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ORIGINAL PAPER

Seismic hazard and site-specific ground motion for typical ports of Gujarat

Jaykumar Shukla · Deepankar Choudhury

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Abstract Economic importance of major ports is well known, and if ports are located in seismically active regions, then site-specific seismic hazard studies are essential to mitigate the seismic risk of the ports. Seismic design of port sites and related structures can be accomplished in three steps that include assessment of regional seismicity, geotechnical hazards, and soil structure interaction analysis. In the present study, site-specific probabilistic seismic hazard analysis is performed to identify the seismic hazard associated with four typical port sites of Gujarat state (bounded by 20°–25.5°N and 68°–75°E) of India viz. Kandla, Mundra, Hazira, and Dahej ports. The primary aim of the study is to develop consistent seismic ground motion for the structures within the four port sites for different three levels of ground shaking, i.e., operating level earthquake (72 years return period), contingency level earthquake (CLE) (475 year return period), and maximum considered earthquake (2,475 year return period). The geotechnical characterization for each port site is carried out using available geotechnical data. Shear wave velocities of the soil profile are estimated from SPT blow counts using various empirical formulae. Seismicity of the Gujarat region is modeled through delineating the 40 fault sources based on the seismotectonic setting. The Gujarat state is divided into three regions, i.e., Kachchh, Saurashtra, and Mainland Gujarat, and regional recurrence relations are assigned in the form of Gutenberg-Richter parameters in order to calculate seismic hazard associated with each port site. The horizontal component of ground acceleration for three levels of ground shaking is estimated by using different ground motion attenuation relations (GMAR) including one country-specific GMAR for Peninsular India. Uncertainty in seismic hazard computations is handled by using logic tree approach to develop uniform hazard spectra for 5% damping which are consistent with the specified three levels of ground shaking. Using recorded acceleration time history of Bhuj 2001 earthquake as the input time motion, synthetic time histories are generated to match the developed designed response spectra to study site-specific responses of port sites during different levels of ground shaking. It is observed that the Mundra and Kandla port sites are most vulnerable sites for seismic

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J. Shukla · D. Choudhury (✉)
Department of Civil Engineering, Indian Institute of Technology Bombay, Powai,
Mumbai 400 076, India
e-mail: dc@civil.iitb.ac.in; dchoudhury@iitb.ac.in

hazard as estimated CLE ground motion is in order of 0.79 and 0.48 g for Mundra and Kandla port sites, respectively. Hazira and Dahej port sites have comparatively less hazard with estimated CLE ground motion of 0.17 and 0.11 g, respectively. The ground amplification factor is observed at all sites which ranges from 1.3 to 2.0 for the frequency range of 1.0–2.7 Hz. The obtained spectral accelerations for the three levels of ground motions and obtained transfer functions for each port sites are compared with provisions made in Indian seismic code IS:1893-Part 1 (2002). The outcome of present study is recommended for further performance-based design to evaluate the seismic response of the port structures with respect to various performance levels.

Keywords Probabilistic seismic hazard · Uniform hazard spectra · Site-specific ground motion · Ground response analysis · Amplification factor · Port sites · SPT blow count

1 Introduction

Ports are lifeline systems that function as embarkation, terminus, storage and maintenance facilities for the transport of cargos and people via water. In view of the importance of the ports in today's era, it is very clear that the extended loss due to non-function of major ports for any reason could have major regional, national, and even worldwide economic impacts. The port structures are frequently exposed to failure under severe seismic loading, for example, the Hyogoken Nambu earthquake of January 17, 1995, had resulted in extended closure of the port of Kobe (Sixth largest container port in the world; Werner 1998) with extensive cost for repairs. Within the life of port structure, severe event may be considered as rare event but the consequences will be so large that the failure of particular port can be a major issue of national interest and huge economic loss. The eye-opening failure of port facilities during earthquakes is observed during the Loma Prieta earthquake of 1989, the Kobe earthquake of 1995, and the Kocaeli earthquake of 1999 (Werner 1998; PIANC 2001; Takahashi and Takemura 2005 etc.). Earthquakes thus pose low probability but high consequence threats to port structures. Further, the scenario is more critical if the port sites are located within the seismically vulnerable area like Gujarat state of India. Even during the Bhuj Earthquake of 2001, the liquefaction driven failures are reported in nearby port facilities (Madabushi and Haigh 2005; Dash et al. 2008). Many pile supported buildings, warehouses and cargo berths in the Kandla port area were damaged during the same event. Dash et al. (2008) showed that during Bhuj earthquake of 2001, 10 m thick loose to medium dense fine saturated sand was liquefied at Kandla port site and resulted severe damage at the mat-pile foundation which was supporting customs office tower. During strong shaking under seismic conditions, liquefaction, lateral spreading, slope instability, soil structure interaction, and site-specific ground motions are of the major geotechnical concerns for port structures.

2 Objective and overview of methodology

Based on the above discussions, engineers may wish to design port facilities for continued operation and damage control as well as protection of life safety. However, such important aspect of performance-based design is still scarce in Indian scenario and in absence of clear dedicated provision in the design codes, engineers in India often follow the design provisions given in seismic code which is made for building constructions, i.e., IS: 1893 (2002). Hence, the prime

Table 1 Ground motion and performance level under seismic condition

Designation	Chance of exceedance in 50 years (%)	Earthquake return period	Earthquake designation	Expected performance
Level 1	50	72	Operational level earthquake (OLE/OBE)	Minor damage, no interruption of service
Level 2	10	475	Contingency level earthquake (CLE)	Service interrupted for up to several months, but facilities are economically repairable
Level 3	2	2,475	Maximum considered earthquake (MCE)	Non collapse of facilities but beyond economical repair

objective of this study is to evaluate the potential seismic hazard for some typical port sites of Gujarat region of India to develop site-specific ground motions for three levels of ground shaking. Kandla port, Mundra Port, Dahej port, and Hazira port are selected as the sites for present study, and these sites are considered to be the busiest ports in western part of India. In absence of specific and updated seismic provisions for ports in India, the recommendations from Werner (1998) and PIANC (2001) are referred as guideline documents to develop the three levels of ground motions (Table 1) for Gujarat. Regional seismicity and site geology are reviewed to establish most up-to-date understanding on geological features and faults contributing to the seismic hazard at selected port sites. Geotechnical characterization affecting the site response is interpreted based on review of available geotechnical data from the project sites located within the port and adjoining area. Probabilistic seismic hazard analysis is performed by using the seven ground motion attenuation relations (GMARs) commonly used worldwide including the country-specific ground motion attenuation relations developed by Raghu Kanth and Iyengar (2007) for Peninsular India. Epistemic uncertainties are addressed through the use of logic trees. Uniform hazard spectra (UHS) for the Level 1 ground motions (i.e., operating level earthquake (OLE) having 50% probability of exceedance in 50 years corresponding to an average return period of about 72 years), Level 2 ground motions (i.e., contingency level earthquake (CLE) having 10% probability of being exceeded in 50 years corresponding to an average return period of about 475 years), and Level 3 ground motion (i.e., maximum considered earthquake having 2% probability in 50 years corresponding to an average return period of about 2,475 years) are developed in order to estimate the possible ground motions at bed rock level. Using the recorded acceleration time history of Bhuj earthquake of 2001, the artificial ground motions are then scaled up to match the developed uniform hazard spectra for each level of ground motions. Using the representative geotechnical profile encountered at the site, local site conditions were then incorporated using well-known computer code SHAKE91 (Idriss and Sun 1992) taking into consideration the equivalent linear model to finally get expected free-field ground motion at surface level.

3 Study areas

3.1 Kandla port

Kandla port (latitude: 23.03°N, longitude 70.13°E) is a protected natural harbor, situated in the Kandla Creek, and is 90 km from the mouth of the Gulf of Kachchh, India. Maharao

Khengarji III of Kachchh built an RCC jetty in 1931 where ships with draft of 8.8 m could berth round the year. In 1955, Kandla was declared as a major port by the Transport Ministry of Independent India, and almost twelve states of India are dependent on the Kandla port for bulk cargo handling. Kandla port has 10 berths, 6 oil jetties, 1 maintenance jetty, 1 dry dock, and small jetties for small vessels with present cargo handling capacity around 40 million ton per annum (MTPA). Future plans include development of additional four dry cargo berths and an offshore berthing facility involving huge investments.

3.2 Mundra port

Mundra port (latitude: 22.74°N; longitude: 69.71°E) is located at 60 km west of Gandhidham in Kachchh district of Gujarat, India. The port was initiated in 1998 by the Adani Group as logistics base for their international trade operations when the port sector in India was opened for private operators. It is an independent and commercial port with 8 multipurpose berths, 4 container berths, and a single point mooring (SPM), presently capable of handling of 30 MTPA cargo and has future plan to achieve 50 MTPA by the fast track developments.

3.3 Hazira port

Hazira (Surat) port (latitude: 21.13°N, longitude: 72.64°E) is situated on the west side of the Hazira (District Surat) peninsula, Gujarat, India. The major development of the port in form of liquefied natural gas (LNG) terminal was carried out by Royal Dutch Shell group. Further developments in the form of construction of private bulk handling facilities by various manufacturing groups are in progress and considerable amount of money is invested to accommodate further vessel handling capacity for the future growth of this port.

3.4 Dahej port

Gujarat Chemical Port Terminal Company Limited (GCPTCL) (latitude: 21.69°N, longitude: 72.535°E) is the most modern commercial port and storage terminal located at Dahej, (District: Bharuch), Gujarat, India in the Gulf of Khambhat (Cambay) on the west coast of India. The Port is capable of handling vessels of 6,000 DWT to 60,000 DWT, and the present Storage Terminal capacity is about 300,000 cubic meters of hazardous liquid and gaseous chemicals falling in ‘A’, ‘B’, and ‘General’ classes. The location also includes some private ports within the Dahej area including some future port facilities.

4 Seismicity of Gujarat

Gujarat state (bounded by Latitude 20°–25.5°N and Longitude 68°–75°E) is seismically one of the most active regions in India, which has experienced two significant damaging earthquakes in 1819 ($M_w = 7.8$) and 2001 ($M_w = 7.7$) and seven earthquakes of magnitude $M_w \geq 6.0$ during the past two centuries (Rastogi 2004). Petersen et al. (2004) tested the sensitivity of seismic hazard to three fault source models for the Kachchh region, Gujarat, and observed the recurrence intervals of 266–533 years on one of these faults. Tripathi (2006), Yadav et al. (2008), and Choudhury and Shukla (2011) worked out a

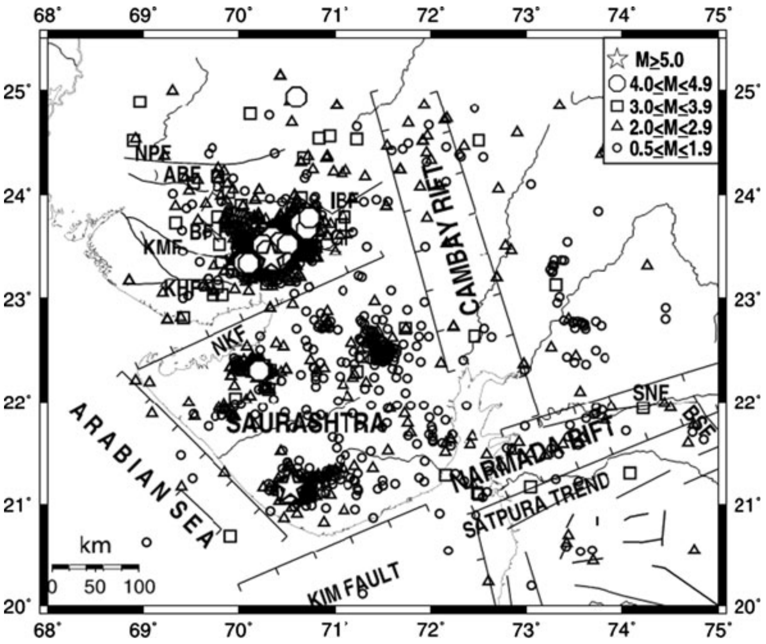

Fig. 1 Epicenters of earthquakes during August 2006 to December 2008 recorded by ISR network (Ref. Annual report of ISR 08-09, http://www.isr.gujarat.gov.in)

probabilistic hazard assessment for Kachchh region by considering various probability distribution functions. The probabilistic seismic hazard assessment of Gujarat is a major issue presently since it experienced a catastrophic event on January 26, 2001 ($M_w = 7.7$) resulting in a huge loss of lives (14,000) and property. According to the seismic zonation map of India as given in IS: 1893-Part I (2002), Gujarat state falls in all four different seismic zones. Kachchh and the adjoining region along with the Pakistan border fall under Zone-V (highest seismic zone). Zone-IV covers a narrow fringe of the northern Kathiawar peninsula and the remaining part of Kachchh. The rest of Gujarat state falls under Zone-III, except a small eastern part bordering Madhya Pradesh state as Zone-II. Various researchers have described the seismicity of Gujarat and adjoining regions, i.e., Bilham et al. (2001), Biswas (2005), Gupta (2006), GSI (2000), Malik et al. (1999), Tripathi (2006), Yadav et al. (2008, 2010). The Gujarat region has experienced random seismic activity at several places such as Junagadh, Jamnagar, Dwarka, Paliyad, Rajkot, Ghogha, Bhavnagar, Narmada rift zone, and Cambay rift zone. During the year 2008, 1,842 shocks with moment magnitude M_w from 0.5 to 4.4 were recorded in Gujarat state. Figure 1 describes the locations of epicenters for various earthquakes recorded during 2006–2008 throughout entire Gujarat State Seismic Network (GS-Net) as established by Institute of Seismological Research (ISR), Gujarat. Large and moderate earthquakes are likely to occur in the future (Choudhury and Shukla 2011), and it is essential to assess the hazard to aid engineers and public officials in making decisions that will influence the economic and life safety policies for Gujarat region (Petersen et al. 2004). According to IS:1893-Part 1 (2002), Kandla and Mundra port sites are located in seismic Zone-V, whereas Hazira and Dahej port sites are located in seismic Zone-III in the seismic zonation map of India.

5 Geotechnical characterization of soils in study areas

Representative soil profiles are established through careful evaluations of the available geotechnical data from the geotechnical investigation carried out for the particular port locations. As boring investigation represented most of the available information, in present study, evaluation efforts are largely concerned with assimilations of the various soil descriptions, SPT blow count, and density data indicated. Shear wave velocity for every layer is estimated from the measured SPT blow counts (*N*-value) using ten imperial correlations given by Imai and Yoshimura (1970), Imai (1977), Seed and Idriss (1981), Imai and Tonouchi (1982), Jinan (1987)*, Iyisan (1996), Athanasopoulos (1995)*, Jafari et al. (1997), Yokota et al. (1991)*, Kiku (2001)* (*see Dikmen 2009), and Mhaske and Choudhury (2011) on the correlations available in various literatures worldwide. The four typical soil profiles used in present analysis are described in Tables 2, 3, 4, and 5. Measured SPT blow count variations are given in the Fig. 2. Estimated shear wave velocity data are plotted in the Fig. 3, and average value of the all estimated shear wave velocity is considered for further site-specific ground response analysis for port sites.

Table 2 Typical soil profile at Kandla port site

Depth			Unit weight (kN/m^3)	Average SPT-value	Description	Modulus reduction curve and damping curve selected
From	To	Thk. (m)				
0	17	17	15	10	Soft clay	Sun et al. (1988)
17	20	3	15	17	Stiff clay	Vucetic and Dobry (1991)
20	24	4	18	35–40	Medium silty sand	Idriss (1990), upper range
24	29	5	17	50	Stiff to very stiff clay	Vucetic and Dobry (1991)
29	32	3	18	>50	Dense silty sandy gravels	Roblee and Chiou (2004)

Table 3 Typical soil profile at Mundra port site

Depth			Unit weight (kN/m^3)	Average SPT-value	Description	Modulus reduction curve and damping curve selected
From	To	Thk. (m)				
0	9	9	17	8	Loose to medium dense silty sand	Seed and Idriss (1970); average
9	13	4	18.5	10–35	Yellow to gray dense sand	Idriss (1990), upper range
13	20	7	17	28–39	Sandy silty clay	Vucetic and Dobry (1991), PI = 30
20	30	10	18.5	30–50	Very dense to dense silty sand	Idriss (1990), upper range
30	38	8	20	40–50	Completely to highly weathered yellow sandstone	

Table 4 Typical soil profile at Hazira port site

Depth			Unit weight (kN/m^3)	Average *N*-value	Description	Modulus reduction curve and damping curve selected
From	To	Thk (m)				
0	4.5	4.5	16	4–9	Light greenish fine grained sandy silt	Vucetic and Dobry (1991); PI = 30
4.5	10.5	6.0	17	9	Light greenish fine-medium grained sand	Seed and Idriss (1970); average
10.5	18.0	7.5	17	17–28	Brownish sandy clay with intermediate plasticity	Vucetic and Dobry (1991)
18.0	23.0	5.0	18	28–50	Brownish sandy silt	Seed and Idriss (1970); average
23.0	30	7.0	19	>50	Medium coarse grained sand with gravel	Idriss (1990), upper range

Table 5 Typical soil profile at Dahej port site

Depth			Unit weight (kN/m^3)	Average SPT-value	Description	Modulus reduction curve and damping curve selected
From	To	Thk (m)				
0	8	8	18	11–32	Dark gray fine to medium sand	Seed and Idriss (1970); average
8	14	6	14	10–39	Stiff clay	Vucetic and Dobry (1991)
14	32	18	19	19–58	Medium dense silty fine to medium sand	Idriss (1990), upper range
32	36	4	16	>50	Stiff clay	Vucetic and Dobry (1991)
36	48	12	20	>50	Very dense fine to medium silty sand	Seed et al. (1986)

6 Probabilistic seismic hazard analysis (PSHA) for ports of Gujarat

The hazard analysis is performed according to the procedures proposed by Cornell (1968) and McGuire (1976). It is now most widely used approach to the problem for determining the characteristics of strong ground motion for earthquake engineering. The analysis is based on modeling the occurrence of an earthquake as a homogenous Poisson's process and the estimation of a peak ground acceleration (PGA) at a selected site in accordance with appropriate PGA-distance ground motion attenuation relationships (GMARs). In essence, the Probabilistic Seismic Hazard Analysis (PSHA) is expressed in terms of probability of exceedance per unit time period, of a given measure of ground motion intensity at a site by integrating the contributions of available geological, seismological, and statistical information. The annual hazard curves are the result of the probabilistic hazard analysis for a site; for a given region, the hazard maps can be obtained by simultaneously making hazard analysis for many sites in the selected region and constructing the contour map for specified ground motion levels corresponding to given return periods. The analysis of seismic hazard at given site requires an approach for estimating

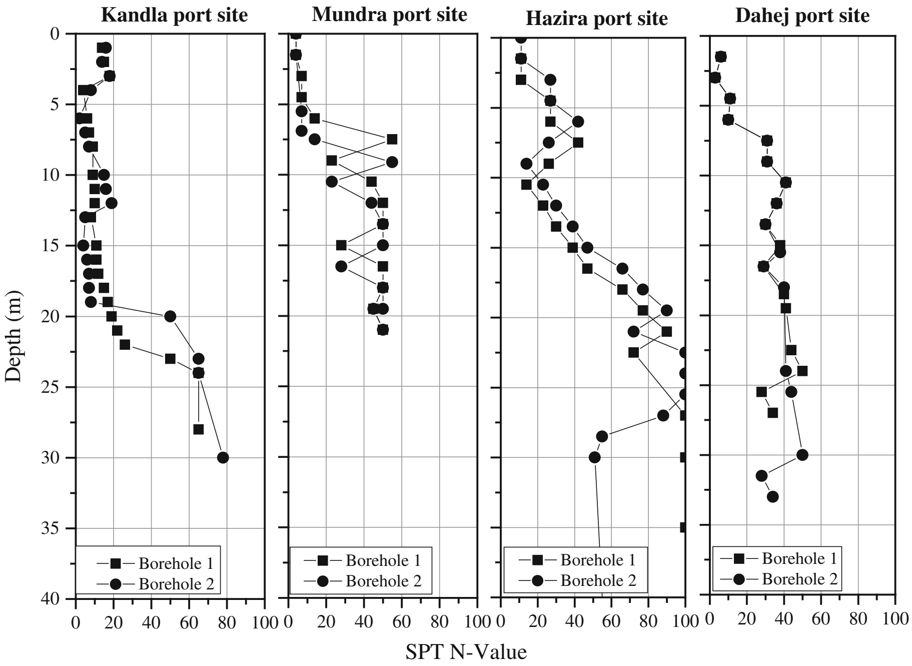

Fig. 2 Typical variation of SPT N-values at various port sites of Gujarat

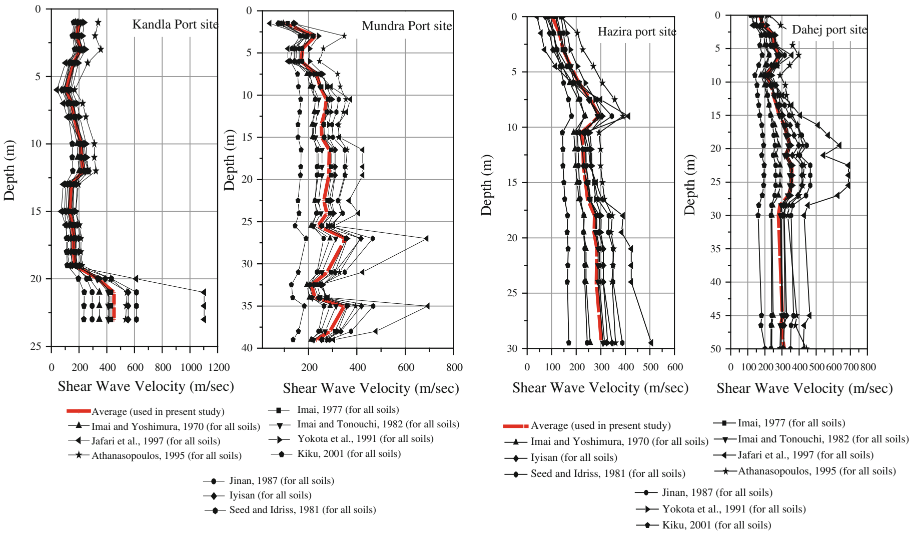

Fig. 3 Typical variation of the estimated shear wave velocity at various port sites of Gujarat

the probability that particular level of ground motion will be exceeded at a selected location in some period of interest (usually expressed in return periods). In the present study, the entire Gujarat region is divided into three sub-regions based on the seismo-tectonic setting and probable fault map is prepared (Fig. 4). The prepared fault map is then used to calculate the probabilistic seismic hazard associated with port sites. Detailed methodologies adopted along with simplification made for the present study are described in the following sections.

6.1 Seismic source modeling

Seismic source modeling usually includes the delineation of seismic source zones into area and fault sources (line sources) according to geological and tectonic features of the region. In the present study, various port sites are selected as the target and a control region of radius 250 km around the port site as center is used for further investigation. Since earthquakes occurring at epicentral distance greater than 250 km do not generally cause

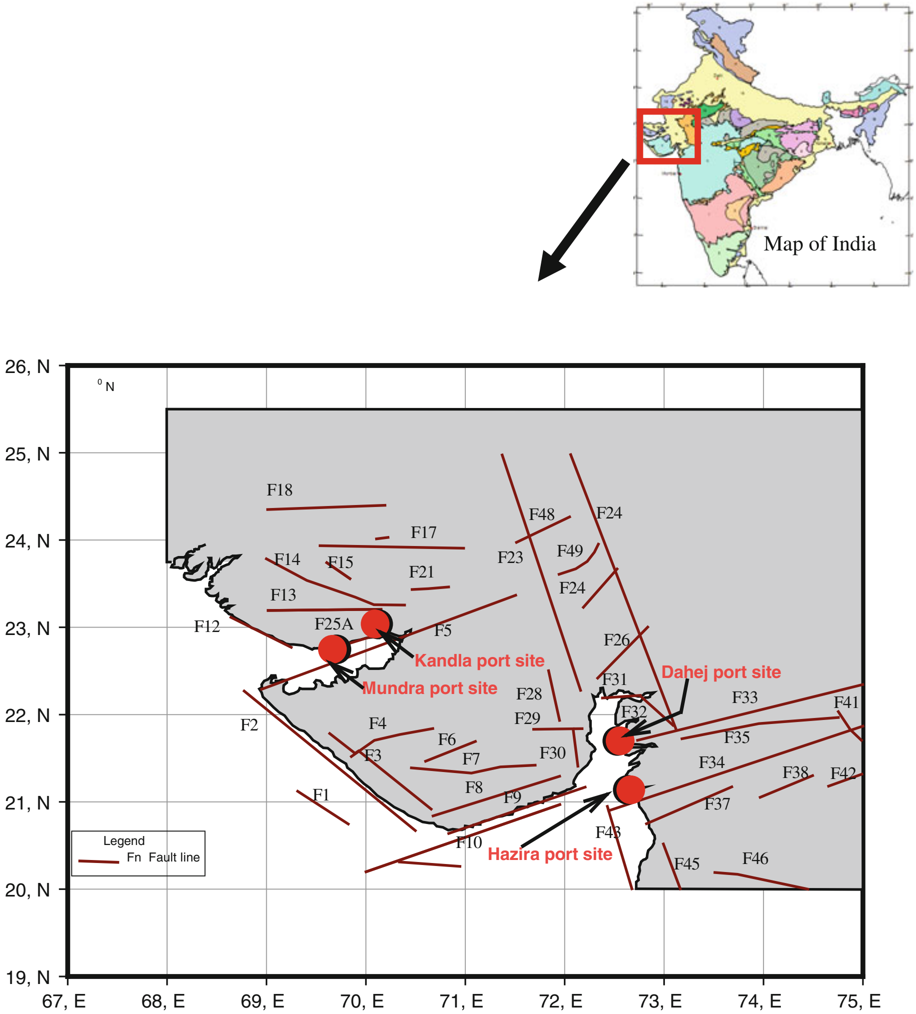

Fig. 4 Fault map used for the present seismic hazard analysis with locations of port sites in Gujarat

structural damage, the faults located beyond maximum distance of 250 km from a particular site are not considered as the tectonic features for port site under consideration. A total of 40 major faults, along with major earthquake events, which influence seismic hazard at Gujarat, are considered in the present study as also given by Shukla and Choudhury (2011).

6.2 Magnitude recurrence relationship

Development of a magnitude recurrence relationship is done based on the historical and geological data in the form

$$\mathrm{Log}(N) = a - bM \tag{1}$$

as proposed by Gutenberg and Richter (1944), where $N =$ Number of earthquake per year, $M =$ earthquake magnitude, a, $b =$ Gutenberg and Richter parameters. Using earthquake catalog of Institute of Seismological Research, Gujarat, the Gutenberg–Richter (G–R) recurrence relationships for three regions of Gujarat as proposed by Choudhury and Shukla (2011) are adopted for the present study for further analysis. These regional recurrence relations are then converted in fault recurrence relations using the procedure adopted by Raghu Kanth and Iyengar (2006), Anbazhagan et al. (2009), and Shukla and Choudhury (2011). Assuming one-third of the total fault length as rupture length, the maximum magnitude each fault can produce is estimated by using the relationship given by Bonilla et al. (1984), Nowroozi (1985), Slemmon (1989), and Wells and Coppersmith (1994). The minimum values out of the estimated maximum earthquake magnitude using the relationships are then assigned to each delineated faults (Fig. 4) for probabilistic seismic hazard analysis.

6.3 Recurrence forecasting and seismic hazard

It is assumed that the occurrence of earthquakes in a seismic source can be estimated from Poisson's process. Then, the probability that a given site, a ground motion parameter, Z, will exceed a specific level, z, during the specified time, T, is represented by the expression.

$$P(Z > z) = 1 - e^{v(z)T} \leq v(z)T \tag{2}$$

where $v(z)$ is the average frequency during the time period T in terms of mean annual rate of exceedance. Above equation allows one to compute the probability of exceeding ($Z > z$) specified level for a given magnitude and distance. The magnitude and distance of the future earthquakes are not yet known, but by selecting their probability distributions that can be combined by using the total probability theorem in form of the following equation

$$P(Z > z) = \int_{m_{\min}}^{m_{\max}} \int_{0}^{r_{\max}} P(Z > z)/m, r) f_M(m) f_R(r) \mathrm{d}r \mathrm{d}m \tag{3}$$

where $P(Z > z/m, r)$ comes from the ground motion model as given by Eq. 2, $f_M(m)$ and $f_R(r)$ are selected probability distribution function for magnitude and distance, and we then integrate over all considered magnitude (i.e., $m_{\min} = 4$ and $m_{\max} =$ maximum magnitude correspond to each fault) and distances (0–250 km in the present study). The integration operation adds up the conditional probabilities of exceedance associated with all possible magnitudes and distances. Equation 3 is a probability of exceedance given and earthquake and does not include any information about how often earthquakes occur on the source of interest. With some modifications, rate of $Z > z$ can be computed, rather than the probability of $Z > z$ for given occurrence of an earthquake.

$$\lambda(Z > z) = \lambda(M > m_{\min}) \int\limits_{m_{\min}}^{m_{\max}} \int\limits_{0}^{r_{\max}} P(Z > z)/m, r) f_M(m) f_R(r) \mathrm{d}r \mathrm{d}m \tag{4}$$

where $\lambda(M > m_{\min})$ is the rate of occurrence of earthquakes greater than $m_{\min}$ ($M_w = 4$) from the source, and $\lambda(Z > z)$ is the rate of $Z > z$. To generalize the analysis further, in the present study, cases with more than one fault source are considered. Recognizing that the rate of $Z > z$ when considering all source is simply the sum of the rates of $Z > z$ from each individual source, one can finally write

$$\lambda(Z > z) = \sum_{i=1}^{n_{source}} \lambda(M_i > m_{\min}) \int\limits_{m_{\min}}^{m_{\max}} \int\limits_{0}^{r_{\max}} P(Z > z)/m, r) f_M(m) f_R(r) \mathrm{d}r \mathrm{d}m \tag{5}$$

6.4 Ground motion attenuation relationships (GMARs)

Ground motion attenuation relations are used to predict the attenuation of ground motions as function of distance from the earthquake location. Raghu Kanth and Iyengar (2007) had proposed an empirical GMAR for Peninsular India based on the stochastic seismological model and compared it with instrumented data from Koyna (1967) and Bhuj (2001) earthquakes. Apart from the GMAR given by Raghu Kanth and Iyengar (2007), several other GMARs were also employed to have a chance for comparison for the present study. For shallow crustal earthquakes, GMAR proposed by Abrahamson and Silva (1997) is applicable and used in the present study. Comparison made by Petersen et al. (2004) has revealed that the crustal intraplate relation of Frankel et al. (1996) yields ground motions similar to the strong ground motion data recorded from the 2001 earthquake at large distances. In the present study, the crustal intraplate GMARs from Toro et al. (1997), Frankel et al. (1996), and other GMARS given by Boore et al. (1997), Campbell (1997) and Sadigh et al. (1997) are also considered for the comparison.

7 Seismic hazard computations

For each port site, the total hazard contribution given by each fault within the control region of 250 km ($r_{\max}$) is evaluated using Eq. 5 and GMARs to finally obtain the total hazard in terms of probability of exceedance for different level of ground motions.The OLE, CLE, and MCE were represented in the present study with 50, 10, and 2% probability of exceedance in 50 years (i.e., with 72, 475, and 2,475 year return periods), respectively. The seismic hazard is computed at 12 spectral periods ranging from 0 to 4 s for each site under consideration. To make the results of probabilistic seismic hazard assessment clearer and more useful for engineering use, deaggregation procedure is used. The mean hazard by seismic source for each site was identified and further used to develop uniform hazard spectra for horizontal component of ground motion. The epistemic uncertainty in the hazard was handled using the logic tree approach as adopted by Shukla and Choudhury (2011).

8 Uniform hazard spectra and synthetic time histories

Numerical seismic analysis of soil profile and port facilities includes acceleration time history representation of the site-specific ground motions. These accelerogram should be consistent with the design spectra developed for the site and should represent the anticipated shaking given by return period based spectra. The horizontal component of the uniform hazard spectra for the rock site corresponding to return periods of the 72, 475, and 2,475 years and 5% damping is developed based on the seismic hazard computations for the each port site as shown in Fig. 5. These generated uniform hazard spectra (UHS) do not represent ground motion for a single earthquake, but may be considered as a combination of the ground motion parameter (i.e., ground acceleration), which will not exceed with a certain probability in specified time span (i.e., 10% in 50 years). Generated UHS are

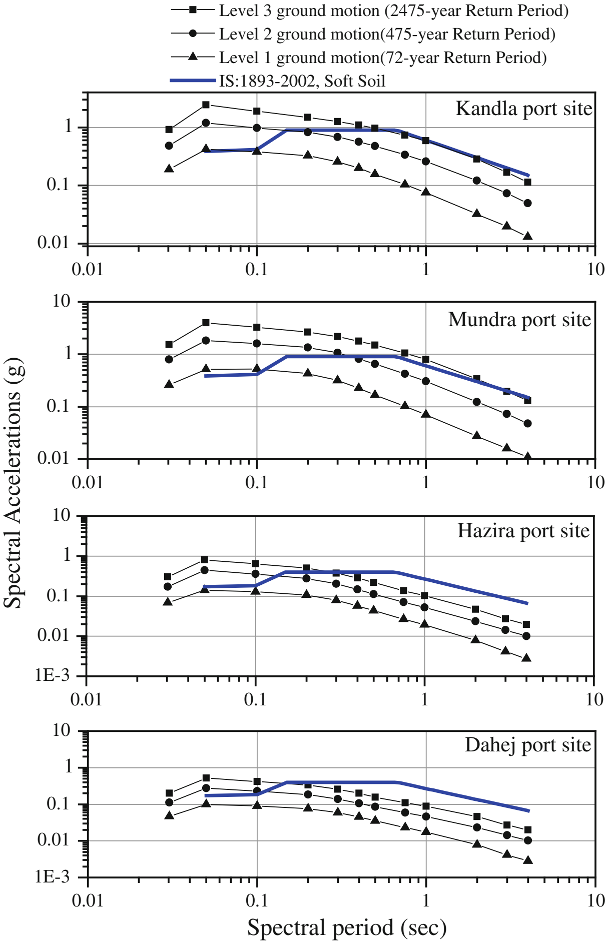

Fig. 5 Uniform hazard spectra (horizontal component for 5% damping) for the different levels of design ground motions for typical port sites compared with specified spectra of IS:1893 (2002)

compared with the response spectra specified by seismic design code of India IS: 1893-Part 1 (2002). The spectral matching procedure is then adopted to generate design ground motion time histories by taking actual earthquake accelerogram and adjusting them to match a design response spectrum developed for each site. By matching uniform hazard spectrum, the design ground motion will consider the likelihood of earthquake occurring at all surrounding faults, as well as the ground motion arising at a site from earthquakes of various magnitudes and distances. The longitudinal components of real ground acceleration time history of the Bhuj earthquake of January 2001, recorded at ground floor of the Passport office building in Ahmedabad, is selected as the input ground motion for the spectral matching. The input ground motion is modified to match the obtained horizontal uniform hazard spectra (UHS) using the program RSPMATCH (Abrahamson 1998) using the time-domain approach. The aim of this approach is to preserve the general non-stationary character of the ground motion in the acceleration, velocity, and displacement while modifying the spectral response to match a given target response spectra. Typical input uniform spectra for three levels of ground shaking, input ground motion spectra of Bhuj earthquake and matched spectra are presented in the Fig. 6 for Hazira port site. The design acceleration time history compatible to three levels of ground motion shaking (i.e., with return periods of 72, 475, and 2,475 years) for each port site are shown in Fig. 7.

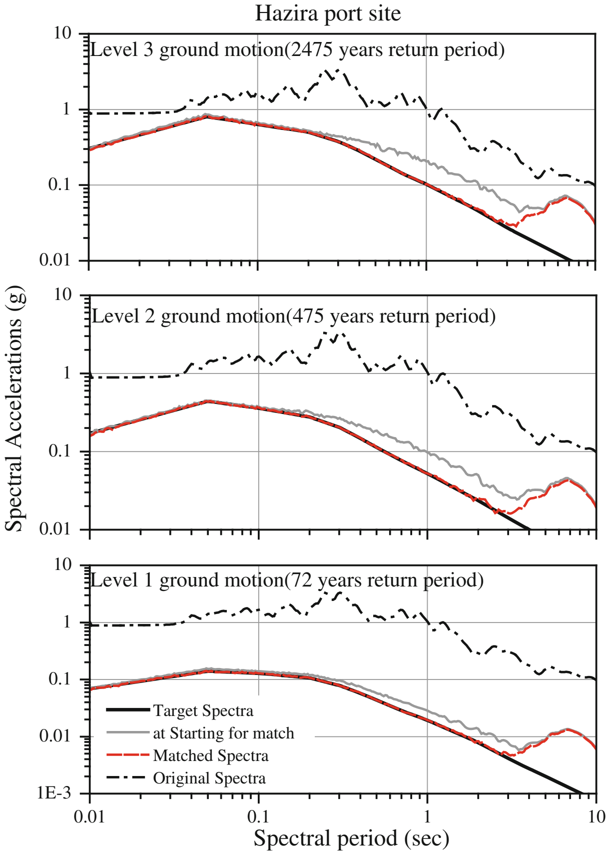

Fig. 6 Typical spectral matching for Hazira port site corresponding to the uniform hazard spectra developed in present study for various design ground motion levels

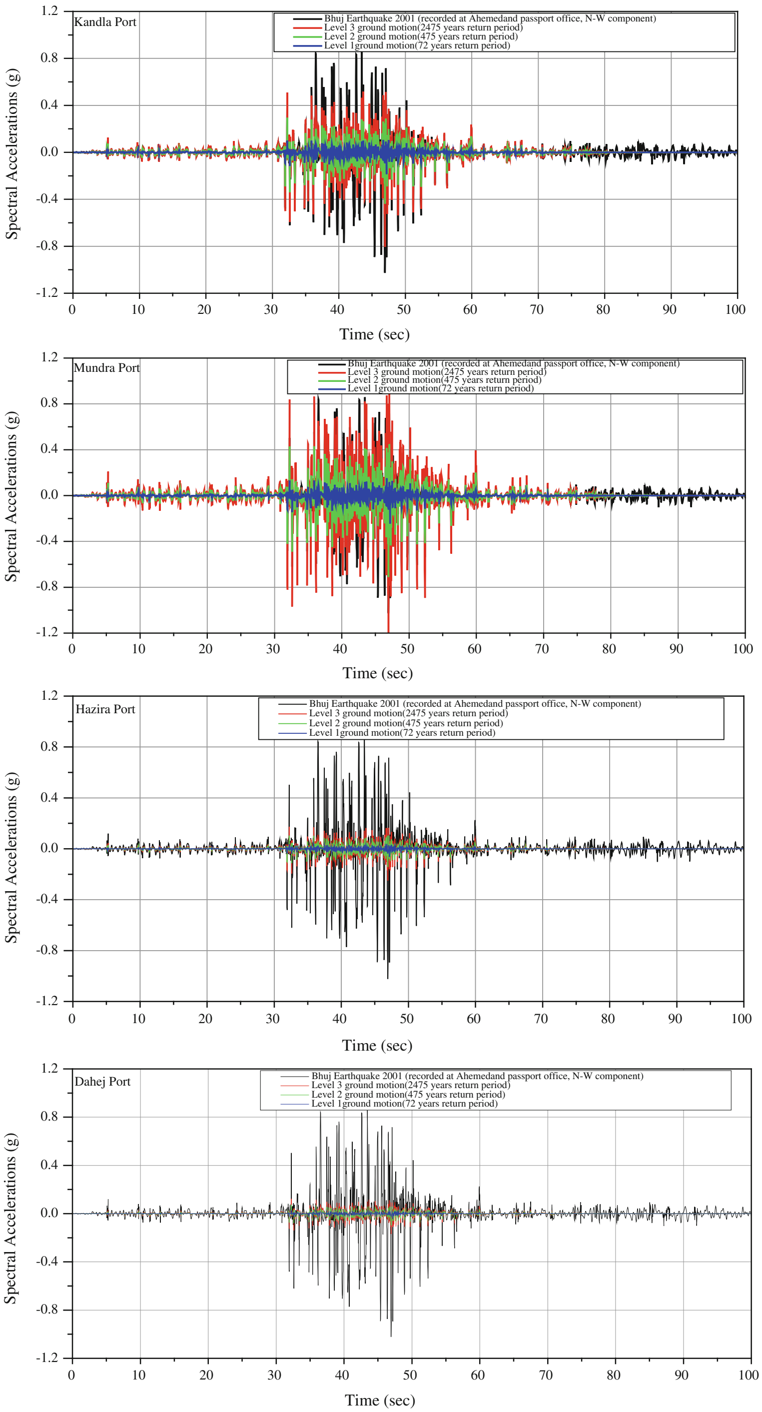

Fig. 7 Generated design ground motions in terms of acceleration time histories for various design levels ground shaking

9 Site-specific ground response analysis

Sub-surface profile and geotechnical characteristics of the soil deposits have strong influence on seismic ground shaking. The variation of ground shaking in space, amplitude, frequency content, and duration are widely referred as “site effects”, which are popularly modeled by using one-dimensional ground models. The variation is manifested as an amplification and/or de-amplification of ground motion amplitudes at all frequencies, which is dependent on many parameters viz. Shear modulus, damping, shear wave velocity, density index, etc. Though the conventional seismic design of geotechnical structures using pseudo-static approach (Choudhury and Subba Rao 2002; Choudhury et al. 2004; Subba Rao and Choudhury 2005) does not include these major aspects of earthquake loading related to soil parameters, but the need for such study has been well known in recent days.

Based on the one-dimensional ground response analysis theory, site-specific ground response analysis has been incorporated for the specified port sites as was done by other researchers like Choudhury and Savoikar (2009), Phanikanth et al. (2011), etc. for other sites. Assuming equivalent linear model, one-dimensional ground response calculations are made by using computer program SHAKE91 (Idriss and Sun 1992), which is a widely accepted numerical method of analysis. It is important to note that the program assumes horizontally layered soil deposits subjected to vertically propagating shear wave and only recognizes nonlinear stress–strain behavior of soil in the form of shear strain-dependent equivalent linear shear modulus and damping values. The soil profiles along with assumed modulus reduction curves and damping curves are listed in Tables 2, 3, 4, and 5 using the raw data obtained from various investigation reports. The average shear wave velocity used in the ground response analysis is given in Fig. 4. For modulus reduction curves and damping curves, various models are selected based on the soil properties. For soft clay, models proposed by Sun et al. (1988) are used, whereas for stiffer clay formations, models proposed by Vucetic and Dobry (1991) are used based on plasticity index properties. For loose silty and sandy formations, models recommended by Seed and Idriss (1970) are selected. For medium to dense sandy formations, models proposed by Seed et al. (1986) and Idriss (1990) are used in calculations, and models proposed by Roblee and Chiou (2004) are used for gravelly formations. The simple qualitative and quantitative estimation of site effects is often expressed by the comparative response spectra (time domain or frequency domain) and the amplification factor. The results from the performed ground response analysis are presented (Fig. 8) in the form of pseudo-acceleration response spectra and transfer function (amplification factor) obtained for each layer.

10 Discussions and conclusions

10.1 Comparative soil profile and shear wave velocity

Soil properties at the four port sites studied can be compared in terms of SPT blow count and estimated shear wave velocity. Kandla port site has SPT blow count ranging 0–20 up to depth of 18 m, with soft soil profile compared with all other port sites. Mundra port has SPT blow count 30–40 for the depths from 8 to 25 m with comparative denser profile. Hazira port site has average SPT blow count from 8 to 22 for the depth ranging from 6 to 20 m. Dahej port site has the stiffest soil profile compared with all other sites having SPT blow count up to 80 for the depth 20 m. The estimated shear wave velocity estimated by using 10 empirical formulae is described in Fig. 3. From the comparison, it is quite clear that formula given by Imai (1977)

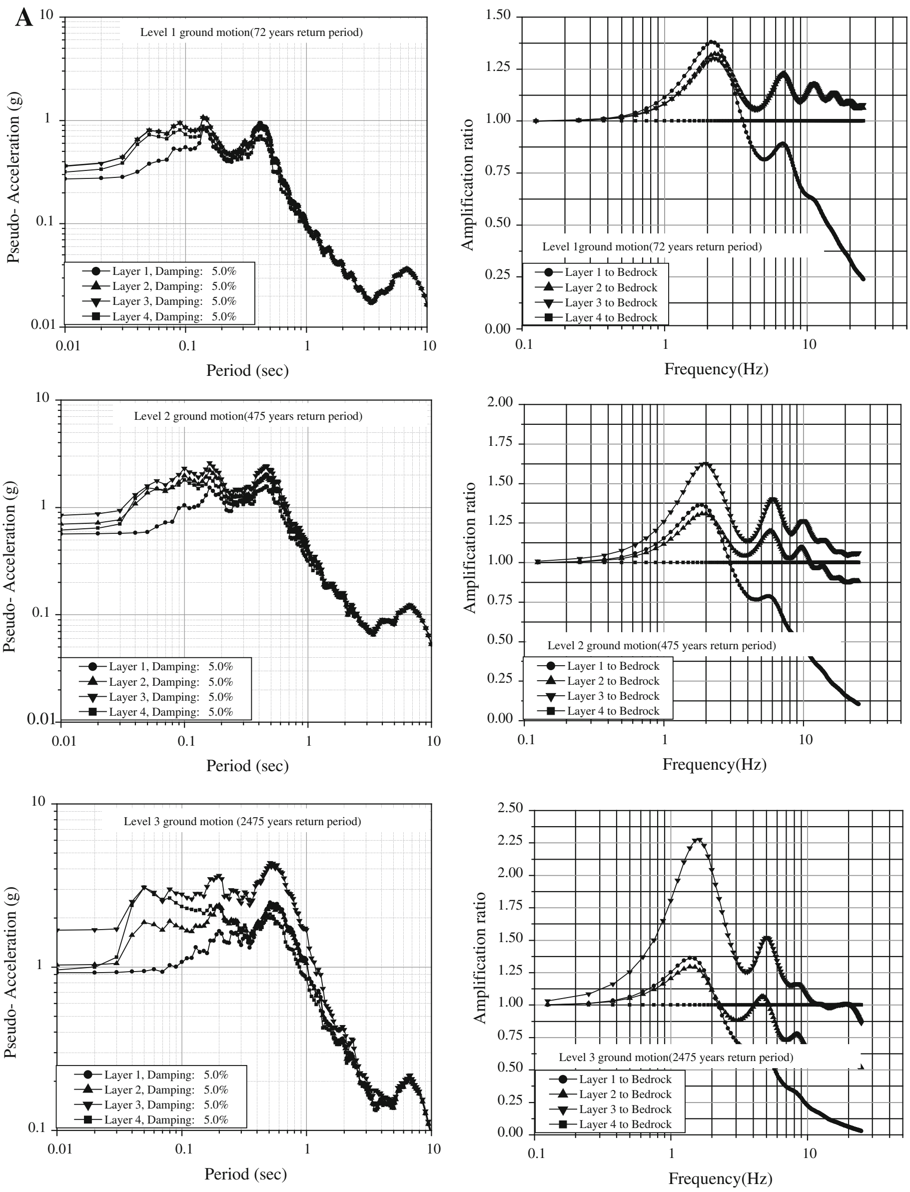

Fig. 8 **a** Pseudo-acceleration response spectra and amplification ratio for the Kandla port site for three design ground motions. **b** Pseudo-acceleration response spectra and amplification ratio for the Mundra port site for three design ground motions. **c** Pseudo-acceleration response spectra and amplification ratio for the Hazira port site for three design ground motions. **d** Pseudo-acceleration response spectra and amplification ratio for the Dahej port site for three design ground motions

predicts the shear wave velocity very close to the average compared with the other formulae. Lower bound estimate is observed using the formula given by Kiku (Dikmen 2009), and upper bound estimate is observed using the formula given by Athanasopoulos (Dikmen 2009) and Jafari et al. (1997) out of 10 empirical formulae used.

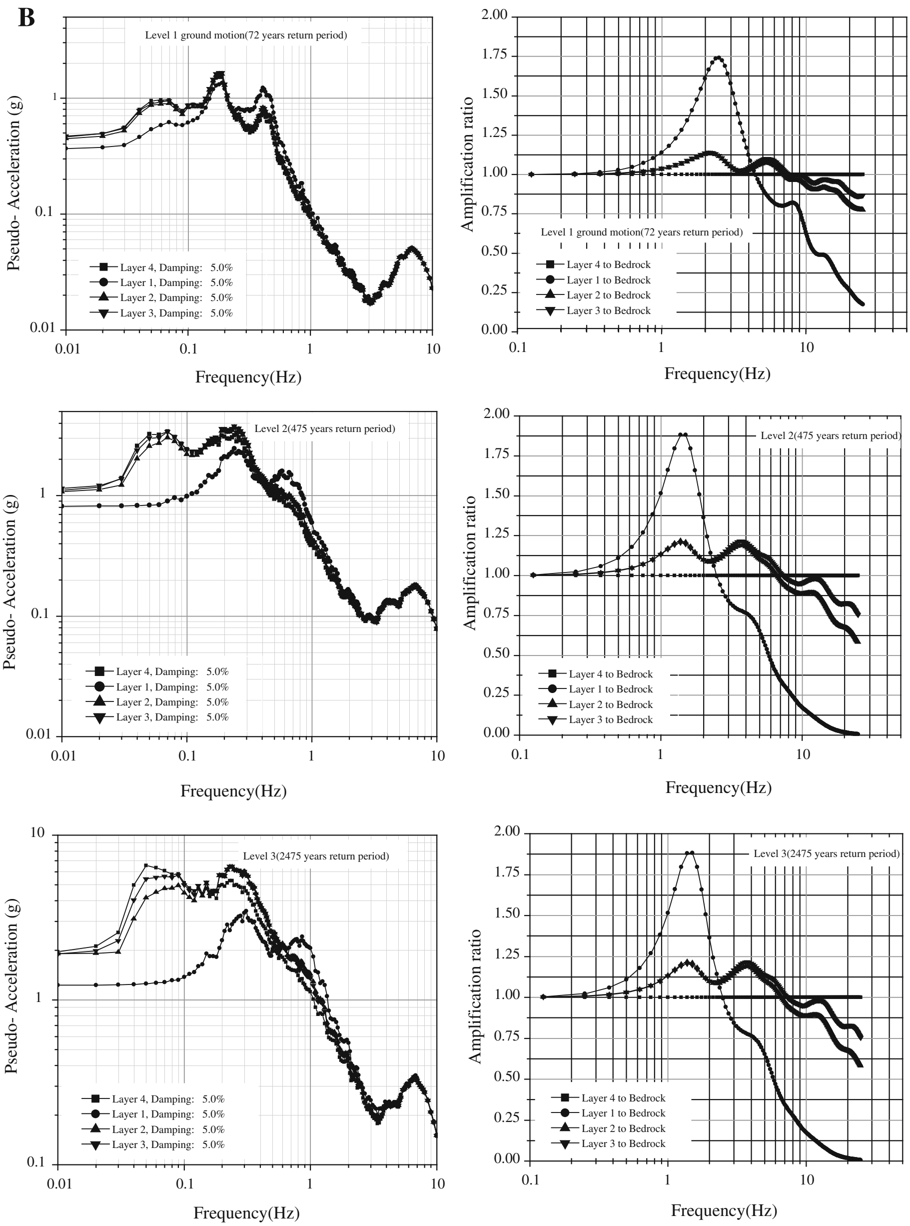

Fig. 8 continued

10.2 Seismic hazard computations and uniform hazard spectra (UHS)

Seismic hazard computed for each port site using the weighted average of all the GMARs is given in Table 6. From the deaggregation of the seismic hazard, it is observed that for fault F13, F25A, F14, and F12 are having major contributions of the expected seismic hazard for Kandla port site and fault F25A and F13 contribute largely for Mundra port site.

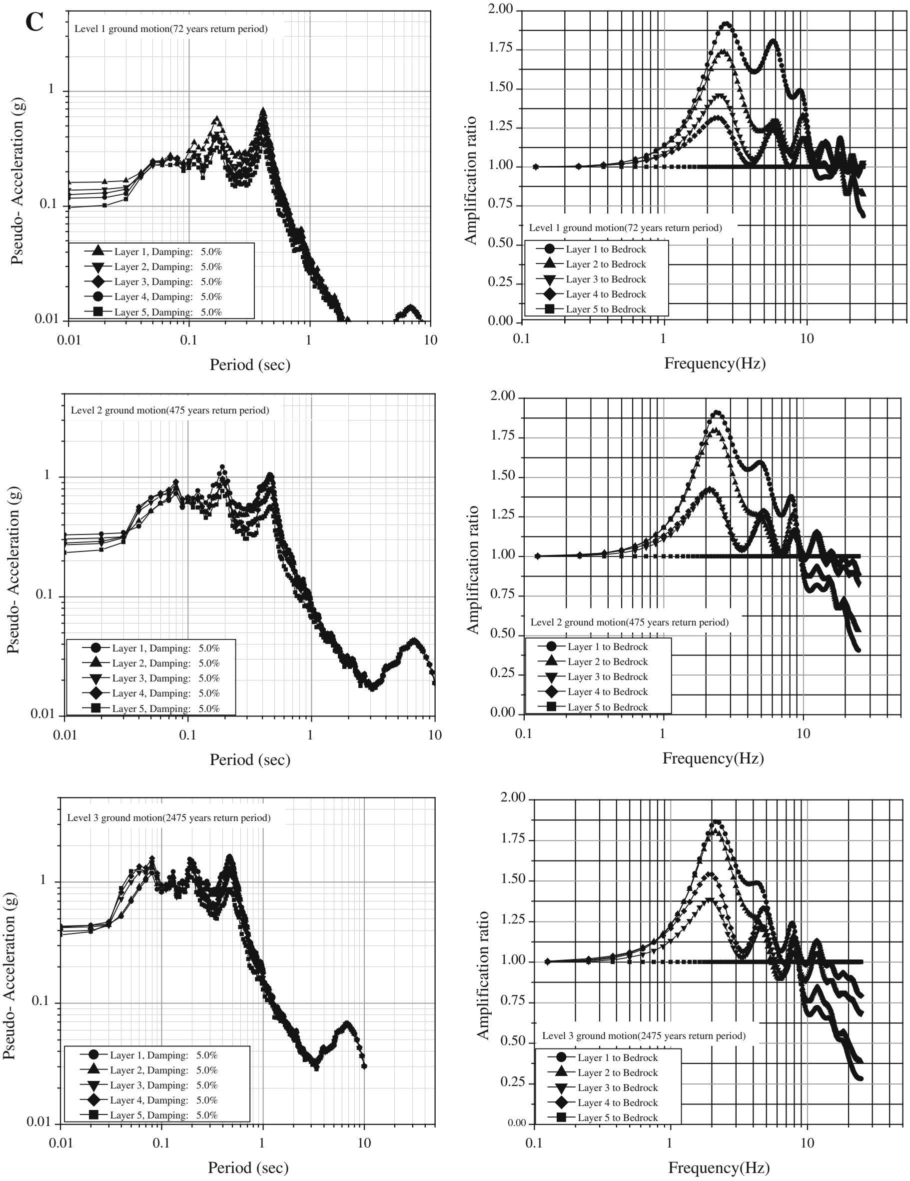

Fig. 8 continued

For Hazira port site F34 and for Dahej port site, F33 and F30 contribute largely for expected seismic hazard. The computed hazard for the various port sites is described in Table 6. For frequency of exceedance of 0.01, the computed hazard shows higher hazard for Kandla and Mundra port site with PGA, 0.236 and 0.18 g, respectively, whereas for Hazira and Mundra ports, almost same hazard with PGA, 0.13 and 0.137 g, respectively, are obtained. Similarly, the hazard values are computed for other time periods and used in development of uniform hazard spectra.

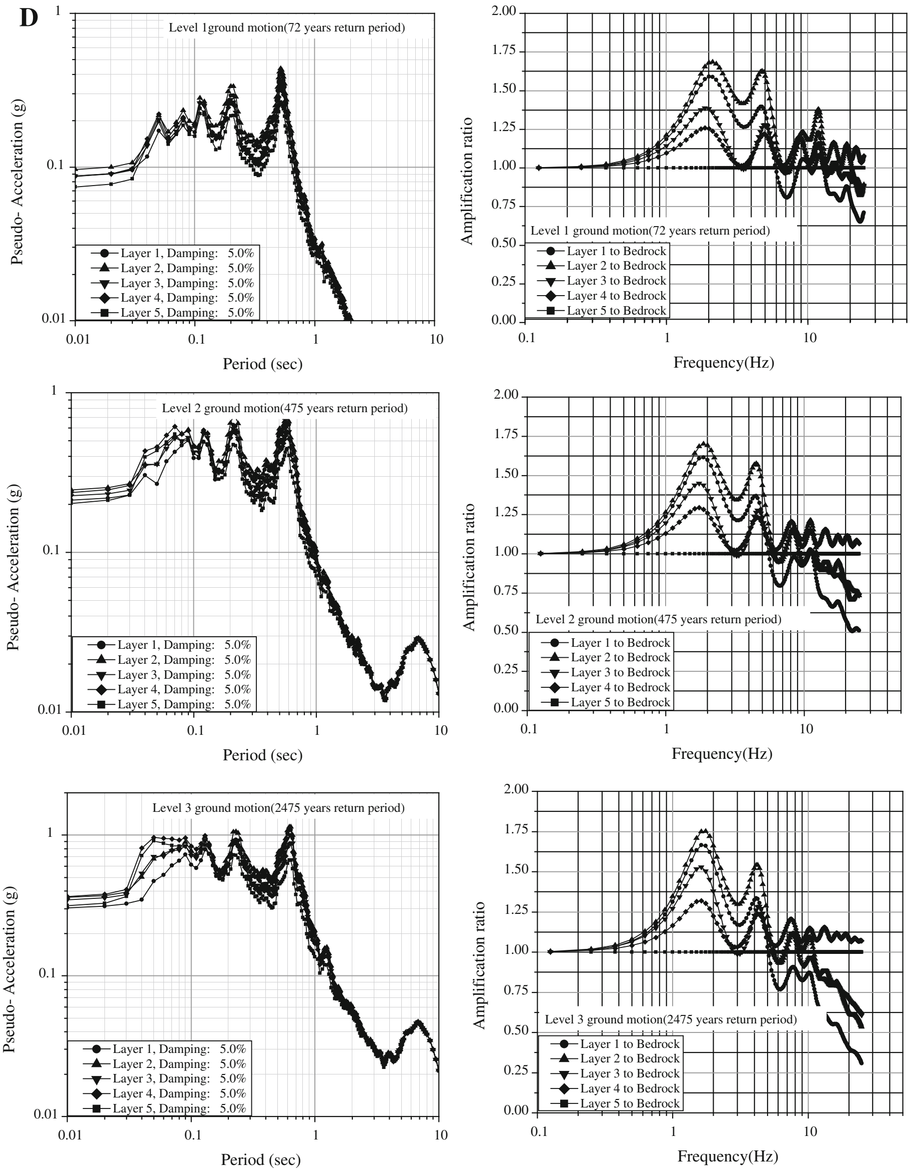

Fig. 8 continued

Uniform hazard spectra for the three levels of ground motions as per guidelines given by PIANC (2001) are developed for the four port sites studied representing uniform level of probabilistic seismic hazard at all periods. In present study, the 5% damping is selected in order to compare the generated spectra with the spectra specified by IS: 1893 Part I (2002). Sokolov (2000) has noted that Uniform Hazard Spectra generated this way can represent spectra of small and large, nearby and distant earthquake events. The obtained spectral accelerations for few specified time periods are given in Table 7. For Mundra port site, the

Table 6 Total hazard computed for horizontal ground motion for 5% damping at zero period

Annual frequency of exceedance	Peak (horizontal) ground acceleration (g)			
	Mundra port site	Kandla port site	Hazira port site	Dahej port site
0.0001	0.710	0.713	0.711	0.717
0.001	0.506	0.527	0.463	0.504
0.01	0.180	0.236	0.130	0.137
0.02	0.106	0.164	0.061	0.057
0.05	0.053	0.084	0.021	0.012
0.07	0.042	0.059	0.014	0.006
0.1	0.033	0.038	0.007	0.003
0.2	0.019	0.013	0.001	~0.00
0.3	0.012	0.006	~0.00	~0.00
0.4	0.008	0.003	~0.00	~0.00
0.5	0.005	0.002	~0.00	~0.00
0.7	0.003	0.001	~0.00	~0.00
1	0.001	~0.00	~0.00	~0.00
2	~0.00	~0.00	~0.00	~0.00
3	~0.00	~0.00	~0.00	~0.00

obtained spectral accelerations are highest compared with all other sites. This is possibly due to its proximity of the faults F13 and F25A, whereas expected spectral acceleration for Kandla is comparatively less. The lowest spectral acceleration is obtained for Dahej port site. Having been close to the Narmada Son Lineament (F34), Hazira port site has greater spectral acceleration compared with the Dahej port site. For level 1 ground motions (return period of 72 years), the expected ground motions are 0.19, 0.26, 0.069, and 0.046 g for Kandla, Mundra, Hazira, and Dahej port sites, respectively, and similarly can be obtained from the Fig. 7 for other level of ground motions for seismic design purposes. Though it is not explicitly mentioned in the code, but in the foreword of the code IS:1893-Part 1 (2002), it has been assumed that the specified MCE (Maximum Considered Earthquake) spectra correspond to 100 years of exposure time with 50% confidence level, whereas DBE (Design Basis Earthquake)corresponds to 50 years of exposure time and with 90% confidence level. This further shows that the specified code which is specifically described for buildings cannot be used for port structures directly and this has been also demonstrated by the guidelines given by PIANC (2001) and Werner (1998). It is also clear from the comparison with IS: 1893-Part 1 (2002) spectra that specified spectra given in the code underestimate the ground motions at lower time periods. Corresponding time histories are further estimated through RSPMATCH code for the UHS obtained for three level of ground motion for all four port sites (Fig. 7) to use them in performance-based design and time history analysis.

10.3 Ground response analysis and site amplifications

Using generated time histories for three levels of ground motions for each port site, the results of ground response analysis are typically presented in the form of the spectral response and transfer function calculated for each layer of the soil profile (Fig. 8). For Kandla port site, the observed amplification factor is observed to be around 1.37 for frequency range between 1.37 and 2.1 Hz. It is also observed that the amplification factor

Table 7 Computed horizontal component of spectral acceleration for 5% damping for few reference time periods

Time period (s)	Spectral acceleration (g)											
	Kandla port site			Mundra port site			Hazira port site			Dahej port site		
	Level 3 (2,475-year return period)	Level 2 (475-year return period)	Level 1 (72-year return period)	Level 3 (2,475-year return period)	Level 2 (475-year return period)	Level 1 (72-year return period)	Level 3 (2,475-year return period)	Level 2 (475-year return period)	Level 1 (72-year return period)	Level 3 (2,475-year return period)	Level 2 (475-year return Period)	Level 1 (72-year return period)
0.0 (PGA)	0.918	0.482	0.190	1.525	0.793	0.261	0.303	0.171	0.069	0.200	0.111	0.046
0.05	2.440	1.196	0.418	3.999	1.826	0.513	0.804	0.442	0.140	0.518	0.274	0.099
0.1	1.885	0.975	0.377	3.265	1.607	0.523	0.637	0.360	0.129	0.416	0.228	0.089
0.2	1.486	0.822	0.328	2.649	1.346	0.429	0.501	0.277	0.107	0.335	0.183	0.076
0.5	0.967	0.475	0.156	1.491	0.649	0.167	0.219	0.113	0.043	0.156	0.085	0.035
1	0.586	0.260	0.076	0.796	0.305	0.071	0.103	0.052	0.019	0.089	0.046	0.017

for free-field ground motion (Layer 1) has higher value compared with other layers. For Mundra port site, amplification factors are found to be from 1.94 to 1.74 for free-field ground motions, for the frequency range between 1.0 and 2.5 Hz. For Level 1 ground motion, layer 1 has greater amplification factor, whereas for Level 2 and Level 3 ground motions, layer 2 observed to be amplified more compared with other layers. For Hazira port site, the amplification factors are from 1.86 to 1.91 for the frequency range between 2.2 and 2.74 Hz. For level 2 and level 3 ground motions, amplification factors for layer 2 are greater than layer 1. For Dahej port site, the amplification factors are from 1.59 to 1.61 for the frequency range between 2 and 1.6 Hz for three levels of ground motions. The amplification of the layer 2 is observed to be more compared with other layers of soil profile. Statistical analyses of ground amplification records have shown that PGA is most likely to amplify when fundamental resonant frequency of site exceeds 2–3 Hz (Pitilakis 2004) and the same has been observed in the present study. This behavior of amplification of the spectral acceleration may be attributed to the soft soil deposits subjected to strong dynamic loading which makes the ground weaker (decrease in shear strength), and hence peak acceleration becomes smaller and the predominant period of soil profile is shifted to higher value due to non-linear behavior (Pitilakis 2004). Consequently, amplification occurs under small ground shaking with decrease in absolute value as the ground shaking level is increased.

The frequency dependence of the site amplification has shown common properties at all sites for all design ground motions. The increase in amplification factor is quite clear as level of ground shaking increased for all port sites. The ground response analysis has shown clearly that effective amplification by a factor above 1.3–2.0 occurs in the frequency band of 1–3 Hz. Although the port sites were located on different sedimentary units, significant variation in the amplification characteristics was not detected except for Mundra and Hazira port sites where free-field ground motions are less compared with the internal layers. Considerable damage to cargo berth of Kandla port site due to ground amplification and liquefactions is well within the observed response obtained in the present study.

The results of the present study demonstrate that integrated approach for evaluating "site-specific" seismic hazard in terms of ground motion parameters and site amplification study provides an accurate prediction of "site and region-dependent" ground motion parameters for the port sites of Gujarat. The amplitudes of the uniform hazard spectra strictly depend on the local soil conditions, and one single design code, i.e., IS: 1893-Part 1 (2002), is not adequate for port structures and the structures within the port area of Gujarat. The proposed study describes the methodology which can be used as basis for estimation of probabilistic (return period-dependent) site-specific ground motions in terms of engineering ground motion parameters for performance-based designs which are consistent with recommendation given by PIANC (2001) and Werner (1998). For design of waterfront structures in port sites under seismic conditions as was mentioned by various researchers like Choudhury and Ahmad (2007a, b, 2008), Ahmad and Choudhury (2008) etc., such input values will be helpful to recommend future direction for improving the current state of seismic risk reduction practice for ports in India. The outcome of the results is in form of site-specific Uniform Hazard Spectra (UHS) which may serve as resource document for engineers, planners, and administrators of port authorities, government, consulting engineering firms.

It is important to note that no liquefaction studies have been carried out in the present study and separate study should be attempted to make more robust recommendations for such topic as was done by Mhaske and Choudhury (2010) for Mumbai city. It is also imperative to note that the geotechnical characterization is based on the available information and representative soil profiles are adopted in the present study. However, to estimate more precisely, evaluation of fresh, structure-specific soil profile and actual dynamic properties are recommended as future scope of study.

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