Site Classification of the Strong Motion Stations of Uttarakhand, India, based on Generalized Inversion and Horizontal to Vertical Spectral Ratio Methods

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ABSTRACT: PESMOS is a significant source of ground motion records in India consisting of earthquake (EQ) records from nearly 300 recording stations located across the country. The site classification of these stations given by PESMOS is based on the physical description of local geology and not based on in-situ field tests. Thus, there exist an ambiguity in the assessment of local site conditions for these recording stations. Knowledge of accurate SC is essential in order to use accelerograms from these recording stations for both seismic hazard as well as site response analysis. In the absence of field study data, accelerograms from these stations can be used to estimate site class (SC) of the recording stations. In the present study, SC of 4 recording stations situated in the region of Garhwal Uttarakand is determined based on predominant frequency (f_{peak}) obtained using Generalized Inversion Technique (GINV) and Horizontal to Vertical Spectral Ratio method (HVSR). The value of f_{peak} obtained from both two above methods show 1:1 matching. Further, a clear difference in the SCs suggested by PESMOS and the one obtained from the present study are observed.

Keywords: *PESMOS; Site Class; Generalized Inversion Technique; Horizontal to Vertical Spectral Ratio, Garhwal Uttrakhand*

1. Introduction

Modification of the characteristic of the incoming seismic waves by soil known as local site effect is a major reason for the higher level of ground shaking occurring during an earthquake (EQ) at soil site in comparison to adjacent rock site. Local site effect causes abnormal EQ damage pattern such that for the same earthquake event, the intensity of ground shaking at different sites may vary drastically, even when the epicenter distances are same. 1991 Uttarkashi EQ (Mw=6.8), 1999 Chamoli EQ, 2001 Bhuj earthquake (Mw=7.7) and 2011 Sikkim earthquake are few examples from India where local site effect playing an important role in triggering damages at sites on soft soils even though located at larger epicentral distances.

The Himalayan arc extending from Kashmir in the northwest to Arunachal Pradesh in the northeast is amongst most the seismically active regions in the world having encountered four major EQs (M ≥ 8.0) in the last 120 years. The region falls within the seismic zones IV and V as per Bureau of Indian Standards (BIS 2002). 300 state of the art strong motion recording stations have been installed across the country in order to understand the ongoing seismicity by the Ministry of Earth Science. EQ records from these recording stations are available in PESMOS (www.pesmos.in). Along with the ground motion records, SC of a particular station is also given by PESMOS. However, the site classification provided by PESMOS is purely based on the physical description of local geology and not based on in-situ field tests (Mittal et al 2012). An approximate value of average shear wave velocity for 30m (V_{s30}) was assigned to each PESMOS recording station based on SEISAT (2000) and Geological Maps of India following Borcherdt (1994) classification scheme (Mittal et al 2012). Classification scheme used by PESMOS consists of three SCs in accordance with Borcherdt (1994) namely; SC A ($V_{s\,30}$ > 700 m/s), SC B (375 m/s < $V_{s\,30}$ >700 m/s), and SC C ($V_{s\,30}$ < 375 m/s). SC A and SC B refer to firm/hard rock site and soft to firm rock site respectively while SC C refers to soft soil sites. The strong motion data from these stations are useful in seismic hazard evaluation studies and development of regional ground motion prediction relationships (Anbazhagan et al (2013)) Accurate estimation of SC of strong motion station is required for utilizing these records with confidence for proper seismic hazard analysis. In the present study, SC following PESMOS and NEHRP (National Earthquake Hazards Reduction Program)classification scheme for Champawat (Lat. 80.09, Long. 29.33), Darchula (Lat. 80.54, Long. 29.85), Lansdome (Lat. 79.68, Long. 29.84) and Chamoli (Lat. 79.32, Long. 30.41) recording stations in the Garhwal region of Uttarakhand are estimated using GINV as well as HVSR methods.

2. Study Area

All the 4 stations belongs to the Garhwal Himalaya area which is bounded by the main central thrust (MCT) and main boundary thrust (MBT) (Valdiya, 1980). In the recent past, this region has experienced two moderate EQs; the 1991 Uttarakashi EQ (Mw=6.8) and the 1999 Chamoli EQ (Mw=6.6). Majority of the houses in this region are made up of materials like mud, brick, and stones (Sharma et al 2013). This type of construction is highly vulnerable during probable future EQ which may lead to significant loss to life and property.

3. Methodology

The GINV technique was developed by Andrews (1986) by modifying the method of spectral ratio. The spectral acceleration of the i^{th} EQ recorded at the j^{th} recording station, U(f)ij, can be linearly represented in the frequency domain as;

$$\ln \mathrm{U(f)}_{ij} = \ln \mathrm{S(f)}_{i} + \ln \mathrm{P(f)}_{ij} + \ln \mathrm{G(f)}_{j} \qquad (1)$$

Here, $S(f)^i$ is the source effect of the i^{th} earthquake, $P(f)^{ij}$ is the term accounting for the propagation path, and $G(f)^j$ is the site effect. The effect of path attenuation from the spectral content of the record is removed following Andrews 1986 as;

$$\ln \mathrm{U(f)}_{ij} - \ln \mathrm{P(f)}_{ij} = \ln \mathrm{J(f)}_{ij} \quad (2)$$

The value of $\mathrm{P(f)_{ij}}$ in eq. 2 is determined using the equation below;

$$P(f)_{ij} = \frac{1}{R_{ij}}\left[\mathrm{e}^{\frac{(-(\pi\cdot f\cdot R_{ij})}{(Q_S(f)\cdot\beta)}}\right] \quad (3)$$

Where, R is the hypocentral distance, f is the frequency, $Q_s(f)$ is the quality factor for S wave, β is the average shear wave velocity of the crustal medium for the region. In the present study, the values of β is taken as 3.15km/sec and $Q_s(f) = 174\,f^{1.27}$ after Sharma et al (2014). The corrected spectra ($\ln \mathrm{J(f)}_{ij}$) is substituted in eq. 1 giving eq. 4.

$$\ln \mathrm{J(f)}_{ij} = \ln \mathrm{S(f)}_i + \ln \mathrm{G(f)}_j \quad (4)$$

There exists an unconstrained degree of freedom in eq. 4 causing trade-off between source and site effect (Andrews, 1986). To remove this, a constraint condition should be given by choosing at least one reference site. A station located on a rock site is considered as a reference site, and the site effect is set to unity for this site at each frequency (Field and Jacob 1995).

Eq. 4 in matrix form following the notations of Menke (1989) can be written as:

$$\begin{vmatrix} A \\ \\ C \end{vmatrix} \quad m \quad = \quad \begin{vmatrix} b \\ \\ 0 \end{vmatrix}$$

Here, m is the model space matrix (containing only two non-zero elements in each row and column) related to ln $\mathrm{S(f)_i}$ and ln $\mathrm{G(f)_j}$. A is the matrix linear operator and b is the data vector containing the elements related to ln $\mathrm{J(f)_{ij}}$. A row matrix C is added to constrain for the reference station in which C × m = 0. The solution for eq. 4 is obtained using singular value decomposition method (Menke 1989). In the present study, Pithoragarh station is selected as a reference site based on the findings of Sharma et al (2013).

In addition, SC is also estimated using HVSR method, based on the assumption that the vertical component of strong motion is free from soil characteristics. HVSR method is an extension of Nakamura (1989) technique used for the estimation of site effect by microtremor measurements. HVSR is determined as the ratio of 5% damped response spectra of horizontal and vertical components smoothened using a Konno and Ohmachi (1998) window of parameter b=20. The horizontal component is computed by the geometric mean of east-west and north south components.

For the present analyses, the database consists of 12 ground motions recorded during 5 EQ from 2004 to 2012, with magnitudes ranging from 3.5 to 5 while focal depths ranges from 2km to 29km.

4. Result

Figures 1 (a-d) shows the horizontal to vertical ratio curves obtained using GINV (indicated by dotted lines) and HVSR (indicated by solid lines) methods for recording stations at Champawat, Darchula, Lansdome and Chamoli. Curves obtained using GINV and HVSR methods for all the 4 stations exhibits a clear and distinct peaks. f_{peak} for a station is the frequency corresponding to the maximum value of the ratio of horizontal to vertical component (A_{peak}). Similar values of f_{peak} are observed for GINV and HVSR methods. However, larger discrepancies in the value of A_{peak} is seen for all the 4 stations. HVSR gave higher value of A_{peak} compared to GINV for all recording stations except Darchula. Observations worldwide indicates that HVSR overestimates the value of A_{peak}. The value of A_{peak} varies between 1.01 to 8.7 and 5.5 to 7.5 for HVSR and GINV respectively. The values of f_{peak} and A_{peak} obtained by GINV and HVSR method for all the 4 stations obtained in the present study are tabulated in Table 1.

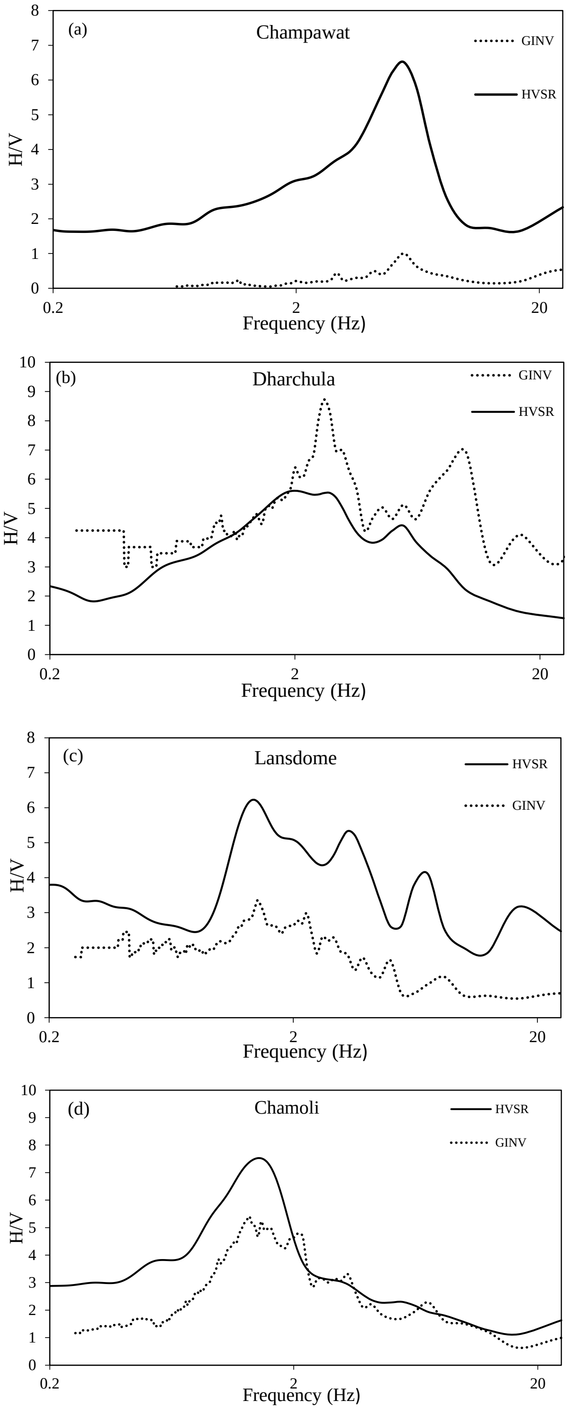

Fig. 1(a-d): GINV and HVSR curves

Table-1 Summary of Peak frequency and Amplification obtained from Model HVSR and HVSR

Recording Station	GINV f_{peak} (Hz)	GINV A_{peak}	HVSR f_{peak} (Hz)	HVSR A_{peak}
-1	-2	-3	-4	-5
Champawat	5.5	1.01	5.5	6.5
Dharchula	2.5	8.7	2.5	5.5
Lansdome	1.35	3.4	1.35	6.21
Chamoli	1.47	5.4	1.41	7.5

Based on the average value of f_{peak}, corresponding value of shear wave velocity at 30m depth (V_{S30}) is calculated and tabulated in Table 2 for all the 4 stations using the eq. 5 given by Kramer, (1996), for a single layer model over half space;

$$V_Z = f_{peak} 4H \tag{5}$$

Here, H is the soil depth (taken as 30m) and V_z is shear wave velocity at depth z. The value of V_{s30} obtained in the present study (Table 2, Column 2) is used to classify the stations based on the classification scheme used by PESMOS (Table 2, Column 4) and is compared with the SC given in PESMOS (Table 2, Column 3). According to the SC given in PESMOS, all four stations belong to SC A indicating rock site. However, based on the present study Darchula, Lansdome and Chamoli stations have f_{peak} values of 2.5Hz, 1.35Hz and 3.5Hz respectively and corresponding V_{s30} values of 300m/s, 162m/s and 177m/s. As per the PESMOS classification scheme these stations belong to SC C based on the present work indicating soft soil sites.

Table-2 Summary of shear wave velocity and site class as per PESMOS and NEHRP classification

Recording Station	V_{s30} (m/s)	Site Class: Given in PESMOS	Site Class: Actual site class (PESMOS scheme)	Site Class: NEHRP
-1	-2	-3	-4	-5
Champawat	660	A	A	C
Dharchula	300	A	C	D
Lansdome	162	A	C	E
Chamoli	177	A	C	E

In addition to the PESMOS classification, SC based on NEHRP classification scheme (Table 2, Column 5) is also estimated for the 4 recoding stations. NEHRP classification scheme consists of 5 SCs namely; SC A (Vs 30 > 1500 m/s), SC B (760 m/s < Vs 30 >1500 m/s), SC C (360 m/s <Vs 30 > 760 m/s), SC D (180 m/s <Vs 30 > 360 m/s) and SC E (Vs 30 <180 m/s). Based on the present work, Champawat belongs to SC C, Darchula belongs to SC D and Lansdome and Chamoli belongs to SC E and thus obtained SC are significantly different from existing SC as per PESMOS. This is clear indication that existing SC in PESMOS is significantly different from SC suggested by ground motion records.

5. Conclusion

In the present study, SC of 4 recording stations located in the Garhwal Uttarakhand region are obtained from recorded accelerograms at these stations using GINV and HVSR methods. The horizontal to vertical ratio curves obtained using HVSR and GINV show similarity in terms of the general shape. The value of f_{peak} obtained from the horizontal to vertical ratio curves using the GINV and HVSR are also found to be similar. Based on the value of f_{peak} ,V_{s30} for the 4 recording stations are calculated for finding the SC. The present study clearly shows a mismatch in SC given by PESMOS and the one obtained from present work The ground motion recorded given in PESMOS for the recording stations cannot be used confidently for any ground response study since the existing SCs for these stations are ambiguous. Based on the present work it is found that while PESMOS gives SC A for selected 4 recording stations, GINV and HVSR suggest that these stations belong to SC C and D. In the absence of geotechnical and geophysical tests data which too quantify the subsoil characteristics and determine SC, GINV and HVSR methods can be used to classify the recording stations.

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