Spectral Estimation of Site Characteristics of an Earth Quake Prone Region

T. Seshunarayana

National Geophysical Research Institute CSIR

N. Sundararajan (✉ sundararajan_n@yahoo.com)

Sultan Qaboos University

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Abstract

The site amplification characteristic is an important part of evaluation of seismic hazard since much of the damage caused by earthquakes may be attributed directly to the ground shaking. Identifying ahead of time such areas which are prone to amplified ground shaking due to earthquake could greatly aid seismic hazard evaluation as well as improved hazard mitigation effects. It is also a well known fact that in most cases site amplification/ shaking is stronger in low shear wave velocity areas. The objective of the present study is to estimate site characteristics of as many as 116 sites in an area of approximately 35 sq.km comprising various geological units including soft alluvial deposits which not only tend to amplify certain frequencies of ground motion but also extend the duration of earth quake that may cause further damage. The basic idea of this study is to decipher the natural ground response during quite period as well as triggered response by spectral analysis. The methodology adopted for the study is modified micro tremor which is based on ambient noise as well as triggered response. Further, the spectral ratio of H/V of ambient noise and triggered data by Nakamura method with short duration data were also estimated. In addition, based on some empirical relations, the site response frequency and amplification were also computed using the shear wave velocity obtained up to a depth of 30 m (V_{S30}) by the method of multichannel analysis of surface wave (MASW) and depth to bed rock estimated through refraction seismic studies. The results of the study has shown that a simple comparison of spectra of quiet time data and triggered time data revealed that in alluvial soils with thick overburden, the signal amplification is more at low frequency (< 10 Hz), whereas in thin overburden the amplification was found to be low at low frequencies. The salient features of the study with merits are presented herein.

Introduction

During earthquakes, the most intense shaking is generally experienced near the rupturing fault and decreases with distance away from it. However, the shaking at one site may be entirely different from another site even though they are at the same distance from the rupture. It is now well known, and widely accepted amongst the earthquake engineering community, that the effect of local surface geology on seismic motion exist and can be large. The damage due to earthquakes is generally large over soft sediments than on firm bedrock outcrops. It is also a well known fact that in most cases site amplification/ shaking is stronger in low shear wave velocity areas. The sediment fill valleys are normally flat terrain with fertile soils, and therefore are attractive locations for human settlements. The National Earthquake Hazards Reduction Program (NEHRP, 1997) of US has defined five soil types based on shear wave velocity (V_s) which in turn help to evaluate the earthquake hazard.

The intensity of seismic ground motion is a function of earthquake magnitude and distance from the seismic source, as well as local soil condition, topography, geological condition, etc. Seismic zonation using Probabilistic Seismic Hazard Assessments (PSHA) are routinely used to estimate seismic intensity, characterized as Peak Ground Acceleration (PGA), Peak Ground Velocity (PGV) or spectral response ordinates for firm ground using the earthquake magnitude and distance from source to site. However,

PSHA do not include consideration of site specific conditions such as surface topography, bedrock geometry and soil condition, which can affect local seismic intensity.

Amplification of ground motions at soft sites above those predicted by PSHA for firm ground has long been recognized from the damage patterns of historical earthquakes. In the last over three decades, comparisons of accelerographs have demonstrated that amplification of seismic motions on soft soil occur relative to adjacent rock sites. Therefore, the effects of local soil conditions on seismic ground motions should be considered for seismic design, damage estimates for future earthquakes and land use planning.

Thus, the two most important factors influencing the level of earthquake ground motion at a site are the magnitude and distance of the earthquake in addition to the influence of a third important factor called the site effect. It is the conditions at a particular location which can increase (amplify) or decrease the level of shaking that is otherwise expected for a given magnitude and distance. Combining this information with where and how often earthquakes of various magnitudes are likely to occur should provide improved assessments of seismic hazard. The site effect is briefly discussed hereunder.

Site Effect

In general, soft alluvial deposits not only tend to amplify certain frequencies of ground motion but also extend the duration, which may cause further damage during earthquakes. However, it gives engineering seismologists the opportunity to perform numerous macro seismic observations during the last century. These studies have shown very clearly that the damage effect associated with such soft deposits might lead to considerable increase in local intensity. The fundamental phenomenon responsible for the amplification of motion over soft sediments is the trapping of seismic waves due to the impedance contrast between sedimentary deposits and the underlying bedrock. When the structure is horizontally layered (1-D), this trapping affects only the body waves traveling up and down in the shallow subsurface layers. When the surface sediments form a 2-D or 3-D structure, i.e., lateral heterogeneities such as thickness variations exist, this trapping also affects the surface waves, which develop on these heterogeneities, and thus reverberate back and forth.

It is a well known fact that seismic waves travel faster through hard rocks than through softer rocks and sediments. As the waves pass from harder to softer rocks it slows down, and the amplitude tend to be large to carry the same amount of energy. Thus, shaking tends to be stronger at sites with shallow softer subsurface layers, where seismic waves travel more slowly. However, in an earthquake, the shaking increases as the thickness of sediment increases. Therefore, two important local geological factors that affect the level of shaking experienced during earthquakes are (1) the softness of the surface rocks and (2) the thickness of surface sediments. It is opined that the shear wave velocity (V_s) up to top 30 m is the indicator of softness of the soils. Both these two conditions (1) and (2) i.e., the softness of the surface rock and the thickness can be studied by MASW.

Review on Site Effect Studies

The first step in forecasting the spatial location and the type of losses is to map the amplification of seismic waves due to soft near surface deposits. One alternative approach in evaluating site effects involves determining the physical properties of local soil setting by conducting borehole and seismic studies. Measured parameters can then be used in theoretical models to predict site response functions. The main disadvantage of this method is relatively the high cost of conducting the necessary geotechnical or geophysical studies that, in many cases, proved to be problematic. Although theoretical approaches are instructive, conducting the necessary sensitivity tests (with respect to different locations and sizes of possible events) and incorporating the inherent uncertainty (with respect to our limited knowledge of the Earth's structure), is usually impractical.

The site response functions, by definition are equivalent to the spectral ratio of horizontal component of strong ground motion record with respect to a reference site located on rock (Rogers, et al., 1984, Singh, et al., 1988, Su, et al., 1998, Beresnev, et al., 1998, Hartzell, 1998, Reinoso and Ordaz, 1999, Zaslavsky and Shapira, 2000). In regions where the seismic activity is relatively low, as in Israel, this type of analysis is usually impracticable. Site response estimation was done using strong motion records (Nath et al., 2000) in Sikkim and weak motion records (Nath et al., 2003) in Delhi region. In loose top soil situation seismometry data may not be good. Many investigators evaluated site response functions from moderate to weak motions of earthquakes (Tucker and King, 1984, King and Tucker, 1984, McGarr, et al., 1989, Field, et al., 1992, Steidl, et al., 1996, Toshinawa, et al., 1997, and Zaslavsky, et al., 2000). The main drawback of the reference site technique is the choice of reference motion, which represents the true input motion to the soil site. According to Steidl (1993), when it is possible, the reference ground motion should be calculated by averaging several rock sites. Steidl, et al., (1996) and Zaslavsky, et al., (2002) show that the assumption of a flat response rock site is often false, mainly due to weathering. Use of these surface rock sites with flat response as reference sites often leads to underestimation of the amplification by a factor of 2 to 4 in the frequency range of 2–7 Hz. Lermo and Garcia, (1993) drew significant results from a nonreference technique, i.e., the receiver function technique, using the horizontal to vertical spectral ratios of shear wave.

Many studies report that the frequency dependence of site response can thus be obtained from measurements made at only one station (Lermo and Garcia 1994, Theodulidis, et al., 1996, Seekins, et al., 1996, Malagnini, et al., 1996 and Zaslavsky, et al., 1995). The implementation of this approach, however, still requires rather frequent occurrence of earthquakes. The idea of evaluating site characteristics from microtremor records originated from the pioneering work by Kanai and Tanaka (1961). They pointed out that predominant frequency of horizontal spectra of microtremor is related to shallow and local geological conditions. Since then, it has been reported that this technique has proved to be effective in estimating fundamental frequency (Tanaka, 1966, Tanaka, et al., 1968, Katz, 1976, Katz and Bellon, 1978, Kagami, et al., 1982, Ohta, et al., 1978, Zaslavsky, 1984 and 1987). However, in most cases, due to the influence of artificial sources from dense population, high traffic and various industries, the resonance frequency cannot be directly identified in the microtremor spectra (Zaslavsky, et al., 2001 and 2002).

Kagami, et al., (1982) proposed that the ratio of the horizontal components of the velocity spectra at the sediment site to those at the rock site could be used as a measure of microseismic ground motion amplification. This technique is widely used for estimating site response (Rovelli, et al., 1991, Field, et al., 1990 and 1992, Hough, et al., 1992, Malagnini, et al., 1996, Gutierrez and Singh, 1992, Dravinski, et al., 1995, Gaull, et al., 1995, Zaslavsky, et al., 1995 and 2000 and Shapira, et al., 2001). The experiments (Zaslavsky, et al., 2000) show that bedrock ground motion can be considered as a good reference site when distances are as smaller as 0.5 km-1.0 km from the soil site.

Nakamura, (1989) hypothesized that site response could be estimated by simply evaluating spectral ratio of horizontal versus vertical component of noise observed at the same site. Most studies show that the H/V ratio obtained from microtremors coincide with response functions of near surface structures (Ohmachi, et al., 1991, Lermo and Chavez-Garcia, 1994, Zaslavsky, et al., 1995, Seekins, et al., 1996, Gitterman, et al., 1996, Konno and Ohmachi 1998, Mucciarelli and Monachesi, 1998, Chavez-Garcia and Cuenca, 1998, Toshinawa, et al., 1997 and Shapira, et al., 2001). There is yet another fact, according to Field and Jacob, (1995), Bonilla, et al., (1997), Horike, et al., (2001) and Satoh, et al., (2001) that the spectral ratio of horizontal to vertical component of microtremors is similar to those obtained from traditional sediment to bedrock spectral ratio of the frequency of the predominant peak earthquake records (Borcherdt, 1970). However the absolute level of site amplification does not correlate with the amplification obtained from this method.

Methodology

The objective of the present study at Jabalpur is to estimate site characteristics of as many as 116 sites. Theoretical computation may not be feasible due to lack of necessary database. Conventional seismic surveys (reflection and refraction surveys) with long/short spreads are not also possible due to urban nature of the area. Use of explosives is prohibitive due to intense habitation. Usual spectral ratio estimation of ambient noise alone by the method of Nakamura (H/V) or reference site method will be time consuming and occasionally give erroneous results for long duration data. Therefore, a modified microtremor methodology was adopted for the study, which is based on ambient noise and triggered response. Three component ambient noise recording was done for a short duration of 2 to 16 seconds without any artificial/ man made movement in the near vicinity of the recording station.

Another set of records with hammer as the source of wave generation at a far distance of about 50 m was also obtained. With the above set up, it was possible to compute the spectra for both quiet and triggered period. The basic idea was to see the natural ground response during quiet period and also the ground response with a hammer hit at about 50 m away. The reason for such a study with triggered response is that it also carries considerable amount of ground roll (Park, et al., 1999). Thus the following methods were useful to evaluate the amplification of as many as 116 locations in Jabalpur, India.

- Comparative study of spectra of ambient noise and triggered data.

- Spectral ratio H/V of ambient noise by Nakamura method with short duration data.
- Spectral ratio H/V of triggered data by Nakamura method with short duration data.
- Spectral ratio of ambient noise with respect to a reference site.
- Spectral ratio of triggered data with respect to a reference site.
- Spectral ratio of triggered data to ambient noise.

Alternately, it is also possible through empirical relations to compute site response frequency and amplification using the harmonic mean of shear wave velocity (V_{s30}) up to a depth of 30 m and depth to bedrock estimated through MASW and refraction studies.

Data Acquisition and Processing

Records of ambient noise and triggered response for 2–16 seconds duration were acquired in all the 116 sites of different geological units. The recording equipment which was used for refraction and MASW studies was used for data acquisition, however with 1 Hz three component geophone. The geophones were arranged in three mutually perpendicular directions. First geophone was arranged in vertical direction and the second geophone was in line with the source direction in horizontal position. The third geophone was arranged along transverse direction to the source position. The spectra of both ambient noise and triggered response at all locations were computed with the help of Matlab software for all the channels up to 50 Hz. The plots were made with the same vertical (amplitude) scale. Red lines represent the spectra for triggered data and broken blue lines represent the spectra of natural (ambient) ground noise. A selected set of five records one each in alluvial soil, Gondwana, basalt, granite and lameta rock sites (Figs. 3a-7a).

The following notations were adopted in the computation.

- V_t is the spectra of vertical component of triggered data,
- V_n is the spectra of vertical component of noise,
- H_{lt} is the spectra of horizontal component of arranged in longitudinal direction of triggered data,
- H_{ln} is the spectra of horizontal component arranged in longitudinal direction of noise,
- H_{tt} is the spectra of horizontal component arranged in transverse direction of triggered data and
- H_{tn} is the spectra of horizontal component arranged in transverse direction of noise.

For calculating spectral ratio of horizontal to vertical, the following procedure was used. First, the true amplitudes were calculated by considering the recording system gain, sensor's generator constant and the number of stacks and then converted in to frequency spectra. The entire data was smoothed both in time and frequency domains using appropriate windows. The Fourier amplitude ratio of the horizontal to vertical component was obtained by the equation given by Rabin Tuladhar, et al., (2004) as:

$$r(f) = \frac{\sqrt{(F_{NS}(f) \times F_{EW}(f))}}{F_{UD}(f)}$$

where $r(f)$ is the horizontal to vertical (H/V) spectral ratio, and F_{NS} , F_{EW} and F_{UD} are the Fourier amplitude spectra along N-S, E-W and up-down (UD) directions respectively. The peak periods of the H/V spectrum shows the predominant periods of the site. The H/V spectra and the predominant periods of ground motion were obtained for all the observation sites. It was observed that the quality of spectra appeared to be reasonably good for data of 16 seconds duration. The computed plots of H/V spectral ratio, which is referred to as Nakamura technique in literature (Nakamura, 1989) are presented for selected sites representing alluvial soil, Gondwana, basalt, granite and lameta rocks and shown in Figs. 3b-7b.

The spectral ratios H/V computed for ambient noise and triggered data are further compared with a reference site. A site with no significant amplification and shallow bedrock was chosen as reference site (Sr-42, Fig. 1.7). Spectral ratios between the reference site and the site under investigation for the above five sites are shown in Figs. 3c -7c. Further, the noise at the site under investigation was considered as reference data in order to estimate the spectral ratio of triggered to ambient noise response. Accordingly, the spectral ratio for individual components V_t/V_n , H_{lt}/H_{ln} , and H_{tt}/H_{tn} were computed for the five sites referenced earlier and given in Figs. 3d -7d.

Site Response by Shear Wave Velocity

Two dimensional site effects, such as surface topography and bedrock geometry, are also known to amplify ground motions, but a few well documented case histories of damage or instrumentation recordings are available to develop even empirical estimates of the magnitude of amplification. Finn, (1991) discussed the available records and analytical methods to predict amplification due to these site effects. However, 2-D site effects remain difficult to predict reliably. Amplification of ground motion due to local soil conditions depends primarily on soil type, properties and thickness. Seed and Idriss, (1982) present approximate magnitudes of amplification for different soil types as a function of peak ground accelerations. This indicates that most soils amplify peak acceleration where the firm ground acceleration is less than 0.1g, with the largest amplification occurring in "soft to medium stiff clay and sand". Idriss, (1990) later improved the amplification curve for soft clay sites, based on additional analysis and data from the Mexico City and Loma Prieta events. They say that the soft clay sites amplify peak accelerations up to 0.4g, beyond which deamplification occurs. Deamplification is a result of the nonlinear behaviour of soil under large strains.

Amplification is thus related to soil type and thickness, and it also depends on the match between the frequency content of the earthquake motions and the natural period(s) of the ground. The natural periods of the ground for an elastic site are given by:

$$T_n = 4H / [(2n-1)(V_{s30})]$$

Where, T_n is the period at mode n , H is the thickness of the soil. For a given earthquake, the response of an elastic site will depend on both thickness of the top soil and shear wave velocity (V_s), which is a measure of soil stiffness. Finn, (1991) shows that for many sites, surface motions are influenced primarily by the top 20 m to 30 m of soil. Therefore, the average shear wave velocity over this depth range is a reasonable indicator of amplification for mapping purposes. The natural period (T) of the ground and response frequency $f = 1/T$ are computed for all the 116 sites. A response frequency plot is shown in Fig. 9a.

Further, Borchardt, et al. (1991) has shown a strong correlation between shear wave velocity and Average Horizontal Spectral Amplifications (AHSA), based on weak motion records as:

$$AHSA = 701 / (V_{s30})$$

However, when nonlinear effects become significant during strong ground motion, low strain parameters such as shear wave velocity no longer effectively characterize soil's dynamic response (Finn, 1991). As soil tends to weaken, its shear wave velocity reduces at large strains, which in turn increases the natural period of the deposit. The Average Horizontal Spectral Amplification (AHSA) is shown in Fig. 9b.

Site Amplification by Basin Model

The harmonic mean shear wave velocity up to a depth of 30 m (V_{s30}) is useful for the estimation of the site amplification. Engineering site investigations are usually limited to the upper most 30 m of material and it has become the standard depth for classifying site characteristics. The National Earthquake Hazard Reduction Program (NEHRP), USA for seismic regulations uses the 30 m standard depth as an index for classifying sites for the purpose of defining the amplification. One simple way of accounting for site condition in calculating seismic hazards is to use shear wave velocity in shallow subsurface to classify the materials. The average shear wave velocity of different layers up to 30 m (V_{s30}) has been used to develop site categories that can be used for modifying a calculated ground motion to account for site conditions Wills, et al., (2000). An empirical relation connecting V_{s30} and basin depth (B_{depth}) for determining the site amplification is given by Field, (2000).

$$\text{Amplification} = (V_{s30}/1000)^{-0.704} \cdot e^{(0.12 * B_{depth})}$$

Here, the bedrock depth derived from seismic refraction and MASW studies is considered as basin depth (Fig. 8). An amplification image map based on the above equation is shown in Fig. 9c.

Results And Discussion

The site amplification characteristic is an important part of evaluation of seismic hazard. Much of the damage caused by earthquakes was attributed directly to the ground shaking, with maximum damage in areas where site response is caused by enhanced ground shaking. Identifying ahead of time those areas which are prone to amplified ground shaking due to earthquake could greatly aid seismic hazard

evaluation as well as improved hazard mitigation effects (Lisa World and Jim Mori, 2000). The spectral study helped to estimate the response of the ground i.e., the frequency and amplification at which the signal is getting excited.

It was observed from the spectral study that in alluvial soils with thick overburden, the signal amplification was more at low frequency (< 10 Hz), whereas in thin overburden areas the amplification was low (Figs. 3a -7a). This spectral study is a rapid way of estimating the site condition instead of using short period seismometers for long duration. The spectral ratio obtained for triggered data found to be better due to high amplitudes of the ground roll (Figs. 3b-7b). The study of spectral ratio of both ambient and triggered data clearly brought out that the amplification levels are more in thick (about 30 m) alluvial soil sites at low frequencies and not so high in shallow hard rock sites. Reference site technique has clearly brought out the frequency band (2–6 Hz) and maximum amplification (2.5) as is evident from Figs. 3c -7c.

The results of spectral ratio between triggered response to noise of all three components (V_t/V_n , H_{lt}/H_{ln} , and H_{tt}/H_{tn}) shown in Figs. 3d-7d is not satisfactory. The reason may be attributed to in-sufficient data length (16 sec) for this particular case. The amplification images based on ASHA (Fig. 9b) and the empirical relation based on basin depth as well as (V_{S30}) of (Fig. 9c) are identical thereby substantiating the procedure adopted. It also showed that the expected maximum amplification is about 2.5 in the frequency band of 2–6 Hz in west and northwestern portion of Jabalpur.

Conclusions

- The spectral study helped to estimate the response of the ground i.e., the frequency at which the signal is getting excited at each location.
- The procedure adopted here to acquire the data is a rapid way of estimating the site condition instead of using short period seismometers for long duration (2 to 3 days). The available short duration data (16 sec) was used for estimating the site amplification using different techniques, which enabled to evaluate the comparative merits and demerits.
- The simple comparison of spectra of quiet time data and triggered time data revealed that in alluvial soils with thick overburden, the signal amplification is more at low frequency (< 10 Hz), whereas in thin overburden the amplification was found to be low at low frequencies.
- H/V and reference site techniques, even with short duration data are found to be good.
- Use of triggered data rather than ambient noise alone will have added advantage.
- The estimation of site amplification and frequency response from shear wave velocity and bedrock depth through empiric all relations found to be very satisfactory.

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Figures

Figure 1

Seismic zonation map of India (the area of study Jabalpur is in zone III).

(a)

(b)

Figure 2

(a) Geology of the area of study and (b) locations of sites spread over in all geological rock units.

Figure 3

Spectral characteristics of alluvial site wherein (a) Spectra of triggered and noise of vertical(V), horizontal longitudinal (HL) and horizontal transverse (HT) (b) Spectral ratio of horizontal to vertical component. (c) Spectral ratio with reference to a reference site (Sr-42) and (d) Spectral ratio of triggered to noise.

Figure 4

Gondwana

Figure 5

Basalt

Figure 6

Granite

Figure 7

Lameta rock

Figure 8

(a) The shear wave velocity (V_{s30}) up to a depth of 30 m obtained by MASW and (b) the basin depth derived from MASW as well as refraction seismic method.

Figure 9

Estimated (a) frequency response of the ground, (b) ground amplification based on average horizontal spectral amplification and (c) amplification response based on basin depth.