarding local seismic sources posing threat to Delhi, reliable information on earthquake catalogue is not readily available so as to perform a seismic hazard analysis. To take this into account, acceleration time histories are generated for the three postulated earthquakes scenarios of moment magnitude (M_w) of 6.5 at distances of 25, 50 and 100 km. As the fault parameters are not known clearly, Finite source model was not used. As the Specific barrier model is calibrated for large data of intra plate earthquake of similar type region, specific barrier model is considered for the analysis. Typical acceleration time history for each scenario is shown in Figures 7, 8, and 9 and corresponding parameters are given in Table 2.

Table 2. Input Parameters Used for Specific Barrier Model (*SGMS*) for Local Sources (Adopted from Papageorgiou, 2003, 2005; Singh *et al.*, 2004, 2005)

Input Parameter	Value Adopted
Distances	25 *km*, 50 *km, 100 km*
Moment Magnitude (M_w)	6.5
Crustal Shear Wave Velocity, β	3.6 *km/sec*
Crustal Density, ρ	2.85 gm/cm^3
Global Stress Drop, $\Delta\sigma_G$	60 *bar*
Local Stress Drop, $\Delta\sigma_L$	180 *bar*
f_{max}	50 *Hz*
Q – factor	$800\ f^{\,0.42}$
Geometric Attenuation	Bilinear = 1/r for r$\leq$100 *km*

	= $(100r)^{-1/2}$ for r.100 *km*

MEASUREMENT OF SHEAR WAVE VELOCITY USING SASW METHOD

One of the most reliable methods to characterize small strain shear modulus (G_{max}) is in-situ measurement of shear wave velocity (V_s) in the field at small strains using seismic methods. From the measured shear wave velocity (V_s) profile, a small strain shear modulus, G_{max}, can be determined using density, ρ as:

$$G_{\max} = \rho V_s^2 \qquad (1)$$

SASW Method

Spectral Analysis of Surface Waves (SASW) method is used for measuring the shear wave velocity (Vs). A 20 kg sledge hammer and SPT hammers are used as sources up to 8m spacing and more than 8 m spacing respectively. Two vertical geophones of 4.5 Hz and 1 Hz natural frequencies are used for spacing up to 8 m and more than 8 m respectively. Common Receiver Mid Point (CRMP) geometry (Nazarian and Stokoe, 1984) is used for receiver spacing of 2 m, 4 m, 8 m, 16 m, and 24 m/32 m.

An interactive masking is used for eliminating the far field and near field. Experimental dispersion curves are developed for each receiver spacing and combined all the dispersion curves to get the composite dispersion curve and a representative/compact dispersion can be calculated to reduce the number of points for inversion analysis. A typical phase, coherence and experimental dispersion curve for 2m, 4m, 16m, and 24 m spacing at a representative location are shown in Figure 1 and corresponding composite dispersion curve is shown in Figure 2.

An iterative (Nazarian and Stokoe, 1984) inversion analysis is carried out for developing the shear wave velocity profile. As a first approximation in the inversion process, the thickness of the layer is assumed approximately equal to half of the wavelength and shear wave velocity is approximately 1.1 times the phase velocity. By trial and error basis the exact fit between the theoretical and experimental curve has been made. Below the ground water table, a P – wave velocity of 1500 m/s and above ground water table, a Poisson's ratio of 0.33 is used. The final matching of theoretical dispersion curve with the experimental dispersion curve is shown in Figure 2 and the resulting final shear wave velocity profile is shown in Figure 3.

V_{s30} is estimated as 258 *m/s* and by assuming the unit weight of sand as 17.8 kN/m^3 maximum shear modulus(G_{max}) is estimated as 118.5 *MPa* using equation (1).

CORRELATION BETWEEN SHEAR WAVE VELOCITY AND N VALUE

Shear wave velocity is generally measured only for critical structures because of its cost and expertise required. For routine engineering use, it is usually estimated from correlations based on SPT, CPT or index properties. However, in India, the current seismic code (IS 1893: 2002), which has been modified after the devastating "Republic Day Earthquake" that devastated the Kandla Port and other built structures, makes a reference to the shear wave velocity of the soils while classifying the soil type (loose, medium, stiff) only. Additionally, most of the specialized designs that require shear wave velocity as a input, are measured using cross hole or down hole methods that are tedious and expensive. Hence, no effort was made in the past to develop such a correlation.

Shear wave velocity was measured at several locations where the soil is primarily Yamuna Sand and develop an empirical correlation in the similar lines that will be of immense use in design/mitigation strategies. However, while using the proposed V_s - N correlation it should be kept in mind that even small amount of gravel, cobbles or boulders in the soil may affect significantly the values of N and thus, distort the equations of correlation. SASW tests were conducted nearer to the SPT borehole locations and point to point regression analysis is carried out for more than 50 borehole locations up to a depth of around 30 m. Correlation developed for sandy soils of Delhi (Rao and Ramana, 2004) is as follows:

$$V_s = 79N^{0.434} m/s \qquad (2)$$

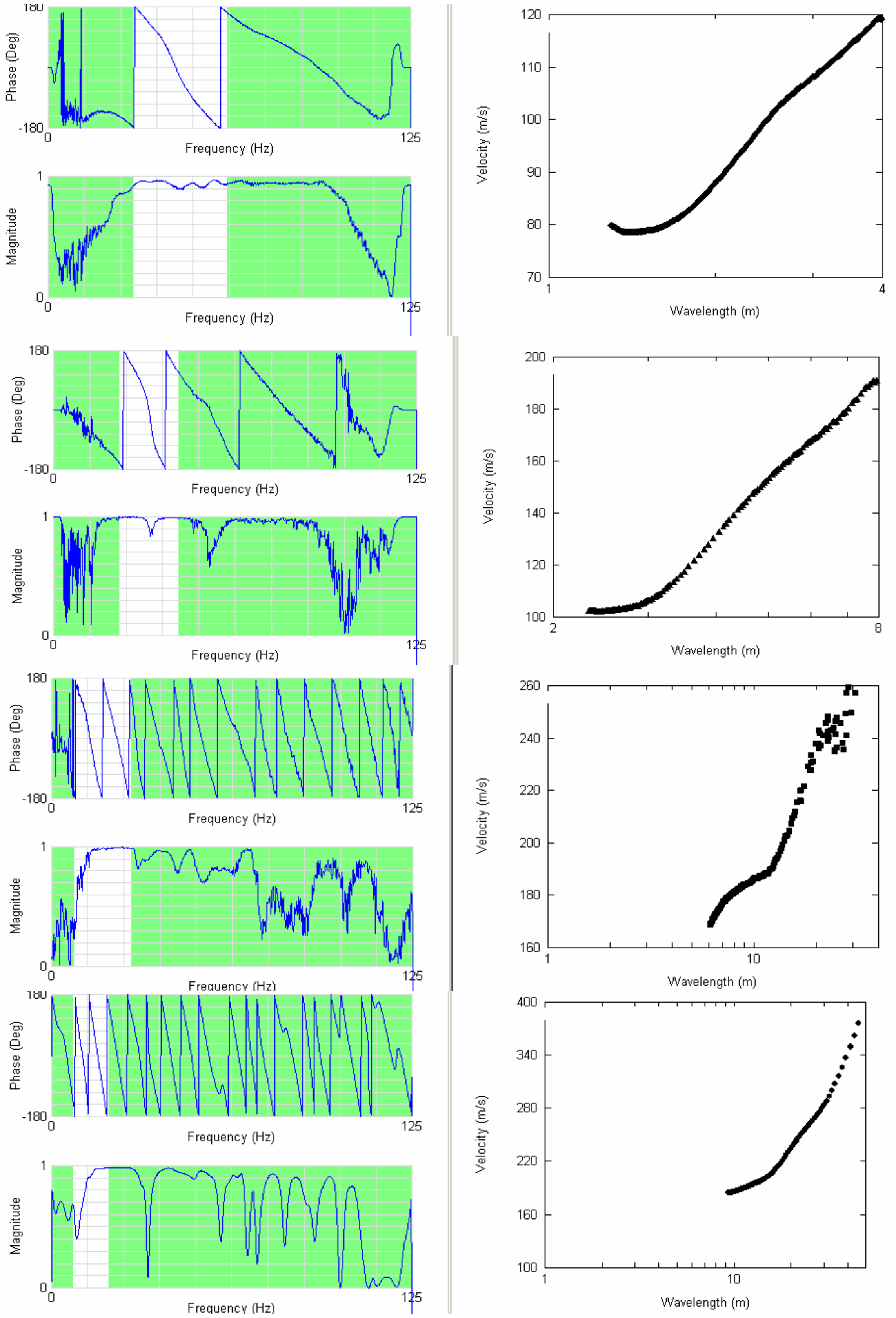

Figure 1. Phase, coherence and corresponding experimental dispersion curves for 2 *m*, 4 *m*, 16 *m*, and 24 *m* spacing

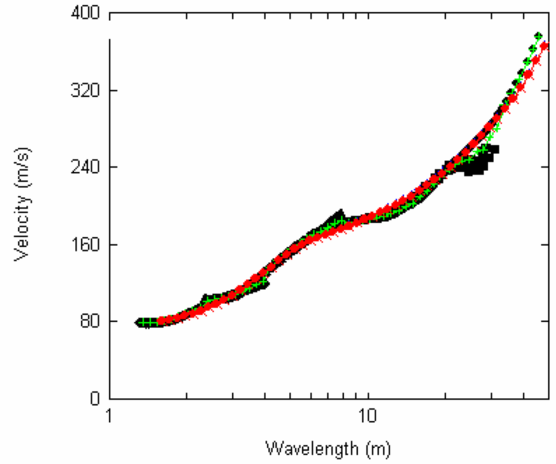

Figure 2. Comparison between theoretical and experimental dispersion curves

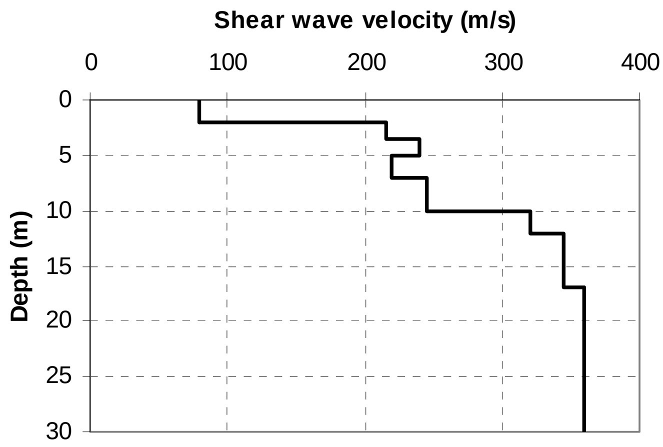

Figure 3. Final shear wave velocity profile with depth

MODULUS REDUCTION AND DAMPING CURVES

Soil Used

Cyclic triaxial tests were conducted on clean Yamuna sand (G_s = 2.66, e_{min} = 0.55, and e_{max} = 1.02) collected from the locations where shear wave velocity was measured. The soil consists of more than 95% sand and the rest 5% is either silt or clay or a combination of both. Hence the soil is considered primarily as sand for the analysis. Based on N –values measured in the field, a relative density of 55% is considered in this study.

Cyclic Triaxial Tests

Strain controlled undrained cyclic triaxial tests are conducted on samples of 70 *mm* diameter and 140 *mm* height as per ASTM D3999 for evaluating the modulus reduction and damping curves. Remolded samples are prepared using moist tamping under compaction method (Ladd, 1978). For all the samples carbon dioxide and deaired water are used for initial saturation (Polito and Martin, 2001) and all the samples are saturated using a back pressure of 300 *kPa* to achieve the *B* values in excess of 0.98. All the tests are conducted at 1 *Hz* frequency of sinusoidal loading at different shear strains on samples at an effective confining pressure (σ'_{3c}) of 100 *kPa*.The hysteretic loops for different strain levels are shown in Figure 4, and the computed variation of shear modulus with strain is shown in Figure 5a.

As the cyclic triaxial tests data can not cover the entire strain range, the generated shear modulus variation curve is matched with the available curves from the literature and observed that, seed and Idriss (1970) curves for average sand is more suitable to represent the Yamuna sand behavior. Hence Seed and Idriss (1970) curves for average sand (from SHAKE database) are used.

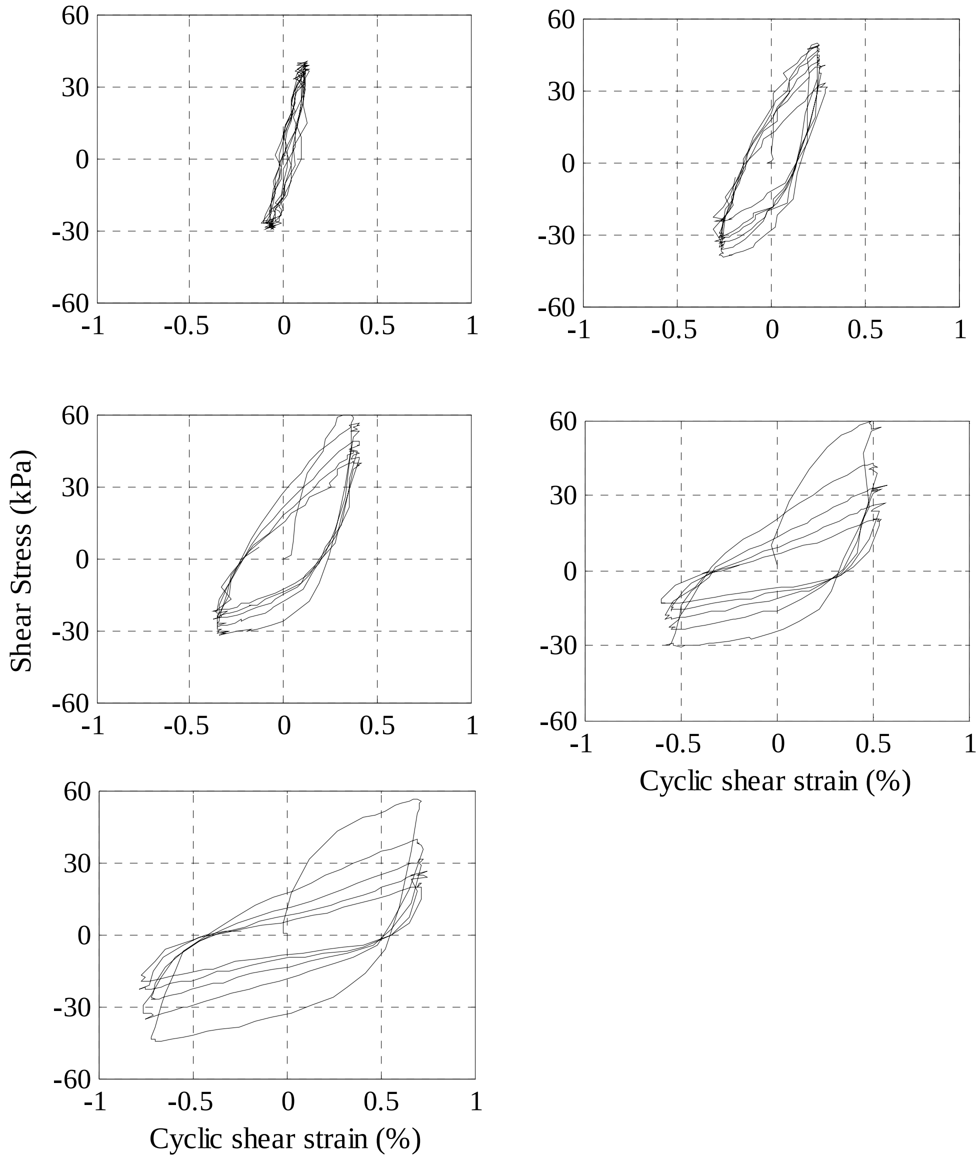

Figure 4. Hysteresis loops for different strain levels for clean Yamuna Sand (σ'_{3c} = 100 *kPa*, *e* = 0.75, *f* = 1 *Hz*)

SITE SPECIFIC GROUND RESPONSE ANALYSES

An equivalent linear one dimensional analysis has been carried out using *SHAKE* for computing ground response at representative soil site in the TransYamuna area of Delhi. Strong ground motion generated from central seismic gap for *Mw* of 8.5 (Figure 6) and local sources (Figures 7-10), shear wave velocities measured using *SASW* method (Figure 3) have been used. Seed and Idriss (1970) average curves for sand, that are matching with the modulus reduction and damping curves of Yamuna sand (Figure 5) based on cyclic traixial test results are used to represent the material nonlinearity. The computed free field motion and the input motion are shown in Figures 6 to 10. The response spectra for all the scenarios are shown in Figure 10.

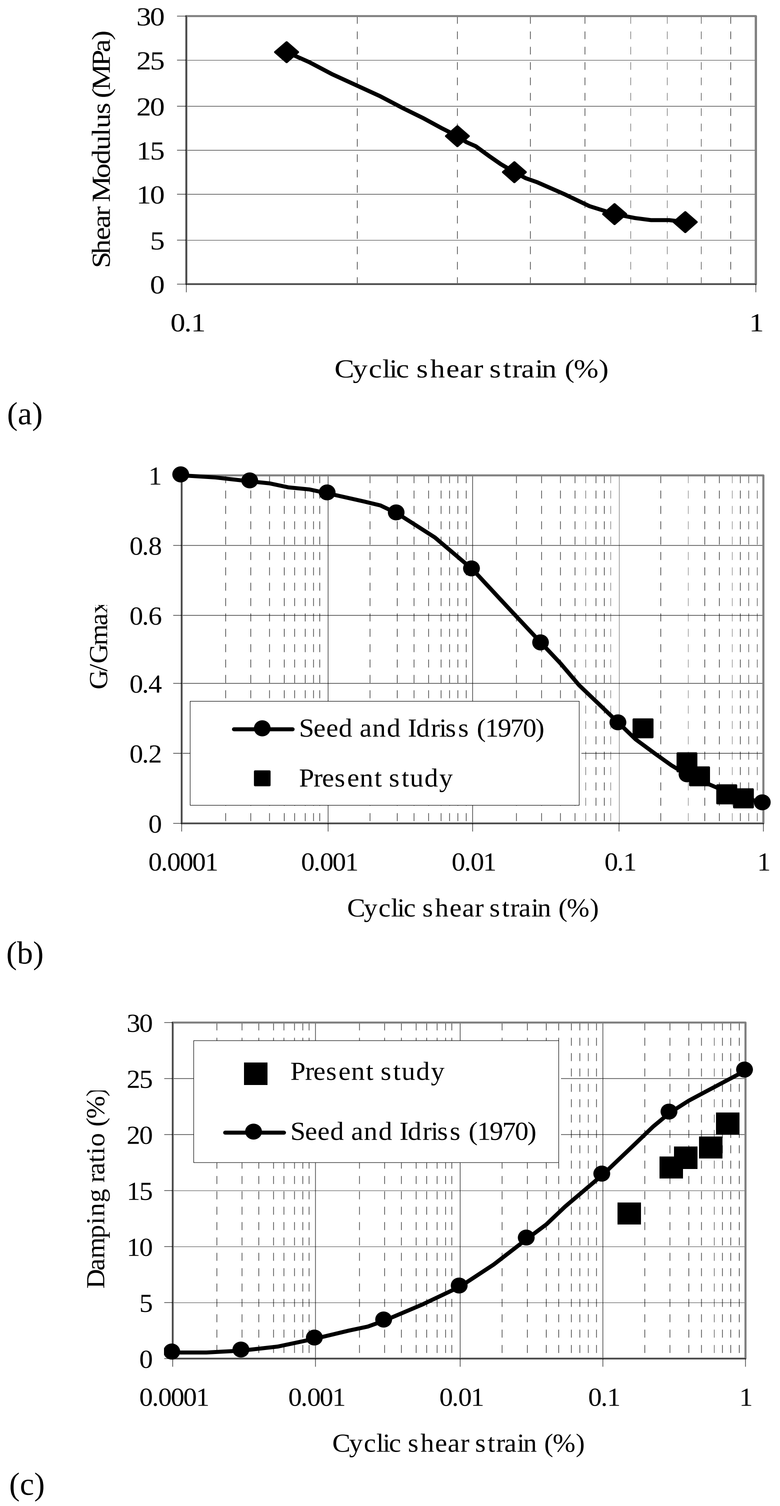

Figure 5. (A). Shear modulus, (B). Normalized shear modulus (G/G_{max}) and (C). Damping ratio variation with shear strain amplitude for Yamuna Sand (e = 0.75, σ'_{3c} = 100 kPa, f = 1 Hz)

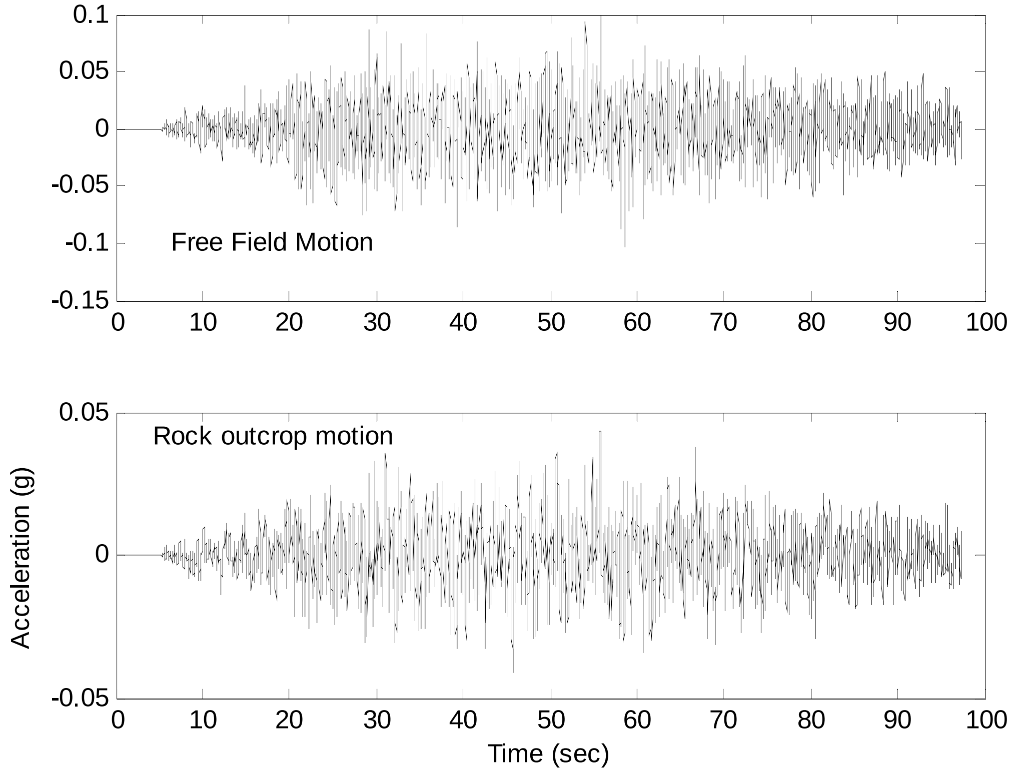

Figure 6. Rock outcrop and corresponding free field motion for earthquakes from central seismic gap

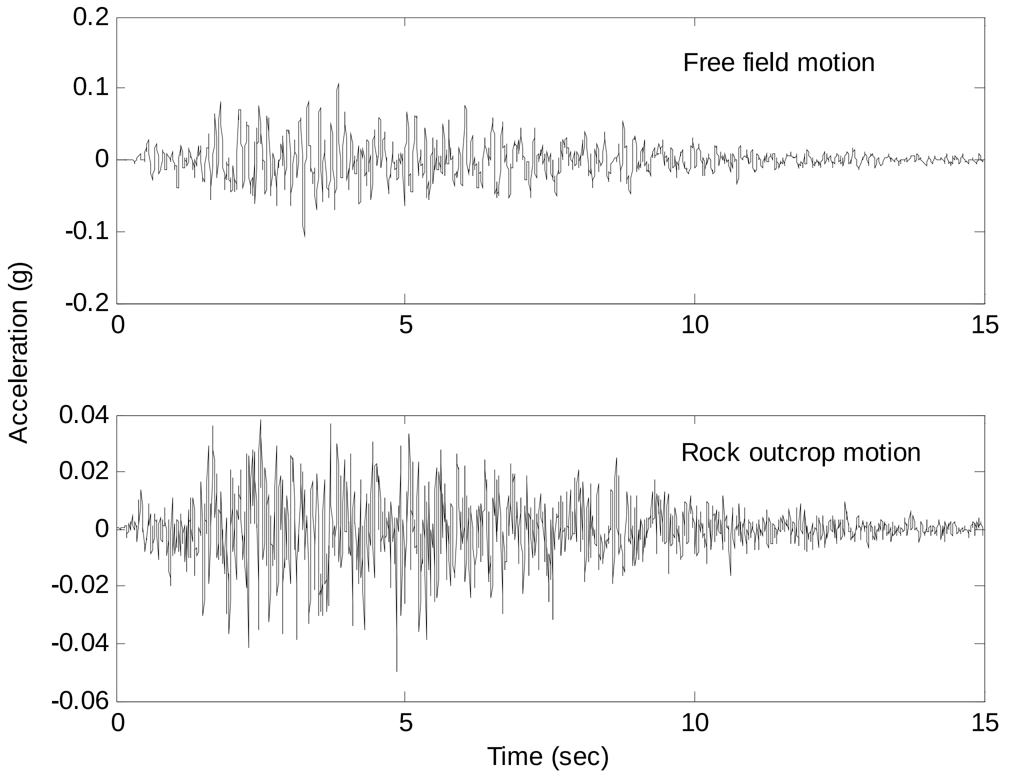

Figure 7. Rock outcrop and corresponding free field motion for M_w of 6.5 at 100 *km*

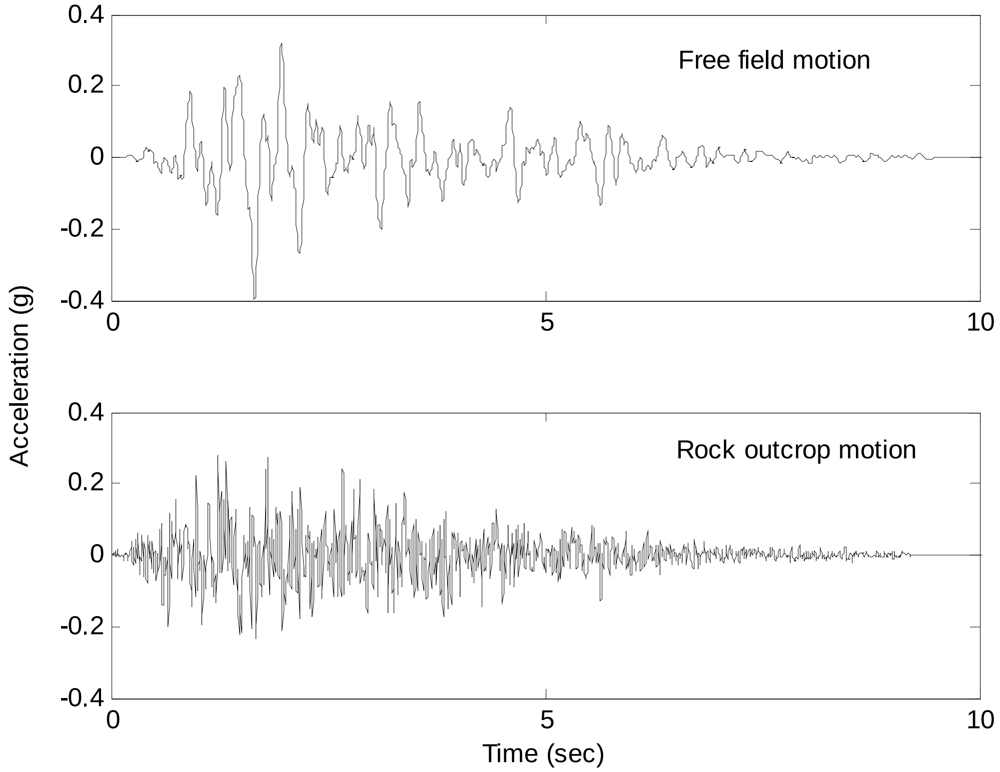

Figure 8. Rock outcrop and corresponding free field motion for M_w of 6.5 at 50 *km*

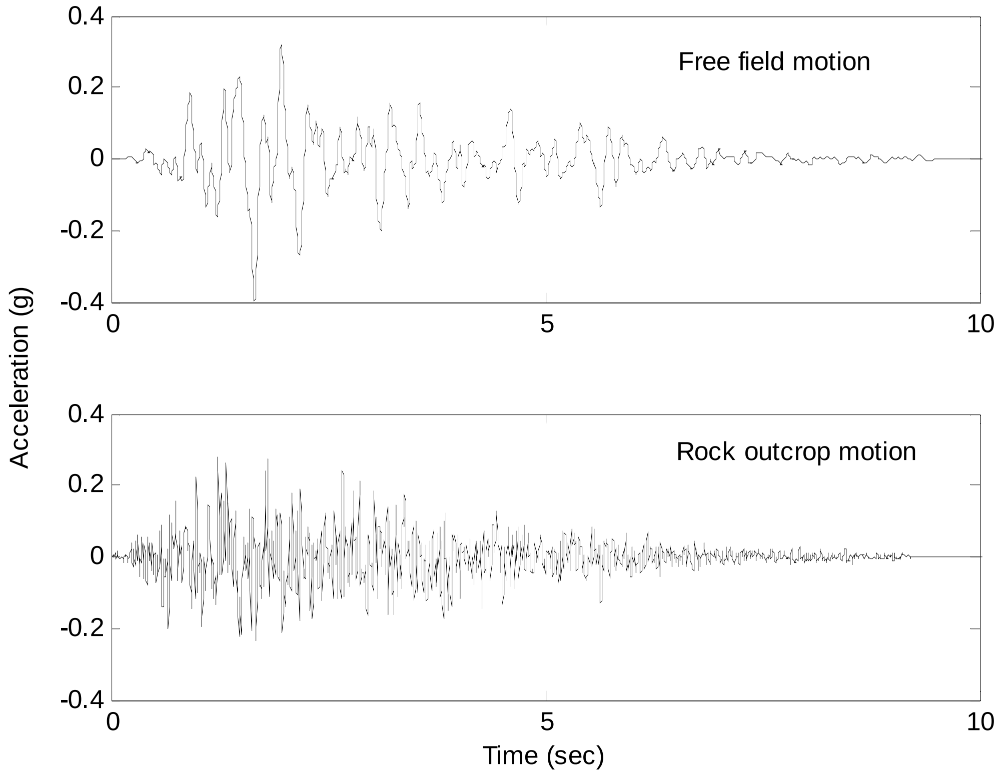

Figure 9. Rock outcrop and corresponding free field motion for M_w of 6.5 at 25 *km*

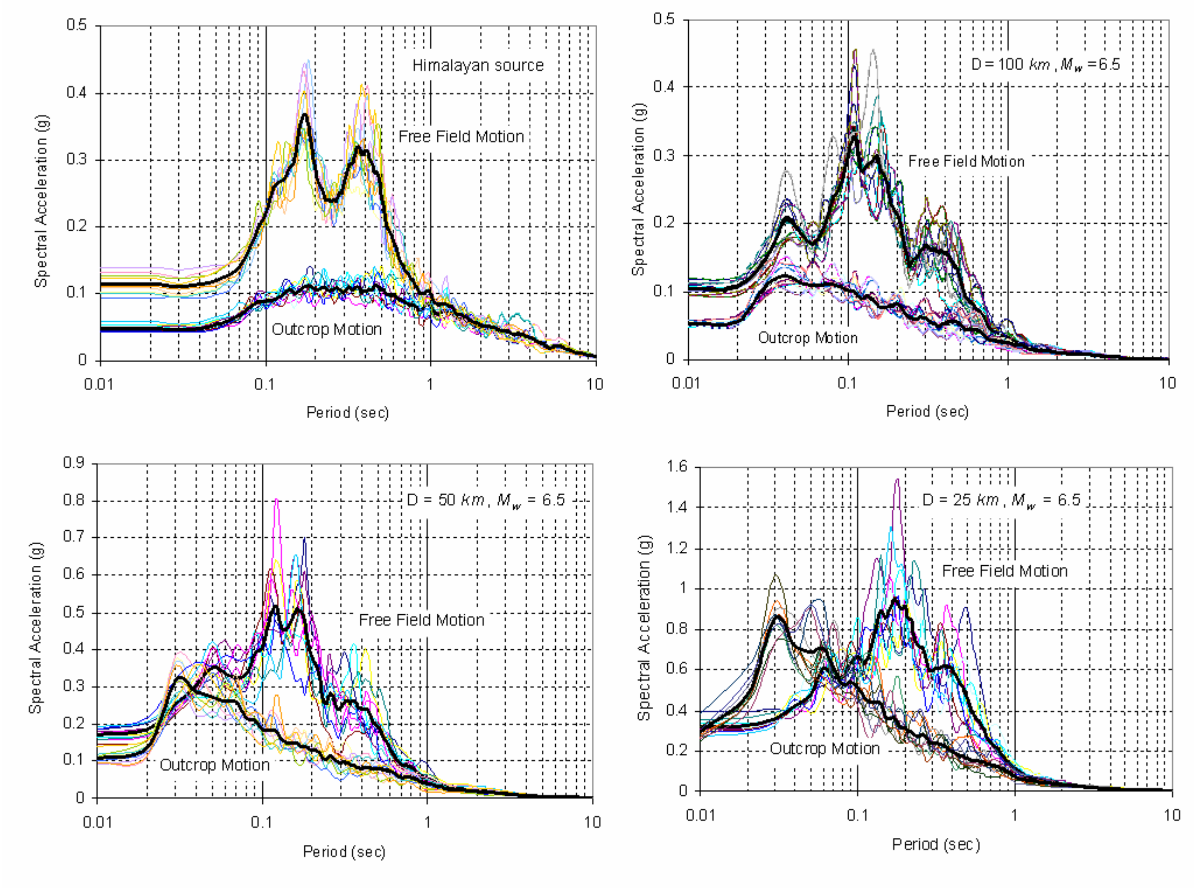

Figure 10. Rock outcrop and corresponding free field response spectra for Himalayan source (long distance) and local sources (M_w of 6.5 at 100, 50 and 25 *km*)

CONCLUSIONS

Possible strong ground motions at Delhi were generated using stochastic models. Shear wave velocity was measured in-situ and correlations between N and V_s are presented. Cyclic triaxial tests were conducted to characterize damping characteristics at high strains. Free field response has been computed using *SHAKE* for representative soil profiles and magnitude of *pga* amplification and spectral amplification has been estimated.

It also observed that spectral amplification due to local sources is controlled by epicentral distance and *pga* amplification almost became negligible when the epicentral distance is very close. For earthquakes from central seismic gap, *pga* amplification as well as spectral amplification was observed to be significant and this has to be considered in the structural design. The spectral amplification on the free field due to earthquakes from central seismic as well as local sources is observed in the periods in between 0.1 sec to 1 sec.

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