



Site response analysis of the Kashmir valley during the 8 October 2005 Kashmir earthquake (M_w 7.6) using a geotechnical dataset

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Abstract

The site response analysis of Kashmir valley during the 8 October 2005 Kashmir earthquake (M_w 7.6) using the standard penetration test ‘N value’ (SPT N) geotechnical dataset is presented. Due to non-availability of the strong motion data records, synthetic ground motions at the bedrock level were generated at each borehole location by the stochastic finite fault method. The soil type-specific relationships between SPT N value and shear wave velocity were used to generate shear wave velocity profiles at each borehole site, which were later interpolated to map the shear wave velocity pattern in the Kashmir valley. The analyses revealed that site classes C and D of the NEHRP classification are dominant in the valley. The site response analysis conducted using the equivalent linear approach with DEEPSOIL showed that the local site conditions play an important role in the transmission of ground motion from the bedrock to the surface in the Kashmir valley, suggesting that it is imperative to consider the site effect in the seismic hazard assessment of the Kashmir valley. A detailed analysis of four important localities of Kashmir valley, namely, Anantnag, Baramulla, Kupwara and Srinagar, was also performed.

Keywords Kashmir · Site response · Earthquake · Stochastic ground motion

Introduction

It is very well established that soft sediments can cause considerable amplification and increase the duration of ground motion during an earthquake, which can consequently increase the severity of damage and destruction; this phenomenon is usually referred to as the site effect (Laoumani and Slimani 2013). The exceptional damage caused to Mexico City (~ 300 km away from the epicenter) during the 19 September Michoacan earthquake of 1985 (M_s 8.1) is the best

example to date of the importance of local site conditions in the damage pattern of an earthquake (Singh et al. 1988). The excessive damage to buildings and infrastructure was attributed to site effects, such as the amplification ratio and resonant frequency of the Mexico City alluvium. It is therefore necessary to consider the contribution of local site effects when designing earthquake-resistant infrastructures and making a seismic hazard assessment of a region (Bindi et al. 2009). Due the importance of site response in seismic hazard analysis, seismic design and seismic microzonation, various studies using different methodologies in different seismic hazard-prone regions have been carried out (e.g. Ordaz and Faccioli 1994; Steidl 2000; Castelli et al. 2016).

We report a site response analysis of the Kashmir Valley during the 8 October 2005 Kashmir earthquake (M_w 7.6) using a geotechnical dataset.

The valley of Kashmir is a picturesque, northwest–southeast directed basin, about 140 km long and 60 km wide, in the northwestern Himalaya. It is a tectonic, Neogene–Quaternary, intermountain basin within the northwest Himalayan fold and thrust belt, where a

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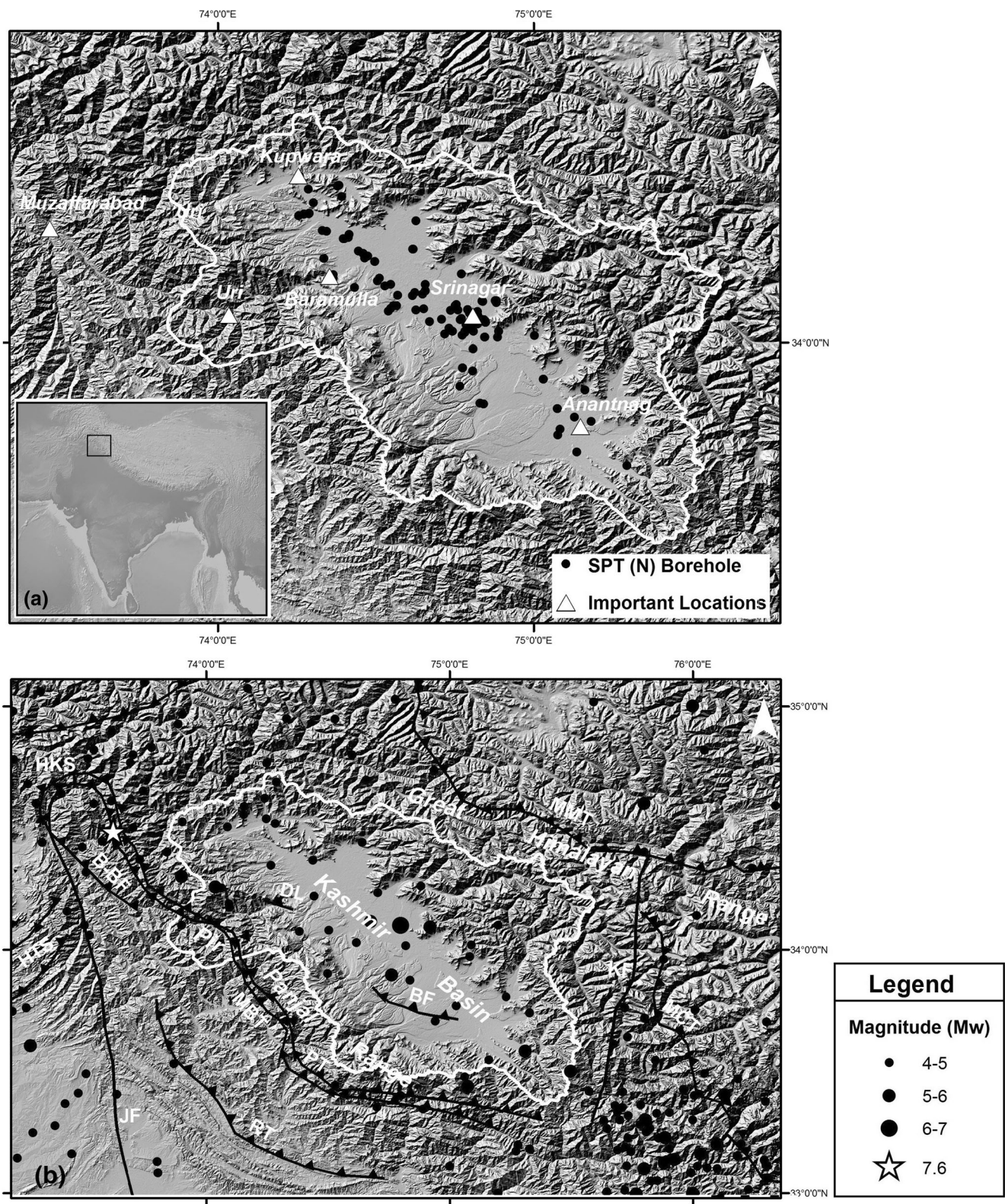


Fig. 1 **a** Map showing important locations and the standard penetration test (SPT) (N = standard penetration value) at borehole sites in Kashmir Valley. **b** Seismotectonic map of the Kashmir Basin and surroundings with main tectonic features. *B-BF* Bagh-Balakot Fault, *BF* Balapur Fault, *DL* Drangbal-Laridora Fault, *HKS* Hazara-Kashmir Syntaxis, *HTS* Hazara Thrust System, *KF* Kishitwar Fault, *JF* Jhelum Fault, *MBT* Main Boundary

Thrust, *MCT* Main Crystalline Thrust, *MMT* Main Mantle Thrust, *PT* Panjal Thrust, *RT* Reasi Thrust. Seismotectonic map of faults are from Dasgupta et al. (2000), *BF* is from Ahmad et al. (2014) and *DL* is from Sana and Nath (2016). *Star* Epicenter of 8 October 2005 Kashmir earthquake (M_w 7.6). **c** Lithology map of Kashmir Valley from Bhatt (1989) with SPT (N) borehole sites and benchmark locations in the Kashmir Valley

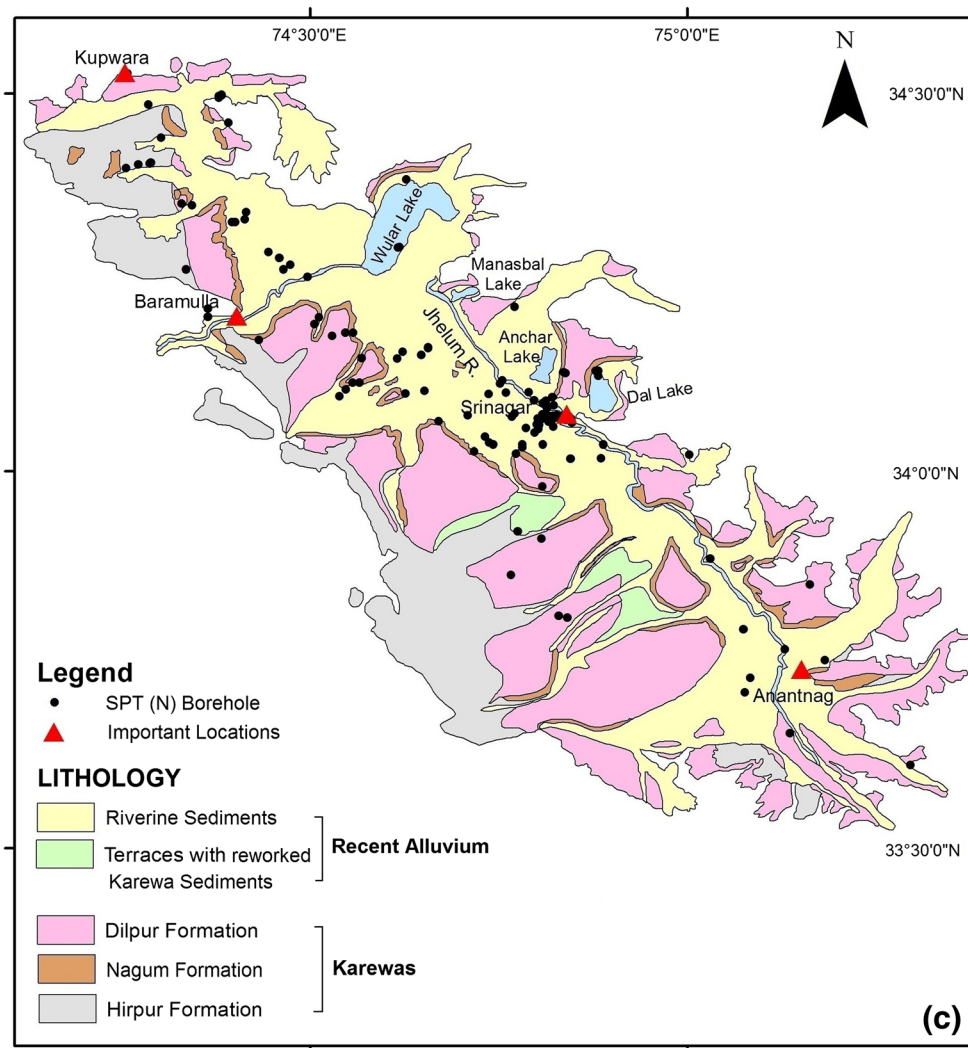


Fig. 1 (continued)

metamorphosed basement is overlain by thick Quaternary to Recent fluvio-lacustrine alluvium and surrounded by Paleozoic and Mesozoic peripheral rocks (Kazmi and Jan 1973). Sedimentation in the Kashmir basin started ~ 4 million years ago. Since then a sedimentary alluvium of > 1300 m thick has been deposited, comprising both older (Karewas) and younger (riverine) sediments. The older sediments are Plio-Pleistocene in age and the Recent sediments date from the late Pleistocene–Holocene. The former are known as the ‘Karewas’ (‘elevated table-land’ in Kashmiri dialect) and have been ascertained to be fluvio-lacustrine in origin. These sediments are synorogenic and have recorded the entire developmental history of the Kashmir basin. The Karewas are soft, unconsolidated, sand–clay–conglomerate deposits that cover nearly half of the Kashmir valley floor (~ 5000 km²), forming flat to mildly inclined elevated landforms, while as the rest of the valley floor is overlain by loose riverine alluvial sediments.

The riverine sediments comprise clay, silt, sand and terraces with reworked Karewa sediments (Burbank and Johnson 1982, 1983; Burbank 1983; Bhatt 1989). The lithology map of the Kashmir basin is shown as Fig. 1c.

Due to the active tectonic set-up in and around this basin (Fig. 1b), this region has experienced various destructive earthquakes (Ambraseys and Douglas 2004), the most recent being the 8 October 2005 Kashmir earthquake (Avouac et al. 2006). The 8 October 2005 Kashmir earthquake of magnitude (M_w) 7.6 caused huge loss to life and property, with about 86,000 people killed and more than 69,000 injured (U.S. Geological Survey [USGS]; <https://earthquake.usgs.gov/learn/today/index.php?month=10&day=8&submit=View+Date>). The worst affected area was Muzaffarabad district, with the northwestern part of the Kashmir Valley also suffering heavy damage, particularly the towns of Uri and Kupwara (80% of Uri town was destroyed) (Fig. 1a). Infrastructure in the Kashmir valley was also heavily damaged, with at least

Fig. 2 Soil profile with SPT N values of a borehole bored at a site in Srinagar

FIELD BORE LOG FOR SUBSURFACE EXPLORATION					Dated:31-01-11 to 05-02-11	Job No: 1								
PROJECT: Transmission Line Tower Construction.					Sheet 3 of 3									
Site / Location: Hanjuk, Soibugh, near Hokarsar, Srinagar, KASHMIR DIVISION					CLIENT: PDD (Survey Division, S&O Wing, Bemina), Srinagar, Kashmir.									
Boring Type: Auger/ Wash					Borehole No: BH-3 (M-4 location)									
Soil/Rock Classification System: IS					Boring Diameter: 150mm									
Seepage water encountered at: NIL (m)					Sampling Type: Standard Split Spoon (With SPT) UDS									
					Elevation Reference: NSL (+0.00)									
					Ground water encountered at: 0.35 (m)									
Depth Interval below NSL (m)	Blow Count (45cm Penetration)				(VISUAL IDENTIFICATION) For TYPE- DS/UDS samples Approximate description of disturbed bored material (Soil colour, Consistency, Grain size, Compressibility etc.)	Remarks	PENETRATION RESISTANCE CHART (Not to scale)							
	0-15cm	15-30cm	30-45cm	SPT values (N)			2	4	6	8	10	12		
1.5m	1	0	0	0	Dark Grey/Blackish silty soil with decomposed organic matter/ Fibrous Peat of high compressibility and soft nature.	(40 % fines, 60% OM)								
3.0m	0	0	0	0	Dark Grey/Blackish silty soil with decomposed organic matter/ Fibrous Peat of high compressibility and soft nature.	(65 % fines, 35% OM)								
4.5m	3	3	3	6	Grey fine sand of loose nature.	(20 % fines, 80% Sand)								
6.0m	3	3	4	7	Grey fine sand of loose nature.	(20 % fines, 80% Sand)								
7.5m	1	2	2	4	Grey silty soil with decomposed fibrous peat/OM of overall very soft consistency.	(75 % fines, 25% OM)								
9.0m	1	2	2	4	Grey silty soil with decomposed fibrous peat/OM of overall very soft consistency.	(80 % fines, 20% OM)								
12.0m	2	3	3	6	Dark Grey silty soil of medium soft consistency, with organic intrusions.	(90 % fines, 10% OM)								
15.0m	2	3	3	6	Dark Grey silty soil of medium soft consistency, with organic intrusions.	(90 % fines, 10% OM)								
18.0m	2	3	4	7	Grey silty soil of medium soft consistency.	(90 % fines with 10% sand/OM)								
21.0m	2	3	4	7	Grey silty soil of medium soft consistency.	(90 % fines with 10% sand/OM)								
24.0m	2	3	3	6	Dark Grey silty soil of medium soft consistency and compressible nature.	(70 % fines, 20% sand, 10% gravel)								
25.0m														

32,335 buildings collapsing in the districts of Anantnag, Baramulla, Jammu and Srinagar. Liquefaction and sandblows also occurred in the northwestern part of the Kashmir

Table 1 Borehole site classification according to the National Earthquake Hazards Reduction Program based on average shear wave velocity to a depth of 30 m

NEHRP site class	Rock/soil type	V _s 30 (m/s)
A	Hard rock	> 1500
B	Rock	760–1500
C	Dense soil/soft rock	360–760
D	Stiff soil	180–360
E	Soft soil	< 180

NEHRP, National Earthquake Hazards Reduction Program; V_s 30, Average shear wave velocity to a depth of 30 m

valley, particularly in some parts of Baramulla (Sana and Nath 2016). Due to the high magnitude and widespread damage trajectory of the 8 October 2005 Kashmir earthquake, the synthetic ground motions of this earthquake at bed-rock level were used as input motion and transmitted to the surface using one-dimensional (1D) shear wave response of the soil column to decipher the site effect.

Standard penetration test data and National Earthquake Hazards Reduction Program site classification

For this study, standard penetration tests (SPT) were carried out and penetration values (N) calculated, conforming to Indian Standard Code IS2131 (Bureau of Indian

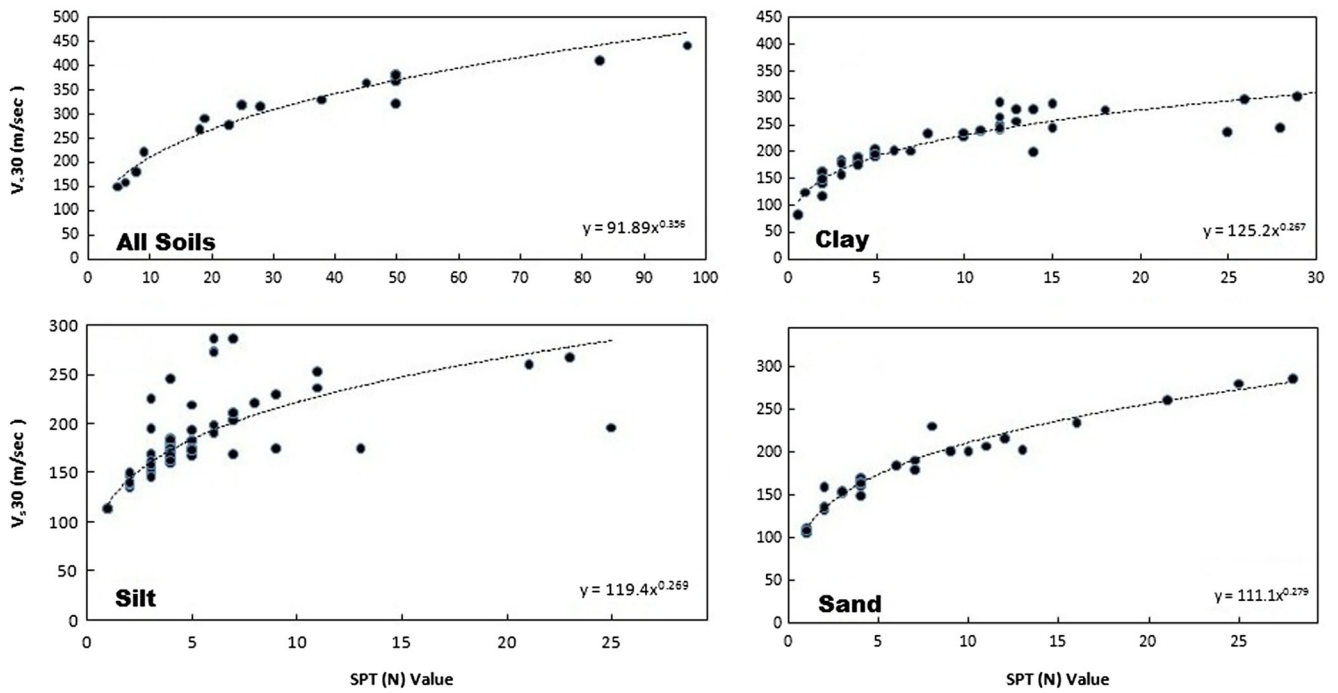


Fig. 3 Average shear wave velocity to a depth of 30 m ($V_{s,30}$) versus SPT N value for different soil types in the Kashmir valley alluvium using various relationships recommended in the Microzonation Handbook

and Seismic Microzonation Manual (2011) published by the Ministry of Earth Sciences, Government of India

Standards 1997), by various geotechnical engineering consultancies and government agencies. Data from a total of 219 SPT boreholes from all over the Kashmir valley are considered for this study. The locations of all boreholes are shown in Fig. 1a, c. Figure 2 shows the detailed soil profile of a borehole from Srinagar city.

National Earthquake Hazards Reduction Program shear wave velocity site classification $V_{s,30}$ map

The obtained SPT N values give an idea about the shear strength of the soil column and behavior of soils under the application of seismic load. In order to determine the dynamic properties of soil, the obtained SPT N values are used to evaluate the shear wave velocity to a depth of 30 m ($V_{s,30}$) using soil type and/or region-specific relationships (Castelli et al. 2016; Ferraro et al. 2016). The National Earthquake Hazards Reduction Program (NEHRP) scheme uses this parameter for site classification to a depth of 30 m (Table 1) for designing earthquake-resistant infrastructure (Kramer 1997). In this study, we calculated the $V_{s,30}$ of soil columns using soil type-specific relationships between the $V_{s,30}$ and SPT N values. These relationships were obtained by the power law regression of various soil type-specific equations recommended in the Seismic Microzonation Handbook and Seismic Microzonation Manual (2011) by the Ministry of Earth Sciences, Government of India. The results of regression are shown in Fig. 3. The coefficients obtained from the regression analysis were used to develop equations to calculate the $V_{s,30}$ from the SPT N values for each soil type in the Kashmir valley (Fig. 3). The average of each soil column was interpolated in the geographic

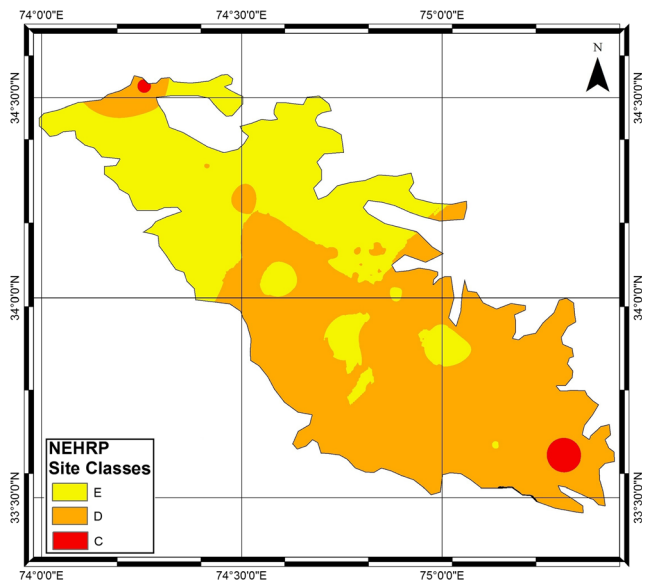


Fig. 4 Distribution of $V_{s,30}$ in the Kashmir basin

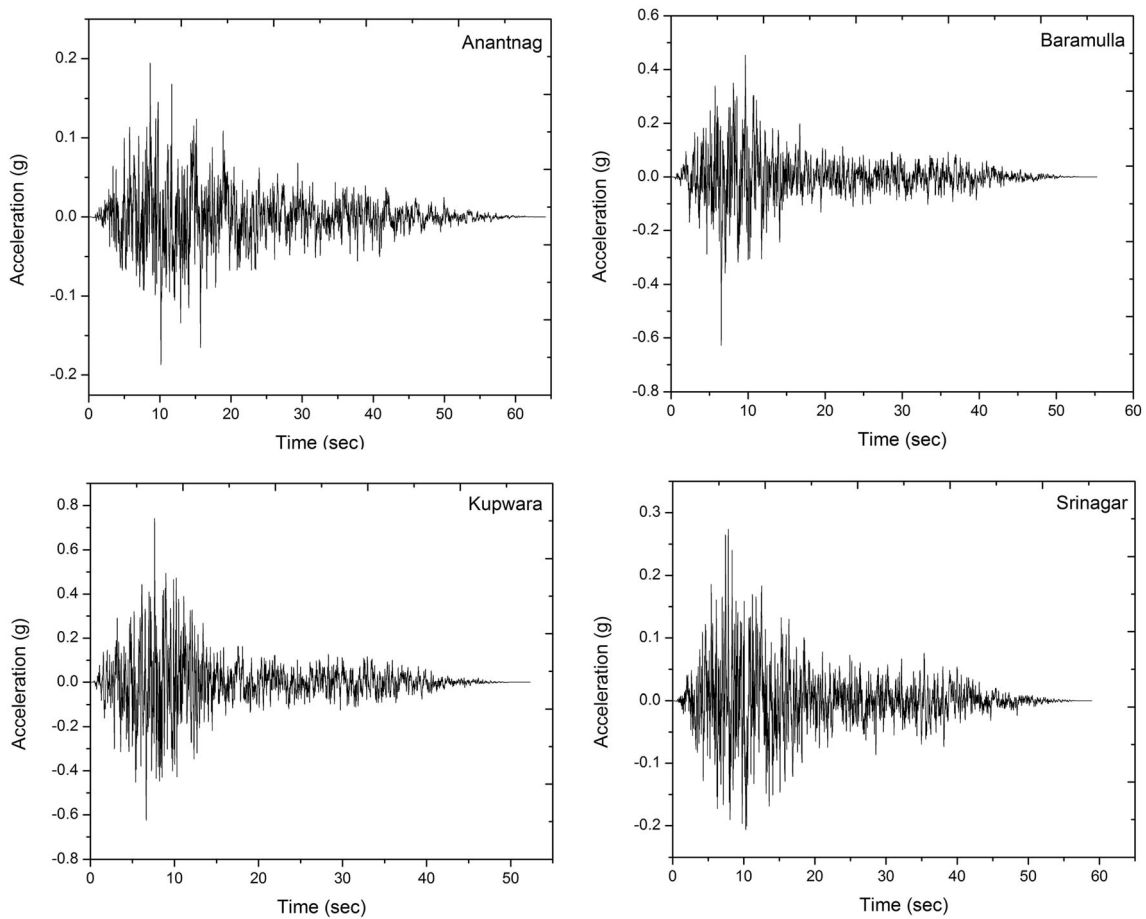


Fig. 5 Synthetic ground motions of 8 October 2005 Kashmir earthquake (M_w 7.6) at Anantnag, Baramulla, Kupwara and Srinagar at the engineering bedrock level

Table 2 Source parameters used for simulation of the peak ground acceleration of the 8 October 2005 Kashmir earthquake (M_w 7.6) at each borehole location

Parameter	Value
Strike	334°
Dip	34°
Hypocenter	34.38°N/73.47°E
Focal depth (km)	12
Magnitude (M_w)	7.6
Fault length/width (Km)	97/32
Stress drop (bar)	91.5
Shear wave velocity (Km/s)	3.12
Crustal density (g/cm^3)	3.20
Qs	$253f^{0.8}$
K	0.03

PGA. Peak ground acceleration; Qs, quality factor; K, kappa (parameter of high-cut filter, in seconds)

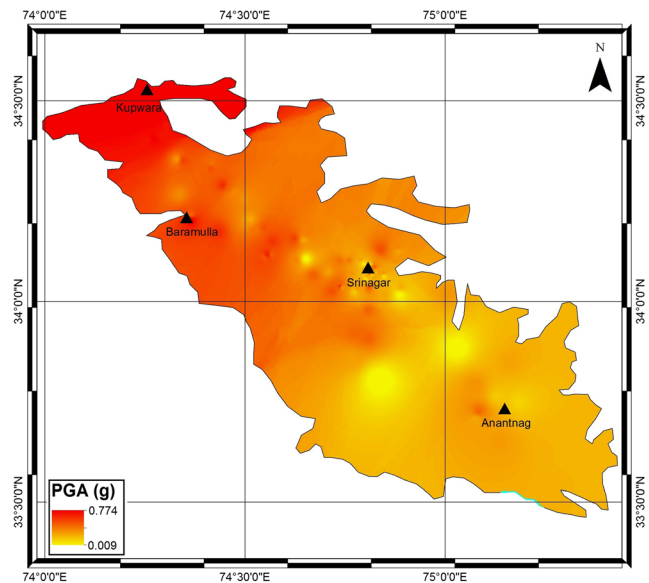


Fig. 6 Peak ground acceleration (PGA) of the 8 October 2005 Kashmir earthquake (M_w 7.6) at the surface level in the Kashmir valley

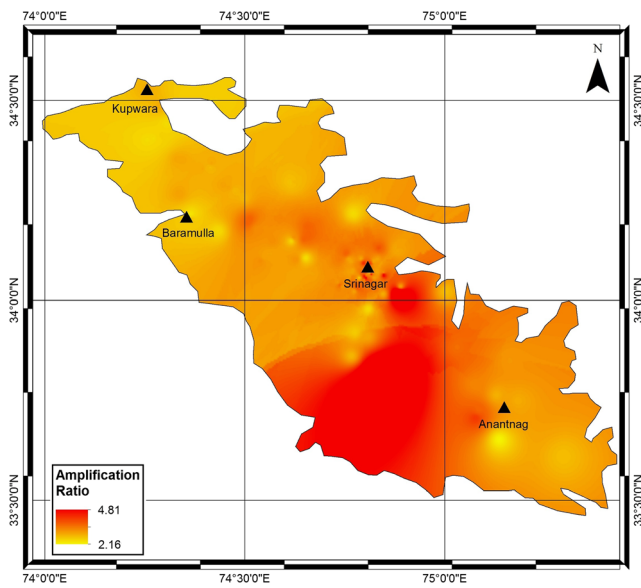


Fig. 7 Amplification ratio map of the Kashmir valley

information system (GIS) environment to generate the V_{s30} map of Kashmir valley alluvium, classified according to the NEHRP site classification scheme (Fig. 4). The inverse distance weighted (IDW) interpolation method was used to interpolate the V_{s30} values to obtain the $V_{s,30}$ map. The basic assumption in IDW method is that the influence of the variable, V_{s30} in the present case, decreases with increasing distance from the sampled point, i.e. the location of the SPT borehole.

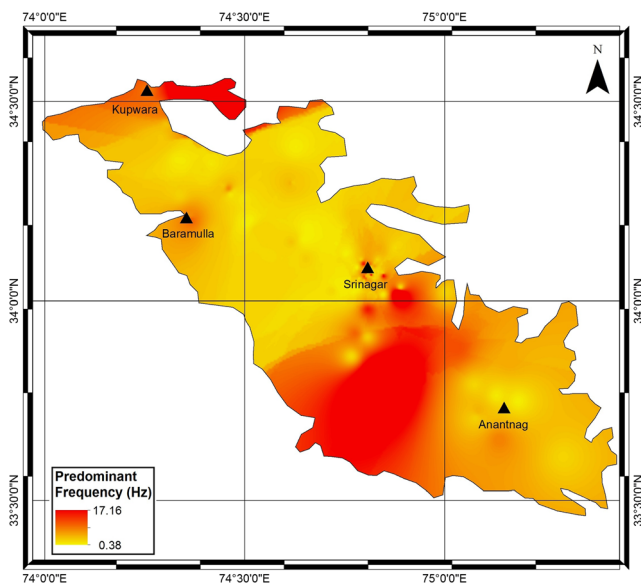


Fig. 8 Predominant frequency (Hz) map of the Kashmir valley

Methodology

Synthetic ground motion generation

Due to the inaccessibility of the strong motion records of 8 October 2005 Kashmir earthquake, we used the synthetic ground motion records in our study (Sana 2017). The synthetic ground motions were generated by the stochastic dynamic corner-frequency method of Motezidian and Atkinson (2005) at each borehole location. The stochastic finite-fault model as represented by Beresnev and Atkinson (1998) is:

$$A(\omega) = 2(\omega)^2 S(\omega) \exp(-\pi\kappa f) e^{-\frac{R}{2Q\beta}} \tag{1}$$

where, $A(\omega)$ is the Fourier amplitude site spectrum, $S(\omega)$ is the seismic source spectrum, the term $\exp(-\pi\kappa f)$ represents the filtering function in terms of spectral decay parameter κ (Anderson and Hough 1984), 'R' is the distance between site and source, 'Q' is the quality factor and ' β ' is the shear wave velocity (km/s).

The Beresnev and Atkinson (1998) technique is not sensitive to higher frequencies, and this problem was overcome by the introduction of dynamic corner frequency concept by Motezidian and Atkinson (2005). By replacing ' $f' = \frac{\omega}{2\pi}$ ' in Eq. (1) the acceleration spectrum (A_{ij}) of a shear wave generated from the (ij th) sub-fault can be described as:

$$A_{ij}(f) = \left\{ \frac{CM_{0ij}(2\pi f)^2}{[1 + (f_{0ij})^2]} \right\} \left\{ \frac{\exp(-\pi f \kappa) \exp\left(-\frac{\pi f R_{ij}}{Q\beta}\right)}{R_{ij}} \right\} \tag{2}$$

Where C is a constant, M_{0ij} is the seismic moment, f_{0ij} is the corner frequency and R_{ij} is the distance from the observation point. The constant C is a collective representation of radiation pattern ($\mathfrak{R}^{\theta,\varphi}$), free surface amplification (F) and density (ρ in g/cm^3), and is equivalent to $\mathfrak{R}^{\theta,\varphi} FV / 4\pi\rho\beta^3$, where V represents the division of the horizontal into two components. The corner frequency (f_{0ij}) is given by:

$$f_{0ij} = 4.9E + 6 \beta(\Delta\sigma) / M_{0ij} \tag{3}$$

where $\Delta\sigma$ is the stress drop (bars).

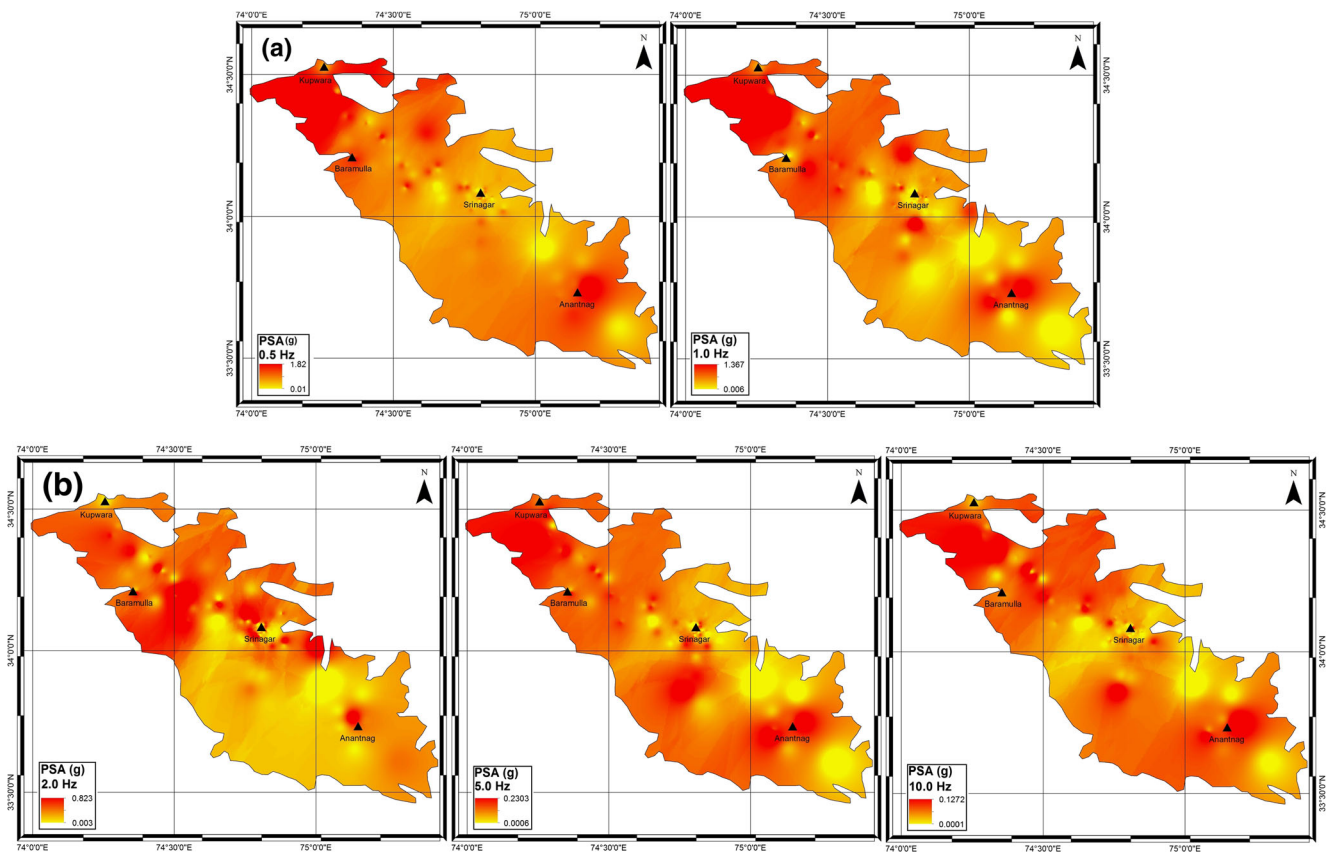


Fig. 9 a Pseudo-spectral acceleration (PSA) (g) distribution with 5% damping at frequencies of 0.5 and 1.0 Hz. b PSA (g) distribution with 5% damping at frequencies of 2.0, 5.0 and 10.0 Hz

1D site response analysis

The aim of 1D site response analysis is to analyze the vertical propagation of horizontal shear waves through the horizontally layered soil column from the elastic bedrock, which is assumed to extend to an infinite depth. The 1D site response analysis is carried out either using a non-linear approach (e.g. Ferraro et al. 2016) or an equivalent linear approach. In the present study, ground response analysis was carried out by the equivalent linear approach using DEEPSOIL, a 1D site response analysis platform (Hashash et al. 2016). In the equivalent linear approach, the non-linearity of the shear modulus and damping ratio (%) are accounted for through the use of equivalent linear soil properties using an iterative procedure to obtain values for modulus and damping compatible with the effective strains in each layer. Corresponding soil properties of each layer are modeled by using the small-strain shear modulus reduction (G/G_{\max}) and damping ratio (%) versus shear strain curves, where 'G' is the shear modulus at a given

point and ' G_{\max} ' is the initial shear modulus. The (G/G_{\max}) and damping ratio curves are defined using discrete points at various strain levels. An elaborate and detailed analysis of the equivalent linear approach is provided in Hashash et al. (2016).

Results of the site response analysis of Kashmir valley

The V_{s30} for all 219 SPT boreholes sites was evaluated using the derived V_{s30} relationships for soil types prevalent in the Kashmir valley. The obtained V_{s30} values show that site classes C, D and E of the NEHRP site classification scheme prevail in Kashmir valley, with site classes C and D being the dominant classes. The synthetic ground motions of 8 October 2005 Kashmir earthquake were then generated at the engineering bedrock level for all of the the SPT borehole locations in the Kashmir valley (Sana 2017). The generated ground motions were used as inputs

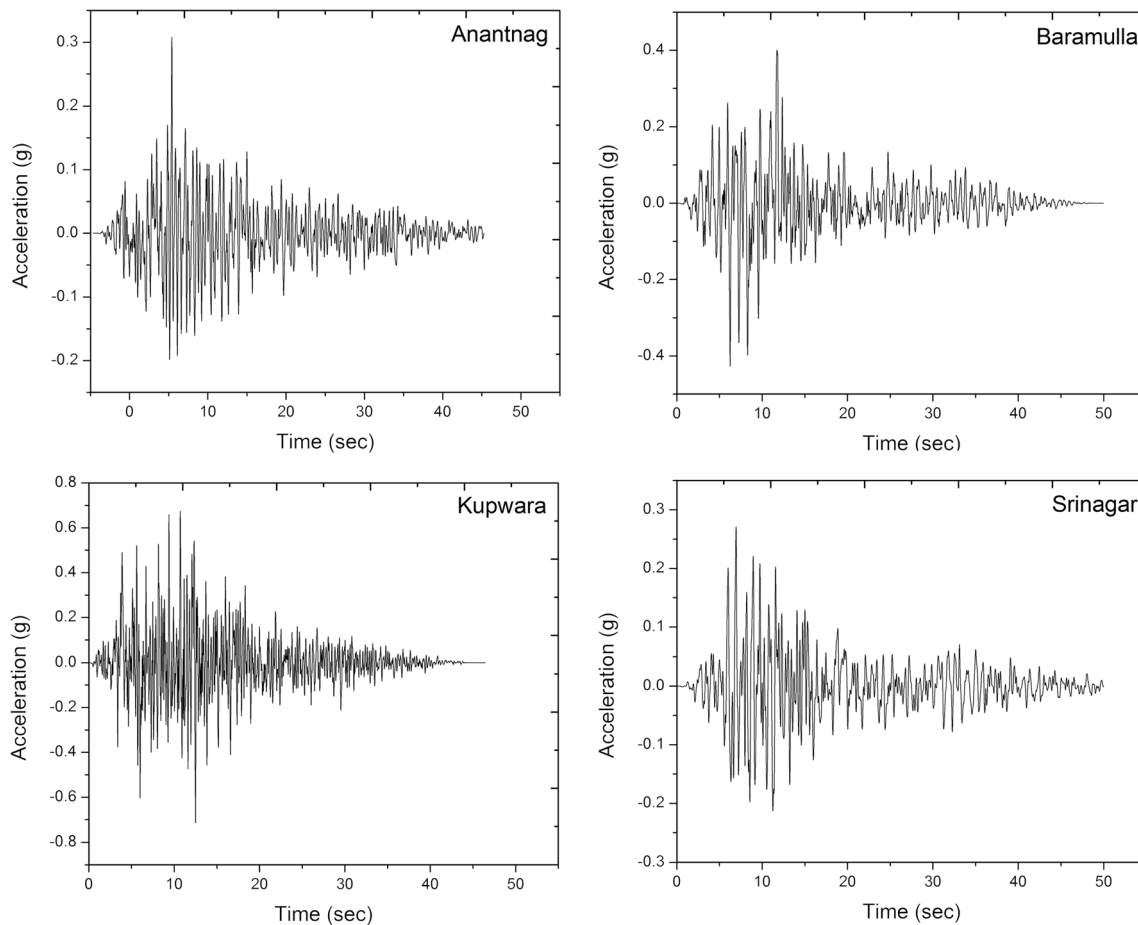


Fig. 10 Synthetic ground motions of the 8 October 2005 Kashmir earthquake (M_w 7.6) at the surface in Anantnag, Baramulla, Kupwara and Srinagar

and transmitted through all of the the 219 SPT boreholes. The synthetic seismograms for Anantnag, Baramulla, Kupwara and Srinagar in the engineering bedrock are shown in Fig. 5. The source parameters are taken from Singh et al. (2006), Mandal et al. (2007) and Raghunath (Raghukanth 2008) and shown in Table 2.

For the entire Kashmir valley, the obtained site response parameters for all SPT borehole locations were interpolated in the GIS environment to generate the site response maps. The peak ground acceleration (PGA), amplification ratio and predominant frequency at the surface level of Kashmir valley in relation to the 8 October 2005 Kashmir earthquake (M_w 7.6) are shown as Figs. 6, 7 and 8, respectively. The PGA at the surface can be seen to range from 0.09 to 0.77 g and not to be evenly distributed due to variations in the soil profile across the valley. It is clear that the PGA at the engineering bed rock is influenced by proximity to the epicenter while at the surface level is

clearly influenced by the soil profile. The PGA is considerably higher in the northwestern part of the valley, mainly due to its relatively closer proximity to the epicenter of the earthquake. The unevenness in the PGA distribution in the central and southeastern part of the valley, with relatively thick deposits of soft sediments, illustrates the site effect. From the seismic hazard perspective, ground motions with PGA of ≥ 0.3 g are more destructive to engineering structures; however, high PGA with very high frequencies and of short duration is less destructive to the engineering structures (Christenson 1994). The amplification ratio is defined as the factor by which the PGA increases from the engineering bed rock to the surface. Evaluation of the amplification ratio results show that this ratio ranges from 2.1 to 4.8 in the valley alluvium and that the values are higher in the southeastern part of the valley. These areas are characterized by a lower V_{s30} and relatively thick sediment cover. The The predominant frequency of the

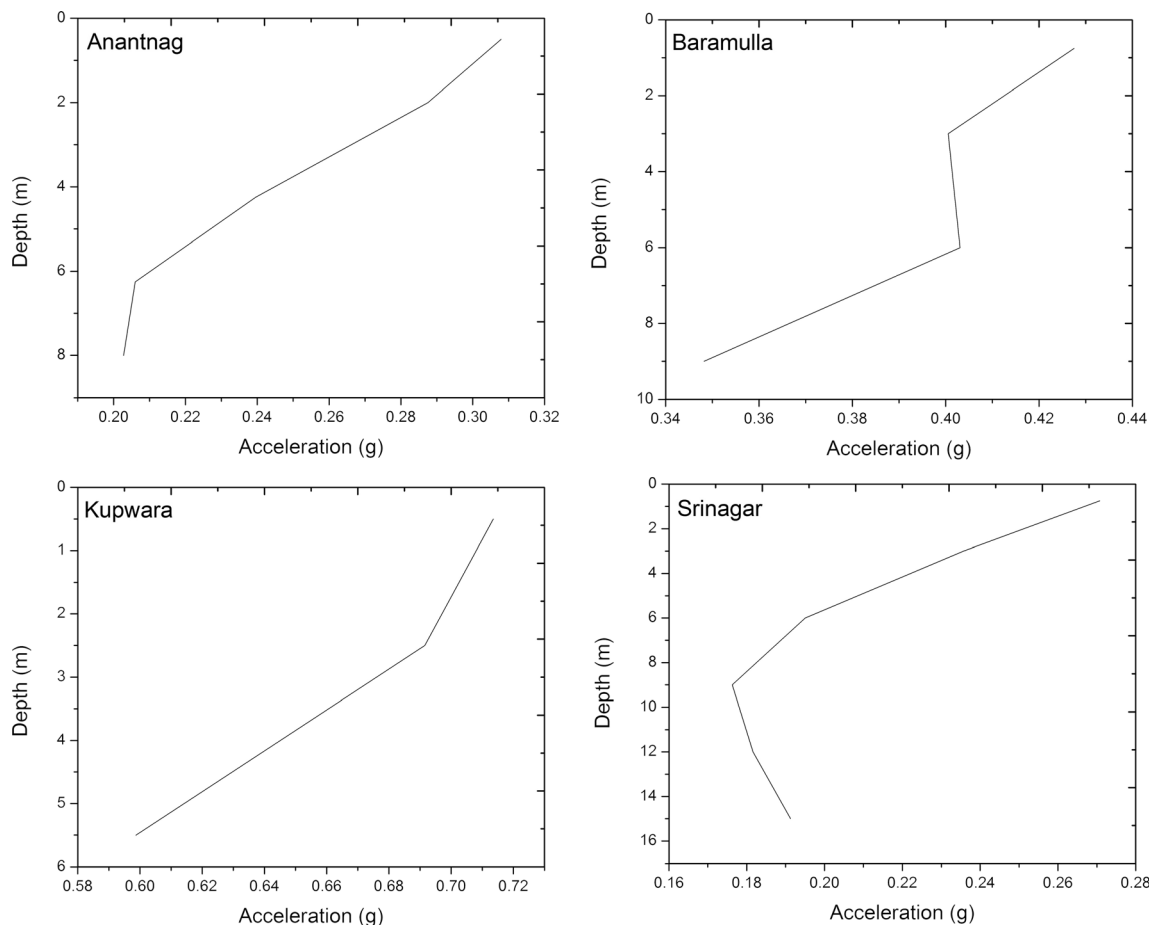


Fig. 11 Variations in PGA with depth at Anantnag, Baramulla, Kupwara and Srinagar

Fourier spectrum was found to be higher in the northeastern and southeastern parts of the Kashmir valley. Both the amplification ratio and predominant frequency have major effects on the severity of damage caused to the buildings in an area affected by the earthquake. Low-rise buildings (one to two-storey) are more vulnerable to strong, high-frequency ground motions which are strongest near the epicenter and dissipate with increasing distance, and strong, low-frequency ground motions are more destructive to high-rise buildings. Low-frequency ground motions dissipate much slower than high-frequency ground motions and thus can cause damage at great distances from the epicenter. Also, high-rise buildings are amplified more in the central parts of a basin while thin sediment cover over shallow bedrock amplifies the high-frequency ground motions that are most destructive to low-rise buildings. In terms of the material and type of building, unreinforced brick or masonry structures are more vulnerable to destruction than low-rise wooden frame houses and reinforced

steel-framed high-rise buildings (Christenson 1994). In the present case, the Kupwara and Uri (Baramulla) regions were the areas worst affected by the 8 October 2005 Kashmir earthquake. These areas are characterized by having been less distant from the epicenter, subjected to relatively strong high-frequency ground motions and being areas of thin soil cover over shallow bedrock. All of these factors can be described as being ideal for the destruction of the mostly, low-rise unreinforced stone masonry dwellings of these areas.

The spectral acceleration maps at 0.5, 1.0, 2.0, 5.0 and 10 Hz are shown in Fig. 9a, b. The spectral accelerations were evaluated at these frequencies as the natural frequencies of single-storey dwellings through to high-rise buildings fall within this range.

The complete site response analysis of boreholes from Anantnag, Baramulla, Kupwara and Srinagar is shown in Figs. 10, 11, 12 and 13, respectively. The synthetic ground motions at the surface of these locations are shown in Fig.

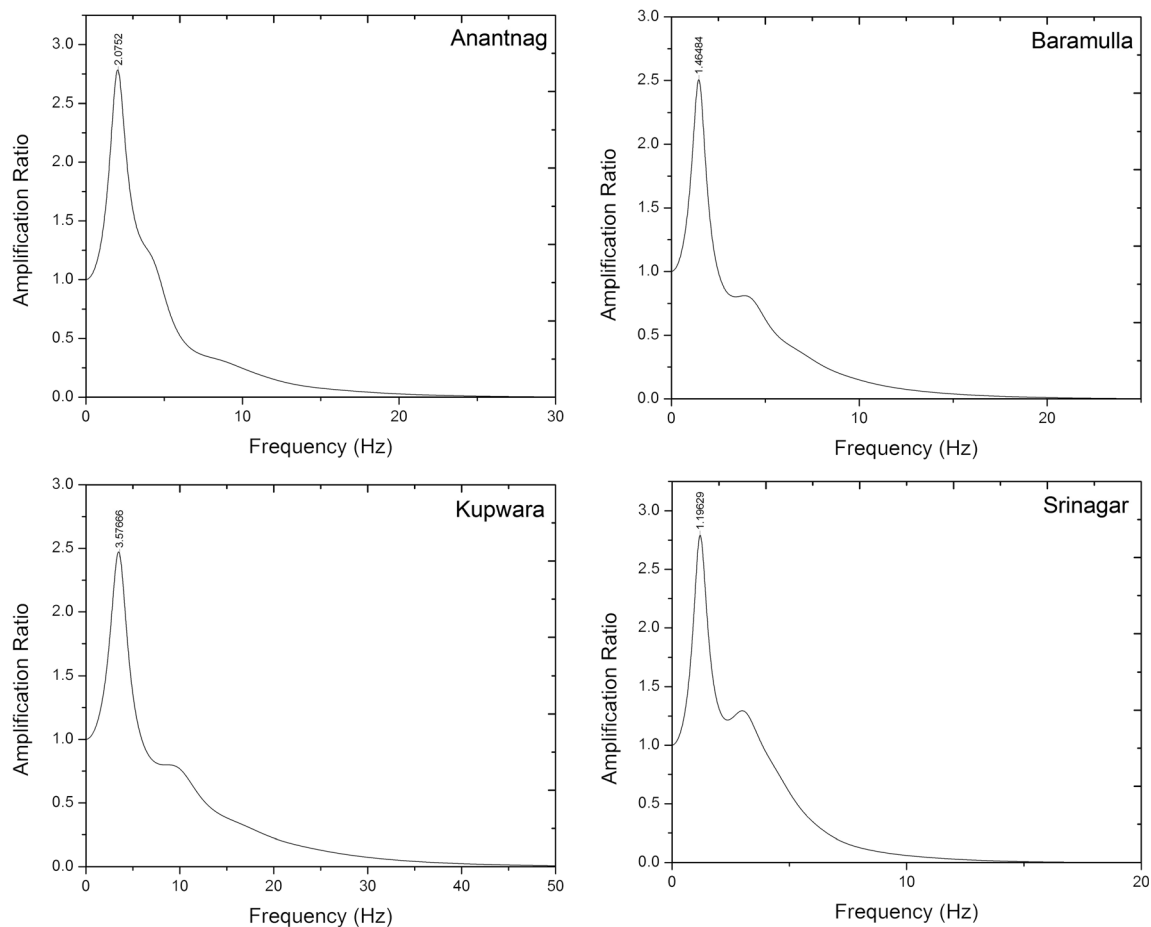


Fig. 12 Amplification between surface and base motion at Anantnag, Baramulla, Kupwara and Srinagar

10. The time history of acceleration from a particular depth to the surface of the soil profile of each location is shown in Fig. 11, revealing that there is a considerable variation in PGA with depth. It is clear that the PGA increases considerably as it approaches the surface. The Fourier amplification ratio plots (Fig. 12), with a peak amplification ratio of the particular frequency, are also shown in Table 3. Finally, spectral acceleration at the ground surface, i.e. the response spectra with 5% damping, is shown for the benchmark sites in Fig. 13. In terms of the benchmark sites, Anantnag, Baramulla, Kupwara and Srinagar have a predominant frequency of 2, 1.5, 3.6 and 1 Hz, respectively, which matches the natural frequency of four-, five-, two and ten-storey buildings, respectively.

Discussion and conclusion

The site response analysis of the Kashmir valley during the disastrous 8 October 2005 Kashmir earthquake (M_w 7.6) and

the detailed site effect analysis of soil profiles at Anantnag, Baramulla, Kupwara and Srinagar are presented in this study. A total of 219 SPT N boreholes were analyzed with the aim to study the dynamic properties of the soil and to evaluate the behavior of soils upon application of seismic load. The SPT N values were used to evaluate the V_{s30} for all borehole locations. In the NEHRP site classification scheme, site classes C, D and E are prevalent in the Kashmir valley, with site classes D and E being the dominant ones. PGA at the surface was found to range from 0.09 g to 0.77 g, being considerably higher in the northwestern part of the valley, mainly due to the closer proximity to the epicenter of the earthquake. This uneven distribution in the PGA also illustrates that the lithology of the Kashmir valley alluvium is not uniform and varies in terms of dynamic soil properties. These ground motions caused a high degree of damage and destruction in this part of Kashmir, particularly in Baramulla (Uri) and Kupwara, which is evident from the PGA at the surface (0.43 and 0.71 g, respectively).

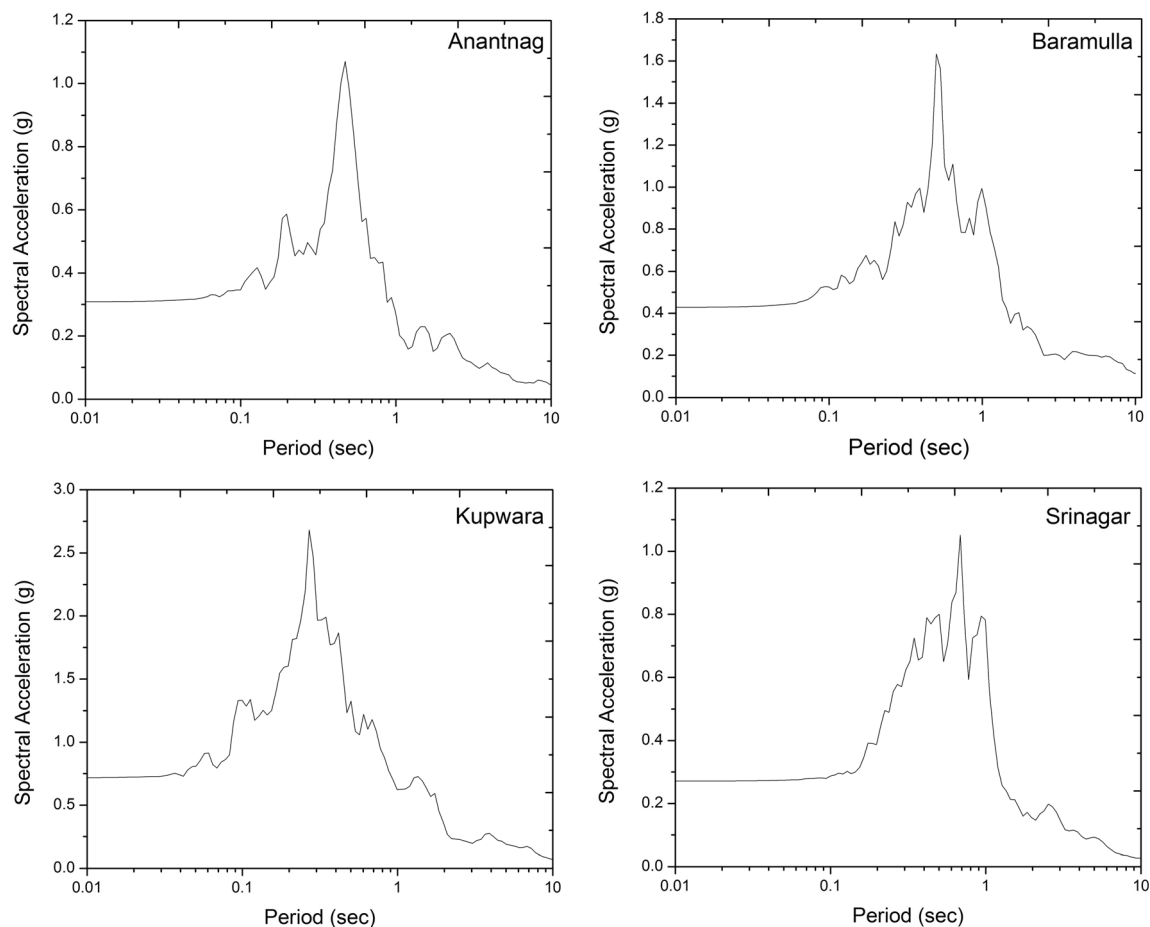


Fig. 13 Response spectra for 5% damping at ground surface for Anantnag, Baramulla, Kupwara and Srinagar

The PGA increases in value at the surface, showing a considerable increase with decreasing depth up to the surface level, thereby illustrating the site effect. The amplification ratio varies from 2.1 to 4.8 across the valley, with higher values in the central and southeastern parts of the valley, mainly attributable to the thick sediment cover. The predominant Fourier frequency varies from 0.38 to 17.16 Hz, with the dominant range being 0.38–4.11 Hz and mostly found in the northwestern side of the

valley. These frequencies match the natural frequency of two- to ten-storey buildings. To represent the natural frequency of low-rise through to high-rise buildings we also developed spectral maps at 0.5, 1.0, 2.0, 5.0 and 10 Hz. The predominant frequency at each benchmark site—Anantnag, Baramulla, Kupwara and Srinagar—was found to be 2, 1.5, 3.6 and 1 Hz, respectively, which matches the natural frequency of four-, five-, two and ten-storey buildings, respectively.

Table 3 Amplification ratios at a particular frequency for the four benchmark locations across the Kashmir valley

Name of site	Location of site	Distance from epicenter (km)	Frequency (Hz)	Amplification ratio
Anantnag	33°43'52.05" N/ 75°08'55.32" E	170	2.1	2.8
Baramulla	34°11'56.58" N/ 74°20'59.82" E	79	1.5	2.5
Kupwara	34°31'34.24" N/ 74°15'16.61" E	62	3.6	2.5
Srinagar	34°05'01.17" N/ 74°47'50.53" E	121	1.2	2.8

In summary, the results of this study can be used as a basis to carry out seismic microzonation of Srinagar city as well as other major towns in the Kashmir basin.

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