Equivalent-Linear and Nonlinear Seismic Ground Response Analysis of Important Sites in Amaravati Capital Region, Andhra Pradesh, India

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ABSTRACT: The characteristics of bedrock motion are examined using seismic ground response analysis to determine the impact of the regional soil layers overlaying the bedrock, with the use of two programs, DEEPSOIL and SHAKE. The diversity in the seismic ground response is investigated for a variety of input parameters, including soil geometry, the use of various shear moduli, damping curves, and analytical techniques. The present study attempted to study the local site effects for important towns like Amaravati, Velagapudi, Nekkallu, and Abburaju Palem in the Amaravati capital region by adopting both the equivalent linear and non-linear approaches. The ground responses are observed for the synthetic accelerograms obtained from 2001 Bhuj earthquake motion as seed accelerogram and results are presented in the form of response spectrum, acceleration time histories, and Amplification ratio. The peak ground acceleration and amplification factor for the Velagapudi soil site are found to be the highest among the four soil sites with a value of 0.149 g. The maximum surface acceleration obtained for Amaravati, Nekkallu, and Abburaju Palem is 0.09 g, 0.084 g, and 0.128 g, respectively for a given input motion. The amplification ratio for maximum acceleration is found to be 4 at a frequency of 2.5 Hz for Velagapudi, 3.5 at a frequency of 5.5 Hz for Abburaju Palem, 3.4 at a frequency of 3.5 for Amaravati and 3.85 at a frequency of 10 Hz for Nekkallu town respectively. The mean spectral values obtained by equivalent linear analysis are found to be higher than that of the non-linear analysis.

KEYWORDS: Equivalent linear ground response analysis, Non-linear ground response analysis, Pseudo spectral acceleration, Fourier amplification ratio, Maximum surface acceleration, and Amaravati capital region.

1. INTRODUCTION

Seismic waves originating from fault rupture travels through several kilometres of bedrock and a few meters of soil layers. The bedrock does not imply to change in ground motion parameters, but soil presented at a site plays an important role in modifying the ground motion parameters such as amplitude, frequency content, and duration. The modified bedrock ground motion reaches the ground surface via soil media and causes severe damage to infrastructure.

Site-specific seismic hazard analysis is the best way to identify the effects associated with the earthquake hazards. The seismic hazard analysis of any site is incomplete without the aid of seismic ground response analysis. Seismic ground response analysis is the first step of any seismic soil structure interaction study. The development of response spectra, determination of surface ground motions, assessment of dynamic stresses and strains of liquefaction hazards, and calculation of earthquake-induced forces are all possible with the help of seismic ground response analysis (Kramer 1996). The geometry of the soil column can be found in the bore log data obtained from the site. The dynamic properties such as shear wave velocity, shear modulus, and damping ratio of soil can be measured in both field and laboratory. However, such tests are carried out in seismically active regions and rarely conducted for seismically inactive regions. The dynamic properties of soil in the present study are estimated using available correlations with available field measurements such as SPT-*N* or Cone penetration resistance. The uncertainties associated with the selection of suitable correlation, choice of published damping curves, characteristics of bedrock motion at the site, and selection of the method of analysis of ground response analysis need to be quantified in terms of their influence on the output parameters (Rathje et al., 2010).

The seismic history of Peninsular India, identified by significant earthquakes in places like Bhadrachalam (1969, M_w 5.9), Latur (1993, M_w 6.1), Jabalpur (1997, M_w 5.8), and Bhuj (2001, M_w 6.2), highlights the need of seismic study of the current study area. The topography, bedrock nature, and depositional soil geometry have been identified as primary factors influencing local modifications to underlying ground motion. As the study area transitions from seismically moderate to an active region, as indicated in the literature, there is an urgent need for seismic ground response analysis. This analysis is crucial to safeguard the lives and assets of residents, especially considering the imminent establishment of the new capital city. A knowledge of ground response is indispensable for assessing the vulnerability of structures and infrastructure to potential earthquakes.

From the earlier days, seismologists and geotechnical engineers are working towards the development of quantitative methods for predicting ground response and thus developed one-dimensional, two-dimensional, and three-dimensional ground response analysis methods. Predicting the free field response for upcoming smart cities like Amaravati is very important due to its rapid urbanization, and upcoming infrastructure. A variety of techniques are available for ground response analysis. The methods can be grouped into three categories such as i) Linear analysis ii) Equivalent linear analysis and iii) Nonlinear analysis.

Amaravati is the proposed capital city of the Indian state of Andhra Pradesh, which is located on the bank of the Krishna River with a geographical area of 217 km^2 and a population of about 0.1 million (2011 census). Goodess et al. (2019) forecasted Amaravati's population based on its urbanization and industrial growth to be about 3.58 million by the end of 2050. As per the Indian seismic code, Amaravati falls under seismic zone III with a zone factor of 0.16 g, which represents a moderate risk zone of damage subjected to VII severity on the Medvedev-Sponeheur-Karnik (MSK) scale. Amaravati also falls under the intraplate stable continental region of the Indian Peninsula. However, the recent devastating earthquakes that occurred in Peninsular India warned about the seismic stability of sensitive engineering structures in every region in India.

The Bhuj earthquake of January 26, 2001, and the 1985 Mexico City earthquake are the best examples of liquefaction failure causing devasting earthquakes in history. As per, the Indian government estimates 13,572 died and 21,456 were injured during the Bhuj earthquake. Ahmedabad city which is located 200 km away from the epicenter of the Bhuj earthquake also affected severely due to the highly amplified soil strata that existed at the site. Hence it is necessary to conduct seismic ground response analysis for every region in the country. In the present study, both Equivalent linear analysis and Nonlinear analysis have been adopted for conducting ground response analysis for Amaravati.

2. PREVIOUS STUDIES

Since the 1920s, researchers have recognized the significance of site impacts on seismic motion. There was numerous research carried out on the local site effects.

Generalized inversions, horizontal-to-vertical spectral ratios, soil-to-rock spectral ratios, and other side effects have all been evaluated using ground motion data (e.g., Nakamura 1988, Field and Jacob 1995, Yamazaki and Ansary 1997, Badet and Tobit 2001). Analytical methods for site response analysis involve many parameters which affect earthquake ground motion and the response spectra of a site. Seed and Idriss (1970), Schnabel et al. (1972) and Hwang and Lee (1991) investigated the effects of site parameters such as secant shear modulus, low strain damping ratio, types of sand and clay, the location of the water table, and depth of bedrock.

Chiu et al. (2008) conducted a one-dimensional seismic ground response analysis for the Silicon Valley Rapid Transit project. The ground response was tested for different input motions, shear wave velocity profiles, and different methods of ground response analysis. The output of the equivalent linear analysis and nonlinear analysis were compared. Kwok et al. (2008) reported the outcome of the predictions and compared them with the measurements and discussed the residuals between the data and models. Arslan and Sayahi (2006) attempted to give a critical overview of the field of ground response analysis. The author carried out a sensitive study on the output of the ground response analysis for different types of input parameters such as dynamic properties of soil, input motion, and method of analysis. Strong research on nonlinear ground response analysis was carried out over the globe (Sun et al., 2005, Kwok et al., 2007, Rathje et al., 2010, Philips et al., 2012, Raghunandan 2012, and Qodri et al., 2021).

Mase et al. (2018a) conducted nonlinear site response analysis for four important soil sites in Chiang Rai, Chiangmai and Thailand and Myanmar boarder by using seismic ground motions developed from next generation attenuation models for Teraly earthquake of M_w 6.8. Mase et al. (2018b) studied site specific analysis of ground response for Taralay earthquake which was occurred on 24th March 2011 in Northern Thailand. The spectral responses obtained for both equivalent linear and nonlinear approaches were compared with seismic code of Thailand. The author found that the peak ground acceleration at ground surface obtained from both equivalent linear and nonlinear approaches gives high amplification factor. Mase et al. (2019) explored the liquefaction resistance behavior of sand through cyclic triaxial tests, revealing that the liquefaction resistance of sandy soil samples is influenced by the applied deviator stress.

Mase and Likitlersuang (2021a) studied a comprehensive liquefaction potential assessment based on seismic ground response analysis. Peak ground acceleration values at the ground surface, derived from the seismic analysis, were utilized in empirical analyses to assess liquefaction potential. The results underscored the vulnerability of certain locations within the region to liquefaction during seismic events, reinforcing the evidence of liquefaction observed during the M_w 6.1 Mae Lao Earthquake.

Mase et al. (2022a) dealt with a meticulous investigation of liquefaction at the Izumio site in Osaka, Japan focusing on sand layers under varying ground motion conditions during a strong earthquake. The study integrates the site investigations, finite element liquefaction site response analysis, and empirical validation to provide a comprehensive understanding of liquefaction potential in the region. The authors highlight the liquefaction tendency in the cyclic behaviors of the sandy layers, emphasizing their critical role during strong earthquakes, where excess pore water pressure reaches the liquefaction threshold. The integration of numerical analysis, empirical validation, and the agreement with prior research findings enhances the reliability and applicability of the results. This study not only advances our understanding of liquefaction mechanisms but also provides practical implications for earthquake preparedness and risk management in the study area.

Mase et al. (2023) introduced a novel approach to assess liquefaction potential through the application of simplified energy concept, utilizing data obtained during the seismic event of M_w 8.6 Bengkalu-Mentawai earthquake in Bengkulu city, Indonesia. The author had done comprehensive site investigations at 38 sites, integrating seismic data and soil characteristics. One dimensional seismic response analysis was subsequently employed to ascertain in the peak ground acceleration within each layer of the study area.

In India, ground response analysis was carried out for important cities like Mumbai (Phanikanth et al., 2011, Goa (Naik and Choudhury, 2014), Desai and Choudhury, 2015), Kolkata (Chatterjee and Choudhury, 2013), and Haryana (Puri et al., 2018). The current study aims to comprehensively understand the diverse methods employed to replicate soil behavior under seismic loading, particularly for the proposed capital city of Andhra Pradesh, Amaravati. In this study, an attempt was made to conduct the ground response analysis at four strategically important locations within Amaravati, considering the variations in both methods used and soil types.

3. GEOLOGY AND SEISMOTECTONIC OF THE STUDY AREA

The proposed capital city Amaravati will be developed on the banks of the Krishna River, which is situated 10 km southwest of Vijayawada, 25 km north of Guntur, and 45 km South-East of Tenali, surrounding coromandel coast of the coastal region in Andhra Pradesh, India. The study area lies between the latitude (16°24'36"N – 16°35'24"N) and longitude (80°24'25"E – 80°36'18"E).

Geologically Amaravati city constitutes the Precambrian rocks such as Khondalites and Charnockites (3000 million years old) trending in Northeast and Southwest directions, Proterozoic Kadapa rocks (600 million years old) are found south to the Amaravati (Ramaswamy and Murthy, 1973) and the Krishna basin mainly constitutes Alluvial soils, laterite soils, red soils, and black cotton soils.

The information about the dynamic properties of soil for the present study area is not available. Various researchers have done extensive investigations to correlate the intensity of damage with surface geological properties obtained from ambient noise vibrations (Mase et al., 2020). The extensive microtremor testing for the boreholes of Amaravati city has been performed to estimate the local site effects by Manne and Satyam (2013). In microtremor testing, the horizontal to vertical spectral ratio (HVSR) technique has been used to record the ambient vibrations and spectral ratio. The HVSR amplitude is obtained by Equation (1).

$$HVSR = \sqrt{\frac{F_{NS}^2+F_{EW}^2}{F_V^2}} \tag{1}$$

F_V, F_{NS}, and F_{EW} are the Fourier amplitude spectra of vertical, north-south, and east west components, respectively.

Smoothened HVSR spectra have been generated to precisely identify peak frequency using the moving average technique. After obtaining the HVSR curve, the Open HVSR program has been used to estimate the Vs profile for every location. A typical inversion curve and V_s profiles were obtained for specified borehole locations. The Vs profiles obtained from HVSR curves were used for the graphical validation of the proposed correlation, which was used in the current study.

The dynamic properties such as shear wave velocity, shear modulus, and damping curves were chosen based on the developed SPT-*N* and V_s correlation by Kumar et al. (2022) and published damping curves from the DEEPSOIL and SHAKE.

Kumar et al. (2022) attempted to establish the relationship between uncorrected SPT-N and V_S for Amaravati city. The empirical correlations are initially developed using the SPT-N value obtained by boreholes and V_S obtained from available literature for similar soil conditions. Equal weighting was initially allocated to the most representative correlations of V_S and SPT-N for the Indian subcontinent, and Vs values are calculated. The metrics obtained from graphical validation for the proposed correlations were presented in Table 1.

Table 1 Proposed correlations between SPT-*N* and Vs with R^2 and r

Soil Type	Proposed Correlation	Coefficient of regression (R^2)	Coefficient of correlation (r)
All soils	$V_s = 72.21\ N^{0.409}$	0.99862	0.999266
Sandy soils	$V_s = 88.575\ N^{0.353}$	0.99906	0.999495
Clayey soils	$V_s = 84.93\ N^{0.374}$	0.99879	0.999424

4. METHODOLOGY

A total of 22 boreholes data have been collected from various investigative agencies. The locations of the boreholes are as shown in Figure 1. From the acquisition of borehole investigation data, modelling of the topographic configuration is performed by dividing the profile into layers with similar geotechnical properties using boring logs. Various properties of soil layers like bulk density, plasticity index, and angle of friction have been obtained from the laboratory. The basic 1D wave equation for uniform, damped soil resting on rigid bedrock is given in Equation (2). (Kramer, 1996)

$$\rho \frac{\partial^2 u}{\partial t^2} = G \frac{\partial^2 u}{\partial z^2} + \eta \frac{\partial^3 u}{\partial z^2 \partial t} \qquad (2)$$

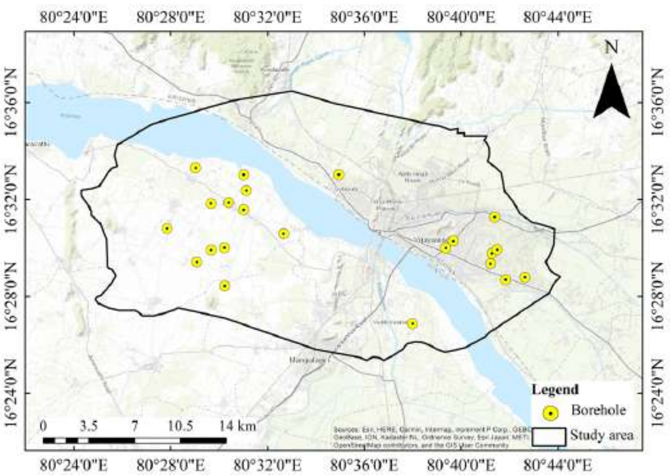


Figure 1 Borehole locations considered for the present study

The 1D equivalent linear analysis is conducted using SHAKE2000 for analyzing the ground response of soils during seismic events. In this method, the nonlinear soil behavior is approximated as an equivalent linear system with effective stiffness and damping. It simplifies the complex nonlinear behavior of soils by assuming linear elastic properties, suitable for low to moderate seismic events. Globally, to observe the seismic behavior on the various sites researchers mentioned model is relevant in predicting ground motions (Plengisiri et al., 2017; Quodri et al., 2021; Mase et al., 2022b). In the present study, Nonlinear ground response analysis is conducted using DEEPSOIL. The GQ/H model was used for nonlinear ground response analysis.

In the present study, 12 boreholes were selected for the ground response analysis from four important locations. Among, four boreholes' profiles one from each town are shown in Figure 2.

Location: Abburaju Palem Borehole 1 (BH-1)				Date: 03/08/2016	
Depth (m)	Dia of Borehole	Blow Counts	Bulk Density (Kn/m3)	Graphic Log	Soil Description
1.5	150 mm	16	18.5		Inorganic silty sand (SM)
3		19			
4.5		22			
6		30			
7.5		23			
9		28			
10.5		14	19.4		Inorganic clay with high plasticity (CH)
12		22			
13.5		26			
15		28			
16.5		54			
20		–	–		Hard Rock
25		–			
30		–			

2(a)

Location: Amaravati Borehole 1 (BH-1)				Date: 10/10/2014	
Depth (m)	Dia of Borehole	Blow Counts	Bulk Density (Kn/m3)	Graphic Log	Soil Description
1	150 mm	–	–		Inorganic clay with high plasticity (CH)
1.5		9	19.4		
2.5		–			
3		–			
4.5		12			
5		–			
6		11			
7.5		19			
8		–	18.5		Inorganic silty sand (SM)
9		21			
10.5		25			
11		–			
12		26			
13.5		25			
14		–			
15		21			
16.5		23			
17		–	19.68		Sand(S)
18		20			
19.5		23			

2(b)

Location: Nekkallu Borehole 1 (BH-1)					Date: 05/14/2017
Depth (m)	**Dia of Borehole**	**Blow Counts**	**Bulk Density (Kn/m3)**	**Graphic Log**	**Soil Description**
1	150 mm	9	19.68		Inorganic sandy clay (SC)
3		11			
4		19			
5		23			
6.5		–			
12		–			
13.5		–	–		Hard Rock

2(c)

Location: Velagapudi Borehole 1 (BH-1)					Date: 17/07/2017
Depth (m)	**Dia of Borehole**	**Blow Counts**	**Bulk Density (Kn/m3)**	**Graphic Log**	**Soil Description**
1	150 mm	8	19.4		Inorganic clay with high plasticity (CH)
3		10			
5		14			
8		10			
9.5		12			
11		11			
12.5		18			
14		15			
15.5		21			
17		16			
18.5		22			
20		20			
21.5		23			
23		25			
24.5		27			
26		20			
28		–	–		Hard Rock
30		–	–		
32		–	–		
36		–	–		

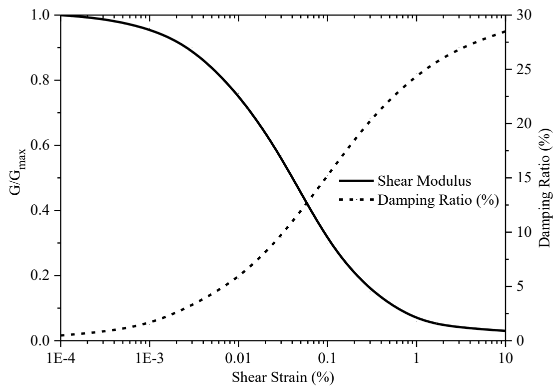
2(d)

Figure 2 Typical borelog details of a) Abburaju Palem b) Amaravati c) Nekkallu d) Velagapudi

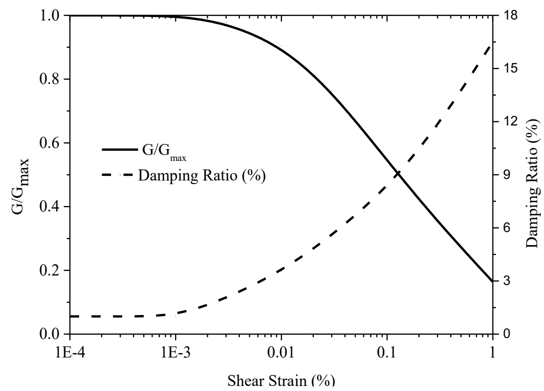
4.1 Modulus Reduction and Damping Curves

The selection of soil model for the ground response analysis plays a crucial role for accurate estimation (Thay et al., 2013; Mase et al., 2021b; Sukkarak et al., 2021). In the present study, a Hardening soil model was chosen for the ground response analysis to accurate simulation. Hardening soil models capture the nonlinear behavior of soils more accurately compared to linear or equivalent linear models. Soils often exhibit nonlinear behavior under large strains or cyclic loading conditions, which can significantly affect the ground response during seismic events. Hardening soil models account for phenomena such as strain-dependent stiffness, strength degradation, and hysteresis loops, providing a more realistic representation of soil response. Hardening soil models can handle complex soil profiles and boundary conditions more effectively than simpler models. They can simulate heterogeneous soil layers, irregular soil geometries, and complex loading scenarios encountered in real-world engineering projects.

The Equivalent Linear (EL) method is a numerical approach that involves an iterative procedure to determine the shear modulus and damping ratio of soils. The selection of these properties depends on the type of soil being analyzed. For this study, the modulus reduction, and damping curves for cohesionless soil are based on Seed et al. (1989), while for cohesive soil, Vucetic and Dobry (1991) have been utilized. Seed and Idriss's (1970) models are selected for use in the analysis of loose sandy and silty formations. When evaluating harder clay formations, the models presented by Vucetic and Dobry (1991) are used to take into consideration the plasticity index features. On the other hand, soft clay formations are assessed using the models that were proposed by Sun et al. (1988). The G/G_{max} and damping ratio (%) have been defined as the functions of shear strain (%). The damping curves chosen in the present study are as shown in Figure 3.



3(a)



3(b)

Figure 3 Damping curves for a) Cohesionless soil b) Cohesive soil

4.2 Estimation of V_S Profile

In this study, authors utilized shear wave velocity (V_S) profiles that were developed based on the V_S and SPT-N correlations proposed by Kumar et al. (2022) specifically for this study area. The correlations are as follows:

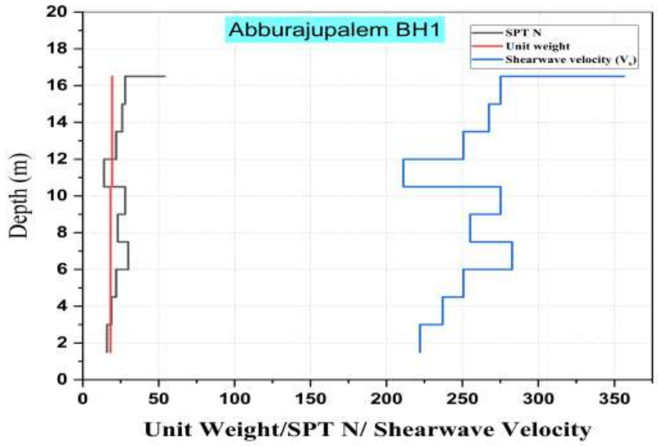
$$V_S = 72.21N^{0.409} \tag{2}$$

$$V_S = 88.575N^{0.353} \tag{3}$$

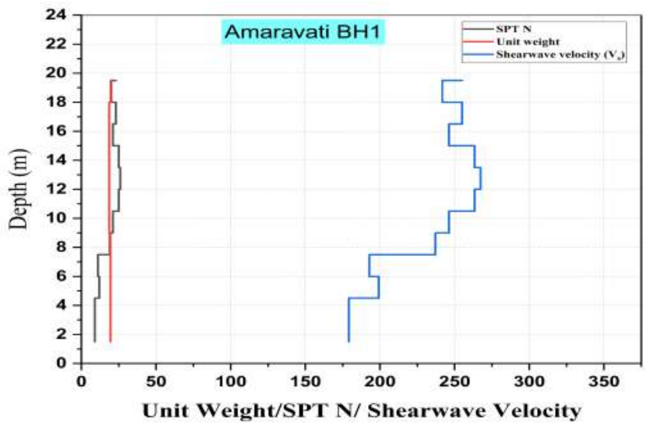
$$V_S = 72.21N^{0.374} \tag{4}$$

Each equation corresponds to a specific soil condition: Equation (2) is for all soil types, Equation (3) is for sandy soils, and Equation (4), is for clayey soils.

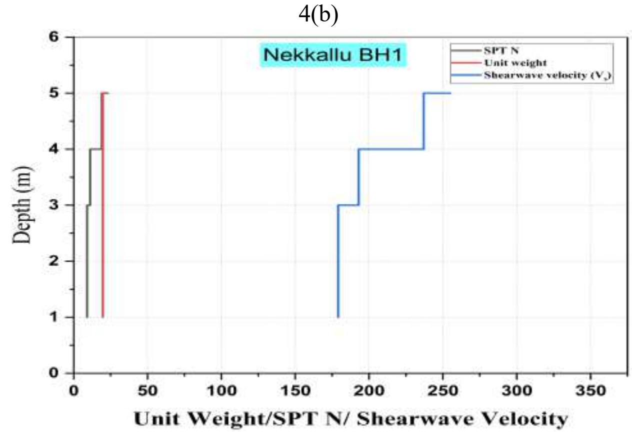
The soil profile equipped by SPT N, Unit weight, depth of soil and shear wave velocity were shown in Figure 4.



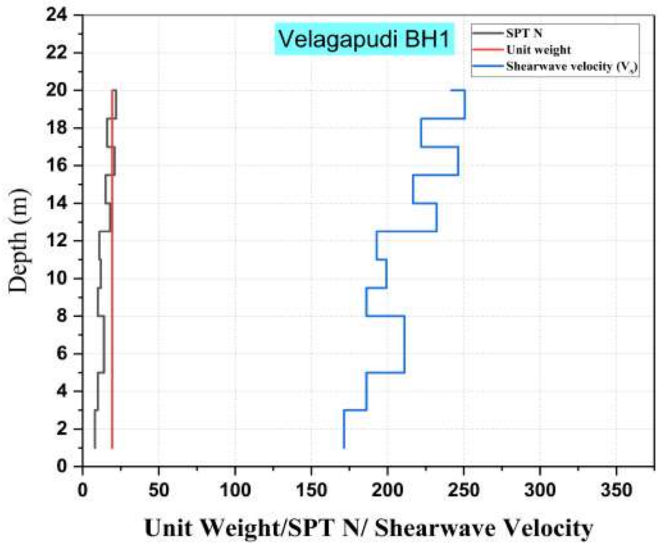
4(a)



4(b)



4(c)



4(d)

Figure 4 Soil profiles equipped by Unit weight, SPT N, Shear wave velocity and depth of soil a) Abburaju palem b) Amaravati c) Nekkallu d) Velagapudi

4.3 Selection of Earthquake Motion

Due to the unavailability of real earthquake records in the study area, a thorough seismic assessment was conducted through the development of synthetic accelerograms. Seismomatch software was employed, the ground motion prediction due to the earthquake is selected from the Satyannarayana and Rajesh (2023) study. The 2001 Bhuj earthquake motion is occurred at a part of peninsular India, in which present study area located. The expected ground motions for the present study were calculated based on the historical earthquake data, fault map and seismic hazard assessment (Satyannarayana and Rajesh 2021). The present study area has similar geotechnical and geological properties of the epicenter of the 2001 Bhuj earthquake motion. Hence, the 2001 Bhuj earthquake motion is considered as a seed accelerogram with a peak ground acceleration (PGA) of 0.106 g to develop synthetic accelerogram for each site and the ground motion characters were shown in Table 2.

Table 2 Characteristics of ground motion considered for the ground response analysis.

S. No	Characteristics	Bhuj Earthquake motion
1	Date of occurrence	26-01-2001
2	Magnitude	6.6
3	Epicentre Lat/Long	60.2320 N / 23.419 E
4	Recording station	Ahmedbad, India
5	Distance of recording station from source	230 Km
6	Peak ground acceleration	0.106 g

The target response spectrum for each town was derived from the Satyannarayana and Rajesh (2023) study, forming the basis for a comprehensive seismic evaluation. The selected seed acceleration time history is visually depicted in Figure 5. Synthetic acceleration time histories for Abbaurajupalem, Amaravati, Nekkallu, and Velagapudi are illustrated in Figures 6(a) to 6(d), respectively. Notably, Velagapudi exhibits the highest peak horizontal acceleration at 0.08 g, followed by Amaravati and Abbaurajupalem at 0.07 g, and Nekkallu at 0.06 g. To discern variations in the soil model, three borehole data sets were considered for each town. The results are meticulously presented in the form of surface accelerograms, amplification factors, and response spectra for each borehole data. Peak values from both equivalent linear and nonlinear analyses are reported and systematically compared. The results section provides a detailed exploration of shear wave velocity profiles, offering critical insights into the dynamic characteristics of subsurface layers at each location. Furthermore, the study investigates the variation of peak ground acceleration along the depth, emphasizing the influence of different soil strata on seismic response. Velagapudi's distinction for exhibiting the highest peak horizontal acceleration, providing crucial insights into the seismic vulnerability of specific locations. Comparative assessments of Amaravati, Abbaurajupalem, and Nekkallu underscore the nuanced seismic characteristics of each area, reinforcing the importance of realistic soil models for accurate seismic hazard assessments.

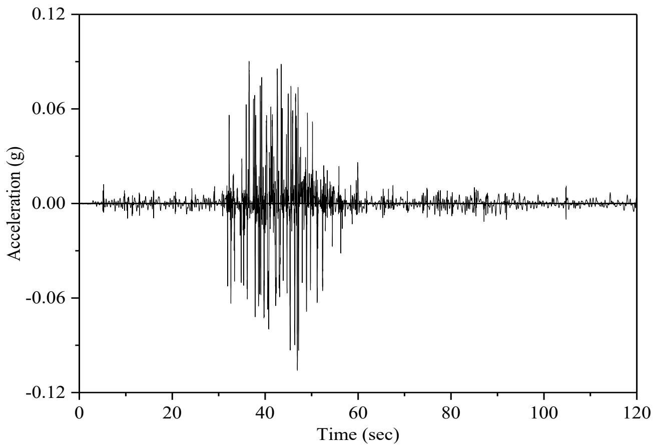
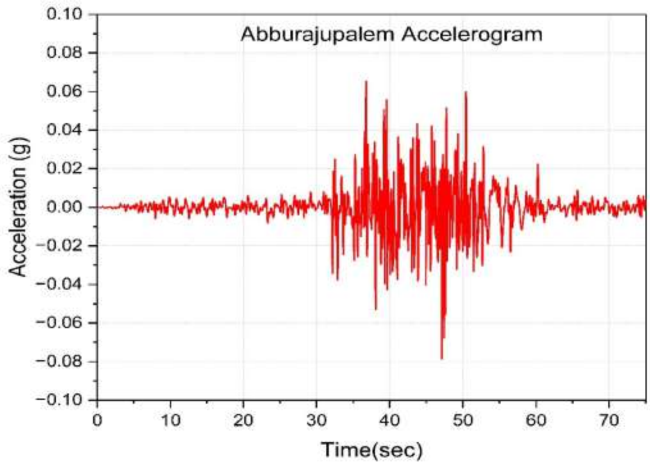
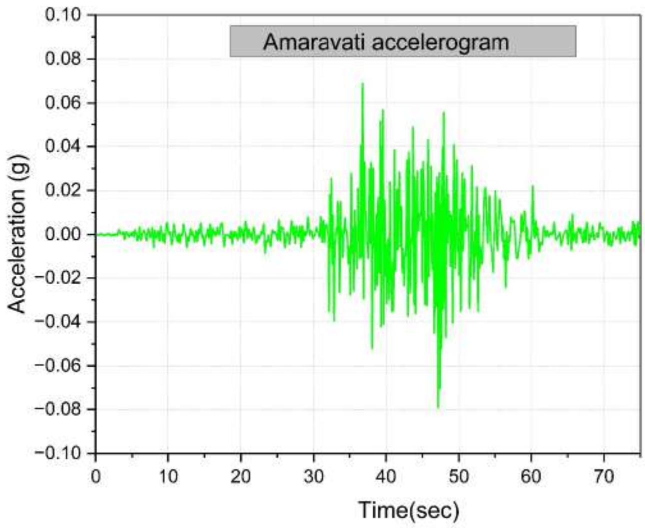


Figure 5 2001 Bhuj earthquake motion



6(a)



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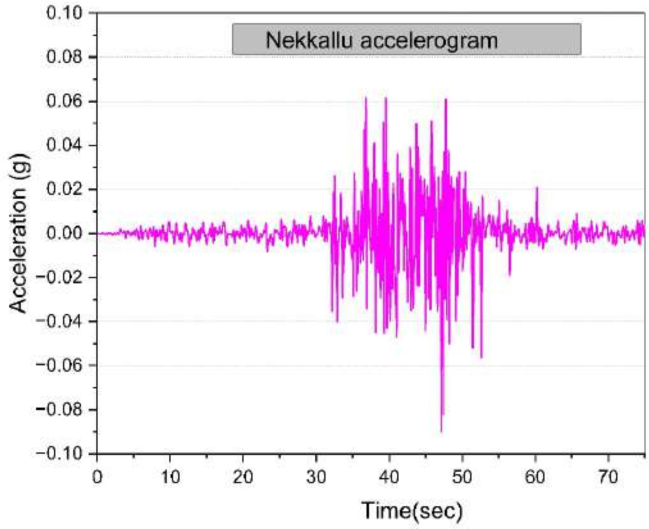

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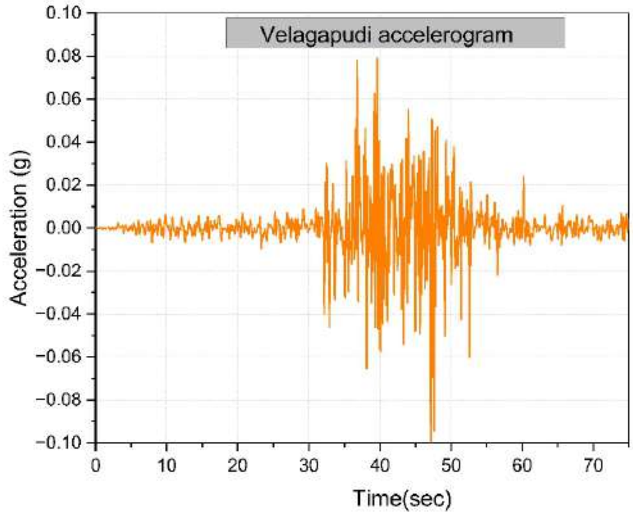


6(d)

Figure 6 Synthetic acceleration time histories for a) Abburajupalem b) Amaravati c) Nekkallu d) Velagapudi

5. RESULTS AND DISCUSSIONS

As seismic waves propagate through the soil column, the bedrock input motion tends to experience amplification. The degree of amplification is influenced by various factors, including the type of soil, the thickness of the soil layer, soil stiffness, and the impedance contrast between the soil and the underlying bedrock. For all the locations considered in the study, the ground surface acceleration time histories were computed to observe the amplification effects caused by these factors.

5.1 Equivalent Linear Ground Response Analysis

The Seismomatch software was utilised to obtain synthetic accelerograms, and the equivalent linear ground response analysis was performed on borehole data from four significant towns located within the capital region of Amaravati with SHAKE 2000 software. The programme is designed to handle horizontally layered soil deposits that are subjected to vertically propagated shear waves. As a result of the individual soil features of each location, the research makes use of a variety of models for modulus reduction and damping curves.

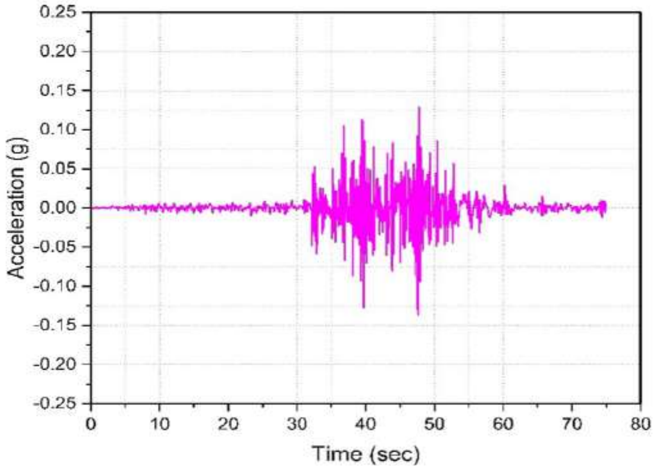
After applying the relevant models, 1D equivalent linear analysis is performed, and the obtained results are discussed in the subsequent sections. These results shed light on the ground response characteristics and the amplification potential of the soil at the studied locations under seismic loading.

5.1.1 Surface Accelerograms

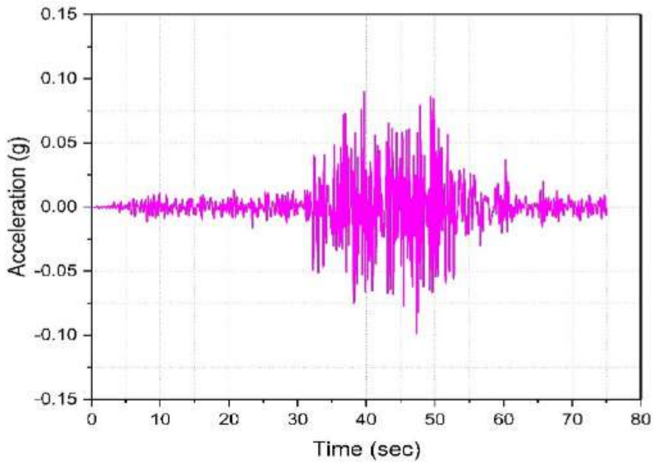
The surface acceleration time histories that were obtained for four different locations. Abburajupalem, Amaravati, Nekkallu, and Velagapudi were exposed to the corresponding synthetic accelerograms are displayed in Figures 7(a) to 7(d), respectively. For providing clear visibility, the surface accelerogram of the single borehole that receives the highest PHA was displayed for each location. After doing an analysis of the surface accelerations of all drilling data, it has become abundantly evident that the borehole BH1 at the Velagapudi location has the largest surface acceleration.

Borehole BH2 at both Abburaju Palem and Amaravati has the highest peak horizontal acceleration (PHA) of 0.128 g and 0.09 g respectively, surpassing the other two boreholes in both sites. This is obvious from Figures 7(a) and 7(b), which show that the borehole possesses the highest PHA. Moving on to Nekkallu, Figure 7(c) reveals that borehole BH1 records the highest peak horizontal acceleration, reaching a PHA of 0.084 g. In the meantime, Figure 7(d) demonstrates that borehole BH1 at Velagapudi also experiences a significant PHA of 0.149 g.

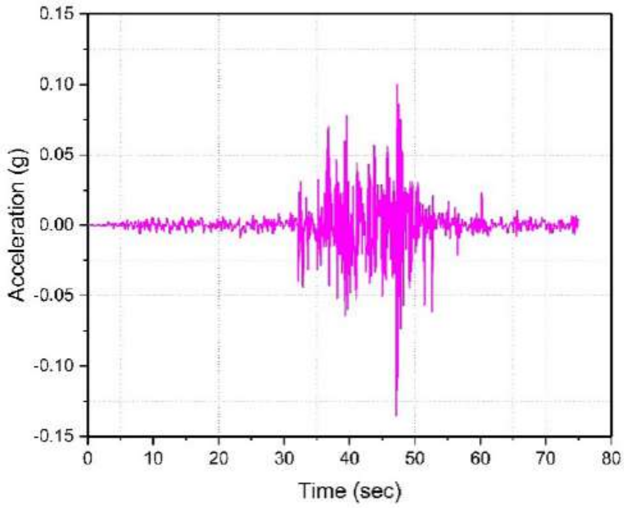
Because the Velagapudi soil sites are primarily made of soft saturated soils, the considerable amplification that was seen at these locations can be attributed to the fact that these soils can amplify the bedrock input motion. On the other hand, the shallow hard stratum that is found in the Nekkallu region exhibits amplification effects that are lesser in intensity. In the event of future earthquakes, these findings offer engineers with knowledge that may be used to make predictions on the ground shaking levels that structures may experience. The accelerograms that were obtained are used as input motion records for dynamic analysis, which enables simulations of how structures will react to seismic forces. This analysis helps verify that the seismic design is adequate and guarantees that the structures can endure the ground motion that is anticipated.



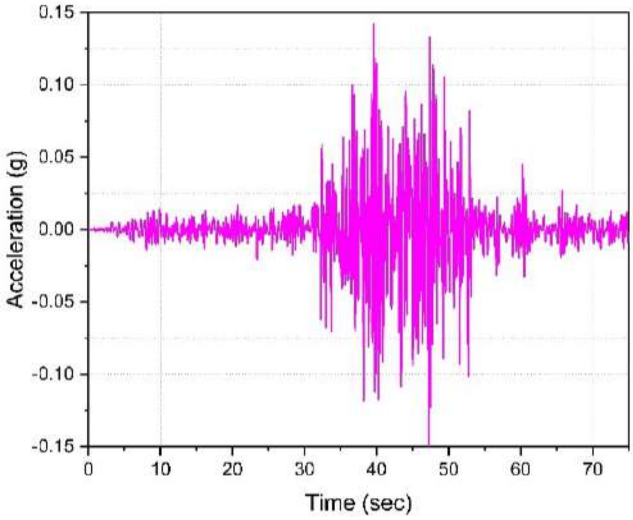
7(a)



7(b)



7(c)

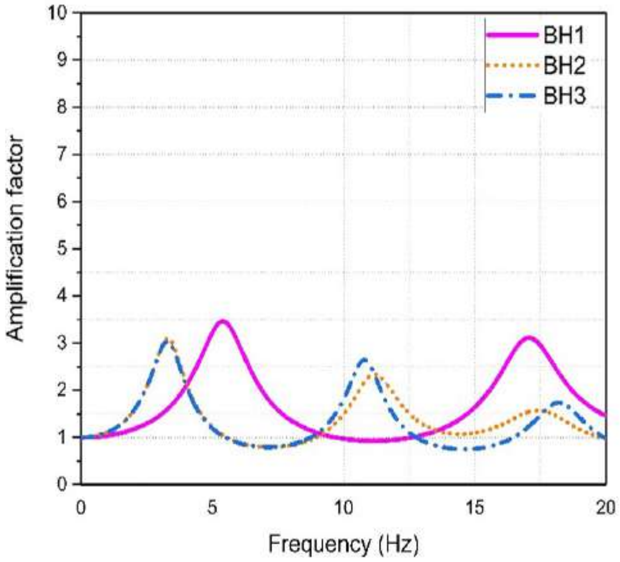


7(d)

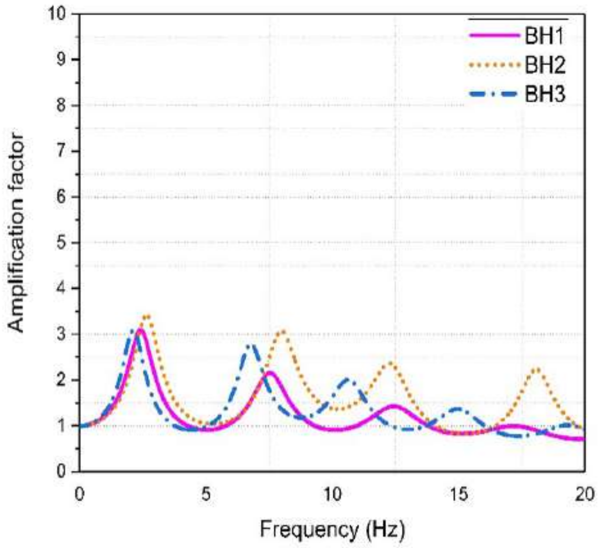
Figure 7 Surface accelerogram a) Abburaju Palem b) Amaravati c) Nekkallu d) Velagapudi

5.1.2 Amplification Factor

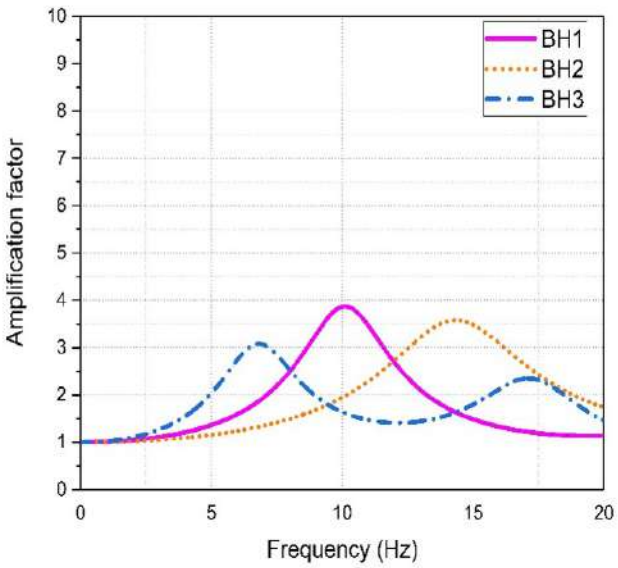
The amplification factor is referred to as the ratio of spectral acceleration at the ground surface to the spectral acceleration at bedrock in various periods. The Amplification factor for Abburaju Palem, Amaravati, Nekkallu, and Velagapudi towns are presented in Figures 8(a) to 8(d), respectively.



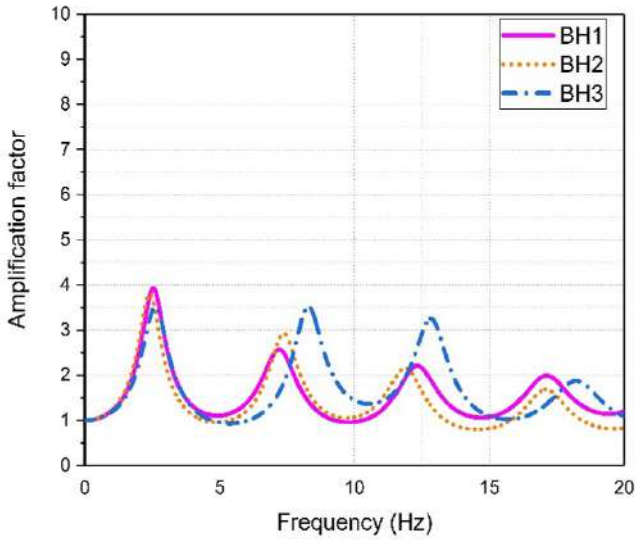
8(a)



8(b)



8(c)



8(d)

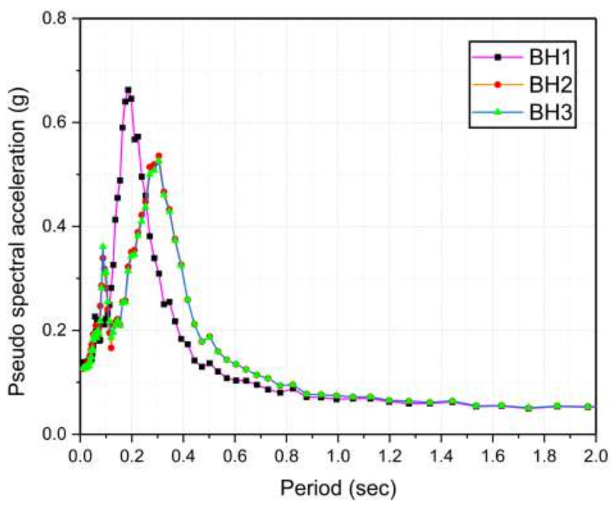
Figure 8 Amplification factor a) Abburaju Palem b) Amaravati c) Nekkallu d) Velagapudi

According to Figure 8(a), it becomes apparent that the BH1 site in Abburaju Palem exhibits the amplification factor of 3.5 at a frequency of 5.35 Hz. Similarly, in Figure 8(b), the Amaravati BH2 site exhibits an amplification factor of 3.4 at a frequency of 2.5 Hz. Moving to the Nekkallu soil sites in Figure 8(c), it is observed that they show the amplification factor in the higher frequency range of 8.75-10 Hz. As for the Velgapudi town in Figure 8(d), all the soil sites (BH1, BH2, and BH3) exhibit slightly similar amplification factors, at smaller frequencies of less than 2.5 Hz. Interestingly, it is evident that the amplification factor is generally higher at smaller frequencies compared to the higher frequencies for all soil sites within the Amaravati capital region.

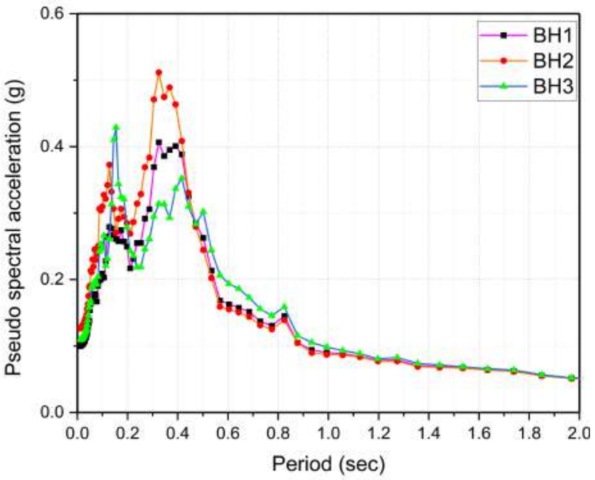
5.1.3 Response Spectrum

The acceleration response spectrum for all the soil sites was developed using the synthetic accelerograms, with a 5% damping ratio, and the results are presented in Figures 9(a) to 9(d), respectively.

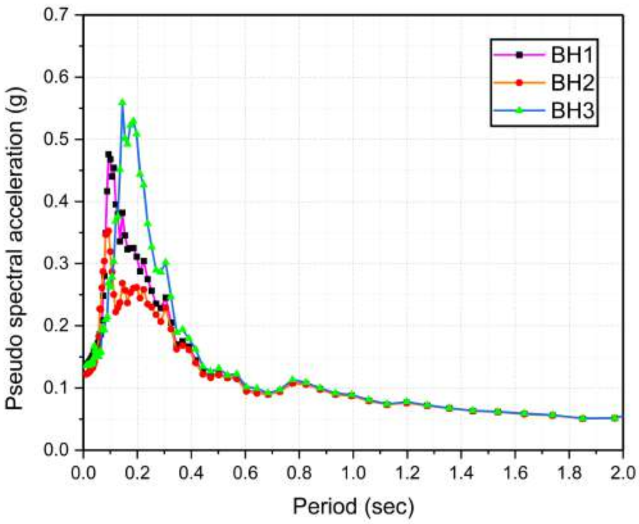
In Figure 9(a), the peak spectral acceleration for the BH1 soil site in Abburajupalem was found to be approximately 0.68 g at a period of 0.20 s, which is the highest among all the towns. Figure 9(b) shows that at Amaravati town, the peak spectral acceleration for the BH2 soil site is about 0.52 g at a period of 0.32 s.



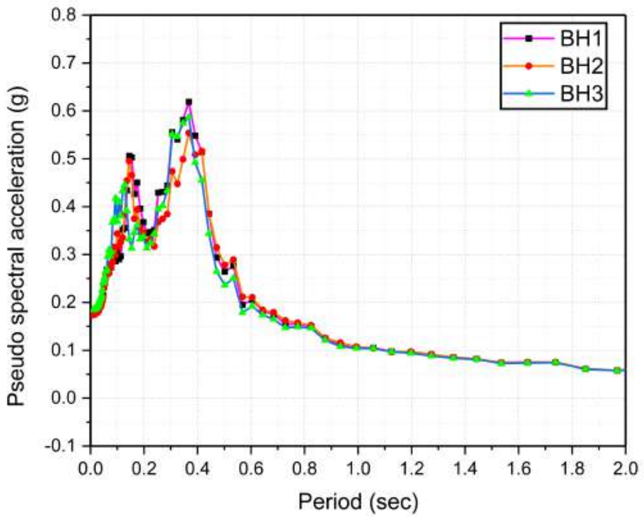
9(a)



9(b)



9(c)



9(d)

Figure 9 Response spectrum a) Abburaju Palem b) Amaravati c) Nekkallu d) Velagapudi

Similarly, for the Nekkallu and Velgapudi soil sites in Figures 9(c) and 9(d), respectively, the peak spectral acceleration is observed to be 0.63 g and 0.6 g at a period of 0.2 s and 0.4 s, respectively for the BH3 site.

Based on the above observations, it is concluded that the natural period of the soil sites in the study area is approximately 0.3 s. Moreover, the spectral acceleration values at higher natural time periods are significantly lower compared to the shorter time periods for all the considered locations. This information is vital for understanding the seismic behavior of the sites and designing earthquake-resistant structures to effectively mitigate seismic hazards in the area. The spectral acceleration from IS 1893 Part 1 were shown in Figure 10. The obtained spectral response spectrum for each town were compared with the spectral response spectrum of Zone III IS 1893 Part 1. It is observed that the spectral response spectrum is not conservative for the amplified ground motion for none of the selected sites.

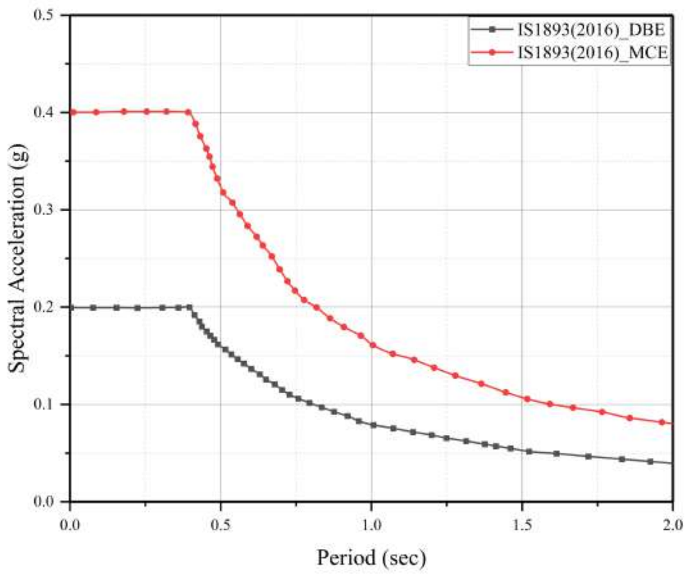
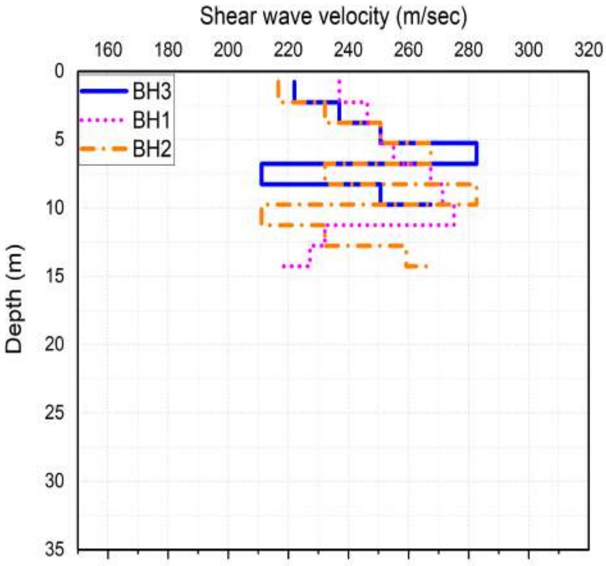


Figure 10 Spectral response spectrum for ZONE III from IS 1893 PART 1

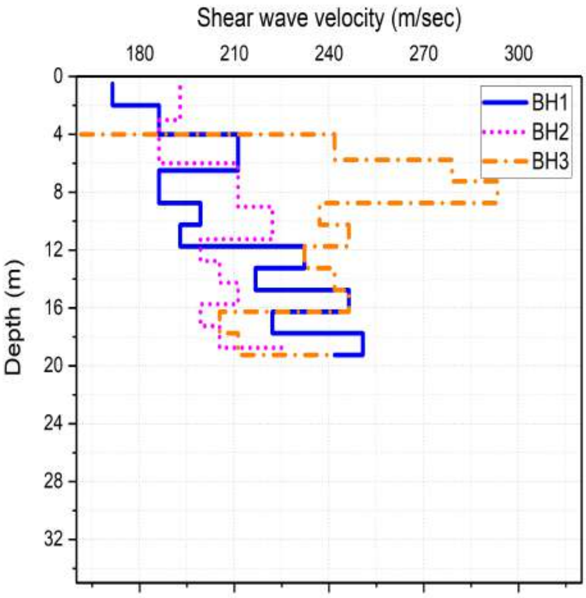
5.1.4 Variation of Peak Ground Acceleration (PGA) and Shear Wave Velocity with Depth

A comprehensive investigation into the impact that different soil layers have on ground amplification is carried out in the current work. An explanation of the variation of shear wave velocity with depth is provided for each of the soil sites in Figures 11(a) through 11(d). When compared to other sites, the shear wave velocity at the Nekkallu soil site is seen to be significantly higher (Figure 11c). Additionally, Figure 11(d) demonstrates that the shear wave velocity at the Velagapudi soil site remains rather consistent during the whole experiment. The region of Nekkallu is advantageous because it has a predominant hard stratum and soil that has a high density, both of which lead to a more effective transmission of seismic shear waves.

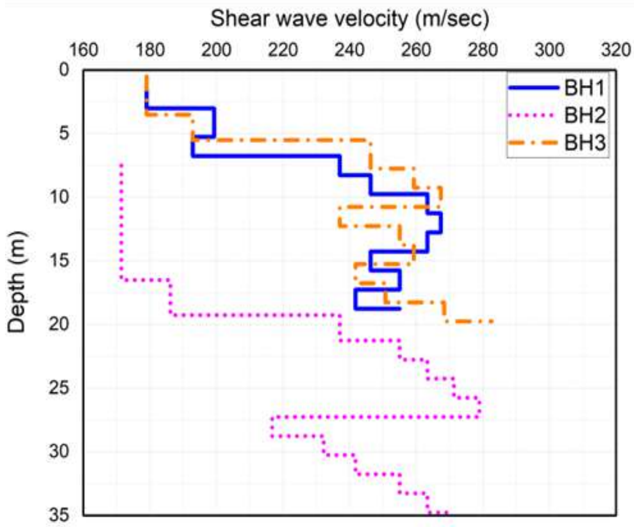
The total seismic stability of the region is improved because of this geological advantage, which also has the potential to lessen the amount of ground displacement that occurs during earthquakes. On the other hand, the soil locations of the remaining three towns, Amaravati, Abburaju Palem, and Velagapudi, are composed of soils that are either less consolidated or softer. This might result in stronger ground amplification effects during seismic occurrences. It is vital to understand these variations in soil qualities to construct earthquake-resistant structures that are customised to the individual geological circumstances of each area. This will ensure the safety and resilience of the communities that are in these locations.



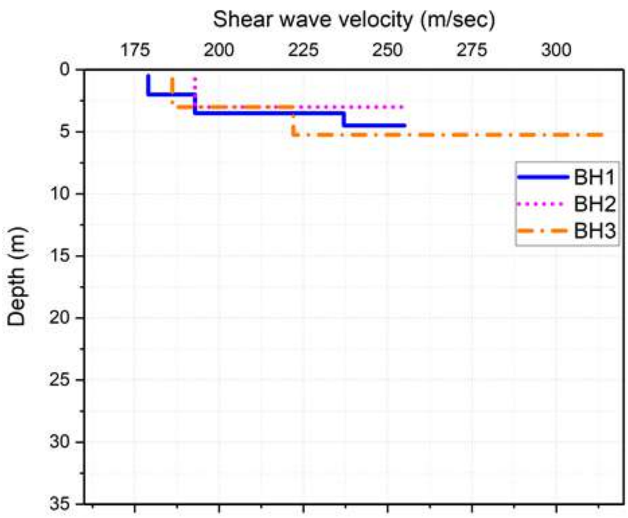
11(a)



11(b)



11(c)



11(d)

Figure 11 Variation of shearwave velocity with depth a) Abburaju Palem b) Amaravati c) Nekkallu d) Velagapudi

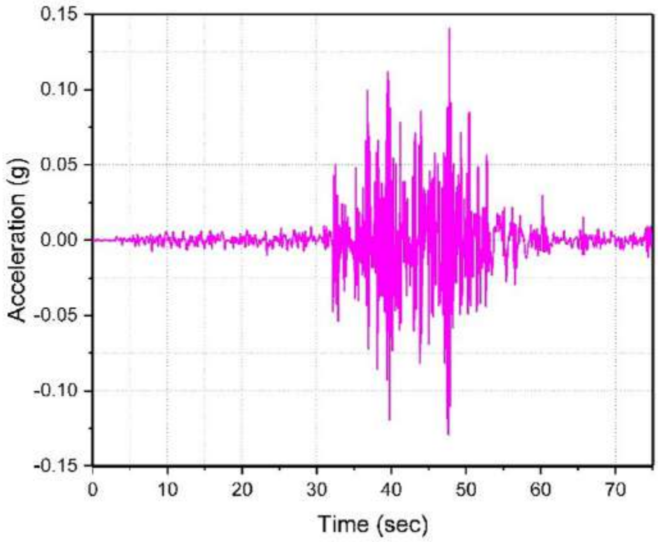
5.2 Nonlinear Ground Response Analysis

In this study, a nonlinear ground response analysis was conducted for three borehole data from four significant towns in Amaravati's capital region. The DEEPSOIL software was utilized to simulate the real input motion of the Bhuj earthquake that occurred in 2001. The analysis aimed to investigate the ground response characteristics at the selected locations and assess the seismic behavior of the soil sites.

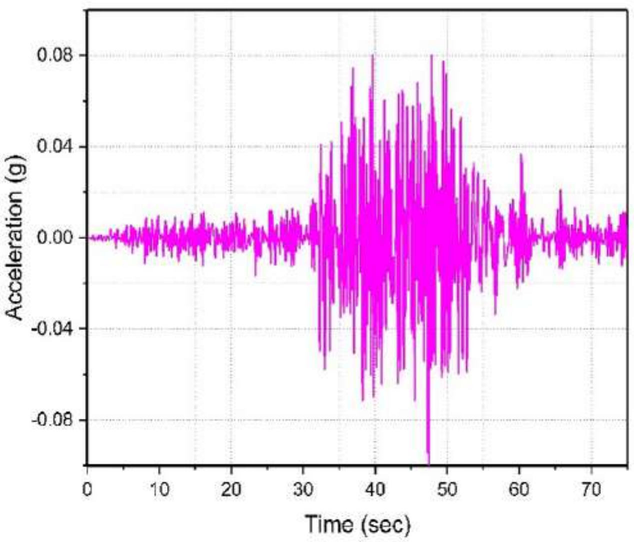
5.2.1 Surface Accelerograms

According to the results of the study shown in Figures 12(a) to 12(d), the boreholes in Abburaju Palem and Velagapudi, particularly BH2, had the highest surface spectral accelerations (PHAs) of 0.148 g and 0.125 g when compared to other locations. This finding indicates that these soil areas are more vulnerable to higher ground accelerations during earthquakes.

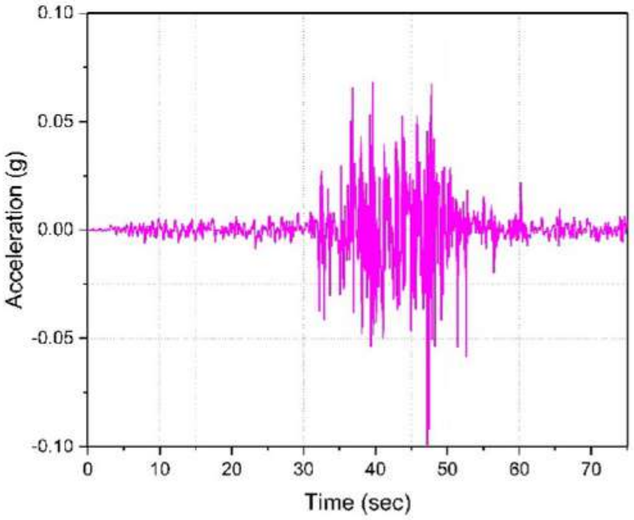
On the other hand, the analysis indicates that the Amaravati and Nekkallu towns show relatively lower surface accelerations at their respective borehole locations as represented as 0.08 g and 0.075 g, respectively.



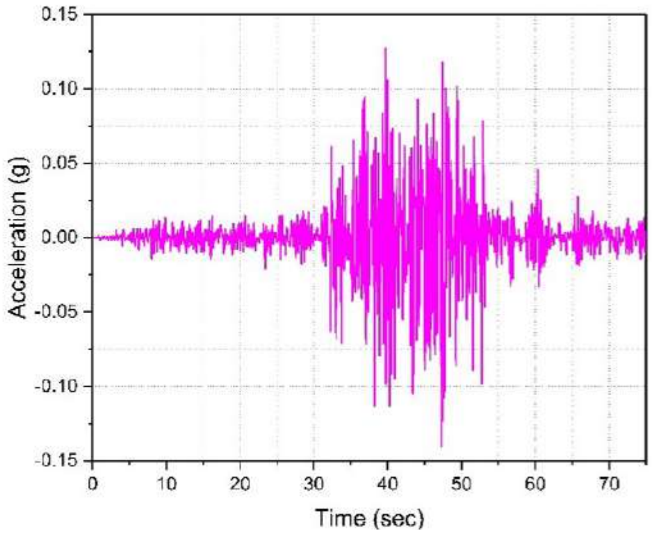
12(a)



12(b)



12(c)

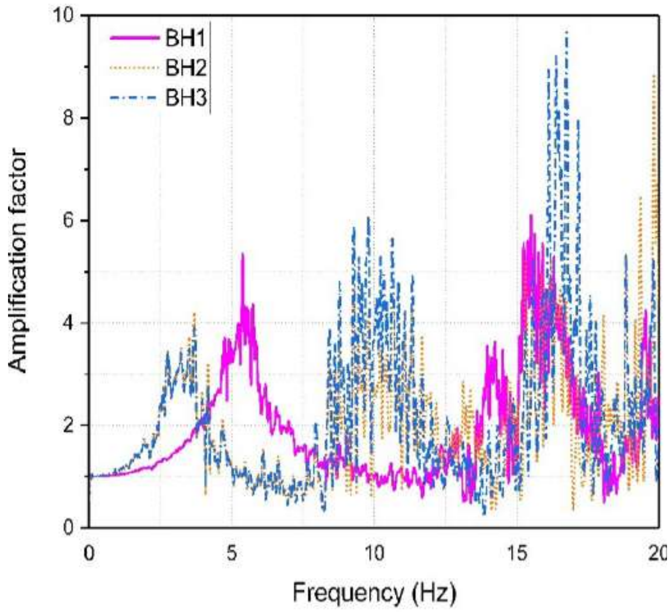


12(d)

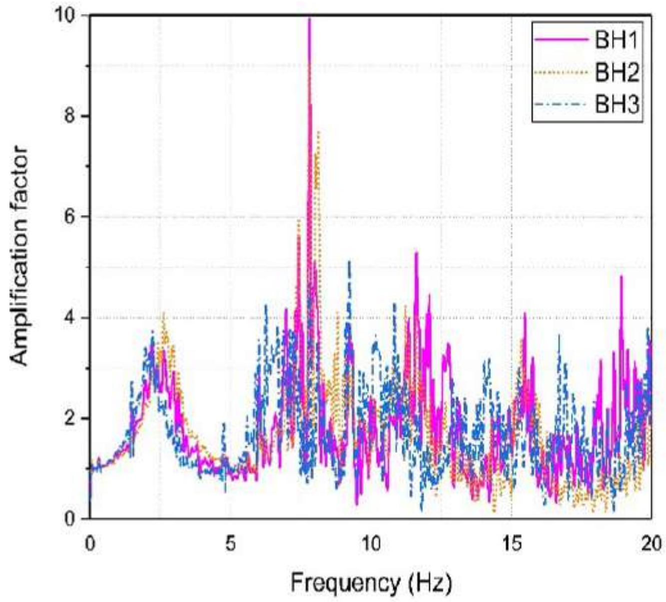
Figure 12 Surface accelerograms obtained in nonlinear analysis a) Abburaju Plaem b) Amaravati c) Nekkallu d) Velagapudi

5.2.2 Amplification Factor

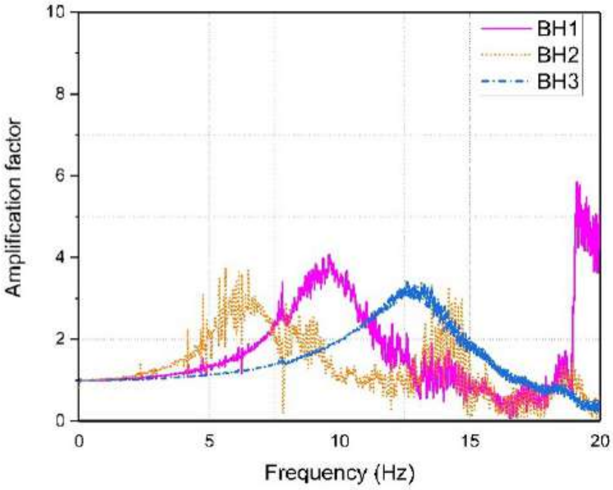
The Amplification factor for Abburaju Palem, Amaravati, Nekkallu, and Velagapudi towns are presented in Figures 13(a) to 13(d), respectively. From Figure 13(a) it is noticed that the BH3 site at the Abburaju Palem gives the highest amplification factor of 5.48 at a frequency of 10 Hz, similarly for the Amaravati BH2 site the amplification factor was observed to be 6.25 at a frequency of 7.5 Hz (Figure 13(b)). Nekkallu soil sites have the lowest amplification factor of 3.9 among all the sites at frequency of 9 Hz (Figure 13(c)). The Velgapudi town showed an amplification factor slightly similar for all the soil sites such as BH1, BH2, and BH3, which is observed to be 4.6 at a smaller frequency of less than 2.5 Hz. It is noticeable that the amplification factor is high at smaller frequencies as compared to the higher frequencies for all soil sites that existed in the Amaravati capital region.



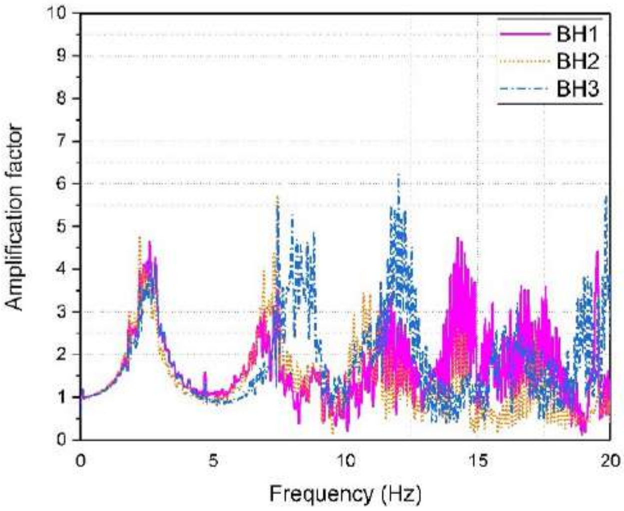
13(a)



13(b)



13(c)



13(d)

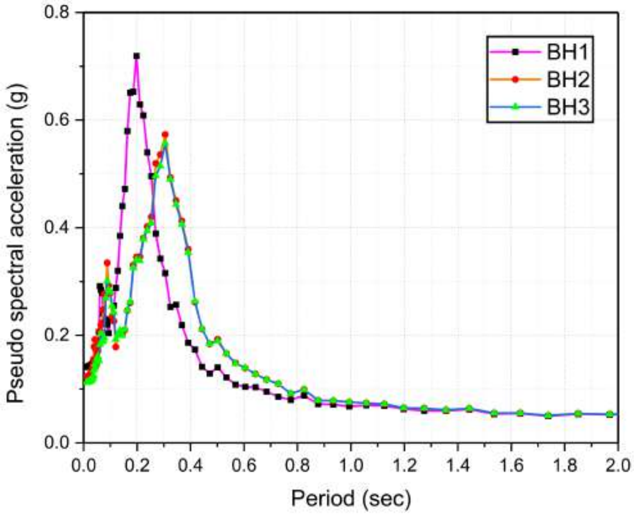
Figure 13 Amplification factor obtained in nonlinear analysis a) Abburaju Palem b) Amaravati c) Nekkallu d) Velagapudi

5.2.3 Response Spectrum

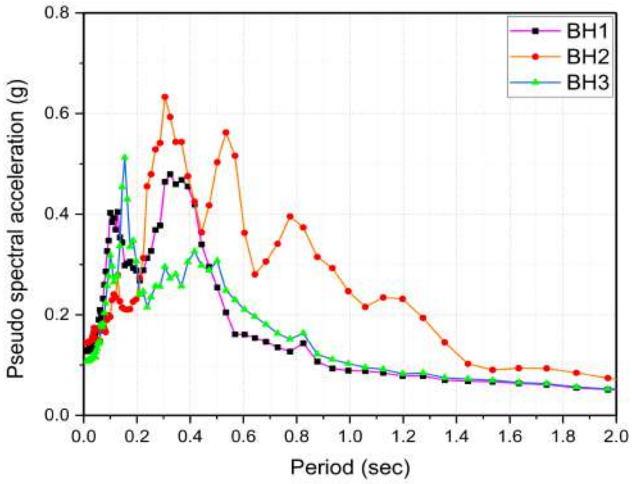
The acceleration response spectrum for all the soil sites was developed using the synthetic accelerograms as input motion, considering a damping ratio of 5%. The results are presented in Figure 14(a) to 14(d), respectively for the Abburaju Palem, Amaravati, Nekkallu, and Velgapudi towns. From Figure 14(a), it is observed that the peak spectral accelerations for the Abburaju Palem soil sites are approximately 0.72 g, occurring at a period of 0.2 s. This value is the highest among all the towns, indicating a relatively higher level of ground shaking at this location.

Moving to Amaravati in Figure 14(b), the peak spectral acceleration of Amaravati is found to be around 0.62 g, occurring at a period of 0.3 s for the BH2 soil site. For the Nekkallu and Velgapudi soil sites in Figures 14(c) and 14(d), respectively, the peak spectral accelerations are observed to be 0.55 g and 0.6 g at a period of 0.2 s and 0.4 s for the BH3 and BH1 sites, respectively.

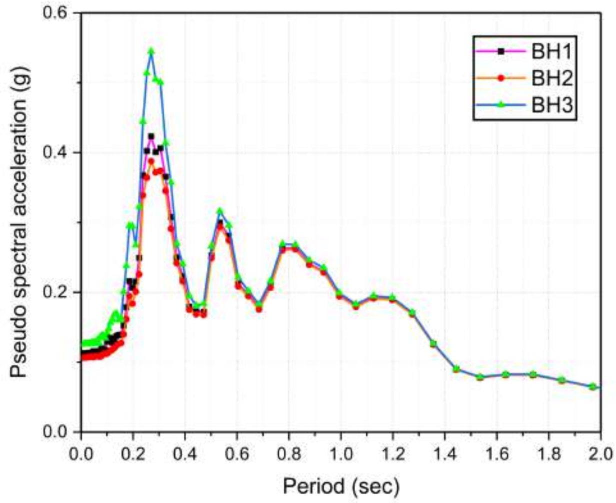
Based on these observations, it is concluded that the natural period of the soil sites in the study area is approximately 0.3 s. Furthermore, the spectral acceleration values decrease significantly at higher natural periods compared to the shorter time periods for all soil sites in the Amaravati capital region.



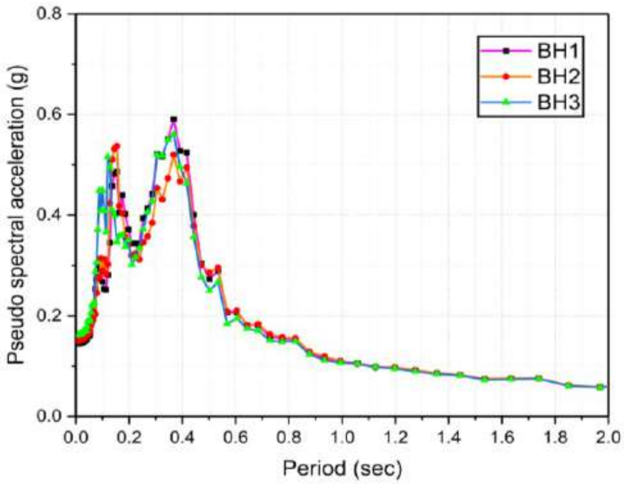
14(a)



14(b)



14(c)



14(d)

Figure 14 Response spectrum obtained in nonlinear analysis a) Abburaju Plaem b) Amaravati c) Nekkallu d) Velagapudi

6. CONCLUSIONS

Ground response analysis of four important towns of soil sites considering the input motion as synthetic accelerograms obtained from seed accelerogram as the 2001 Bhuj earthquake motion, were presented. Both the equivalent linear and non-linear analyses were conducted. The following are major contributions of the study:

- From the Present study it is recommended that the seismic hazard analysis along with the ground response analysis should be carried out for every region of India.
- The local soil sites showed significant amplification of responses and are discussed thoroughly. It is noticed that the local soil sites have a potential influence in modifying ground response.
- The mean spectral values obtained from the equivalent linear analysis are higher than those obtained from the nonlinear analysis. This highlights the significant influence of the analysis method on the ground response analysis. Further, the results obtained by both analyses are higher than the values recommended by IS 1893 part 1 (2016).
- Amaravati, Abburaju Palem, and Velagapudi, consist of softer soils resulting in higher ground amplification.
- The response spectra obtained for 5% damping may be used for earthquake resistant design in the absence of any site-specific data for similar sites of Amaravati capital region.
- Spectral accelerations of the major portion of the study area are found to be in the range of 0.6 to 0.7 g at a period range of 0.25-0.5s.

7. APPLICATIONS

- IS: 1893 Part 1 (2016) provides ground motion recommendations without explicit local site effects; the present study goes further by recommending ground motions associated with local site effects for the entire Amaravati region. This additional information can be valuable for making informed decisions related to performance-based design and disaster preparedness.
- IS: 1893 Part 1 (2016) does not provide a region-specific guideline for earthquake resistant design of structures for the present study area. By considering regional seismicity, which refers to the historical seismic activity in a particular area, and site-specific conditions, such as local soil properties and geological features, the study aims to create a more robust and tailored approach to estimating ground motion.

8. LIMITATIONS

- Lateral variations in soil properties that can significantly influence ground response are not considered in the present study.
- 1D analysis methods may not fully capture the complex nonlinear behavior of soils under strong shaking, especially in liquefiable and soft soil sites. Owing to these limitations, the presented results need to be used cautiously.
- The current study's ground motion parameters only consider one-dimensional wave propagation; however, considering three-dimensional wave propagation may result in different results because of the impacts of basin geometry and topography.
- Although the borehole data is collected only from highly reliable sources, the inherent limitation of uncertainties of the data will always exist.
- The present study could benefit from further enhancement through the inclusion of sensitivity analysis for the ground response analysis results. This additional step would provide valuable insights into the robustness and reliability of the obtained findings.

9. ACKNOWLEDGMENTS

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