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Prediction of Ground Response Spectrum of Jalandhar City of Punjab using Non-Linear Ground Response Analysis

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Abstract. The increasing occurrence of seismic activities worldwide, along with the growing emphasis on microzonation, has highlighted the crucial role of soil properties in seismic assessment. In this study, a non-linear Ground Response Analysis (GRA) was performed to evaluate the effects of earthquakes on local soil conditions. The software DEEPSOIL v6.1 was used to generate response spectra for 35 borehole locations in Jalandhar, Punjab, using available geotechnical data.

Bedrock motion data were incorporated from PESMOS and COSMOS databases. Shear wave velocity was estimated empirically by establishing a correlation with Standard Penetration Test (SPT-N) values. Based on the calculated average shear wave velocity up to a depth of 30 meters, 20 borehole sites were classified according to the guidelines of the National Earthquake Hazards Reduction Program (NEHRP).

The results of the analysis were further applied to a real construction project to derive practical insights. Seismic analysis was conducted using STAAD Pro to evaluate base shear, considering various load combinations. The obtained results were compared with both site-specific response spectra and those prescribed by the Indian Standard (IS) code to identify any variations. This comparison helps in assessing the accuracy and effectiveness of the design with respect to site-specific conditions and regulatory requirements.

1. Introduction

Following the breakup of Pangaea, Gondwanaland experienced significant tectonic activity and continental drift, leading to its fragmentation into present-day landmasses such as Africa, India, and Australia. The Indian plate, characterized by a relatively thinner lithosphere, underwent rapid northward movement at an approximate rate of 5 cm per year toward the Eurasian plate [1]. This tectonic interaction increased the susceptibility of the region to natural hazards, particularly earthquakes.

In India, seismic design practices have traditionally relied on historical earthquake data, which often leads to the identification of fault lines and seismic sources only after the occurrence of an event. The 2001 Bhuj earthquake serves as a notable example, which subsequently led to the sixth revision of IS 1893, now divided into five parts addressing earthquake-resistant design for various structures.

Although proper seismic design can significantly mitigate earthquake risks, India's advancements in tradition, culture, technology, and knowledge have not been fully reflected in its earthquake-resistant construction practices. A more forward-looking approach to seismic design is necessary; however, current IS code recommendations are not entirely aligned with such considerations. Additionally, the seismic coefficients provided in the code are partly based on American datasets [2].

The seismic design provisions in IS 1893 (2016) are primarily based on macrozonation. The use of such broad zonation maps may result in either underestimation or overestimation of a region's seismic resistance capacity. This limitation highlights the need to shift toward microzonation, which incorporates site-specific geotechnical properties and the dynamic characteristics of structures.

The significance of local site conditions in influencing earthquake impacts has been demonstrated in several major seismic events worldwide, including the 1985 Mexico City earthquake, the 1989 Loma Prieta earthquake, the 1995 Kobe earthquake, and the 1999 İzmit earthquake. These events revealed that even areas located 100–300 km away from the epicenter experienced severe damage due to the amplification effects of local soil and site conditions. The Bhuj earthquake (2001) is also a notable example of damage occurring 250 km away from the epicentre. These incidents occur due to the1
influence of soil conditions on ground motion, resulting in increased amplitude and modifications to the spectral content and duration of the ground shaking. Site-specific ground response analysis is conducted to understand and assess these effects by studying the unique soil conditions present at a given location [3].Usage of such minute properties of site for seismic design will help in predicting the futuristic scope of seismic tremors as well, hence reducing the risk. The difference in the distance seismic waves travel in rock versus soil highlights the significant impact that soil has on shaping ground motion and its interpretation [4].

Numerous studies have consistently demonstrated the significant influence of soil layer properties on the amplification of seismic waves. This relationship is illustrated in Figure 1, which highlights the correlation between soil characteristics and seismic wave amplification. Therefore, the dynamic properties of soil play a crucial role in the seismic analysis of structures. These properties include shear wave velocity (Vs), Poisson's ratio, soil density, damping ratio, and stiffness.

Shear wave velocity (Vs), defined as the speed at which shear waves propagate through soil, is a key parameter for assessing the soil's response to seismic loading. Although various surface-based geophysical methods are widely used to estimate Vs, they still face certain limitations and continue to evolve [5]. Additionally, such methods require specialized expertise and can be difficult to implement in densely populated urban areas.

To address these challenges, an alternative approach involves establishing empirical correlations between Vs and the Standard Penetration Test (SPT-N) values obtained from borehole investigations. This method offers a practical and accessible means of estimating Vs when direct measurement techniques are not feasible.

In the present study, data from 35 boreholes in the Jalandhar region were utilized to estimate Vs using an empirical relationship developed by Bajaj et al., based on Vs values obtained from 276 locations through Multichannel Analysis of Surface Waves (MASW) [6]. Furthermore, site characterization was performed based on the average shear wave velocity up to a depth of 30 meters, in accordance with NEHRP guidelines [7].

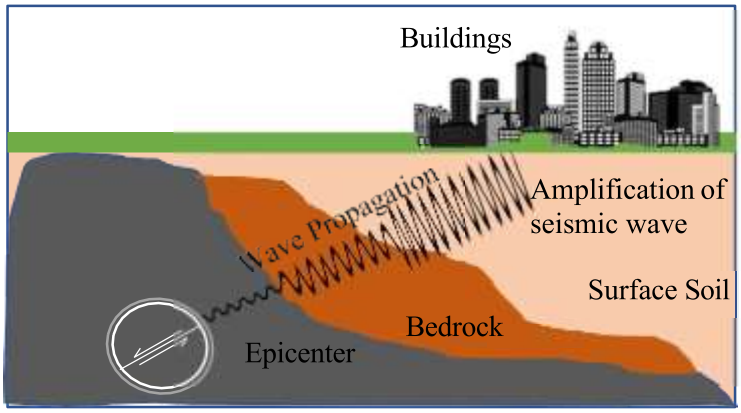

Figure 1. Seismic Wave Propagation

Currently in India IS 1893-2016 (Part 1) is used for earthquake resistant structure design [8]. the equivalent static force method and non-linear dynamic analysis, specifically the response spectrum method. In non-linear dynamic analysis, the structural model considered provides an estimation of deformations for different degrees of freedom. To determine the model responses, several combination methods are available, such as the Absolute Sum Method (ABS) method, Complete Quadratic Combination (CQC) method, Square Root of the Sum of the Squares SRSS method, and TEN (10PCT;10percent method). These combination methods are employed to calculate the combined effect of seismic forces on the structure, allowing for an assessment of its response [9]. The base shear plays a crucial role in the design against earthquakes as it represents the maximum lateral force anticipated at the foundation of a building due to seismic activity. It is a significant consideration for anti-seismic design and is influenced by various factors. These factors encompass the structure's inherent characteristics such as its natural frequency of oscillation, the ductility and overstrength provided by different structural arrangements, the soil conditions present at the construction site, and the overall weight of the structure.

DEEPSOILv6.1, a software tool for 1-Dimensional site response analysis, was employed in this research study to conduct non-linear site-specific response analysis[10]. Jalandhar, which is a city of Punjab which belongs to zone IV and high-risk zone is used for the analysis. And the analysis is done using 35 bore hole data collected from the site. During further progress of work base shear is calculated for a multistorey building designed with IS 1893-2016 response spectrum analysis and compared it with the base shear values obtained by using response spectrum obtained from site specific response analysis.

According to N. Ambraseys, the Himalayan region has undergone significant destruction due to previous seismic events [11]. As per Jade et al. the northern and eastern boundaries of the India plate are adjacent to the Eurasia plate, while its western boundary borders the Arabian plate, and to the south, it is bounded by the Somalia, Capricorn, and Australia plates [12].

Punjab is located in a fore-deep, which is a depression in the Himalayan foreland that varies in depth and has been converted into flat plains through prolonged and active sedimentation. Significant amounts of flexure and dislocation have been observed at the northern end of this area, which is demarcated by the Himalayan Frontal Thrust to the north. According to the earthquake hazard map displayed in figure 2, approximately 50% of the northern region in the state is prone to experiencing MSK Intensity VIII. Additionally, about 45% of the area is estimated to encounter Intensity VII.

Figure 2. Earthquake Hazard Map [19]

Jalandhar, a notable city with rich historical significance, is situated in the Doaba region of north- western Punjab, India. It is located on a highly fertile and intensively irrigated plain between the Beas and Sutlej rivers. The city covers a land area of approximately 2632 km^2 and is positioned at latitude 31.326°N and longitude 75.576°E. Based on data collected by Global Seismic Hazard Assessment Program (GSHAP), the state of Punjab is located in an area with moderate to high seismic hazard, and Jalandhar specifically falls under the high seismic hazard zone. In the present study nonlinear site- specific analysis is carried out using V_S values generated by 35 SPT-N values collected from the sites of Jalandhar. The location of bore hole data collected is provided in the figure 3.

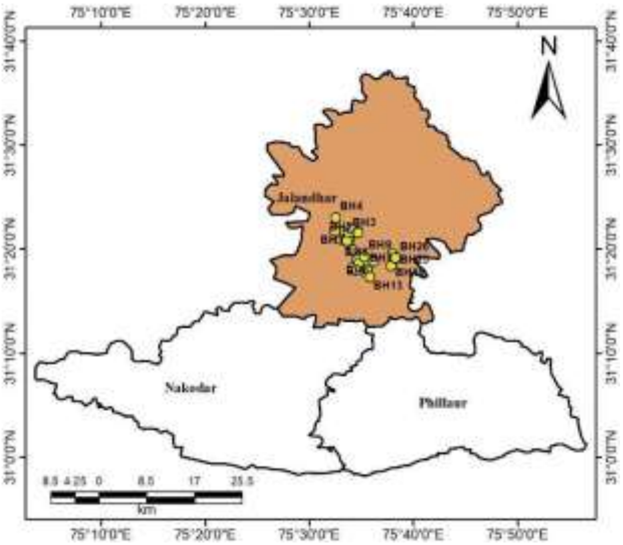

Figure 3. Location of Bore Hole Data

2. Methodology

The procedure of ground response analysis includes main steps such as site characterisation, dynamic characterisation, input motion selection, selection of analysis type, interpretation of results and validation of these data by comparing it with real time buildings. figure 4 illustrates the sequential steps followed in the present study for conducting site-specific response analysis.

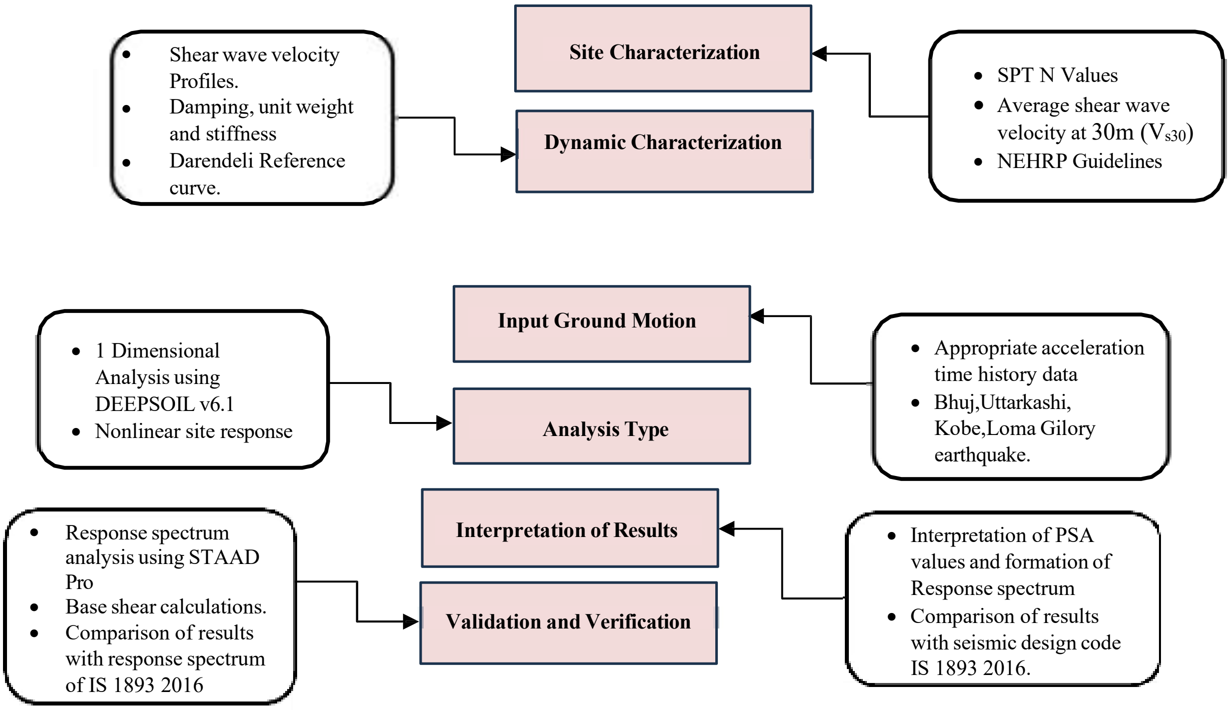

Figure 4. Methodology for site specific Response

2.1. Site characterisation

Shear wave velocity (V_S) is a significant dynamic characteristic of soil that holds crucial importance in seismic investigations. Vs is utilized as a parameter to estimate the natural period of the soil profile at various frequencies and to assess the amplitude and intensity of ground motion resulting from earthquake activity. Determining V_S can be achieved through direct or indirect methods. Direct geophysical methods such as Cross hole and down hole tests directly measure V_S within the soil. Indirect methods involve surface wave tests, including Spectral Analysis of Surface Waves (SASW) and Multichannel Analysis of Surface Waves (MASW), which indirectly estimate V_S based on the properties of surface waves. However, these tests require skilled technicians and the uneconomical nature of these test had made the availability of results scanty. To overcome these problems correlations are used connecting SPT N values to find out the dynamic properties. Several such relations are available. The general relation between SPT N and V_S is of the form

$$V_S = a(N)^b \qquad [6](1)$$

In the Equation (1), 'a' and 'b' are regression coefficients, which are used to determine the relationship between V_S and another parameter. In this case, the parameter 'N' refers to the SPT (Standard Penetration Test) value. Many researches had found correlations based on their research and by regression analysis appropriate correlation can be found which are suitable for the study area [13].

The research conducted by P. Anbazhagan and K. Bajaj [6], as well as the draft of IS 1893-2016.[14] evaluated the correlation between SPT-N (Standard Penetration Test-N value) and Vs (shear wave velocity) values. The correlations developed by P. Anbazhagan et al. were derived from deep soil sites in the Indo Gangetic Basin, specifically focusing on the Punjab-Haryana region (PHR), Uttar Pradesh region, and Bihar region. In the present study, the correlations used were based on the analysis of 76 V_S profiles with corresponding SPT-N data specifically for the PHR region. Additionally, a total of 276 V_S profiles with SPT-N data were considered, encompassing all three regions.

For un-corrected SPT-N values

$$V_S = 64.23(N)^{0.48} \qquad [6](2)$$

For corrected SPT-N values

$$V_S = 62.55(N)^{0.54} \qquad [6](3)$$

V_S is the Shear wave velocity and N is the SPT value.

The correlation provided by Draft of IS 1893-2023 are based on corrected SPT-N values for cohesion less and cohesive soils.

For cohesion less soils

$$V_S = 80(N)^{0.33} \qquad [14](4)$$

For cohesive soils

$$V_S = 100(N)^{0.33} \qquad [14](5)$$

The initial step for seismic hazard analysis is site characterisation. After the determination of shear wave velocity Vs average value at a particular depth can be found using equation 6.

$$V_{si} = \frac{\sum d_i}{\sum_{i=1}^{n} d_i/V_i} \qquad [7](6)$$

$\sum d_i$ Represents the cumulative depth. From the NEHRP guidelines the soil sites with lower V_S values will have more effect with seismic waves [7].

In order to determine the site classification following the NEHRP guidelines [7], Equation (6) is utilized to calculate the average shear wave velocity at a depth of 30m. The average shear wave velocity obtained from the boreholes falls within the range of 298.217 m/s to 531.332 m/s, as specified by Equation (2) and (3), and ranges from 263.468 m/s to 376.695 m/s, as indicated by Equation (4) and (5). Using this information, a total of 20 borehole sites are categorised as either C or D, which signifies either very dense soil and soft rock or stiff soil, as illustrated in Table 1.

Table 1. Site Characterisation based on NEHRP Guidelines

Borehole	Average V_S 30(m/s) as per Equation (3)	NEHRP Classification	Average V_S 30(m/s) as per Equation (4) and (5)	NEHRP Classification
BH1	450.8106	C	340.7413	D
BH2	510.7807	C	366.7861	C
BH3	358.2948	D	294.2407	D
BH4	479.5245	C	352.4076	D
BH5	418.4565	C	325.9387	D
BH6	502.0261	C	364.6113	C
BH7	298.2173	D	263.4679	D
BH8	423.886	C	326.515	D
BH9	475.3251	C	351.1371	D
BH10	490.7465	C	358.5302	D
BH11	491.5282	C	358.2815	D
BH12	503.0989	C	363.4487	C
BH13	448.6641	C	339.0034	D
BH14	428.8886	C	328.7702	D
BH15	531.3322	C	376.6946	C
BH16	438.5196	C	334.0154	D
BH17	477.0594	C	353.157	D
BH18	433.1254	C	330.9128	D
BH19	342.2919	D	285.7588	D
BH20	355.8721	D	292.7733	D

Since the correlation provided by P Anbazhgan et al. is more region-specific further study is based on the Vs obtained by equation (3).

2.2. Dynamic Characterisation

The development of the soil profile involved considering the unit weight and Vs for each layer at their respective depths. During this process, a minimum damping of 5% was applied. The analysis relied on the reference curve established in Darendeli's 2001 study.

During the development of the soil profile, the unit weight and shear wave velocity for each layer at their respective depths were taken into account. A minimum damping of 5% was applied throughout the process. The analysis relied on a reference curve based on the study conducted by Mehmet Baris Darendeli in 2001. Mehmet Baris Darendeli conducted tests on 20 soil samples to characterize the material. From these tests empirical curves are derived for the formulation of empirical equations [15]. These equations are utilized in DEEPSOIL for further calculations. The bedrock V_S value used in the analysis is 760 m/s, and the unit weight is taken as 24.5 kN/m^2 with damping of 2% [16].*Input Motion*

In order to carry out Nonlinear analysis and time domain solution type ground response analysis appropriate input motion is an important factor. The ground motions applied to the soil profile is collected from the PESMOS [17] and COSMOS [18] website. The ground motion parameters are provided in the Table 2. Acceleration time history data of the corresponding motions is plotted in figure 5

Table 2. Properties of Input Ground Motion.

Parameters	Loma Prieta	Uttarkashi	Kobe	Bhuj	Himachal-Punjab
Year of Occurrence	1989	1991	1995	2001	2010
Magnitude (Mw)	7.0	6.8	6.9	7.6	4.6
PGA	0.357	0.25	0.821	0.08	0.04
Recording Station	Corralitos	Bhatwari	Nishi-Akashi	Ahmedabad	Jalandhar

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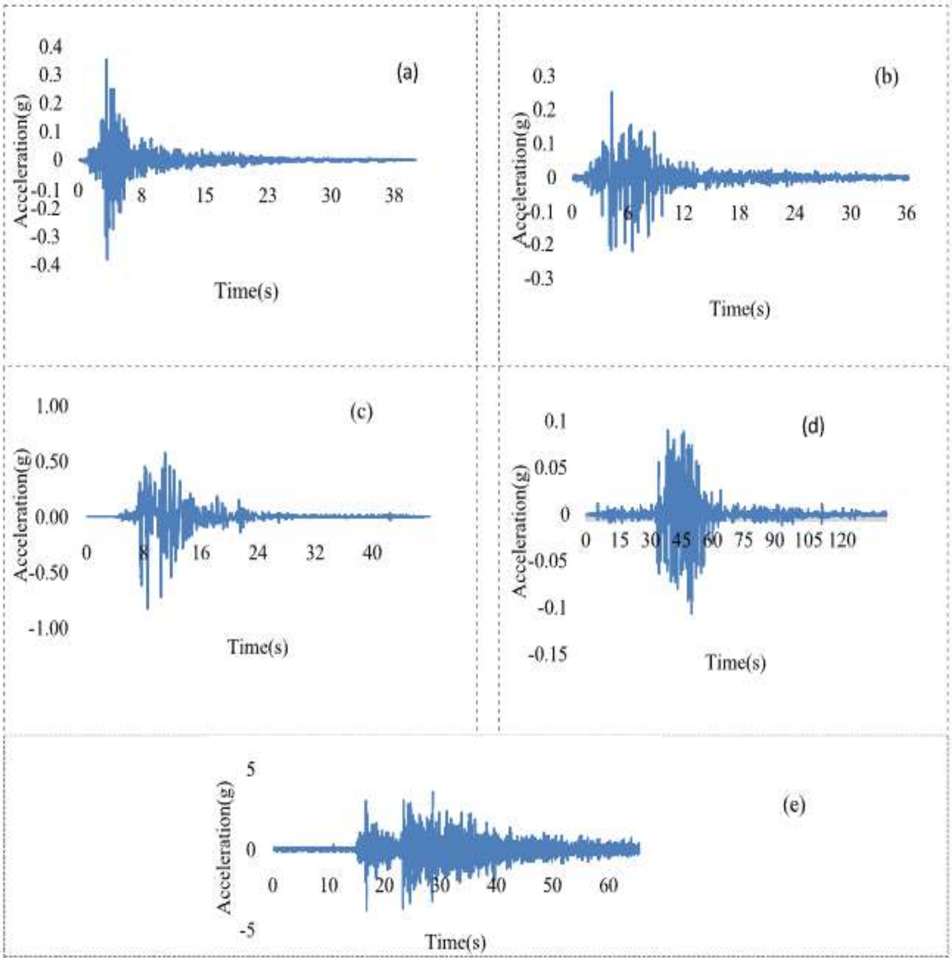


Figure 5. Time History data of (a) Loma Prieta, (b)Uttarkashi, (c) Kobe, (d) Bhuj and (e) Himachal Punjab border Earthquake

2.3. Site specific response analysis

Site response analysis is carried out using DEEPSOIL software. From the analysis definition, nonlinear method of time domain analysis is selected. Followed by soil profile details are provided. To ensure an accurate analysis elastic half space is selected for bedrock properties. The shear wave velocity of the engineering rock is specified as 750 m/s, and the specific weight of the hard rock is recorded as 24.52 kN/m^3. A damping ratio of 2% will be utilized. Using these different time history data Peak Spectral Acceleration (PSA) values are obtained for each layer of 20 borehole data. From these values average value of PSA is calculated to obtained PSA of a particular bore hole. Further maximum value of PSA among 20 bore hole data is used to conduct analysis using response spectrum method. The obtained PSA values with respect to period for different ground motions is plotted in figure 6.

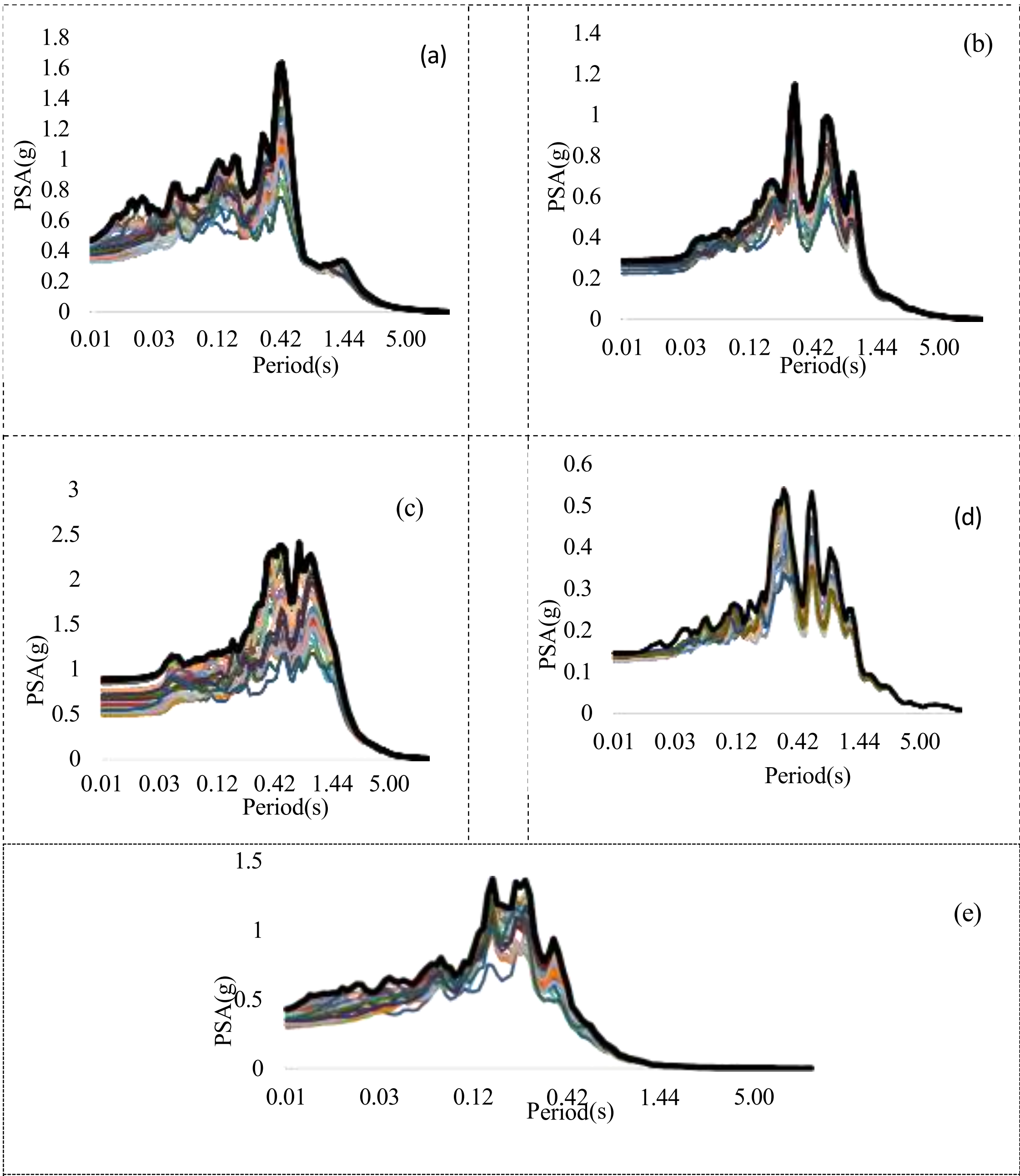


Figure 6. Response spectrum obtained for 20 borehole data with (a) Loma Prieta, (b)Uttarkashi, (c) Kobe, (d) Bhuj and (e) Himachal Punjab border Earthquake

For the proper understanding of obtained site-specific response, a comparison is made by analysing base shear values obtained using site specific response spectrum and IS 1893-2016 response spectrum. For this response spectrum analysis using site specific response spectrum and IS 1893 response spectrum is carried out with the help of STAAD Pro. An already existing 3 storey building is used for this comparison. figure 7 displays both the wireframe and 3D view of the utilized building. The properties of elements in the building are: i) two types of beams -B1-230mmx450mm, B2-300mmx525mm ii) Column-300mmx460mm. Along with self-weight wall load and floor load of 6kN/m^2 are applied as deadload and a live load of 3kN/m^2 is also applied. Load combination using IS 456-2000 with different factors of safety. Modal period and modal weight of building used are 1.021s and, 8.06*10^{-2}kN respectively.

(a)

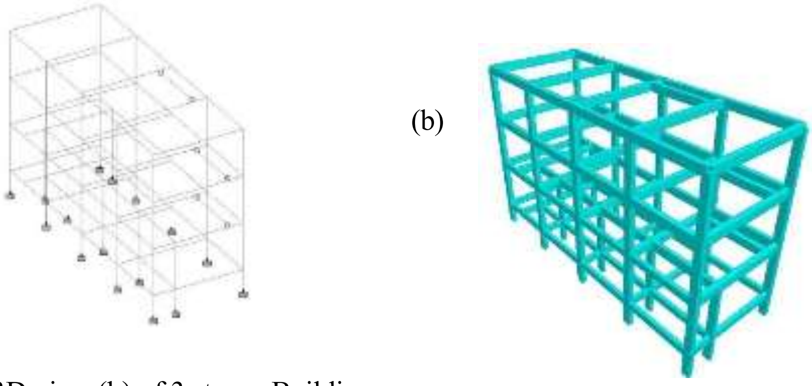
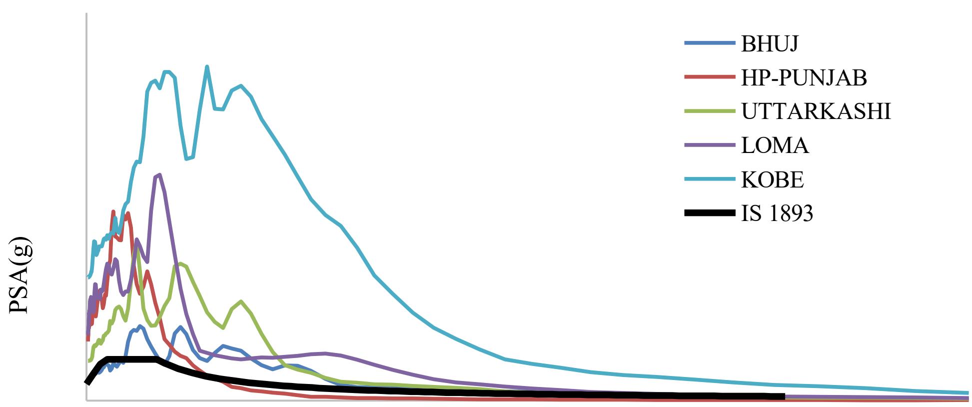


Figure 7. Wireframe (a) and 3D view (b) of 3 storey Building

3. Results and discussion

After the successful completion of Non-linear analysis, response spectrum method of seismic analysis is carried out using STAAD Pro. The comparison of IS 1893-2016 response spectrum obtained using corresponding zone factor (0.24) and importance factor with site specific response using different earthquake motion is illustrated in figure 8.



1.4
1.2
1
0.8
0.6
0.4
0.2
0
0 1 2 3 4 5
Period(s)

Figure 8. Comparison of evaluated response spectra with IS 1893 response spectrum

The seismic analysis of the real building is conducted using response spectrum method. For the analysis using IS 1893-2016 zonation factor is selected based on Zone IV and appropriate reduction and importance factor are also applied. Further using the response spectrum obtained by site specific

response analysis seismic analysis is carried out again and base shear values are noted. The base shear values will give an idea about the lateral force that will affect the building due to the provided ground motion at bedrock. The obtained base shear values by seismic analysis are provided in table 3. For the base shear responses different combination such as SRSS, 10PCT, ABC and CQC are used. The differences between these values are calculated as percentages to offer a more comprehensive evaluation of the results.

Table 3. Base shear values and comparison of base shear values in percentage

		As per IS 1893 2016			As per site specific response analysis			Difference in percentage		
		X	Y	Z	X	Y	Z	X	Y	Z
Bhuj	SRSS	329.77	0.09	461.7	670.88	0.12	845.67	50.85	25.00	45.40
	10PCT	329.77	0.09	461.7	670.88	0.12	845.67	50.85	25.00	45.40
	ABS	405.31	0.1	462.45	780.96	0.15	847.12	48.10	33.33	45.41
	CQC	329.96	0.09	461.78	671.31	0.12	845.85	50.85	25.00	45.41
Uttarkashi	SRSS	329.77	0.09	461.7	1163.44	0.17	1641.94	71.66	47.06	71.88
	10PCT	329.77	0.09	461.7	1163.44	0.17	1641.94	71.66	47.06	71.88
	ABS	405.31	0.1	462.45	1320.07	0.23	1644.96	69.30	56.52	71.89
	CQC	329.96	0.09	461.78	1164.24	0.17	1642.32	71.66	47.06	71.88
Kobe	SRSS	329.77	0.09	461.7	5410.29	0.69	6156.04	93.90	86.96	92.50
	10PCT	329.77	0.09	461.7	5410.29	0.69	6156.04	93.90	86.96	92.50
	ABS	405.31	0.1	462.45	6034.48	0.85	6165.6	93.28	88.24	92.50
	CQC	329.96	0.09	461.78	5412.49	0.7	6157.25	93.90	87.14	92.50
Loma	SRSS	329.77	0.09	461.7	913.96	0.38	905.03	63.92	76.32	48.99
	10PCT	329.77	0.09	461.7	913.96	0.38	905.03	63.92	76.32	48.99
	ABS	405.31	0.1	462.45	1205.07	0.43	907.74	66.37	76.74	49.05
	CQC	329.96	0.09	461.78	914.65	0.38	905.27	63.92	76.32	48.99
Himachal-Punjab	SRSS	329.77	0.09	461.7	294.25	0.26	463.74	-12.07	65.38	0.44
	10PCT	329.77	0.09	461.7	294.25	0.26	463.74	-12.07	65.38	0.44
	ABS	405.31	0.1	462.45	414.3	0.28	464.59	2.17	64.29	0.46
	CQC	329.96	0.09	461.78	294.56	0.26	463.81	-12.02	65.38	0.44

The results indicate that the variation in base shear is strongly influenced by the magnitude of the input ground motion. For high-magnitude earthquake records, such as the Kobe earthquake, the base shear shows an increase of approximately 90%. In contrast, for low-magnitude events, such as those recorded along the Himachal–Punjab border, the base shear values are lower than those obtained from the IS 1893 response spectrum.

This suggests that for earthquakes with magnitudes less than 5, the response spectrum provided in IS 1893:2016 is reasonably adequate. However, structures designed solely based on IS 1893 provisions may not be sufficiently robust to withstand higher-magnitude earthquakes.

The upcoming seventh revision of IS 1893 introduces significant modifications, including the addition of Zone VI, an increase in zone factors, and the incorporation of shear wave velocity for site classification in accordance with NEHRP guidelines. These improvements aim to reduce the disparity between code-based and site-specific response values. Nevertheless, for critical and important structures, site-specific response analysis remains the more reliable and recommended approach for accurate seismic design.

4. Conclusion

In this study a detailed 1Dimensional Nonlinear ground response analysis has been conducted using 20 bore hole data from sites in Jalandhar (Punjab). This analysis takes into account the specific soil properties and characteristics of the region to understand how the local soil conditions impact the ground motions during an earthquake. Time history data of Bhuj Earthquake, Uttarkashi, Kobe, Loma and Himachal-Punjab border are used for site specific response analysis. The major conclusions obtained from the research work is listed below:

- Site characterization was carried out using data from 20 boreholes, applying the correlation proposed by Anbazhagan et al. [6] along with the draft provisions of IS 1893:2023. Based on this, the sites were classified as Class C or D, indicating the presence of dense or stiff soil conditions.

- The non-linear ground response analysis performed for the Jalandhar sites revealed varying peak spectral acceleration values for different input ground motions. The peak spectral accelerations obtained were 0.54g, 1.36g, 1.15g, 1.63g, and 2.41g corresponding to the Bhuj, Himachal–Punjab, Uttarkashi, Loma Prieta, and Kobe earthquake records, respectively.

- A comparison between the response spectra derived from IS 1893:2016 and the site-specific analysis indicates that the latter provides results dependent on earthquake magnitude. For input motions with magnitudes less than 5, particularly along the Himachal–Punjab border, the response spectrum values are found to be nearly consistent with those specified in IS 1893:2016.

- The evaluated base shear values clearly demonstrate the influence of seismic waves on structural response. Response spectrum analysis conducted using STAAD Pro yielded varying base shear values for different ground motions. It was observed that for high-magnitude earthquakes, the variation in base shear can reach up to 90%, whereas for low-magnitude events, the base shear values are comparatively lower. Therefore, for regions with high seismic hazard, such as Jalandhar, site-specific analysis is strongly recommended. However, for areas with low seismic risk, this approach may not be economically feasible.

- The significance of this research area is further emphasized by the draft of the seventh revision of IS 1893, which introduces substantial changes by incorporating parameters aligned with site-specific response analysis.

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