Estimation of Probabilistic Seismic Hazard and Site Specific Ground Motions for Two Ports in Gujarat

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ABSTRACT

Seismic design of modern port sites requires assessment of regional seismicity, site specific ground motions and involves various geotechnical earthquake engineering aspects. Present study quantifies the seismic hazard associated with two most important ports located in the Gulf of Kachchh i.e. Kandla port and Mundra port in Gujarat, India. This study aims to develop site specific seismic ground motions at the two port sites for three different levels of ground shaking corresponding to three earthquake return periods. The site characterization is carried out by using available geotechnical data and estimated shear wave velocity. Uniform hazard spectra and design synthetic time histories for these two port sites are developed by using various equations for ground motion prediction and probabilistic seismic hazard analysis. The obtained ground motions are compared with the provisions of Indian seismic design code IS: 1893 – Part 1 (2002). The site amplification factor is obtained as varying from 1.37 to 1.94 for the frequency range of 1.0 to 2.5 Hz.

Keywords: Seismic hazard, ground motion, ports, site response, amplification.

INTRODUCTION

The extended loss of 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 which are well documented by Werner (1998), PIANC (2001), Shukla and Choudhury (2011). Within the life of port structure, the severe event may be considered as rare event but the consequences will be so large that the failure of port can be a major issue of national interest with huge economic loss. Earthquakes thus pose low probability high consequence threats to port structures. During strong shaking under seismic conditions, liquefaction, lateral spreading, slope instability, soil structure interaction and site specific ground motions are the major geotechnical concerns for port structures. During the Bhuj Earthquake of 2001, the liquefaction driven failures were reported near port facilities (Dash et al., 2008) in India.

PRESENT METHODOLOGY

Prime objective of this study is to evaluate seismic hazard potential for the two most important ports located in Gulf of Kachchh of Gujarat region in India and to develop site specific ground motions for three levels of ground shakings (Table 1). Kandla and Mundra ports are the busiest ports in the region and selected as the target sites in the present study. Geotechnical characterization affecting the site response was interpreted from review of available geotechnical data from the project sites. Probabilistic seismic hazard analysis was performed with the intention to develop Uniform Hazard Spectra (UHS) using the seven popular ground motion prediction equations (GMPEs) including one country specific ground motion attenuation relations developed by Raghu Kanth and Iyengar (2007). Epistemic uncertainties were addressed through the use of logic trees in which spatial variation of b-value is addressed. Using recorded time history of 2001 Bhuj earthquake, artificial ground motions are scaled up to match the developed UHS for each level of ground motions. Using the representative geotechnical profile at the site, local site effects were then investigated using SHAKE91 (Schnabel et al., 1972) by considering equivalent linear model to get expected free field ground motion at surface level.

Table 1. Various Ground Motions Considered in the Present Study.

Designation	Probability of Exceedance	Return period (Years)	Earthquake Designation
Level 1	50 %	72	Operational Earthquake (OLE)
Level 2	10 %	475	Contingency Earthquake (CLE)
Level 3	2 %	2475	Max. Considered Earthquake (MCE)

Kandla port is located at latitude of 23.03^0 N and longitude of 70.13^0 E. It is a natural harbor, situated in the Kandla Creek and is 90 km away from the mouth of the Gulf of Kachch in western part of India. In 1955, Kandla was declared as a major port by the Transport Ministry of India. It serves for twelve states of India to handle bulk materials. Mundra port is located at latitude of 22.74^0 N and longitude of 69.71^0 E. It is located at 60 km away towards west of Gandhidham in Kachch district of Gujarat in western part of India. The port was started in 1998 as logistics base for international trade operations. It is all weather, independent and commercial port.

Gujarat is seismically one of the most active regions in India, which has experienced two major 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, Choudhury and Shukla, 2011). Kachchh and the adjoining region is a seismically most active intra-continental region where high intensity but infrequent earthquakes have occurred. According to the seismic zoning map of India, Gujarat falls in all four different seismic zones (Fig. 1). Kachchh and the adjoining region along with the Pakistan border fall under Zone-V, which is the highest seismic zone in India. Zone-IV covers a narrow portion of the northern Kathiawar peninsula and the remaining part of Kachchh. The other parts of Gujarat are under Zone-III, except a narrow eastern part bordering Madhya Pradesh state with Zone-II. According to IS:1893-Part 1 (2002), Kandla and Mundra port sites are located in seismic Zone-V having maximum peak ground acceleration value about 0.36g as shown in Figure 1.

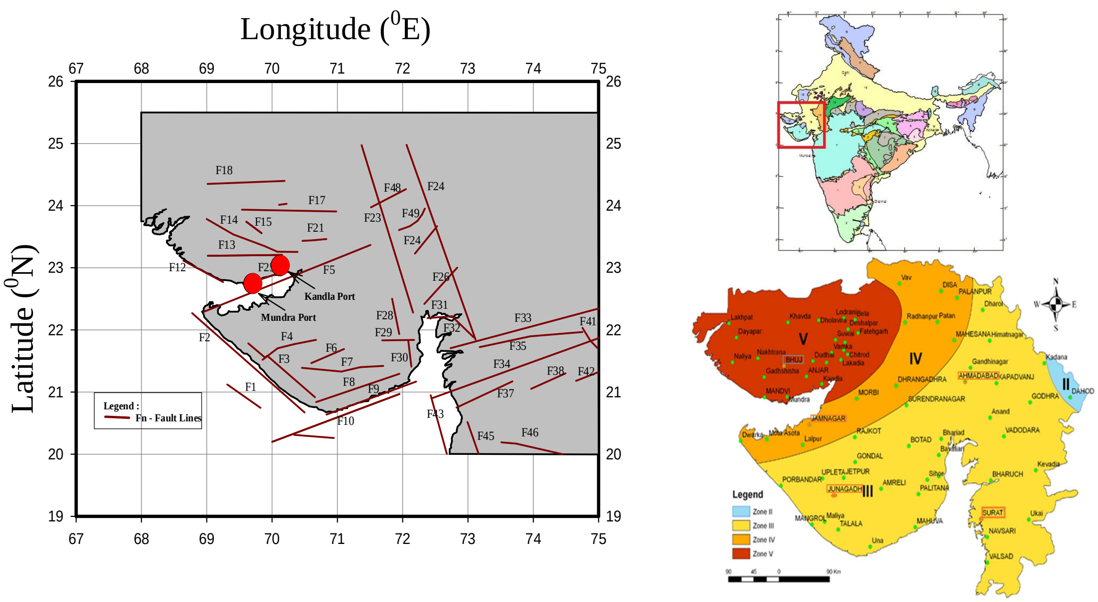

Figure 1. Fault map describing the faults considered in the analysis with geographical location of port sites and seismic zoning map of Gujarat as per IS: 1893-Part 1 (2002) [Modified after Shukla and Choudhury, 2011].

GEOTECHNICAL CHARACTERIZATION

Typical soil profiles are obtained from the geotechnical investigation carried out for the particular port sites and are shown in Figure 2. In the present study, evaluation efforts were largely concerned with data on soil descriptions, SPT blow count and unit weight. The shear wave velocity data for every layer are estimated from the measured SPT blow counts using ten worldwide available empirical correlations (Fig. 2) as was done by Mhaske and Choudhury (2011). Typical soil profiles are shown in Tables 2 and 3, which are used in the ground response analysis.

PROBABILISTIC SEISMIC HAZARD ANALYSIS (PSHA)

Probabilistic seismic hazard analysis has been performed as per procedures given by Cornell (1968). It is now most widely used approach to obtain the characteristics of strong ground motion for engineering design. The analysis of seismic hazard at given site requires an approach for estimating 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) and requires following data.

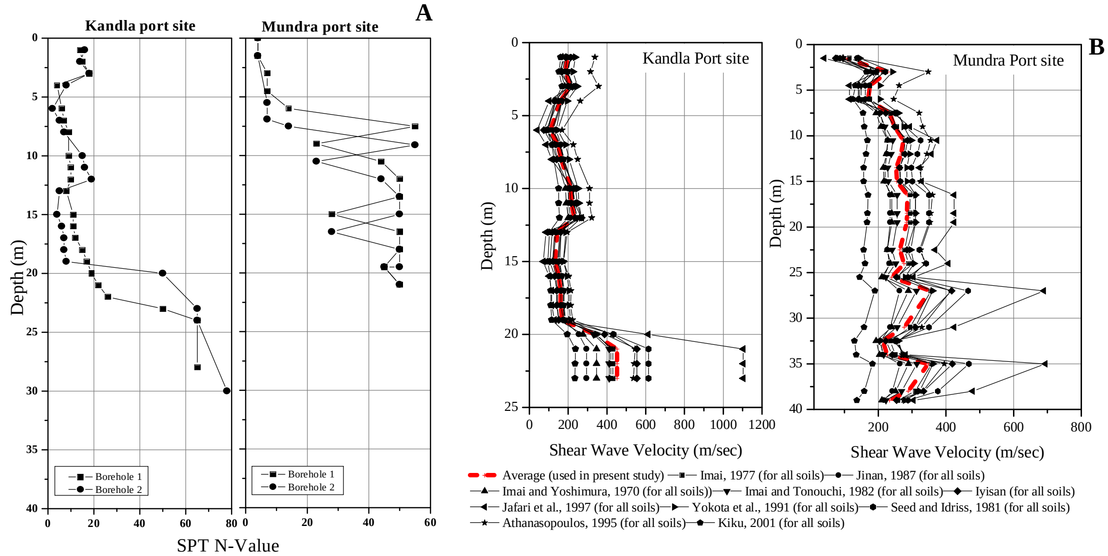

Figure 2. (A) SPT N-value variation at two port sites; (B) estimated shear wave velocity at two port sites [Adapted from Shukla and Choudhury, 2011].

In the present study, two chosen port sites are considered as center with control region having radius of 250 km around each port. The fault map of Gujarat region as suggested by Choudhury and Shukla (2011) with location of chosen port sites is shown in Figure 1. A total of 40 major faults are marked from F1 to F40, which influence seismic hazard at chosen port sites and those are considered in the present study (Figure 1). Faults located beyond 250 km from a site are not considered.

Table 2. Typical Soil Strata at Kandla Port.

Depth (m)	Unit weight (kN/m^3)	Average SPT- ‘N’ value	Description
0 – 17	15	10	Soft clay
17 – 20	15	17	Stiff clay
20 – 24	18	35 – 40	Medium silty sand
24 – 29	17	50	Stiff to very stiff clay
29 – 32	18	>50	Dense silty sandy gravels

Table 3. Typical Soil Strata at Mundra Port.

Depth (m)	Unit weight (kN/m^3)	Average SPT- ‘N’ value	Description
0 – 9	17	8	Loose to medium silty sand
9 – 13	18.5	10-35	Yellow to grey dense sand
13 – 20	17	28-39	Sandy silty clay
20 – 30	18.5	30-50	Very dense to dense silty sand

Source seismicity involves development of a magnitude recurrence relationship based on the historical and geological data in the form,

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

as proposed by Gutenberg and Richter (1944), where N= Number of earthquake per year, M= earthquake magnitude, a, b = Gutenberg and Richter (1944) parameters. The Gutenberg-Richter (G-R) recurrence relationships for three parts of Gujarat was proposed by Choudhury and Shukla (2011) which are adopted in the present study for further analysis. The fault level recurrence relations are then developed. In present study, the maximum cutoff magnitude is calculated based on empirical correlations between fault lengths considering the 1/3 of the total fault length as rupture length using the various empirical relationships.

Ground motion prediction equations (GMPEs) which predict the attenuation of ground motions as function of distance from the earthquake location are selected to compute the ground motion at target site. Apart from the country specific GMPE for Peninsular India given by Raghu Kanth and Iyengar (2007), several other GMPEs were also employed to have a chance for comparison for the present study. For shallow crustal earthquakes GMPE proposed by Abrahamson and Silva (1997) is applicable and used in the present study. The crustal intraplate GMPEs given by Toro et al. (1997) and Frankel et al. (1996) are also included. The GMPEs by Boore et al. (1997), Campbell (1997) and Sadigh et al. (1997) representing the Californian earthquakes were also selected for comparison.

LOGIC TREE USED

Epistemic uncertainties in the hazard computations have been accounted for within a logic-tree framework by considering the following controlling parameters: (1) assigning region specific G-R parameters, (2) including more variation in the b-value based on the values reported by various researchers and characteristic recurrence model, and (3) the use of candidate GMPEs. The spatial variations in b-value is used in the logic tree approach by assigning equal weightages to the b-values proposed by Choudhury and Shukla (2011) and Jaiswal and Sinha (2007). It may be noted that the b-values proposed by Choudhury and Shukla (2011) are region specific i.e. different for Kachchh, Saurashtra and Mainland Gujarat, whereas b-value = 0.92 reported by Jaiswal and Sinha (2007) was for entire Peninsular India.

SEISMIC HAZARD ESTIMATION

The total hazard contribution given by each fault for each port site within the control region of 250 km are evaluated to get the total hazard in terms of probability of exceedance for different level of ground motions. The seismic hazard is computed at 12 spectral periods ranging from 0 to 4 seconds for each site under consideration. The mean hazard by seismic source for each site were quantified and further used to develop uniform hazard spectra for horizontal component of ground motion. For different b-values used in logic tree and a characteristic earthquake model, hazard curves are obtained for the seven GMPEs used which leads to total 28 hazard curves for each port site. The obtained curves (28 nos.) are scaled as per the weightage to obtain final hazard curves for each port site (Figure 3).

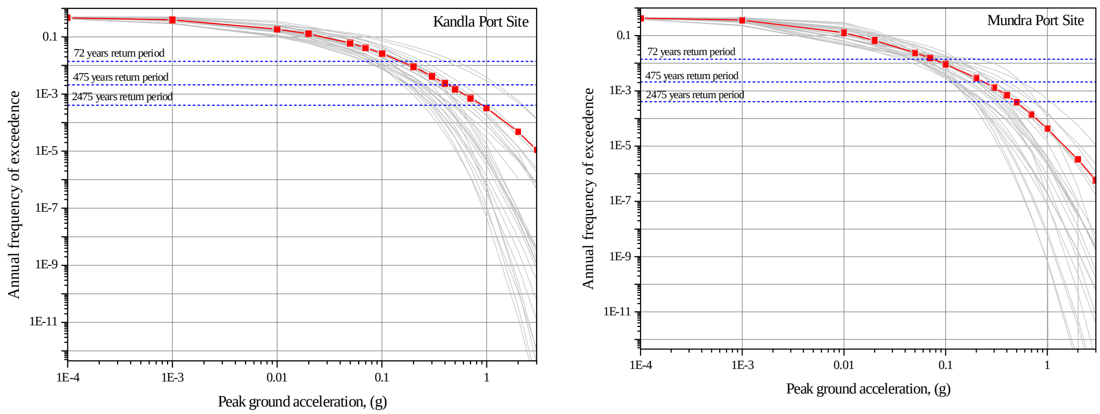

Figure 3. Estimated total seismic hazard for two port sites of Gujarat.

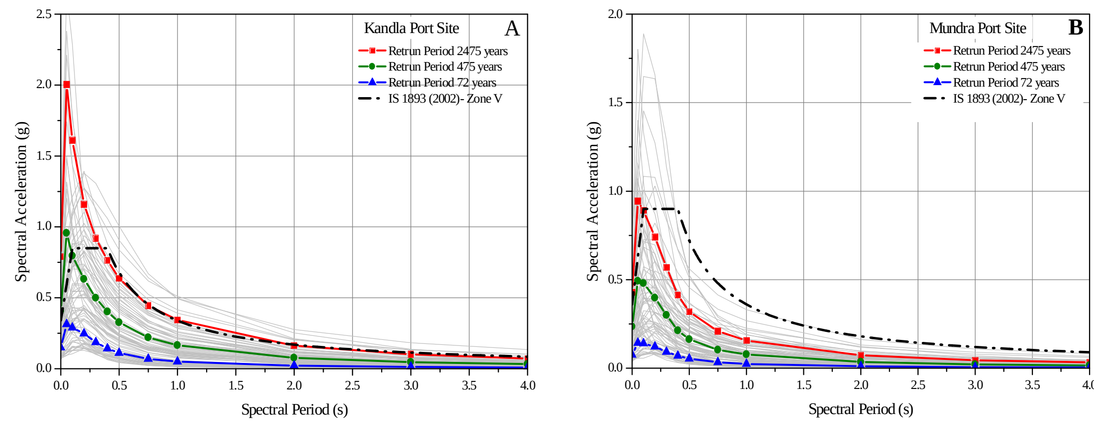

Figure 4. Generated Uniform Hazard Spectra for different levels of ground shaking for (A) Kandla Port site, (B) Mundra Port site.

UNIFORM HAZARD SPECTRA AND SYNTHETIC TIME HISTORIES

The horizontal component of the uniform hazard spectra for the rock site corresponding three levels of ground motions (with return periods of the 72, 475 and 2475 years respectively) and 5% damping, are developed based on the seismic hazard computations for the two port sites (Figure 4). Generated UHS are 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 using computer code RSPMATCH (Abrahmson, 1998). The longitudinal components of actual ground acceleration - time history of the 2001 Bhuj earthquake recorded at ground floor of the Passport office building in Ahmedabad, is selected as the input ground motion for the spectral matching. Typical input uniform spectra for Kandla port site for Level 3 (with return period 2475 years) ground motion, input ground motion spectra of Bhuj earthquake and matched spectra along with generated synthetic time history are presented in the Figure 5.

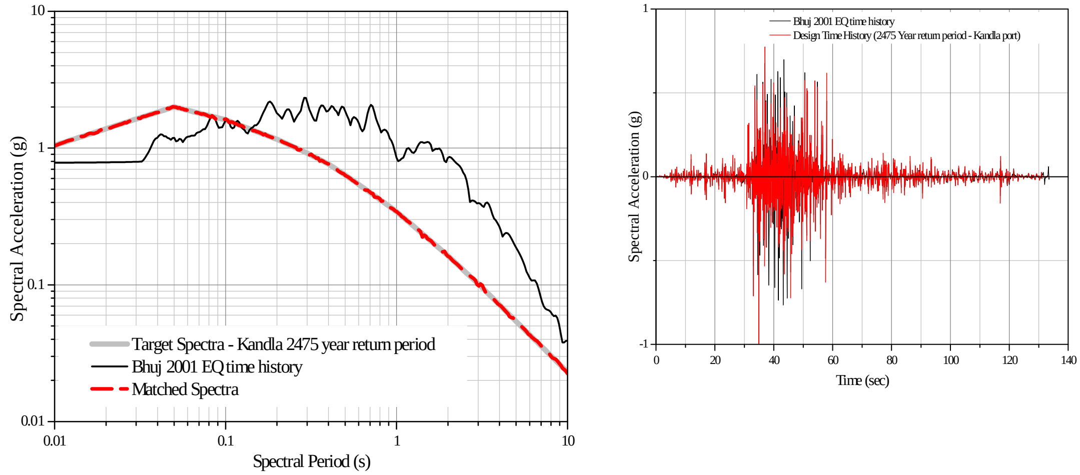

Figure 5. Acceleration spectra of 2001 Bhuj Earthquake matched with design spectra for Kandla Port for Level 3 (return period 2475 years) ground motion along with original and generated time history.

SITE SPECIFIC GROUND RESPONSE ANALYSIS

Based on the one dimensional ground response analysis theory (Phanikanth et al., 2011), the site effects are estimated for the specified port sites assuming equivalent linear model using well known computer code SHAKE91 (Schnabel et al., 1972). Site specific ground response analyses were carried out using SHAKE91 for the representative soil profiles for the port sites using the shear wave velocity data obtained (see Figure 2(B)). Suitable modulus reduction curves and damping curves for various layers are selected based on the soil properties. The results from the performed ground response analysis are obtained in form of pseudo-acceleration response spectra and transfer function (amplification factor) and typically presented in Figure 6 for Level 3 (return period 2475 years) ground motions.

DISCUSSIONS AND CONCLUSIONS

From the deaggregation of the seismic hazard, it is observed that for F13, F25A, F14 and F12 are the major contributors of the expected seismic hazard for Kandla port site and F25A and F13 are major contributing faults for Mundra port site. For frequency of exceedance of 0.01 the computed hazard shows higher seismic hazard for Kandla than Mundra port site. The generated uniform hazard spectra do not represent ground motion for a single earthquake, but may considered as a combination of the ground motion parameter (i.e. ground acceleration), of which will not be exceeded with a certain probability in specified time span (i.e. 10% in 50 years). By matching to 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. For Kandla port site, the obtained spectral accelerations are higher compared to Mundra Port site. This is possibly due to its proximity of the faults F13 and F25A, whereas expected spectral acceleration for Mundra is comparatively less. For Mundra port site estimated PGAs are 0.42g, 0.23g and 0.08g for Level 3, 2 and 1 respectively. These PGAs are 0.6g, 0.34g and 0.1g for Kandla port site (Figure 4) for Level 3, 2 and 1 respectively. This shows that the Kandla port site is seismically more vulnerable compared to Mundra port site. Though it is not explicitly mentioned in the seismic code, but in the foreword of the code IS:1893-Part 1 (2002) it has assumed that the specified MCE (Maximum Considered Earthquake) codal spectra is corresponding to 100 years of exposure time with 50% confidence level whereas DBE (Design Basis Earthquake) is assumed as twice of the MCE values. Hence, IS: 1893 – Part 1 (2002) recommends the Level 3 with PGA =0.36g and Level 2 with PGA =0.18g for both port sites which are underestimating the seismic ground motions at lower time period. These data help for various seismic studies, for example, for liquefaction analysis as was done by Mhaske and Choudhury (2010). Also for seismic design of port structures or waterfront structures as was done by various researchers, like Ahmad and Choudhury (2008), Choudhury and Ahmad (2008) etc., these results will help to consider more realistic input values for seismic design.

The input ground motions were modified to match obtained horizontal uniform hazard spectra using the program RSPMATCH (Abrahamson, 1998) which uses 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. The generated time histories (Figure 5) can be very useful for time history and push over analysis of the structures for performance based design.

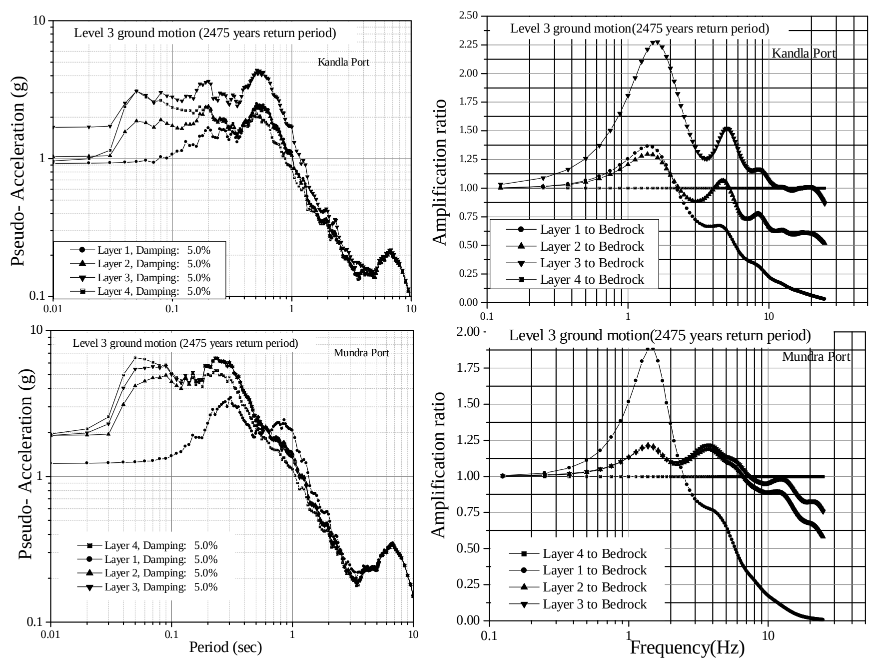

Figure 6. Typical pseudo-acceleration response spectra and amplification ratio for Level 3 (return period 2475 years) ground motions.

For Kandla port site, the observed amplification factor is around 1.37 for frequency range from 1.37 to 2.1 Hz (see Figure 6). It is also observed that the amplification factor for free field ground motion (Layer 1) has higher value compared to other layers. For Mundra port site, amplification factors are about 1.94 to 1.74 for free field ground motions with frequency range from 1.0 to 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 to other layers. 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 and same has been observed in the present study. This behaviour of amplification of spectral acceleration may be attributed to the soft soil deposits subjected to strong dynamic loading which decreases shear strength of soil and hence peak acceleration becomes smaller and the predominant period of soil profile is shifted to higher value.

The results of the present study demonstrate that combination 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 building code i.e. IS: 1893-Part 1 (2002), is not adequate for port structures and the structures within the port area. 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). The study will helpful to recommend future direction for improving the current state of seismic risk reduction practice for ports in India. The outcome of the results in form of site specific Uniform Hazard Spectra (UHS) for various levels of ground shaking can be further used by engineers.

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