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Site Specific Seismic Ground Response Analysis of Major Ports in Odisha, South-Eastern Coastal Region of India: A Case Study

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Abstract - Ports are vital economic arteries for any nation, making the resilience of port infrastructure to seismic events a paramount concern. This study emphasizes the necessity of constructing port facilities capable of withstanding significant seismic forces, particularly peak ground acceleration (PGA), which is crucial for maintaining their operational integrity during earthquakes. The local soil characteristics significantly influence the seismic ground motion, thus emphasizing the necessity of site-specific seismic investigations to enhance the safety of these critical structures. This study addresses the urgent need for site-specific seismic ground response analysis (GRA) in three major port locations in Odisha, India, where local geophysical data is scarce. Using borelog data and empirical correlations, shear wave velocity (V_s) profiles were estimated from standard penetration test (SPT-N) values. The analysis classified the sites based on their average V_s values at a depth of 30 m (V_s30), following the criteria set by the National Earthquake Hazards Reduction Program (NEHRP). These were employed within the DEEPSOIL software framework to perform one-dimensional equivalent linear GRA using three real ground motion records representative of stable continental regions. The analysis computed peak ground acceleration (PGA), amplification factors, response spectra, and Fourier amplitude ratios. Results reveal significant amplification effects, especially at Dhamara port due to soft marine clays, with surface PGA values nearly doubling compared to bedrock input. Results show that surface-level PGA values are amplified up to 1.8 times the bedrock values, with the highest amplification at Dhamara. Fundamental site periods ranged from 0.47 to 0.72 s, and in some period ranges, the site-specific spectra exceeded IS 1893:2016 code spectra, particularly for Site Class E. The findings aid in the design of earthquake-resistant structures in regions where direct site-specific data may not be readily available, facilitating better-informed engineering decisions to enhance the resilience of port infrastructure against earthquakes.

Keywords: seismic hazard, ground response analysis, *PGA*, spectral acceleration, Fourier amplitude ratio

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Introduction

Background

Soil conditions have a large effect on the properties of ground motion in an earthquake. These effects refer to the variation in seismic wave amplification caused by specific geological and soil conditions in a given area. Factors such as soil composition, layering, and subsurface geometry play a significant role in determining how seismic waves are amplified as they travel from the bedrock to the surface. Understanding these site-specific characteristics is essential for accurately assessing seismic hazards and designing structures capable of withstanding ground motions induced by earthquakes (Mishra *et al.*, 2025). Three primary factors influence the ground motion characteristics at a site: source effects, path effects, and site effects.

Source effects refer to the characteristics of the earthquake source itself, including its magnitude, fault rupture mechanism, rupture depth, and direction of rupture propagation. These parameters determine the initial energy release and frequency content of the seismic waves. Path effects account for the modification of seismic waves as they travel from the source to the site through the Earth's crust. Variations in rock properties, fault zones, and crustal heterogeneities affect wave attenuation, scattering, and amplification along the propagation path. Site effects represent the most critical component for local seismic response, especially in soft or layered soils. These are driven by the stratigraphy, stiffness contrast between soil layers, shear wave velocity profiles, depth to bedrock, water table level, and nonlinearity of the soil under cyclic loading. Amplification occurs when the frequency content of incoming waves resonates with the natural frequency of the soil column, leading to increased surface accelerations. In particular, deep, unconsolidated sediments can trap and amplify seismic waves, often resulting in prolonged shaking durations and elevated spectral accelerations.

Increased ground motion amplification can increase the risk of liquefaction, underscoring the importance of comprehensively accounting for local site effects in seismic risk assessments and engineering designs. An area having unconsolidated sedimentary soil layers is prone to amplified ground shaking significantly higher than areas with rock surfaces (Sil and Haloi, 2018). Seismic wave amplification primarily occurs when waves become trapped between various upper soil layers and the bedrock at the bottom. This phenomenon occurs because shear waves travelling upward through loose soil layers encounter less resistance compared to the reflection of downward-propagating waves by rigid strata at the bottom. The resulting wave trapping leads to significant ground motion amplification, frequently resulting in resonance (Al-Ajamee *et al*., 2022). Several catastrophic earthquakes that occurred in recent decades, including the Michoacan earthquake in 1985 (Chavez-Garcia and Bard, 1994), which caused widespread devastation in Mexico City; the Californian earthquake in 1989 known as Loma Prieta (Beroza, 1991); 1994 Phan earthquake in Thailand (Ashford *et al*., 2000), Kobe earthquake which occurred during 1995 in Japan, and the Bhuj earthquake of 2001 in India (M_w = 7.7) (Gupta *et al*., 2001), demonstrated the significant impact of site specific geological and soil properties upon both the amplitude of the ground motion as well as the destruction that occurred as a consequence of these seismic events. Thorough investigations involving both theoretical GRA and empirical surface motion measurements emphasized the criticality of conducting site-specific risk studies while designing structures to withstand earthquakes. These studies provided valuable insights into understanding different geological and soil conditions that significantly impact the response of structures to seismic events. Incorporating site-specific risk assessments into the design process, engineers can develop earthquake-resistant structures that are tailored to the unique characteristics of the location, thereby enhancing overall safety and reducing the potential for damage and loss. In civil engineering practice, site investigation is fundamental prior to any infrastructure development, especially for critical facilities like ports. Subsoil characterization is vital for foundation design, liquefaction assessment, and ground response analysis, as it governs the dynamic behaviour of soil under seismic loading (Mase and Likitlersuang, 2021; Farid *et al*., 2024). Technological advancements in site investigation methods, such as geophysical testing, geotechnical testing, and empirical soil characterization, have been widely adopted to understand subsurface variability (Mase *et al*. 2023). Shear wave velocity (V_s) profiles, in particular, serve as the backbone for dynamic site classification and seismic hazard assessment (Mase *et al*., 2021).

Ports, as lifeline infrastructure, serve critical economic and logistical functions, including cargo transfer, storage, and passenger movement. The disruption of port operations due to seismic events can lead to profound regional and national economic losses. Past earthquakes such as the 1989 Loma Prieta, 1995 Kobe, and 1999 Kocaeli earthquakes have exposed the vulnerability of port structures to strong ground motions (Shukla and Choudhury, 2012; Mishra *et al*., 2024). In India, the 2001 Bhuj earthquake caused liquefaction-induced failures near Kandla Port, damaging pile-supported structures and cargo facilities due to 10 m thick saturated loose-to-medium sands (Desai and Choudhury, 2015). These case studies illustrate that while seismic events affecting ports may be infrequent, their consequences are often catastrophic.

Due to local variations in geological conditions, such as soil types and bedrock characteristics, traditional regional hazard assessments may not accurately capture the unique seismic responses of these locations. Therefore, a focused seismic ground response analysis is essential to design and implement effective earthquake-resistant structures and to develop tailored mitigation strategies that ensure the resilience and safety of critical infrastructures. Ports, which are crucial to the economic vitality of any nation, were particularly vulnerable to this amplified ground motion. To mitigate such destruction in future seismic events, it is imperative to conduct site-specific seismic hazard analyses for ports. This involves assessing regional seismicity and site-specific ground motions and incorporating various aspects of geotechnical earthquake engineering (Singbal *et al*., 2020). Since there are no standard seismic design provisions for Indian ports, the methodologies recommended by (Shukla and Choudhury, 2012) offer a valuable reference framework. Hence, acquiring subsoil data such as V_s profiles becomes essential to evaluate ground motion amplification and develop safe, performance-based designs for port infrastructure in potentially vulnerable coastal regions.

The state of Odisha, located along the south-eastern coast of Peninsular India, holds a unique geostrategic and economic position due to its long coastline, deep alluvial soils, and the presence of major maritime infrastructure. Despite being part of an intraplate region typically classified as tectonically stable, Odisha has experienced several moderate to strong earthquakes in the past. Recent seismic hazard studies further suggest an increasing vulnerability along the Bay of Bengal coast (Khan and Kumar, 2020). The region hosts major ports such as Paradeep, Gopalpur, and Dhamara, which serve as critical nodes for national trade and regional economic connectivity. However, these port facilities are commonly founded on deep, unconsolidated, and potentially liquefiable sediments, making them particularly susceptible to seismic hazards such as ground motion amplification and liquefaction.

In light of these vulnerabilities and the lack of detailed geophysical data, there is an urgent need for site-specific seismic ground response analysis (GRA) to capture local amplification effects and to guide resilient infrastructure design. This study presents a one-dimensional equivalent linear GRA (EQL-GRA) for three key port locations in Odisha, conducted using the DEEPSOIL platform (Hashash *et al*., 2020). Field-based borehole data were utilized to define the subsoil profiles, while three real recorded earthquake motions: Bhuj (M_w *7.7, 2001*), Saguenay (M_w *5.85, 1988*), and Virginia (M_w *5.8, 2011*) were selected as input motions, reflecting tectonic analogues of stable continental regions. In the absence of direct shear wave velocity (V_s) profiles, empirical correlations between SPT-N and V_s specific to Indian soil conditions were employed.

To capture the nonlinear dynamic response of soils, modulus reduction (G/G_{max}) and damping ratio (ζ) curves were adopted and adjusted based on borehole-specific plasticity indices. These parameters were sourced from internationally validated models and tailored for the local soil types observed in Odisha port areas. The outputs of the GRA include key engineering parameters such as peak ground acceleration (PGA) at the surface, amplification factors, response spectra, and the site's natural period. These results offer vital insights into the seismic performance of port facilities and contribute to developing robust, performance-based seismic design strategies for coastal infrastructure in data-scarce regions.

The main focus of this investigation is the major sea ports located in the Odisha region of eastern Peninsular India (PI). The state of Odisha occupies a unique position due to its long coastline, soft sedimentary deposits, and the presence of economically vital port infrastructure. Despite being located in an intraplate region generally considered stable, Odisha has recorded moderate to strong seismic events in the past, and recent studies have indicated an increasing seismic threat along the Bay of Bengal (Khan and Kumar, 2020). Major ports such as Paradeep, Gopalpur, and Dhamara not only support national trade, but also serve as lifelines for regional development and connectivity. These port facilities, often founded on deep, unconsolidated soil layers, are particularly susceptible to seismic ground motion amplification, liquefaction, and other site-specific geotechnical hazards. Therefore, conducting a site-specific seismic ground response analysis (GRA) in these areas is imperative to accurately assess local amplification effects and to develop robust design criteria that ensure structural safety and service continuity under seismic loading. The lack of geophysical data in these zones further increases the need for methodological rigour, making the present study both timely and essential. This paper presents a one-dimensional equivalent linear GRA (*EQL-GRA*) for three port areas in Odisha utilizing the software package DEEPSOIL (Hashash *et al*., 2020). The analysis incorporates field borehole data obtained from several representative sites in the respective ports, diverse input motions and soil dynamic properties to provide detailed insights into the existing practice in which local soil conditions impact the characteristics of ground response within the studied area. To evaluate the seismic response of the selected port sites, three real acceleration-time histories were used as input ground motions: the 2001 Bhuj earthquake (M_w 7.7), the 1988 Saguenay earthquake (M_w 5.85), and the 2011 Virginia earthquake (M_w 5.8). These events, representative of stable continental regions, were selected based on their relevance to the geotectonic setting of Peninsular India. In the absence of direct shear wave velocity (V_s) measurements, V_s profiles were estimated using empirically derived equations calibrated for Indian soil conditions, developed through regression analyses based on standard penetration test (SPT-N) data. To characterize the dynamic behaviour of the soil, two essential parameters were incorporated: modulus reduction curves (G/G_{max}) and damping ratio curves (ζ), each representing the strain-dependent stiffness and energy dissipation characteristics of soils. These curves were adopted following an extensive review of global literature and were customized based on the plasticity and type of soils observed in site-specific borehole logs. The output of the GRA included critical seismic parameters such as the amplification factor, site fundamental period, surface-level peak ground acceleration (PGA), and response spectra. These parameters collectively inform the seismic vulnerability and structural performance of the port facilities under potential future earthquake loading.

Studied Area Details and Its Seismicity

The studied area selected for Figure 1 shows the three major ports in Odisha. The Gopalpur port, located in Ganjam District, on the southern part of the coastal belt of the state, with coordinates 19.3039° N and 84.9655° E, is a natural, deep-water port with significant potential for cargo handling. After undergoing extensive modernisation and development, it emerged as a multipurpose port capable of handling diverse cargo, including bulk, breakbulk, and containers. Gopalpur Port is strategically positioned to cater to trade in the eastern region of India. The Paradeep Port, the oldest and the largest among the three, is located in the Jagatsinghpur District of the state, with coordinates *20.92° N* and *86.57° E.* It is the primary port of Odisha and one of the major ports in India. It is a deep-water port with a capacity to

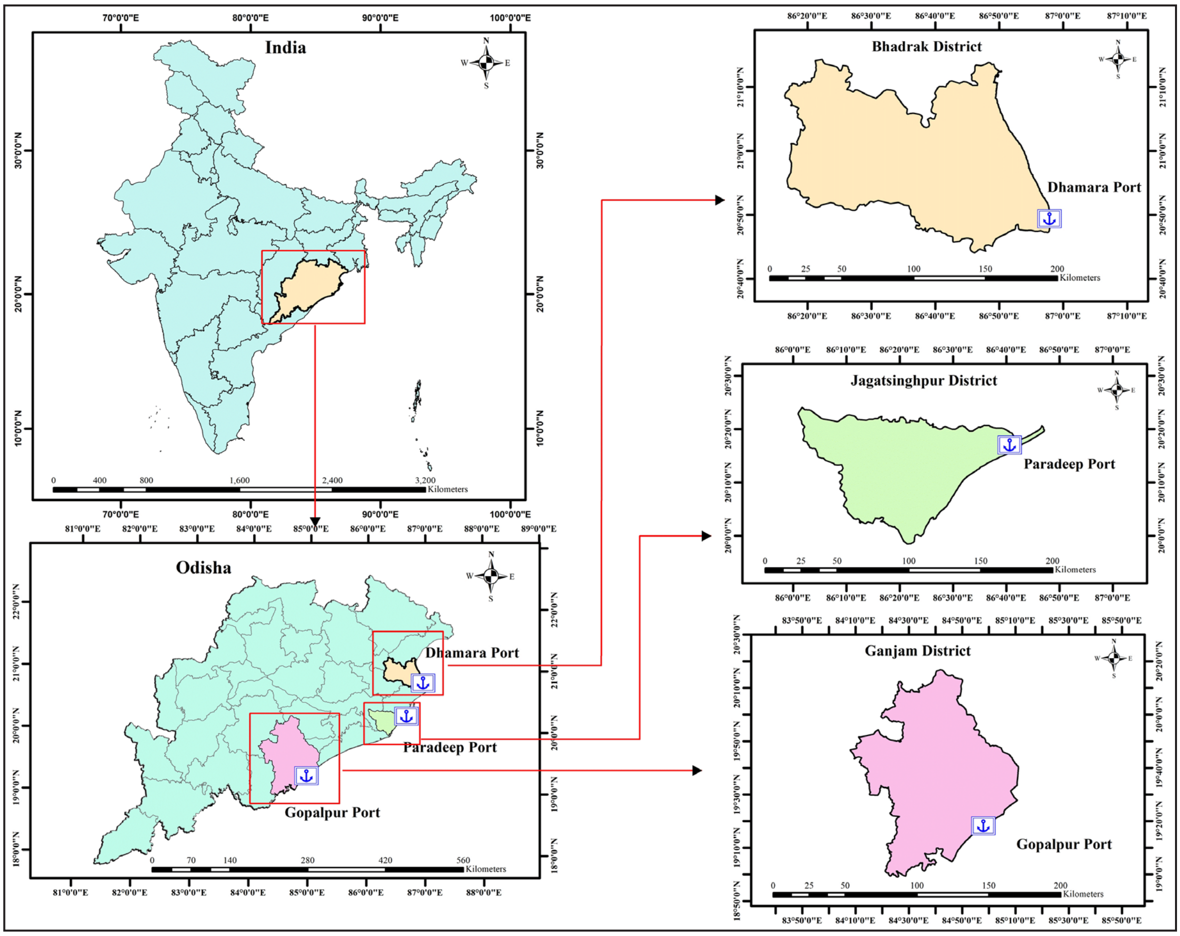

Figure 1. Location of ports in Odisha.

handle a large variety of cargo materials. It serves as a gateway for international trade and is known for its extensive facilities and connectivity. The Dhamara Port, situated in the Bhadrak District with a latitude of 20.8237° N and longitude 86.9640° E, is another major port in Odisha. It is a deep-water, all-weather port that primarily handles bulk cargo, such as coal, iron ore, and other dry bulk commodities. Dhamara Port has modern infrastructure and is known for its strategic location and connectivity to major industrial areas. These ports provide a critical sea route connecting Odisha with other regions of the world, enabling various economic activities (trade, import, export, *etc.*), which contribute to the economic growth and foster regional connectivity. In the current work, local soil data obtained from borehole locations 2, 3, and 4 are used to perform the analysis for Gopalpur, Paradeep, and Dhamara, respectively.

From a perspective of geology, Odisha State is located in the eastern portion of the PI region. The IS 1893 – 2016 code (BSI, 2016) allocates Odisha in seismic zones II and III, which signifies the place is low to moderately seismically active. Historical data show that Odisha State has experienced moderate to large earthquakes. Figure 2 shows the past earthquake events around the studied area during the last 285 years. The earthquake events and intraplate seismic activity in the bay of Bengal have an enormous impact on coastal Odisha due to the soft sediment layers in this region can amplify the seismic waves and exacerbate the damage (Huded and Dash, 2022; Mishra and Sil, 2024). Recently, an earthquake with a magnitude of 6.0 occurred in the bay of Bengal region in 2014 and affected the coastal Odisha (Singh *et al.*, 2015). To assess the seismicity of the region, the authors have done a seismic hazard analysis (SHA) of the

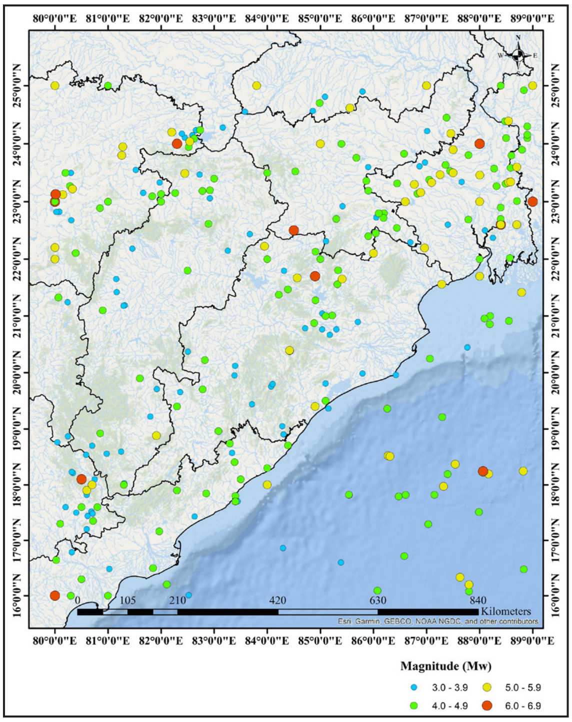

Figure 2. Earthquake events in the last 285 years around the studied area (after declustering).

region. An earthquake catalogue consisting of the event data of 286 years (1737−2023) has been created, and three attenuation models specified for stable continental regions RGKY-07 (Raghukanth and Iyengar, 2007), NDMA-10 (Iyengar *et al*., 2010), and ANBZ-19 (Bajaj and Anbazhagan, 2019) were used with adequate weightage factor in the study. The seismic sources for the current studied area were identified from SEISAT 2000, and recent research articles; the active potential seismic sources were considered in the study. The seismotectonic map of the region is illustrated in Figure 3. The seismic sources considered in this study are adopted from Mishra and Sil (2024). A total of thirty-nine faults have been identified within Odisha and its surrounding regions. Out of these, eighteen faults have been classified as significant in terms of their potential to generate notable ground motion. This classification is based on several factors, including the density of seismic events in proximity to the faults, estimated seismicity parameters, and the geological and tectonic characteristics of each fault. Such categorization allows the analysis to focus on the sources most likely to influence seismic hazard in the studied area. Among the identified sources, the Eocene Hinge Fault, a strike-slip fault extending 470.97 km, is the longest and has recorded the highest magnitude of M_w = 6.86. In contrast, Fault F1, a gravity fault measuring 77.03 km in length, represents the shortest fault in the analysis, with a maximum recorded magnitude of M_w=5.02.

A flowchart showing seismic hazard analysis methodology for Odisha State involved a systematic series of stages, beginning with the preparation of a comprehensive earthquake catalog compiled from multiple sources, is given in Figure 4. The catalog was homogenized to a uniform magnitude scale and declustered to eliminate dependent events, ensuring data consistency. Seismic source zones were identified and characterized following catalog completeness analyses using both the cumulative visual inspection (CUVI) method and the Stepp method, which helped define the completeness periods for different magnitude thresholds. A detailed seismotectonic map was then prepared by integrating geological, tectonic, and seismological information to delineate potential seismic sources. Seismicity parameters, including the Gutenberg-Richter recurrence parameters, were estimated using both the least squares (LSQ) and maximum likelihood (MLH) methods to enhance robustness. The maximum credible earthquake magnitude (M_{max}) for each source was determined through multiple approaches, including NDMA guidelines, the Kijko method, and the RLD method, to ensure conservative and reliable estimates. Ground motion prediction equations (GMPEs) were selected based on source-to-site distance, with RGKY-07 and Bajaj-19 applied for sources within 250 km, and Bajaj-19 and NDMA-10 for more distant sources, with appropriate weighting (Mishra and Sil, 2024). Both deterministic (DSHA) and probabilistic (PSHA) seismic hazard analyses were carried out, accounting for scenario earthquakes, critical distances, and the cumulative effects of all potential sources and associated uncertainties. The resulting bedrock-level peak ground acceleration (PGA) values served as the foundation for

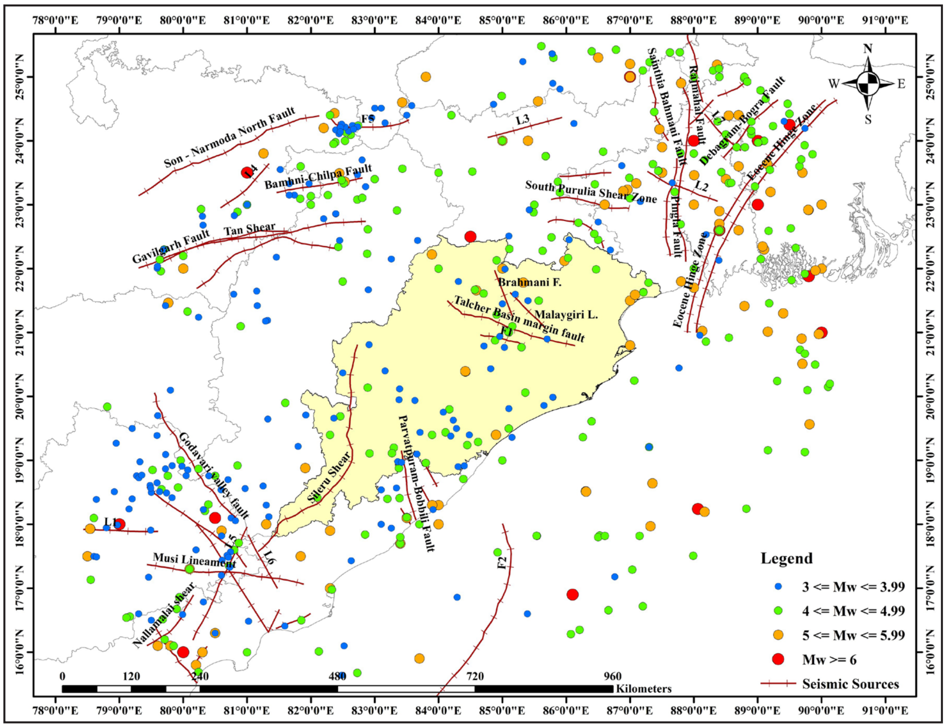

Figure 3. Seismotectonic map of the region.

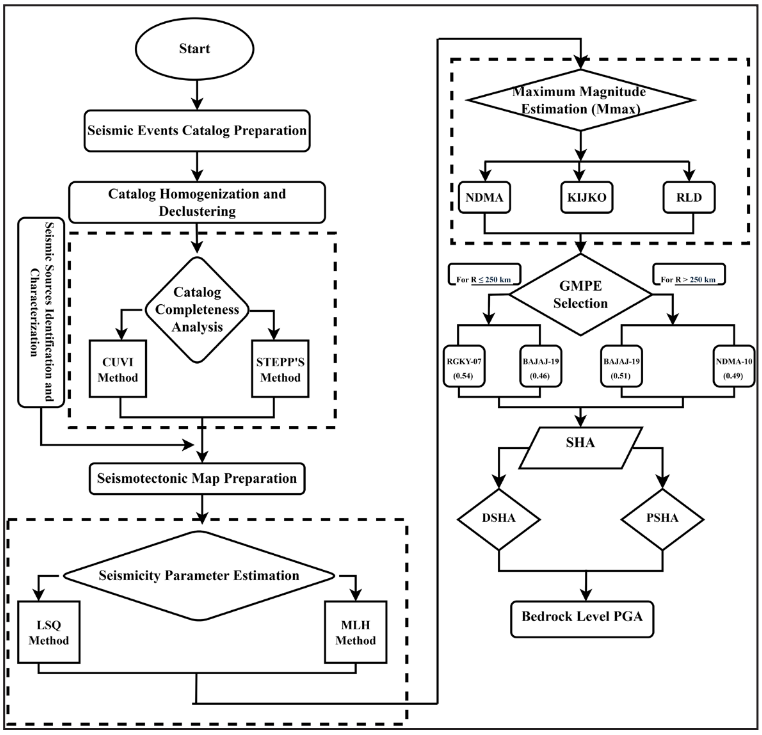

Figure 4. Flowchart illustrating the methodology for SHA.

generating the seismic hazard maps and for the subsequent ground response analysis presented in this study.

The final products of the hazard analysis, i.e., PGA values at bedrock level and the proposed uniform hazard spectra (at bedrock level) for the specific districts, were used for further analysis in this study.

The seismic hazard analysis for Odisha was performed and the final product, *i.e.* bedrock-level peak ground acceleration (PGA) values were estimated at the centre of each 1 km × 1 km grid. To generate a continuous spatial distribution of PGA values across the state, the inverse distance weighting (IDW) interpolation method was employed using ArcGIS 10.7. IDW is a deterministic method widely used in hazard mapping, where values at unsampled locations are estimated as weighted averages of known values, with closer points assigned higher influence. The power parameter for IDW was set to 2, which balances smoothing and local variability. The interpolated PGA values were categorized into four seismic hazard zones for Odisha. The final PGA contour map of 2 % probability of occurrence in the 50-year time period for the region is shown in Figure 5. The PGA values at Gopalpur, Paradeep, and Dhamara are found to be 0.034g, 0.037g, and 0.057g, respectively.

Methodology

Shear Wave Velocity Estimation

To conduct site response analysis, it is essential to have comprehensive soil investigation data that includes detailed information about SPT-N value, V_s, water table depth, unit weight (γ) of soil, soil type, and thickness for each layer. Unfortunately, there is a scarcity of V_s profiles and geophysical test data specific to the area of interest. Consequently, this study's geotechnical investigation relies solely on the currently available SPT-N data. Shear wave velocity (V_s) is widely recognized as a critical parameter for assessing dynamic soil properties and conducting seismic site characterization. Various field and laboratory tests exist to measure shear wave velocity; however, these tests can pose practical challenges and may not always be feasible to perform. Consequently, an alternative approach is to indirectly estimate shear wave velocity by utilizing empirical equations that correlate it with the SPT-N value. This indirect method provides

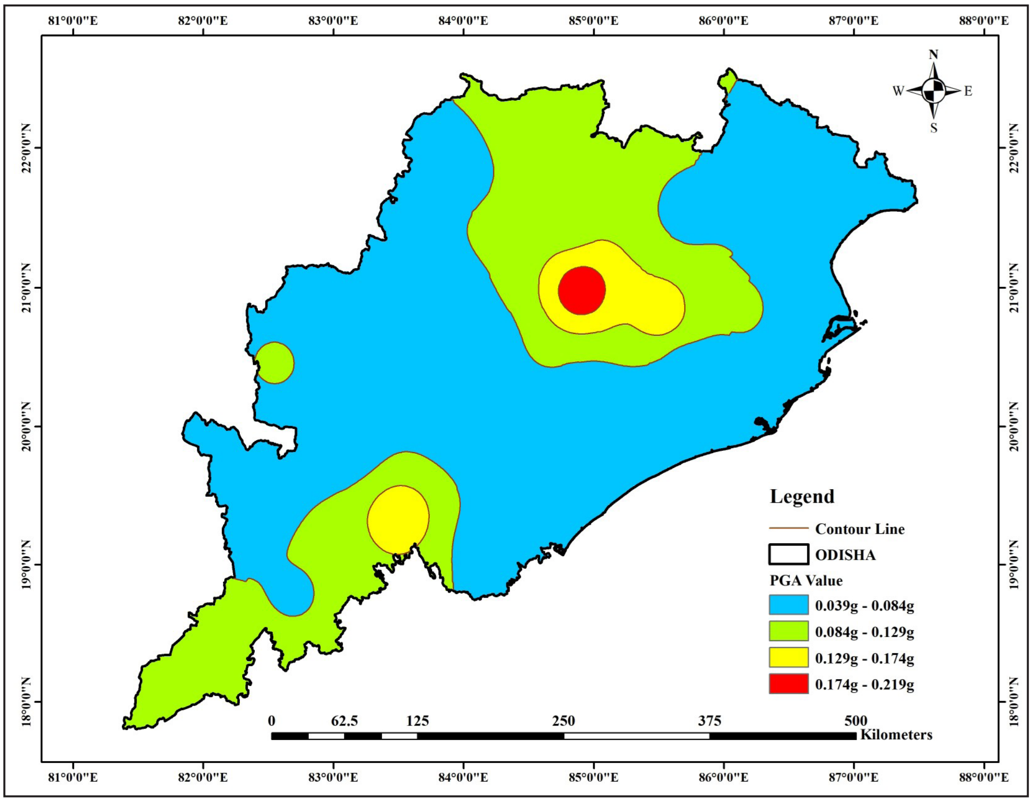

Figure 5. FHD (First Horizontal Derrivative) map modeling.

a practical and convenient means to obtain shear wave velocity when direct testing is impractical or inaccessible. Estimating V_s from SPT-N values involves using empirical correlations or empirical equations. The correlation between SPT-N values and V_s varies depending on the type of soil as well as the specific correlation being used. Statistical regression analyses were conducted to create new correlations for SPT-N values and V_s. The commonly used empirical correlation for estimating V_s from SPT-N values are in the form of $V_s = CN^d$ or $CN_{60}{}^d$, where N is the field SPT-N value and N_{60} is the corrected *SPT-N* value, C and d are empirical constants that depend on the soil condition (Mhaske and Choudhury, 2011). Predominantly, researchers utilized uncorrected SPT-N values, although some opted for corrected SPT-N values in order to establish correlations between SPT-N and V_s. Some researchers also proposed an empirical equation in the form of $V_s = CN + D$, where C and D are the empirical constants (Zheng, 1987); Fumal *et al*., 1985). Hanumantharao and Ramana (2008), Chatterjee and Choudhury (2013), Sil and Sitharam (2014), and Mhaske and Choudhury (2011) developed equations for Indian soil conditions.

In this study, soil borelog profiles were gathered and categorized into three main types: sand, clay, and all soil based on their predominant soil content and grain size distribution. Figure 6 illustrates a typical stratigraphy observed in a sample borelog for each soil type. The shear velocity (V_s) profile for all borelogs was determined using various empirical correlation equations (SPT N-V_s) provided in Table 1. To ensure consistency, certain empirical correlations producing excessively high or low values were excluded from each category.

For the present study, the borelog data from various sites were systematically categorized into three primary groups based on their lithological characteristics and soil composition: (1) All soil profiles, comprising mixed soil types without predominant sand or clay fractions; (2*) Sand profiles*, predominantly consisting of sandy strata; and (3) Clay profiles, characterized by significant clay content across their depth. In the absence of sophisticated geophysical testing, such as crosshole, downhole, or surface wave methods, which provide direct measurement of shear wave velocity (V_s) are often expensive and logistically challenging to conduct at multiple sites. The

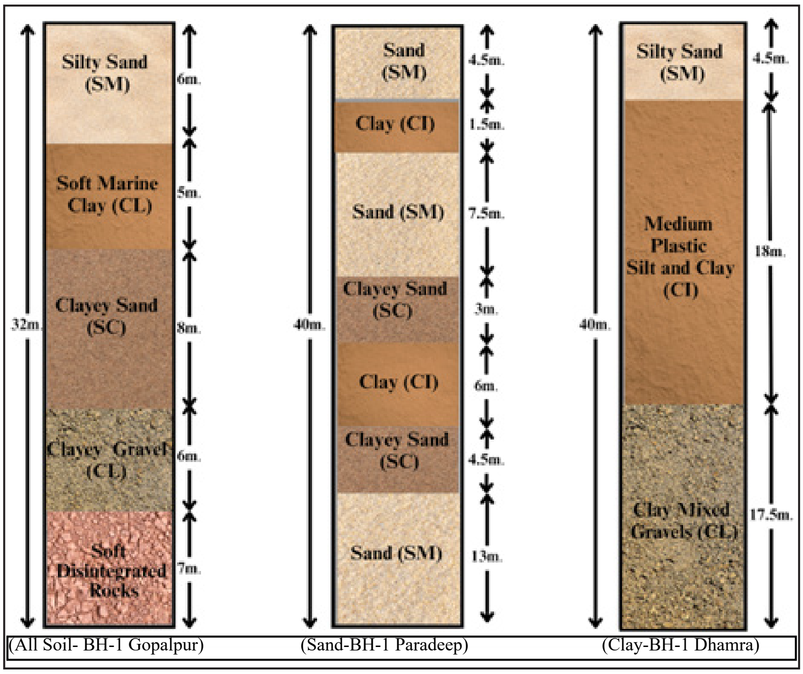

Figure 6. Borelog soil stratigraphy of three different categories.

Table 1. Empirical Equations Considered in The Study

Research Work	All Soil	Sand	Clay
Hanumantharao and Ramana (2008)	V_s=82.6(N)$^{0.43}$	V_s=79(N)$^{0.434}$	V_s=86(N)$^{0.42}$
Anbazhagan *et al*. (2012)	V_s=68.96(N)$^{0.51}$	V_s=60.17(N)$^{0.56}$	V_s=106.63(N)$^{0.39}$
Thaker and Rao (2011)	V_s=59.72(N)$^{0.42}$	V_s=51.21(N)$^{0.45}$	V_s=62.41(N)$^{0.42}$
Singh *et al*. (2021)	V_s=70.05(N)$^{0.49}$		V_s=74.80(N)$^{0.47}$
Maheswari *et al*.1 (2010)	V_s=95.641(N)$^{0.3013}$	V_s= 100.53(N)$^{0.265}$	V_s=89.31(N)$^{0.358}$
Sil and Haloi (2017)	V_s=75.478(N)$^{0.3799}$	V_s=79.217(N)$^{0.3699}$	V_s=99.708(N)$^{0.358}$
Chatterjee and Choudhury (2013)	V_s=78.21(N)$^{0.38}$	V_s=54.82(N)$^{0.53}$	V_s=77.11(N)$^{0.39}$
Mhaske and Choudhury (2011)	V_s=72(N)$^{0.4}$		
Rao and Choudhury (2020)	V_s=84(N)$^{0.38}$		
Shukla and Solanki (2020)	V_s=77.448(N)$^{0.41}$		
Naik *et al*. (2014)	V_s=78.46(N)$^{0.390}$	V_s=84.08N)$^{0.368}$	V_s=81.18(N)$^{0.377}$
Kumar *et al*. (2022)	V_s=72.21N$^{0.409}$	V_s=88.575(N)$^{0.353}$	V_s=84.93(N)$^{0.374}$
Kirar *et al*. (2016)	V_s=99.5N$^{0.345}$	V_s=100.3(N)$^{0.338}$	V_s=94.4(N)$^{0.379}$
Thokchom *et al*. (Kirar *et al*., 2016)	V_s=3.311(N)+160.5	V_s=2.641(N)+189.6	V_s=3.395(N)+156.8
Mehtha and Thakkar (Kumar *et al*., 2022)	V_s=81.71(N)$^{0.346}$		
Maheswari *et al*.2 (2013)		V_s=95(N)$^{0.3}$	

most practical and widely accepted approach is to estimate V_s using empirical correlations with SPT N values. This method offers a cost-effective and reliable means for V_s estimation, particularly in regions like India where extensive SPT data are available as part of routine subsurface investigations.

Accordingly, sixteen well-established empirical correlations developed for Indian soil conditions were initially considered for V_s estimation. However, to enhance the precision and site-specific applicability of V_s predictions for the classified soil types, statistical regression analyses were performed on the compiled borelog data. These analyses yielded new empirical equations of the form: $V_s=aN^b$, where a and b are coefficients derived through regression analysis for each soil type. For instance, in this study, the coefficients for soil, sand, and clay were empirically determined to be the following:

All Soil: $V_s=79.006(N)^{0.395}, R^2=0.99974$ .... (1)

Sand: $V_s=81.322(N)^{0.383} \cdot R^2=0.99926$ ....(2)

Clay: $V_s=86.547(N)^{0.385}, R^2=0.99967$ .... (3)

These newly derived correlations are tailored to Indian geotechnical conditions and are expected to provide V_s estimations for seismic hazard assessments, site classification, and microzonation studies, particularly where direct geophysical measurements are unavailable. Figure 7 shows the comparison of the newly generated equations with the other equations for Indian soil conditions.

All the equations considered are shown in Table 1, and these equations estimate V_s based on SPT-N values. The resulting shear wave velocities from the proposed equations are plotted against the corresponding SPT-N values. A typical borelog profile from the Dhamara Port site is shown in Table 2, and its resulting V_s profile is shown in Figure 8.

Geotechnical Properties and Site Classification

A thorough soil investigation report for each site (borelog with SPT-N) was acquired from concerned organizations pertaining to the port sites. In the study, reports encompass data from four different borehole locations from the Dhamara Port site, two borehole locations from the Gopalpur site, and three borehole locations from the Paradeep Port site. The depth of boreholes varies between 30 m and 60 m. Analysis of the SPT data reveals that Gopalpur Port soil primarily consists of layered deposits, including sand, soft marine clay, clayey sand, clayey gravel, and soft disintegrated rock. The Paradeep Port site consists of sand, clayey sand, and clay. The

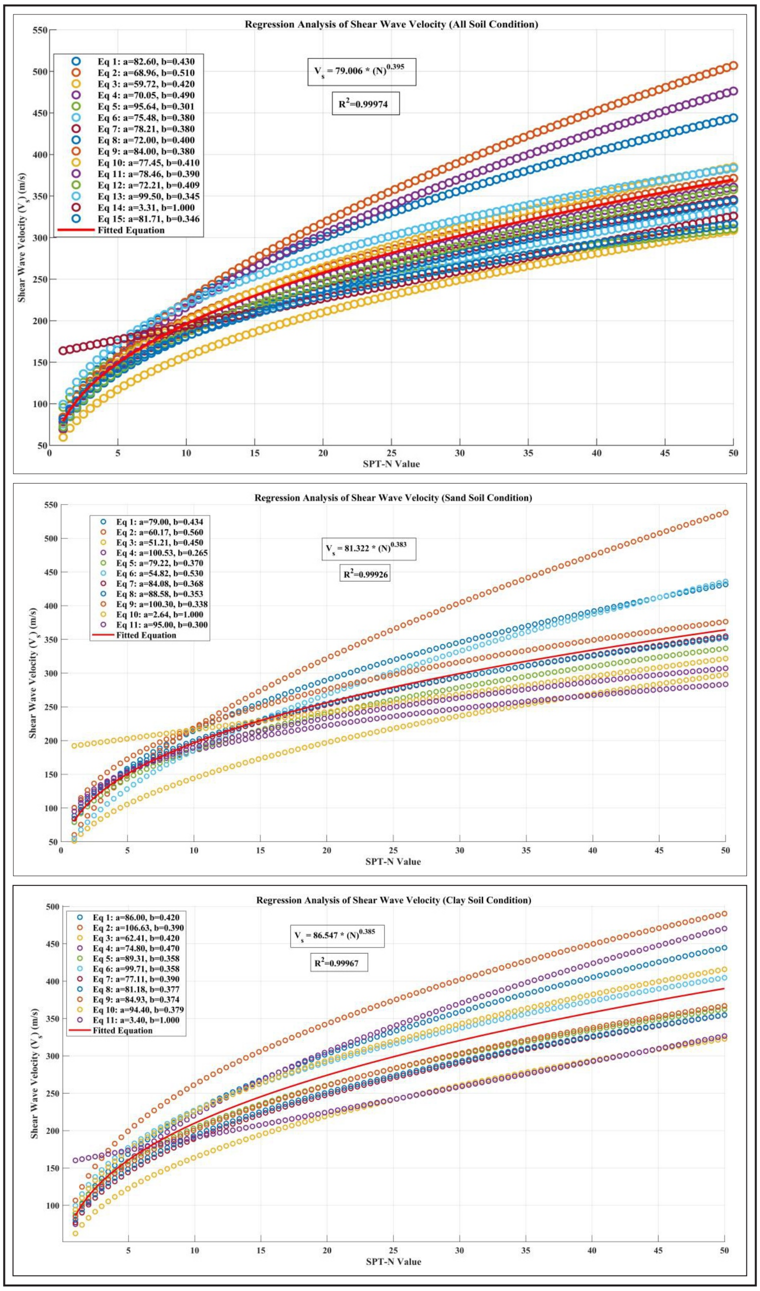

Figure 7. (a). Comparison of the V_s- SPT-N correlations investigated in the study (all soil condition); (b). Comparison of the V_s- SPT-N correlations investigated in the study (sand soil condition); (c). Comparison of the V_s- SPT-N correlations investigated in the study (clay soil condition).

Dhamara Port site soil consists of silty sand, medium plastic silty clay, clayey gravel, and clayey sand.

It is indispensable to characterize a site based on its classification to perform seismic microzonation and location-specific studies (Sitharam and Anbazhagan, 2008). This involves categorizing the site according to the average behaviour of its soil layers under motion, which is primarily determined by shear wave velocity. The NEHRP offers guidelines for estimating V_s of the top 30 m (V_s^{30}) and the average SPT-N value, which are used to assign sites to different classes. The NEHRP guidelines define site classes as A, B, BC, C, CD, D, DE E and F. The goal of this study is to characterize the studied area according to the NEHRP guidelines using V_s^{30} and the average SPT-N value.

Table 2. Soil Profile of BH-1 from Dhamara Port

Type of soil	Depth (m)	SPT N value
Silty sand	1.5	15
	3	5
	4.5	5
	7.5	4
Medium plastic silt and clay	10.5	4
	13.5	3
	16.5	6
	19.5	5
	22.5	17
Clayey gravel	25.5	22
	28.5	23
	30	23.5
	31.5	24
	34.5	31
	37.5	29
	40.5	32

The formula provided by the NEHRP to evaluate average shear wave velocity (V_s^{30}) for the top 30 m is as follows:

$$V_s^{30} = \frac{30}{\sum_{i=1}^{n} \frac{d_i}{v_{si}}} \quad (4)$$

In this study, the thickness of soil layers (di) and their respective shear wave velocities (V_{si}) was considered. The V_s^{30} (the average shear wave velocity in the top 30 m of soil) was calculated using the aforementioned equation (Equation 4). The obtained results are presented in Table 3. As per the results, all four borehole locations at The Dhamara Port site have V_s^{30} values less than 180 m/s. In the Paradeep and Gopalpur sites the V_s values lie between 180 to 360 m/s. These values indicate that the Dhamara site belongs to site classes DE and E; the other two sites (Gopalpur and Paradeep) belong to site class D as per NEHRP classification. Consequently, special design considerations must be considered to ensure the compliance requirements of these site classes.

Ground Response Analysis

In seismic ground response analysis, the response of layered soil deposits to earthquake loading was estimated using ground motion accel-

Table 3. Borelog Site Characterization of Different Ports of Odisha

Borehole Location	Borehole Number	$(Vs)_{30}$ in m/s	Site Class
Dhamara Port	BH-1	181	DE
	BH-2	153	DE
	BH-3	185	DE
	BH-4	138	E
Paradeep Port	BH-1	233	D
	BH-2	221	D
	BH-3	228	D
Gopalpur Port	BH-1	224	D
	BH-2	213	D

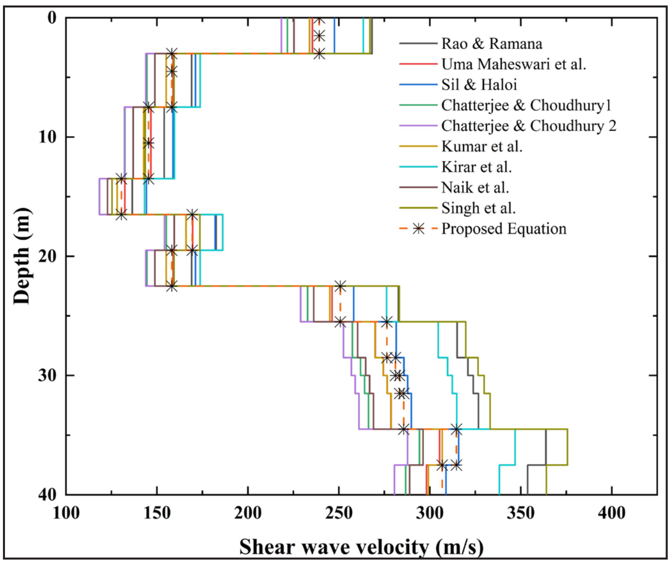

Figure 8. Shear wave velocity (*Vs*) profile for BH-1 Dhamara Port.

eration, stress-strain data, and response spectra. In the present study, the soil behaviour under seismic excitation was evaluated using the equivalent linear method, which facilitates the approximation of nonlinear soil response through frequency domain analysis. This method iteratively determines strain-dependent soil properties, such as shear modulus and damping ratio, by matching the effective shear strain with the computed strain levels in each iteration.

The equivalent linear analysis was performed using the DEEPSOIL software, employing a one-dimensional (1-D) ground response framework. This frequency-domain approach was selected to assess the dynamic response of the soil layers subjected to earthquake loading. The methodology adopted in this study is summarized in the flowchart provided in Figure 9. The bedrock-level PGA values from PSHA were used as input for the analysis. Site characterization was based on SPT borehole data, with V_s30 computed and NEHRP site classes assigned. Ground motions were selected, processed, spectrally matched to the regional UHS, and scaled to the target PGA. Equivalent linear 1-D site response analysis was performed using DEEPSOIL, yielding surface-level PGA, PGV, PGD, amplification factors, Fourier amplitude ratios, and seismic response spectra.

The soil layers were modeled using the pressure-dependent hyperbolic (MKZ) model, which accounts for nonlinear hysteretic behaviour in accordance with Masing rules. The shear wave velocity profile was adopted to characterize the initial stiffness of the soil strata. This model, originally proposed (Matasovic,1993) as a modification of the hyperbolic model developed (Konder and Zelasko, 1963), incorporates two additional parameters (β and s) to adjust the curvature of the backbone stress-strain relationship. The model is expressed as:

$$\tau = \frac{G_0 \gamma}{1 + \beta \left(\frac{\gamma}{\gamma_r}\right)^s} \qquad (5)$$

where:
τ denotes the shear stress,
G_0 is the initial shear modulus,
γ represents the shear strain,
γ_r is the reference strain, and β and s are the curve-fitting parameters.

DEEPSOIL introduced confining pressure dependence (Hashas *et al.*, 2020),

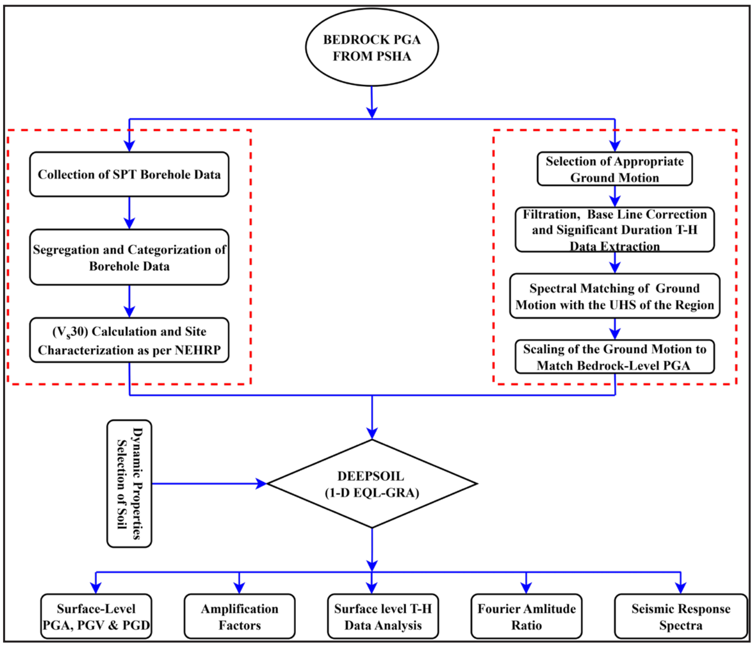

Figure 9. Flowchart of methodology followed for GRA.

$$\gamma_r = Reference\ Strain \left(\frac{\sigma_v'}{Reference\ Stress}\right)^b \text{......... (6)}$$

where:
σ_v' is effective vertical stress, and
b is the pressure-dependence parameter.

Since the model yields zero hysteretic damping at small strains, small-strain damping was added separately:

$$\xi = Small\ Strain\ Damping\ Ratio \left(\frac{1}{\sigma_v'}\right)^d \text{.................. (7)}$$

where:
ξ=Small Strain Damping Ratio and
d controls pressure dependence (zero for pressure-independent damping).

The modulus reduction *(G/G_{max})* and damping ratio *(ξ)* curves, essential for evaluating soil behaviour under seismic loading, were defined as functions of shear strain. These relationships represent the nonlinear variation of stiffness and damping with increasing strain as the soil deforms during earthquake excitation. For analysis, all boreholes were assumed to terminate at bedrock or a very stiff layer, idealized as a rigid half-space that does not significantly affect seismic wave propagation. The subsequent sections provide detailed discussions on the selection of input ground motions and the dynamic properties of the soil layers, which are fundamental to this site-specific ground response analysis.

Selection of Ground Motion

Choosing the correct earthquake motion is an important aspect of conducting site-specific GRA. The location of the studied area selected for this analysis is situated in the stable continental region (SCR) and falls within the seismic zones of II and III as per IS 1893:2016 (BSI, 2016) with low to moderate seismicity. Geologically, this region is located in Peninsular India (PI); this region has witnessed several significant earthquakes in the past. However, except for the earthquake in the Bhuj region on January 26, 2001, having a magnitude of 7.7 M_w, the availability of recorded acceleration-time histories for earthquakes is limited in the PI region. The time-history data of the Bhuj earthquake was captured at the Passport Building in Ahmedabad, which is situated approximately 230 km away from the epicentre (Anbazhagan *et al*., 2012). Given the limited availability of recorded strong motion data for the region, this study is performed using three real ground motion records sourced from stable continental regions. These events consist of the Bhuj earthquake, with a magnitude of M_w=7.7 dated 26th January 2001 and recorded at an epicentral distance of 230 km; the Saguenay earthquake, with a magnitude of *Mw=5.85 dated* 25th November 1988 and recorded at an epicentral distance of 194 km; and the Virginia earthquake, with a magnitude of M_w=5.8 dated 23rd August 2011 and recorded at an epicentral distance of 53.5 km. Data for these earthquakes was obtained from the Consortium of Organizations for Strong Motion Observation Systems (COSMOS) and the PEER ground motion database. To avoid noise and unnecessary data, the recorded acceleration time histories of these events, as shown in Figure 10, were first processed through filtration and baseline correction, and then only the significant duration of the time-history data for each earthquake event was considered in further analysis. To ensure that these ground motions accurately represent the seismic demand at each port site, spectral matching was performed to align the input acceleration time histories with the site-specific Uniform Hazard Spectrum (UHS) derived from the seismic hazard analysis. The spectral matching process modifies the frequency content of the original acceleration record so that its response spectrum closely matches the target UHS across the period range of engineering interest. The *SeismoMatch* software was used to carry out this spectral matching in the time domain. In this process, the spectral acceleration curve of each ground motion was iteratively adjusted to match the target UHS while minimizing distortions to the original acceleration profile. Key considerations in the spectral matching process included:

- Ensuring compatibility with the target UHS

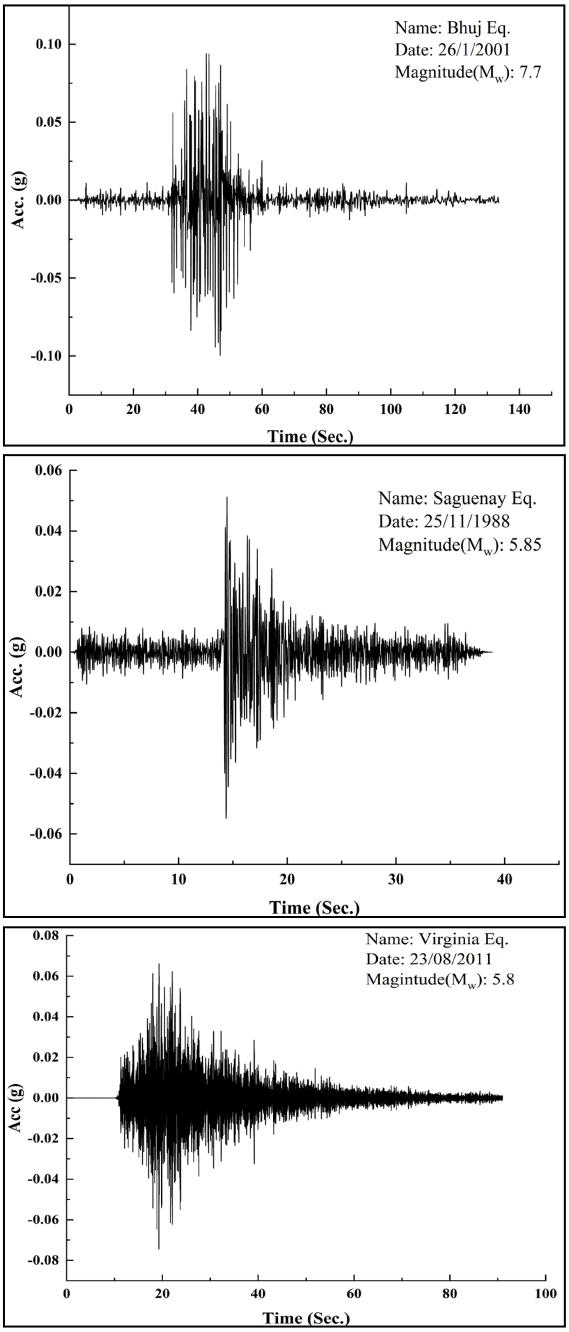

Figure 10. a). Acceleration time history data of Bhuj earthquake; b). Acceleration time history data of Saguenay earthquake; c). Acceleration time history data of Virginia earthquake.

across the specified period range.

- Preserving the realistic characteristics of the original ground motion, including duration, energy content, and acceleration peaks.
- Avoiding excessive smoothing or artificial distortions that could misrepresent seismic demand.
- Applying appropriate scaling to ensure the matched motions are consistent with the site-specific bedrock-level PGA values obtained from PSHA.

The final matched response spectra, demonstrating alignment with the target UHS for each site, are presented in Figure 11, confirming the effectiveness of the spectral matching process.

Selection of Input Dynamic Properties of Soil

The accurate selection of appropriate G/G_{max} curves and ζ-curves are critical aspects of GRA. The G/G_{max} curve and damping curve are regarded as functions of strain for cohesionless soils. However, for cohesive soils, these curves are considered functions of both strain and plasticity index. It is common practice to utilize widely accepted curves in response studies when site-specific curves are not available (Mase *et al.*, 2023; Mase *et al.*, 2021). Over the years, numerous researchers have presented different G/G_{max} and damping ratio values for various soil materials. Among these, the curves developed (Seed and Idriss, 1970), Zhang *et al*. (2005), Darendali *et al*. (2001), Vucetic and Dobry (1991), Amir-Faryar and Aggour (2016), and others have gained widespread usage in representing the dynamic behaviour of soil columns.

If shear G/G_{max} curves and ζ-curves have not been properly selected, then it can result in either underestimation or overestimation of response parameters (Mhaske and Choudhury, 2011). Several researchers, such as Putti *et al.* (2019) for Vishakhapatnam City, Govindaraju and Bhattacharya (2012) for Kolkata, and Sil and Haloi (2018) for Silchar in the location-specific ground motion analysis, have employed specific predefined material based curves. In the process of subdividing Bangalore into zones, Anbazhagan and Sitharam (2008) employed Idriss and Seed's (1970) average curves for sand. In a similar vein, different researchers have utilized different curves for conducting location-specific GRA worldwide. Hence, after performing a thorough review of the literature, the curves have been selected and presented by (Vucetic and Dobry, 1991) for clay with varying

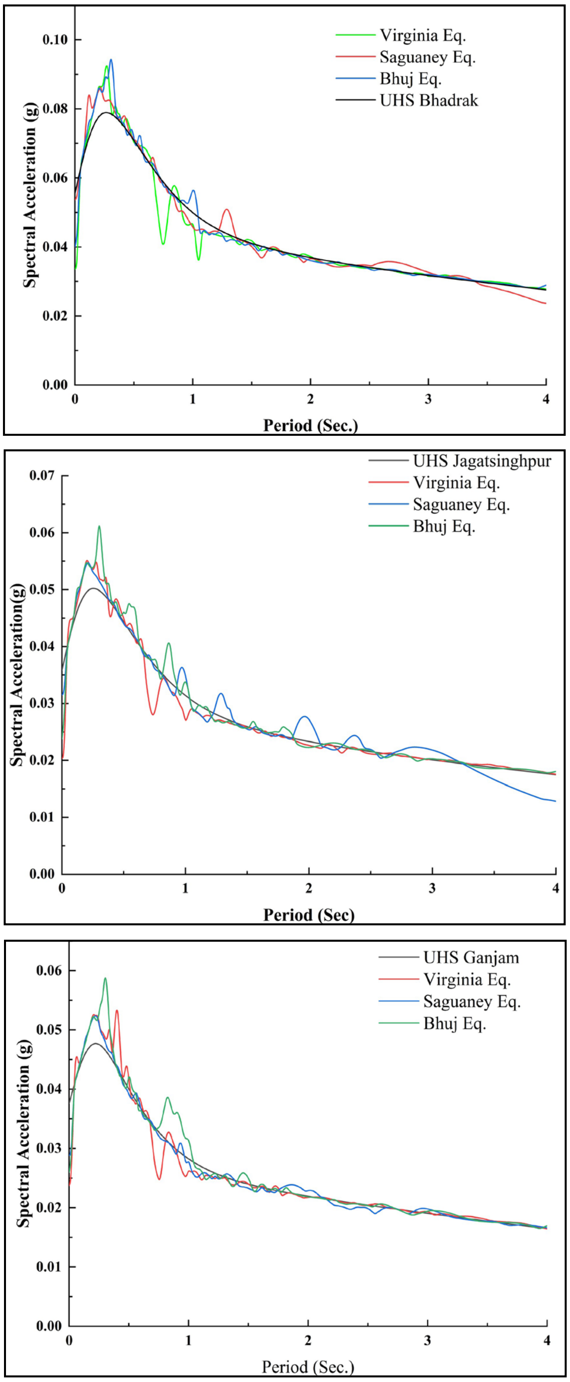

Figure 11. Spectral matching of input motions to site-specific Uniform Hazard Spectra (UHS).

plasticity index and the upper, mean, and lower curves proposed by (Seed and Idriss, 1970) for sand given in Figures 12 (a) and (b) for clay and sandy soils, respectively. However, the standard backbone curves suggested by Vucetic and Dobry (1991) have been adjusted for every layer to align with the reference curve based on the specific plasticity index values.

The severity of strong ground motion and the characteristics of local site conditions are critical factors that impact the damage experienced by structures. In order to have a more lucid understanding of the dynamic behaviour of soil under seismic loading, it becomes necessary to estimate the response of the ground and effects specific to the local site. During a seismic event, the rupture mechanism of the source and the propagation of seismic waves via the underlying rock formations are fundamental processes. These waves subsequently travel through different layers of soil before reaching the designated site. The interaction between the motion of the local underlying bedrock and the overlying soil layers significantly alters the ground response measured at the surface.

Estimating the amplification or deamplification of ground responses as a result of local conditions presents a complex challenge for design engineers, particularly in densely populated cities where a significant portion of the population may be affected by catastrophic earthquakes. Consequently, in this studied area, a one-dimensional (1-D) analysis of ground response (*GRA*) is performed to evaluate the effects of the local site on the modification of ground response, using the equivalent linear approach (EQL). The EQL-GRA has been widely adopted by previous researchers, including Mase and Likitlersuang (2021), Setiawan (2017), Sil and Haloi (2018), Al-Ajamee *et al*. (2022), and J. Shukla and Choudhury (2012), as it provides more accurate results at lower strain levels.

The 1-dimensional propagation method of waves is commonly employed to estimate ground response due to its efficiency, simplicity, and accuracy (Somantri *et al*., 2023). In this study, an equivalent linear analysis of ground response is conducted, assuming that the site is horizontally layered and a single set of stiffness and damping values are used for all frequency components. DEEPSOIL (Hashash *et al*., 2020) is a software application utilized for conducting 1D GRA. It employs an EQL approach to estimate the seismic response of horizontally layered soil deposits in the area of interest, allowing for the flexibility to perform nonlinear, equivalent linear, and linear analyses. The analysis can be conducted in either the time domain or frequency domain. In situations where there are high seismic intensities at the bedrock level or high strain levels in the soil, it is inadequate to represent the behaviour of the entire soil column during an earthquake using a single set of equivalent damping and soil stiffness values for each soil layer. In such cases, propagation of ground motion via deep soil deposits can be simulated using DEEPSOIL as it allows for the inclusion of more soil layers in the soil column, and users can select between frequency-independent and frequency-dependent formulations for the shear modulus. To conduct a GRA in DEEPSOIL, the primary input parameters required are as follows: (1) the ground motion; (2) the shear wave velocity (V_s) profile for various layers at different depths; and (3) the dynamic properties of the soil, which encompass the strain-dependent G/G_{max} curve and ζ-curve. These parameters serve as the fundamental inputs for carrying out an accurate assessment of the ground response.

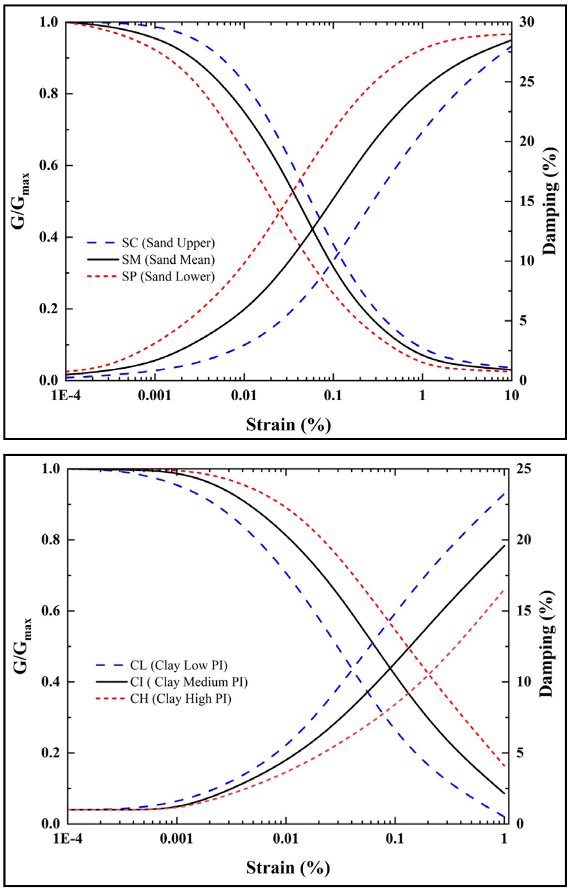

Figure 12. (a). G/G_{max} curves and damping curves sand Idriss and Seed, 1970); (b). G/G_{max} curves and damping curves of Clay (Vucetic and Dobry, 1991).

Results and Discussion

The GRA was performed using input data obtained from the three bedrock motions and various input parameters, including soil type, soil thickness, soil density, depth of water table, shear wave velocity (V_s), G/G_{max}, ζ-curves. The selected acceleration time history was considered for the parametric study. The obtained results include surface-level acceleration-time histories, amplification factors, spectral acceleration and response spectra with 5 % damping. Results from the software were summarized and represented in the form of average spectra to provide insights into the studied area.

The ground response at representative port sites was evaluated, and Figure 13 presents the acceleration-time histories at the surface level for each selected site. Analysis of these histories reveals the maximum surface acceleration values at the Gopalpur site (BH-1) for the Bhuj, Saguaney, and Virginia earthquakes to be approximately 0.074 g, 0.06 g, and 0.09 g, respectively. This indicates ground acceleration amplification of about 1.58 times and 1.5 times compared to the input motion at the bedrock level. Similarly, at The Paradeep Port site (BH-1), the observed surface PGA values were 0.068 g, 0.06 g, and 0.071 g for the Bhuj, Saguaney, and Virginia earthquakes, respectively. At the Dhamara site (BH-1), the surface PGA values were 0.091 g, 0.08 g, and 0.074 g for the same earthquakes, respectively. The average ground acceleration amplification at the Gopalpur site ranged between 2.0 to 2.2, 1.4 to 1.9 at the Paradeep site, and 1.4 to 2.6 at the Dhamara site. The wide variation in amplification factor at the Dhamara site is attributed to the presence of soft marine clay deposits. The range of PGA values at the surface varied from 0.057

g to 0.162 g at the Dhamara site, suggesting classification under seismic *zone -III* of the *IS code*.

In order to gain a deeper understanding of how local sites are influenced by ground motion, their frequency and amplitude parameters have been considered in the present study for considering the site effects. The peak frequency was utilized to indicate the highest amplitude of the soil column in response to the input ground motion. Figure 14 illustrates the Fourier amplitude ratio spectrum for all selected sites. Analysis of Figure 14 indicates that The Dhamara Port site exhibits the highest maximum amplitudes, followed by the Gopalpur and Paradeep sites. Specifically, the maximum Fourier amplitude ratios are 7.05 for the Dhamara site at a frequency of 1.02 Hz, 3.8 for Gopalpur at 2.14 Hz, and 3.89 for Paradeep at 2.19 Hz. It is generally understood that when

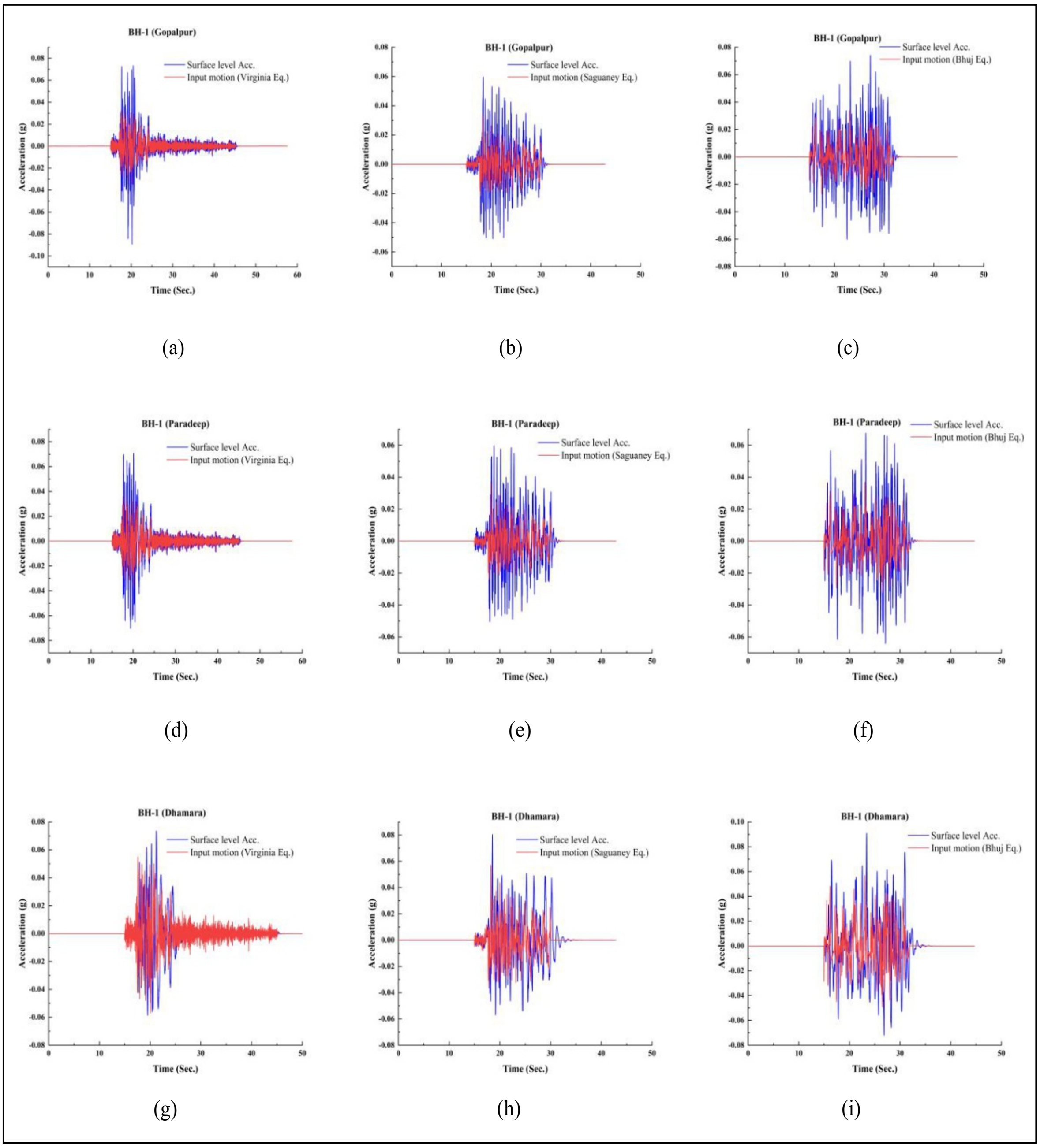

Figure 13. Variation of acceleration at surface level with time period: (a,b,c) Gopalpur site BH-1, (d,e,f) Paradeep site BH-1, (g,h,i) Dhamara site BH-1.

the predominant frequency of the borelog profile closely matches the primary frequency of that same borelog, there is a greater amplification effect. In this case, the obtained amplification results align with this principle, further supporting the correlation between the predominant frequency and amplification effects.

The ground surface acceleration response spectra were assessed for borelogs using the three distinct input motions, depicted in Figure 15. At the Gopalpur site, the analysis revealed that the highest spectral acceleration resulting from the Virginia earthquake occurred at a time period of 0.47 seconds, reaching 0.32 g. This value closely aligns with the fundamental time period of the underlying soil deposit, estimated to be approximately 0.55 seconds. Similarly, the highest spectral acceleration recorded at the Paradeep site was also attributed to the Virginia earthquake motion, registering a magnitude of 0.23 g at a time period of 0.51 seconds. Conversely, at the Dhamara Port site, the maximum spectral acceleration induced by the Virginia motion peaked at 0.42 g, occurring at a time period of 0.48 seconds. This observation underscores the significant influence of the Virginia earthquake motion on soil deposits, contrasting with the minimal impact of the Saguaney motion. Furthermore, analysis of sand profiles reveals high amplification for longer periods, whereas clay profiles exhibit the highest amplification levels.

The degree of site amplification is determined

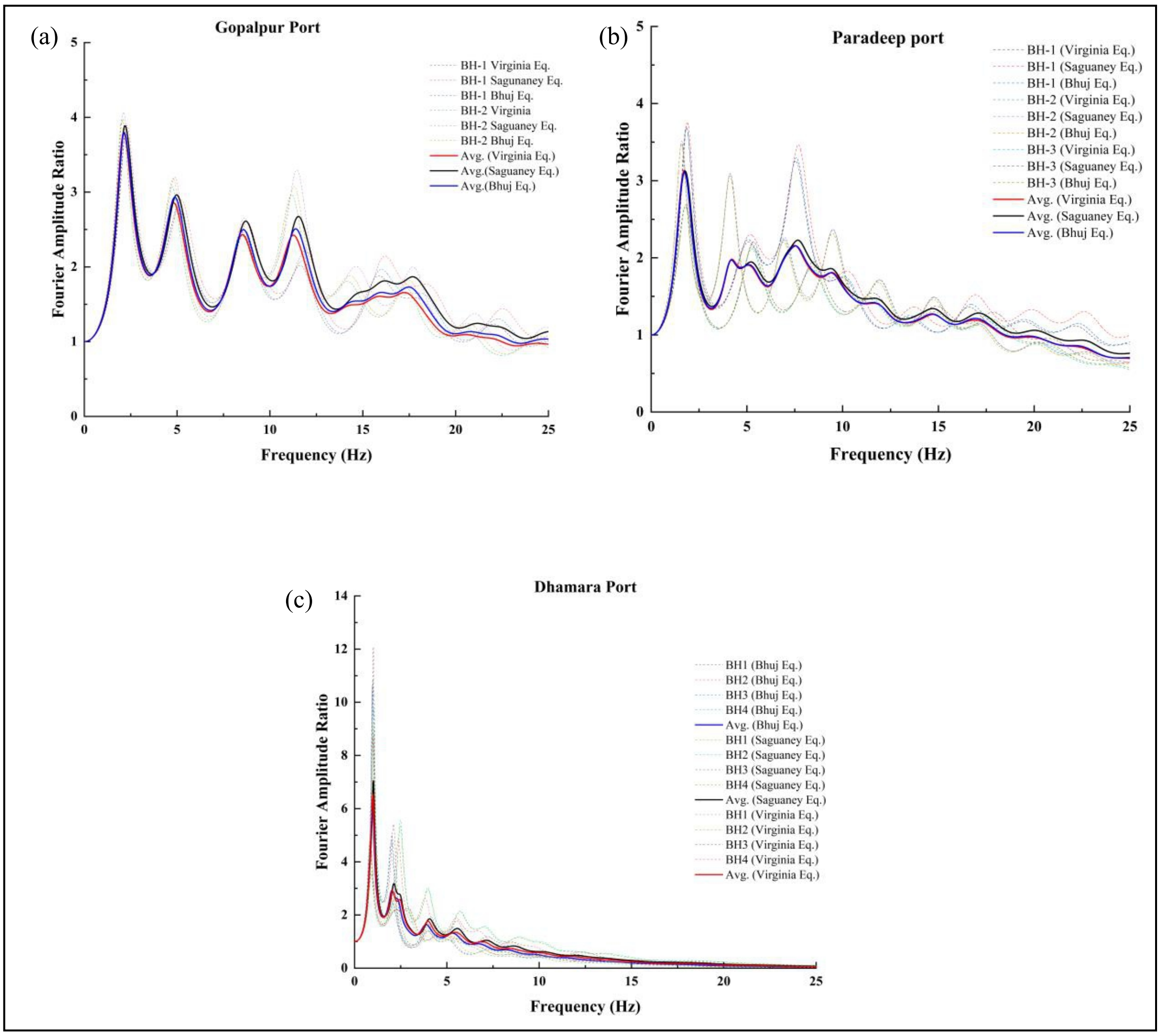

Figure 14. Fourier amplification ratio curves for different input motions at the concerned sites.

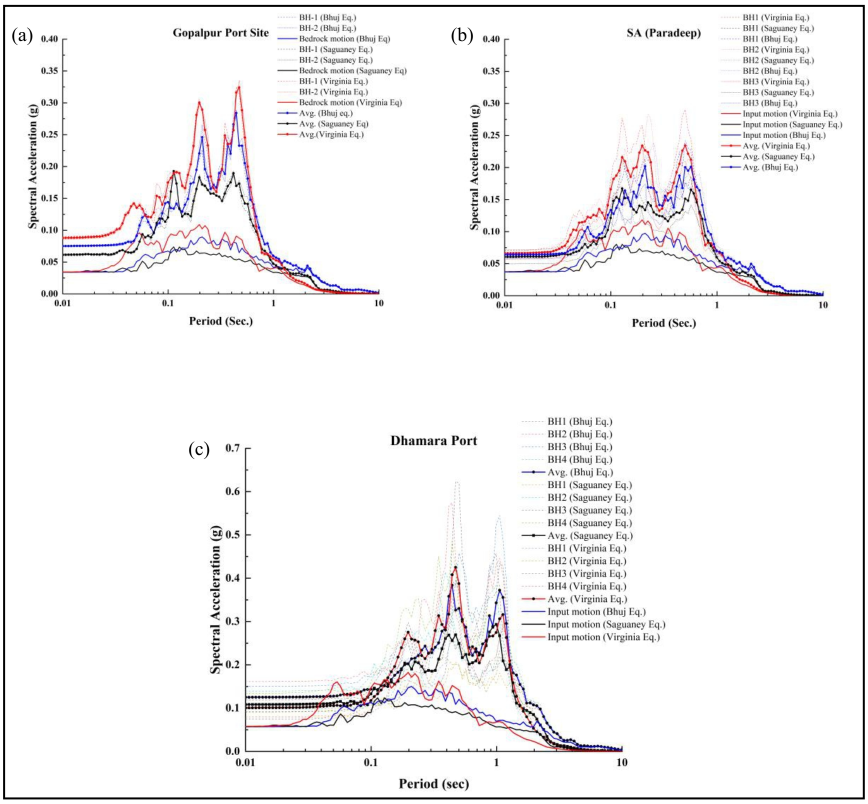

Figure 15. Variation of spectral acceleration at port sites.

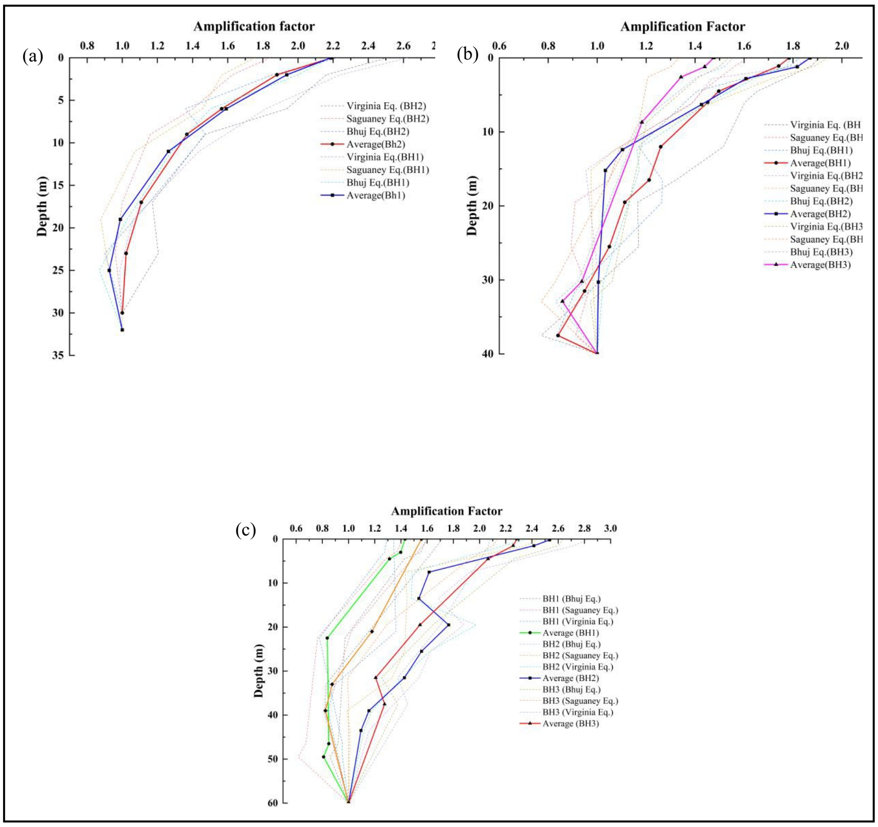

Figure 16. Variation of the amplification factor along with the depth of the soil column.

primarily by the geological structure and subsurface stratification. 'Amplification factor' refers to the ratio of surface spectral acceleration to bedrock motion. Figure 16 illustrates the usual variation in amplification factor across the depths of three port sites. Up to a depth of 20 m from the bedrock, there is minimal variation in the amplification factor. However, beyond this depth, a rapid change occurs with increasing depth, particularly evident at the Dhamara site (*BH-02*), similar to the variation observed in PGA. This abrupt change in PGA and amplification factor results from significant differences in soil stiffness just under the surface. At the soil surface, the maximum amplification factor ranges from 2.0 to 2.2 for the Gopalpur site, 1.4 to 1.9 for the Paradep site, and 1.4 to 2.6 for the Dhamara site, respectively.

The Ground Motion Amplification (GRA) assesses numerous factors for each earthquake, including the amplification factor, Fourier amplitude ratio, PGA, and surface-level time histories. The findings indicate that the ground motion at the bedrock level is intensified by the overlying soil layers. This variation in ground motion can be said to be caused by the nonlinear behaviour of the soil layers. In addition to the detailed ground response analysis, a comparative assessment was conducted between the site-specific spectral acceleration curves and the design spectra prescribed in IS 1893:2016 for seismic Zones II and III across various soil classes as presented in Figure 17.

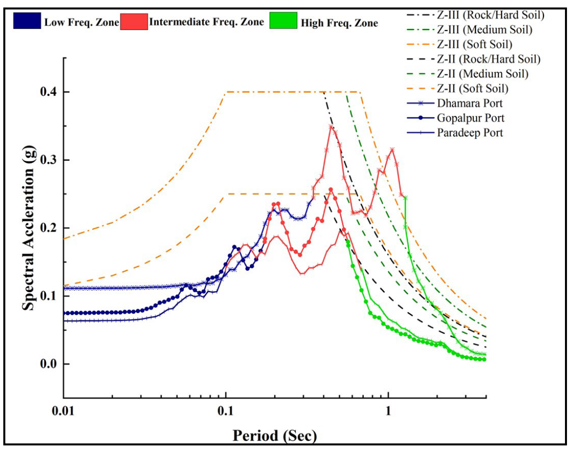

Figure 17. Frequency-Spectral acceleration plot for the ports.

Conclusion

Local soil conditions significantly influence ground motion amplification, as seismic waves traverse various soil layers. Therefore, studying the dynamic behaviour of the soil is crucial for assessing site-specific seismic hazards and designing earthquake-resistant structures that perform well throughout their intended lifespan. Hence, the authors have conducted a GRA for the port sites located in Odisha State in eastern India. The researchers obtained detailed soil investigation reports, including borelog profiles, from various agencies to gather the necessary information. Extensive geological and seismicity studies were also conducted to assess the actual geological configuration of the sites and seismic exposure. Since V_s profile data was unavailable, the authors have estimated the V_s for the various soil profiles using the newly developed empirical equation from established empirical equations that correlate shear wave velocity (V_s) with SPT value (SPT-N). These empirical equations were selected based on the materials present in the borehole log, such as all the relevant soil, sand, and clay conditions. Based upon the estimated V_{s30} profiles obtained from the SPT-N values, the sites were classified as per the guidelines outlined by NEHRP. The results indicated that the Pradeep and Gopalpur Ports are under site class D,, while the Dhamara Port is under site classes DE and E. To analyze the ground response in the area of interest, a 1-dimensional GRA was performed by leveraging DEEPSOIL. Three real recorded acceleration-time histories of three earthquakes: the 1988 Saguaney earthquake of magnitude M_w = 5.85; the 2002 Bhuj earthquake with a magnitude of M_s = 7.7; and the Virginia earthquake with a magnitude of M_w = 5.8 were used as input ground motions in the study with appropriate scaling and spectral matching.

Through the GRA, various parameters including the amplification factor, Fourier amplitude ratio, PGA, and surface-level time histories are evaluated for each earthquake. The results demonstrate that the ground motion experienced at the bedrock level is amplified by the soil layers. This variation in ground motion can be said to be caused by the nonlinear behaviour of the soil layers. In addition to the detailed ground response analysis, a comparative assessment was conducted between the site-specific spectral acceleration curves and the design spectra prescribed in IS 1893:2016 for seismic zones II and III across various soil classes. The results reveal that at critical period ranges, particularly within the intermediate-frequency zone (approximately 0.4 to 0.7 seconds), the site-specific spectral accelerations for the Dhamara, Gopalpur, and Paradeep Port sites exceed the codified design spectra. This discrepancy is most pronounced for the Dhamara Port, which is underlain by soft marine clays and classified as Site Class E, where amplification is significantly higher. The analysis further demonstrates that while IS code spectra offer a general baseline for design, they may underestimate seismic demand for port structures founded on soft, unconsolidated soils. These findings underscore the importance of site-specific seismic ground response analysis in performance-based design and highlight the need for caution when relying solely on generalized national code spectra for critical coastal infrastructure. Moreover, by dividing the spectral response into displacement, velocity, and acceleration, controlled frequency zones, this study offers a practical framework for assigning structural typologies to appropriate frequency bands, thereby mitigating the risk of resonance and enhancing the seismic resilience of port facilities. As per the findings of this study, it can be concluded that the local site conditions in the area can inordinately amplify or modify the ground motion parameters during past and potential future earthquakes. The study results recommend the following:

- Mandatory Site-Specific GRA for Critical Ports - National and state authorities should require site-specific seismic ground response studies for all major ports in coastal Odisha before new construction or major retrofits.
- Code Calibration - The Bureau of Indian Standards (BIS) should consider calibrating IS 1893:2016 design spectra for coastal soft soil sites based on regional site response data to reduce underestimation of seismic demand.
- Enhanced Geotechnical Investigations – Port projects should be supported by an expanded borehole network and direct Vs measurements through cross-hole or down-hole testing to improve subsurface characterization and engineering bedrock identification.
- Integration into Performance-Based Design – Structural design in port areas should incorporate the frequency-zone approach demonstrated here to strategically align structural periods with favourable dynamic response zones.
- Multi-event Hazard Modeling – Design spectra should be generated using a suite of recorded and synthetic ground motions representing a range of magnitudes and frequency content, capturing a more realistic seismic hazard scenario.
- Policy Implementation – Port trust authorities should establish a resilience planning framework where site-specific GRA findings directly inform seismic design, retrofitting, and operational continuity planning.

Limitations and Future Work

While the present study provides valuable site-specific insights into the seismic ground response characteristics of major ports in Odisha, certain limitations must be acknowledged. The shear wave velocity (V_s) profiles were estimated indirectly from Standard Penetration Test (SPT-N) data using empirical correlations rather than direct in situ geophysical measurements such as cross-hole or down-hole testing. The definition of engineering bedrock was based on extrapolated V_s values in cases where borehole depth was insufficient to reach the threshold velocity of 760 m/s. The analysis considered three recorded ground motions representative of stable continental regions; however, inclusion of a broader suite of motions and consideration of varying magnitudes and frequency contents could further enhance robustness. Furthermore, the study relied on a limited number of borehole datasets for each port site, which constrains the spatial resolution of the soil profile characterization. Increasing the number of boreholes and incorporating more comprehensive geotechnical investigations would enhance the accuracy and reliability of the site-specific response predictions. Additionally, the equivalent linear approach adopted in DEEPSOIL may not fully capture nonlinear soil behaviour during intense shaking. Future research should focus on collecting high-resolution geophysical and geotechnical data, validating numerical predictions with local seismic records, and exploring fully nonlinear and probabilistic ground response analyses to strengthen seismic hazard assessments for critical coastal infrastructure.

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