Visakhapatnam Chapter

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Seismic Site Characterization and Dynamic Analysis of Pile Supported Wharf Structure

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Abstract. India being a large subcontinent is prone to traumatic earthquakes causing remarkable destruction to property, life and hindering the development of urban areas. Since past few years the issue of earthquakes has been mentioned by many researchers and agencies. Hence dynamic site characterization is considered as a primary step in any seismic zonation process and it is inclusive of seismic, geotechnical and geological characteristics of the site which gives a preliminary idea of future seismic hazard. In this research paper, an effort has been made to dynamic site characterization of the city of Vishakhapatnam (India) along with dynamic analysis of a pile supported wharf structure located in the study area.

Dynamic site characterization includes ground response analysis which helps in assessment and estimation of local site effects such as liquefaction, settlement of ground, ground deformation, amplification or attenuation of ground motion. Therefore, site characterization and response studies that are a subset of micro zoning process provide us with most important outcomes for the hazard estimation process of a particular region. The basic purpose of dynamic site characterization is rupture mechanism modeling at a particular source, evaluate the wave propagation from the bedrock to the surface, estimate the effect of site conditions and therefore develop a map quantifying the hazard and susceptibility of the study area. Site specific dynamic characterization is helpful in design of buried lifelines such as oil pipelines, sewage and water lines, LPG carrier pipelines, power plants and seismic design of other prominent civil engineering structures.

In the current research dynamic site characterization has been carried out for the city of Vishakhapatnam, Andhra Pradesh (India) using geotechnical, geological and seismotectonic data. Further a pile supported wharf structure is considered in Vishakhapatnam port to study the dynamic behavior and performance analysis of the structure under local site conditions. Wharfs are the structures that are constructed parallel to the shore for mooring of ships. Any damage due to an earthquake to wharfs and berths may lead to inefficiency in port operations. Seismic performance analysis of pile supported wharf is the most neglected and unaddressed part in codal provisions of many of the countries. Seismic vulnerability analysis also provides a framework to assess the both the performance of the system and economic issues on a whole..

Keywords: Dynamic, Microtremor, pile foundation, wharf, ground response.

1 Introduction

Stable central region of Indian peninsula has been considered as a seismically inactive zone earlier before the devastating seismic events of Koyna (1967 Mw = 6.0), Bhadrachalam (1969, Mw = 5.7), Latur (Maharashtra) (1993, Mw = 6.2) and Jabalpur (1997, Mw = 6.1) Bhuj (2001, Mw = 7.7) earthquakes. Historical cases of seismic events in sea ports have shown vulnerability of wharves to threatening earthquakes along with Tsunami right from 325 BC Makran Subduction Zone earthquake (North Arabian Sea) to the recent Tohoku (Japan) March 11, 2011 [1]. The Great Indian ocean earthquake (2004) which damaged many ports across Andaman and Nicobar, Indonesia , Sumatra, Bali as well as in India. Though earthquake has lower probability of occurrence it imposes higher risk to port structures therefore seismic vulnerability assessment of such structures is highly essential. Thus increasing seismicity in Vishakhapatnam along the coast of Bay of Bengal motivated the authors to carry out dynamic site characterization of Vishakhapatnam urban along with Non- linear analysis of pile supported wharf structure in Vishakhapatnam sea port. Seismic hazard assessment, response analysis, liquefaction susceptibility and microtremor testing have been carried out to estimate the predominant ground acceleration, frequency and amplitude of the soils at different locations and hazard maps have been generated from the results of the study.

The most meticulous method for estimating seismic response of a pile supported wharf in terms of inelastic rotations and displacements in plastic hinges is nonlinear time history analysis. As per PIANC [2] guidelines, minimum five spectrum records are recommended. Earthquakes with normal faulting mechanism have been chosen based on the site specific response spectra. The site specific response spectra constructed based on the seismic hazard and local site conditions have shown a variation of 50% when compared with the response spectra provided by Indian seismic code [3]. Hence 5 earthquake events have been selected based on the response spectra and the accelerograms are scaled for PGA varying from 0.1 to 0.5g.Seismic response of the wharf is obtained in terms of maximum displacement.

2 Details of The Study Area

Visakhapatnam (Andhra Pradesh) is one of the important and largest port city of India and is also the most densely populated. Local site effects because of sandy and clay sediments are characteristic of the whole city area. Visakhapatnam urban covers an area of 160sq.km (Fig.1). The city extends between 17° 40′30″–17°45′N and longitudes 83°11′–82°20′ E. The topography of the city is undulated with hills characterized by Eastern Ghats. Major mineral groups available are Khondalites followed by charnockites, quartzites and pegmatities [4]. Red soils, sandy soil, clay and gravel loams are the different soil types identified throughout the city. Groundwater table in the city ranges from 3m to 14m. deeper water levels (>6m) below ground level are identified in North and Eastern parts of the city and shallow water levels of (3-6m) in western and southern locations.

The city is categorized as seismic zone II as per IS 1893:2016 [3] with a zone factor of 0.1g. About 107 low to moderate magnitude earthquakes (1967-2018) have been recorded in about 300Km radius from the city with a magnitude ranging from 2.1 to 5.2. The coast of Bay of Bengal is considered to be a weaker zone with neo-tectonic activities establishing since recent past [5].

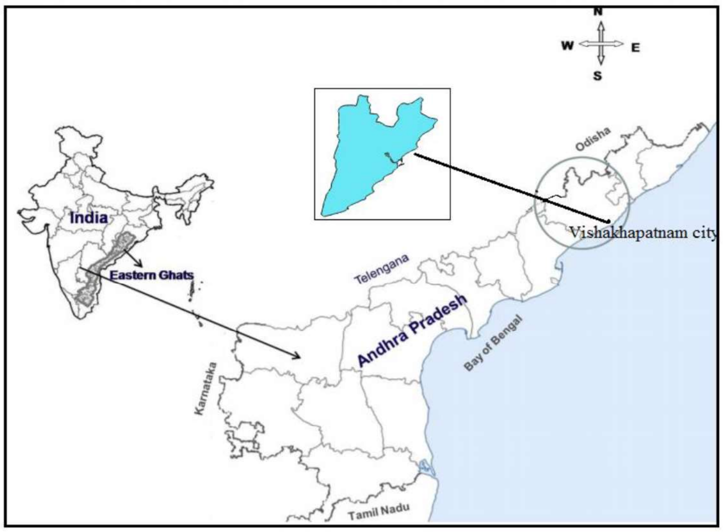

Fig. 1. Location map and political boundaries of Vishakhapatnam (India)[4]

3 Dynamic Site Characterization

Huge research work has been carried out on dynamic site characterization and founded on the different experimental and analytical techniques for the same. It has been observed that though many site specific studies have been conducted in many parts of the world, they are still important for development of infrastructure in a particular location. Therefore in this study site specific dynamic characterization has been attempted along with dynamic response analysis of a pile supported wharf structure using the dynamic parameters. Dynamic site characterization comprises of seismic hazard analysis, 1-D ground response analysis, microtremor testing and liquefaction susceptibility analysis.

3.1 Probabilistic seismic hazard assessment

The seismic hazard analysis alludes to forecasting robust strong ground motion expected at a particular site. This is often necessary for seismic design of structures or for judging the performance of existing structures at a given site during a seismic event. One vital application of hazard analysis is that the development of hazard maps

of a region for generalized applications [6]. Such maps are helpful in designing the earthquake-resistant structures. Ground motion is characterized through hazard parameters at a particular region by estimating annual rate of occurrence.
Seismic history, seismo-tectonics of the region earthquake frequency from potential sources, maximum magnitude, attenuation of strong motion etc., are accounted in seismic hazard models (Figure 2)[7]. A total of 107 seismic events that took place in and around the study area in a span of 190 years (1828- 2018) are considered for analysis. The hazard parameters are found to be a= 2.45 and b= 0.69 (Fig. 3) using Kijko-sellovel [8] approach as the seismic data is found to be incomplete due to unavailability of seismic records.

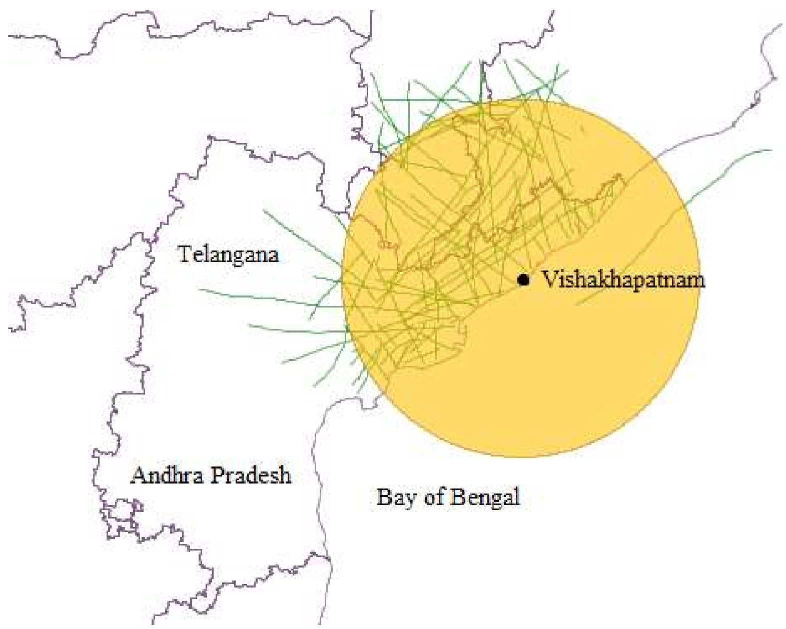

Fig.2. Map showing seismic sources within 300km radius of the study area [4]

From the results, it has been observed that the seismic hazard parameters a, b found a good match with the values from the past research carried out for south or peninsular India. Many of the researchers have established hazard parameters for specific regions across India. The parameters that define the regional recurrence from the current study matches well with past studies i.e., Kaila et al.[9] also suggested b value of 0.7 for peninsular India. Jaiswal and Sinha[10] have suggested value of b is 0.88± 0.7and according to Ram and Rathore [11] the values are a=4.58 and b= 0.891.Apart from the above mentioned studies, Sitharam and Anbazhagan[12] have conducted probabilistic hazard estimation for Bangalore (zone-II) [3] and provided the value of " b" to be in the range of 0.62 - 0.98.

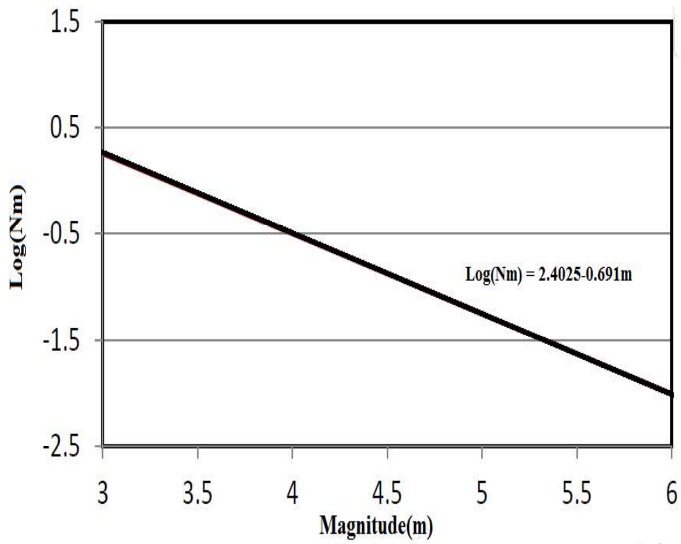

Fig. 3. Frequency - magnitude distribution plot using Kijko-sellovel method[8]

Many researchers developed region specific attenuation relationships from their studies since past, to determine the spectral acceleration (Sa/g) and PGA. The ground motion prediction model (GMPE) gives the variation of ground acceleration with respect to damping ratios and vibration periods for a given magnitude (Mw) and distance (R). In this research hazard curves have been generated for the five potential faults at bed rock level as shown in figure 4. Hazard curves with exceedance probability of 0.1 in 50 years for 475 years return period have been evaluated. As the site is situated in South India, the attenuation relationship given by Raghukanth and Iyengar [13] for peninsular India has been adopted here for hazard curve generation.

$$\ln(Y_{br}) = C_1 + C_2(M\text{-}6) + C_3(M\text{-}6)^2 - \ln(R) - C_4R + \ln(\varepsilon_{br}) \quad (1.0)$$

Y_{br}refers to spectral acceleration (Sa/g) or PGA, M is the moment magnitude whereas R and ε_{br} refers to hypo central distance and error in regression.C_1, C_2, C_3, C_4 are the site specific constants given by Raghukanth and Iyengar [13]for south India region.

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Five potential sources (faults and lineaments) are considered in hazard assessment for developing hazard curves using Raghukanth and Iyengar's[13] ground motion prediction equation and response spectra (Figure 4).The hazard map of the study area have been developed for a structural time period of 0.1 and 0.2 sec. for a probability of 10% . Higher ground accelerations are expected in the fault and shear zone locations as shown in figure 5.

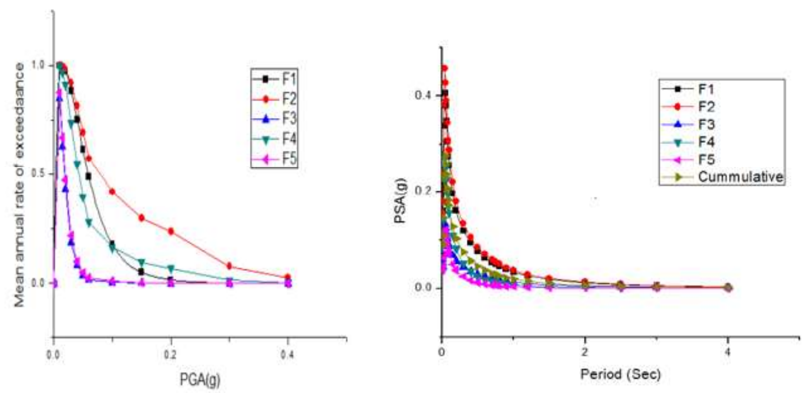


Fig. 4. Hazard curves and UHRS for potential faults at bedrock level

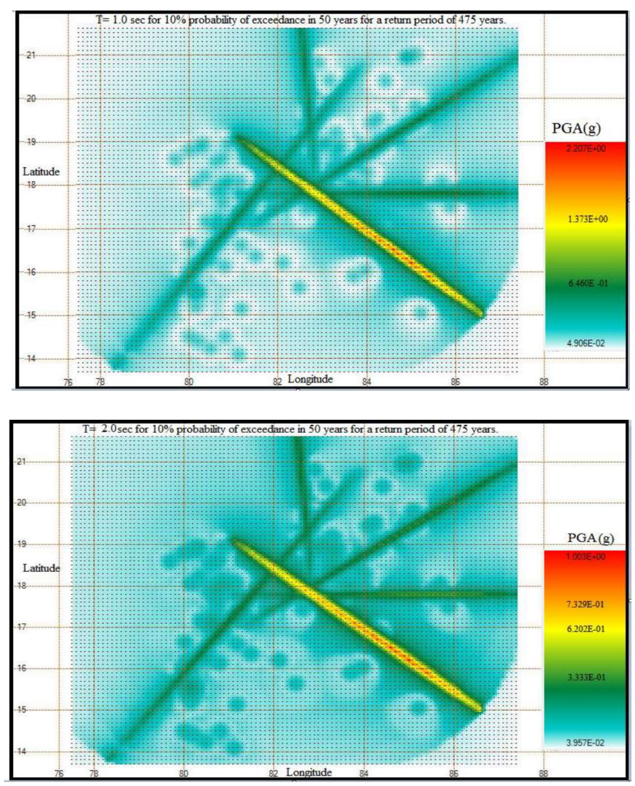


Fig.5. Hazard maps of the study area from PSHA

3.2 Equivalent linear ground response analysis

Wave propagation in 1-D approach is predominantly used for site response with precise results [14]. Here in this research, site response using equivalent linear approach has been conducted, with the initial conditions that the soil in the site is horizontally layered and single damping and stiffness values are used at every frequency component through DEEPSOIL [15]. Damping ratio curves and shear modulus are defined using discrete points. Damping ratio is given to be 5% and shear modulus is interpreted in terms of strain.

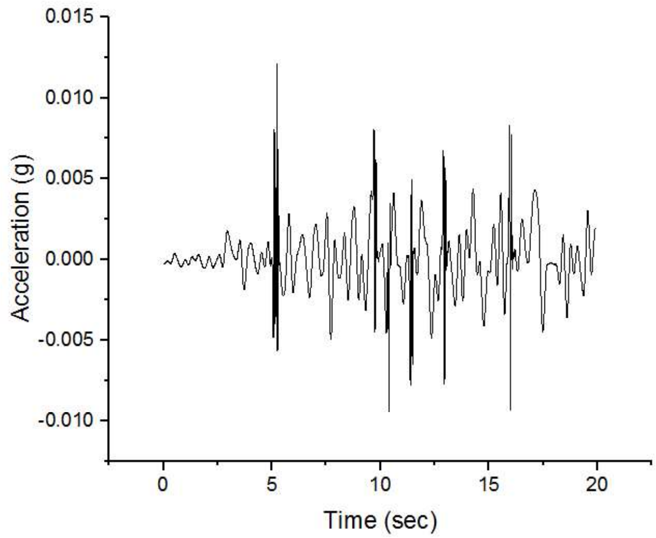


Fig. 6. 2001 Bhuj Earthquake ground motion (Scaled)

For the response analysis, 60 locations with 248 boreholes are considered and the input parameters given are acceleration time history, shear wave velocity of the soils and other dynamic soil characteristics. Bhuj (2001) accelerogram (Fig. 6) of magnitude Mw = 7.7 is used for the analysis with a Peak acceleration of 0.107g for a duration bracketed for 19.98 sec. The geotechnical parameters required are obtained from borehole exploration data. Material properties of each layer of soil are modeled by using modulus reduction and damping versus shear strain curves. Fast Fourier transform (FFT) is carried out and analysis is done for 5% damping.

The Peak Ground Acceleration (PGA) at surface is found to be in the range of 0.08g to 0.14g. Peak spectral amplification factor (PSA) is in the range of 1.0 to 1.6. Amplification factor increased at locations with shallow ground water level leading to the predominant increase in PGA at the surface. PGA values have been used to characterize the study area into different soil classes as shown in figure 7.

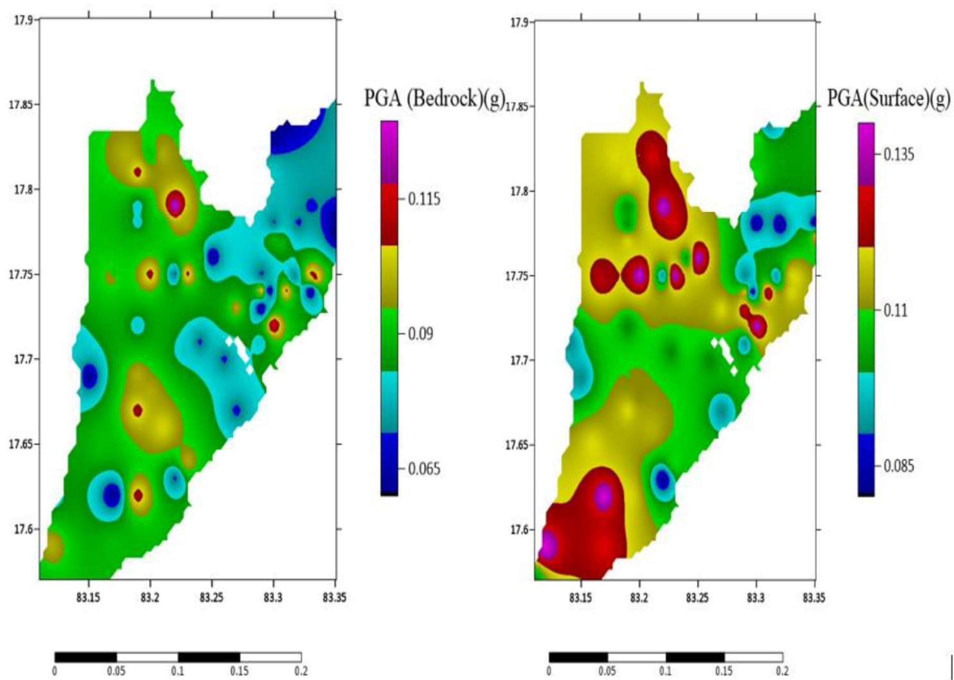


Fig. 7. Acceleration hazard maps at Surface and bed rock

3.3 Microtremor testing

Determination of dynamic soil characteristics using microtremor testing has been widely used since 1980s. But the existing standard spectral ratio method needs a reference site near to the site of interest for testing which may not be possible and easy to choose in complex geological and environmental conditions. There after horizontal to vertical spectral ratio (HVSR) method has been provided by Nakamura [16] and gained importance because of its simplicity. Both standard spectral ratio and HVSR methods give precise results [17] but HVSR method is adopted most the times. Reference site selection is not required while taking recordings, which will be advantageous in densely populated cities. The consistency of HVSR method has been validated by different researchers by comparing the outcomes with the strong motion records analysis [18-21].

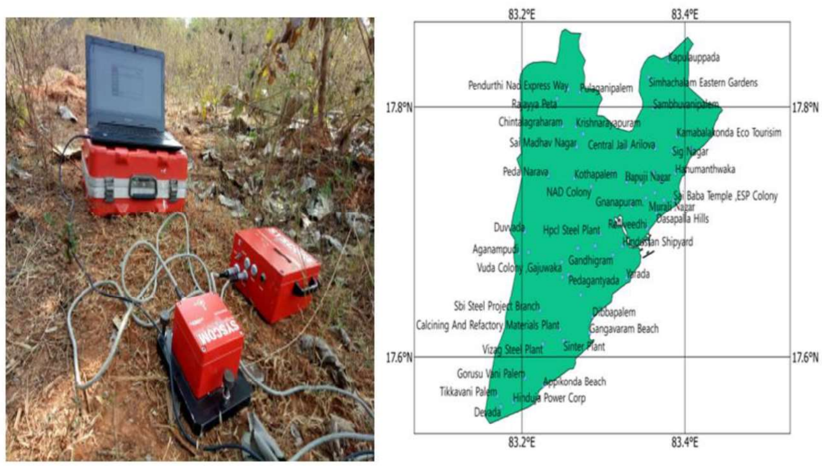


Fig. 8. Instrument set up and microtremor test locations in the study area

A maximum frequency of 10Hz has been considered as cut off frequency for analysis and a classification has been proposed based on geotechnical characteristics, type of the frequency amplitude spectrum and values of frequency and H/V amplitude [22]. Initially the sensor should be leveled upon the ground to avoid baseline errors and ambient noise should be recorded for a duration of 1 hour with 10 seconds of before and after event time. Testing has been carried out at 75 different locations (Fig. 8) scattered all over the city. One vertical and two horizontal components of movement were recorded at every test location from Bheemili to Anakapalli.

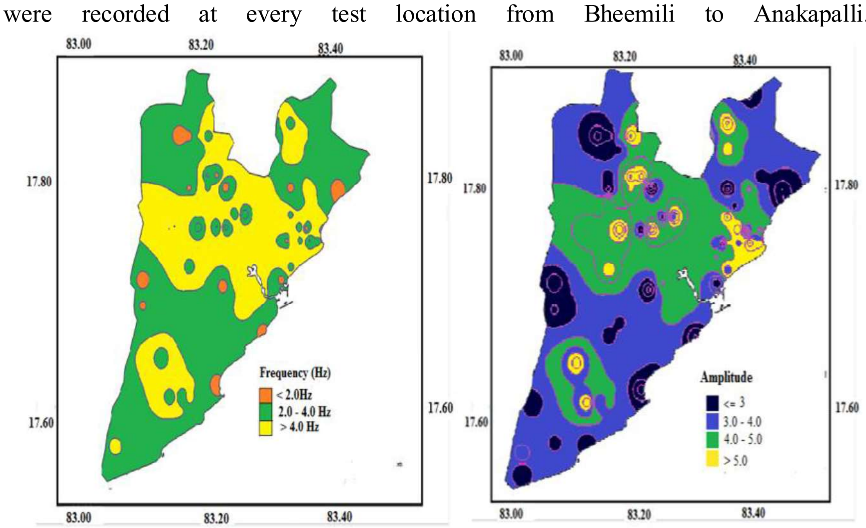


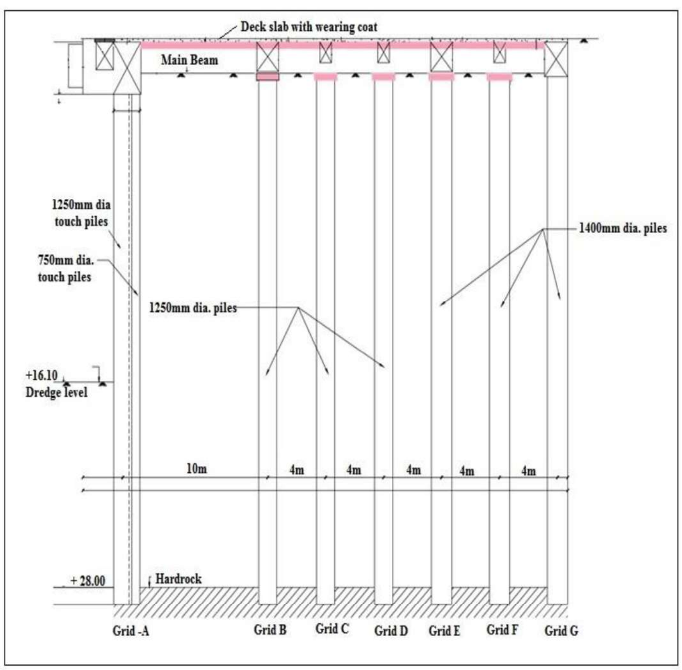
Fig.9. Predominant Frequency and amplitude maps of the study area

The study area has been classified into three different zones based on the frequency and amplitude values as shown in Figure 9.

Potential risk zones with local geology have been identified in the study area from the results through hazard maps (Fig. 9). Resonance effect of the structure and the foundation soil can be identified easily and further critical height of the structure can be decided to avoid resonance. It provides a fundamental basis for seismic hazard assessment and response analysis in densely populated urban areas where there is difficulty in utilizing conventional seismic techniques.

4 Dynamic Analysis of Pile Foundation System of Wharf Structure Using Local Site Conditions

The Port of Visakhapatnam is capable of super cape handling and is the deepest container terminal among the other major ports. It has fully automatic mechanized facilities for handling container cargoes and other import and export activities. The selected wharf in this study is 560m long with 50mm expansion joint provided at every 50.64 m, 33.45m wide, and currently houses 150000 DWT container vessels. It consists of 10 individual units with 50 mm expansion joints provided every 50.64m, constructed with precast / in-situ RCC beams and deck supported on bored cast in situ piles. The thickness of the deck is 0.2 m with a wearing coat of thickness 0.2m on the top; pile spacing is 4.0 m in the longitudinal direction and it varies according to the crane length in the transverse direction.



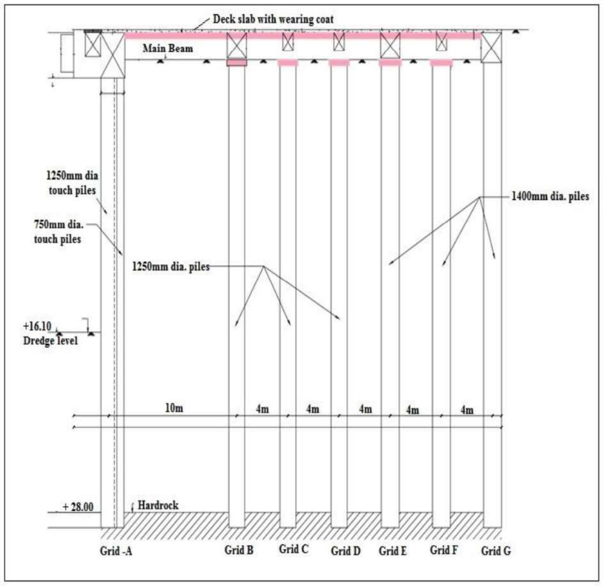


Fig.10. Cross-sectional Details of the wharf structure

A total of seven grids of piles with different cross-sectional details are present to support the wharf system. The Layout of the structure is given in figure 10. The details of the pile grids has been given in Table -1.The plan of the wharf structure considered has been shown in the Fig. 11.

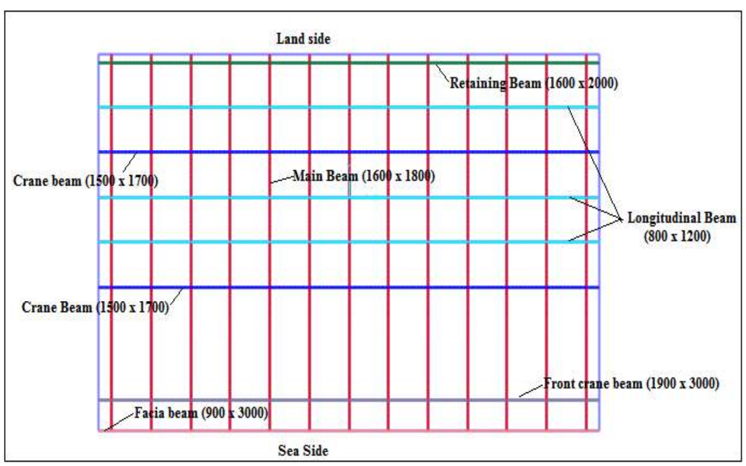


Fig. 11. Plan of the wharf structure considered for the analysis

4.1 Numerical modelling and analysis

Sap 2000 has been used for modelling of the piles and deck system. As the deck bottom is precast spanning in the direction of secondary beams of pile grids A to G, loads from deck slab will be therefore transferred to secondary beams from main beam. piles are modeled using beam elements, rigidly connected to the deck. Winkler's model has been employed to model the effect of soil supporting the pile system. Soil has been represented using spring elements. linear springs (Figure 12) have been used to account the soil structure interaction. Springs are distributed along the length of pile by newmark's distribution. The time period of the structure comes out to be 0.06273 sec from modal frequency analysis.

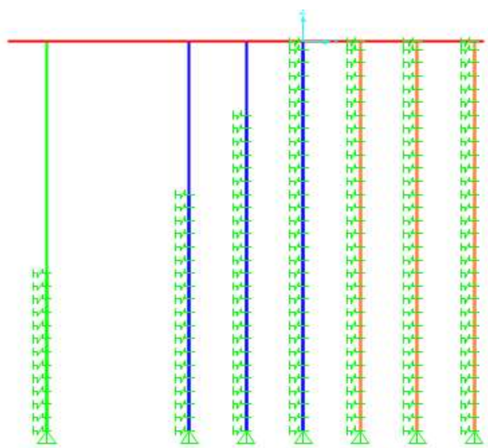


Fig. 12. Modelling of Pile-Soil system in SAP2000

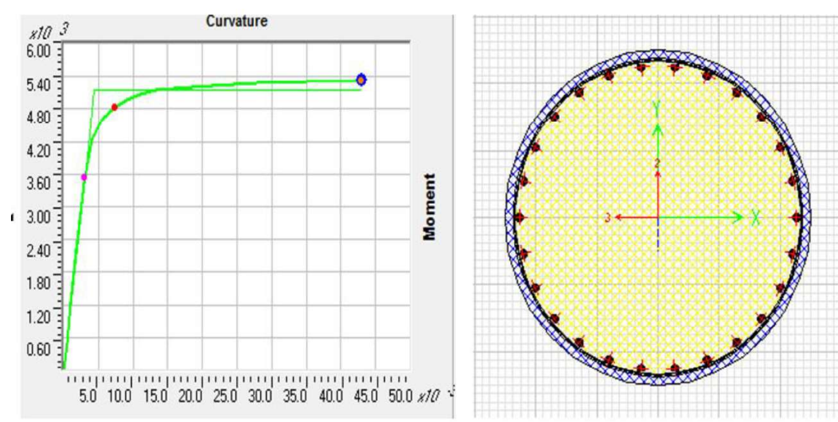


Fig. 13. Moment curvature curve for the critical pile grid -C

Figure 13 shows the cross-section and reinforcement details of the piles of grid - C and the moment–curvature curve, calculated using section designer of Sap 2000. Mander concrete model and simple bilinear steel model is used in the present study to define hinge properties and perform initial pushover analysis. User defined hinges have been assigned at both the ends of the pile and also the beams to capture the plastic rotation.

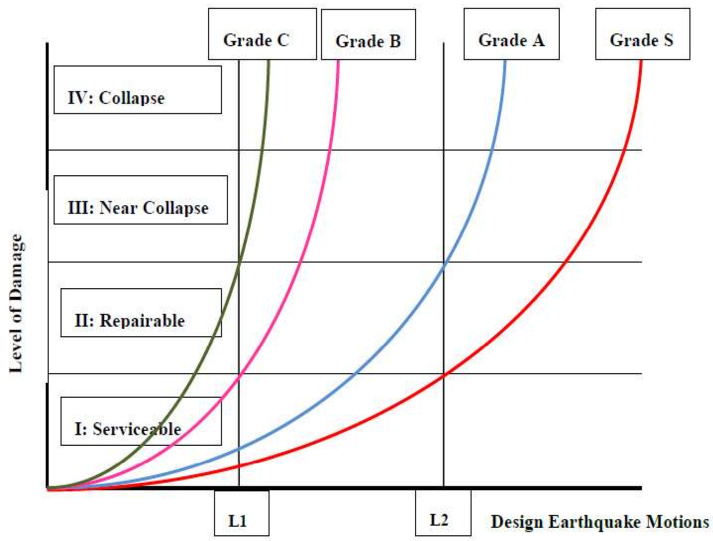


Fig. 14. Schematic figure of performance grades S, A, B and C (PIANC, 2001)

P-M2-M3 and M3 hinges have been assigned to the piles and beams respectively. Pushover analysis is performed to obtain the displacement bounds for various levels of earthquakes as per the guidelines given by PIANC [2] (figure 14).

4.2 Site specific response spectra

ATC40 [23] and PSHA report of National Disaster Management Authority [24] recommends site specific hazard analysis for D type soil, for three levels of earthquakes i.e. L1, L2, and L3. The construction of spectrum requires site specific mapped spectral accelerations for short period - S_s at 0.2s and long period - S_1 at 1s for a return period of 2475 years for 5% damping on rock level, which is 0.176g and 0.048 g respectively as shown in Table 1. Rest of the procedure is followed as per the section 11.4 of ASCE 7-05 [25]. Fig. 15 shows the site specific spectra obtained for L1, L2, and L3 earthquakes.

Table 1. Computed Horizontal component of spectral acceleration for 5 % damping on Type A rock level at selected site

Time Period (Sec)	Spectral Acceleration (g)	
	Level III - L3	Level II - L2
0	0.106	0.07
0.05	0.11	0.123
0.1	0.125	0.176
0.2	0.264	0.096
0.5	0.144	0.069
1	0.072	0.048

The peak ground acceleration values obtained at the site for DBE and MCE are 0.19g, and 0.279g respectively. The values for the site (zone II) as per the default spectra of the Indian standard IS1893 for DBE and MCE are 0.05g and 0.1g. Indian standard does not provide ground motion values for SE.

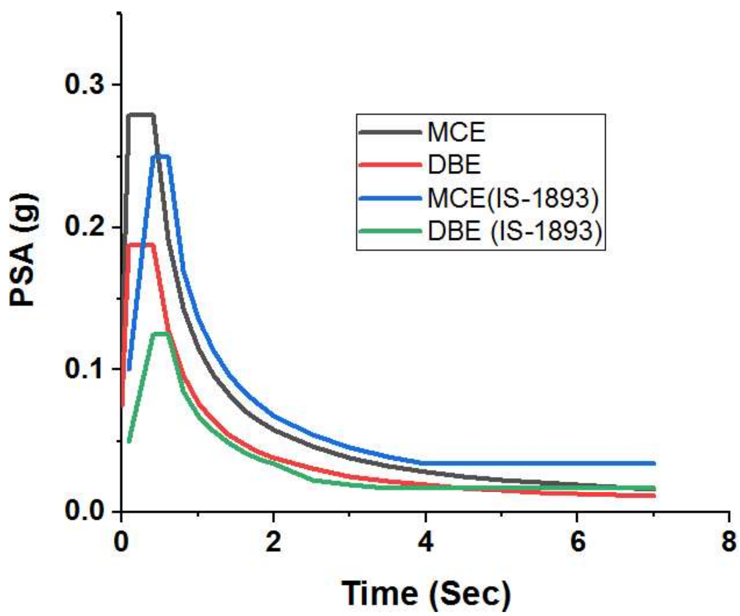


Fig.15. Comparison of spectra obtained as per site and IS-1893

The variation in spectral acceleration values as per site specific spectra with respect to IS1893 part-1[3] is nearly 52% for DBE and 12% for MCE. The Indian standard thus underestimates the ground motions for the site. It is felt that site specific spectra for special structures are essential and revision is recommended in the Indian standard.

4.3 Selection of ground motions

Owing to the absence of past earthquake records for the selected site, five earthquake events were obtained from the PEER [26] ground motion database website, having similar topographical features, soil conditions, magnitude, fault type, and distance from source of earthquake. Clause 17.3.1 and 17.3.2 of ASCE 7-05 [25] for selection of earthquake records have been taken in to consideration. Spectral acceleration v/s time plot for the selected 5 earthquake events is shown in Fig. 16. The earthquake records are normalized and then scaled to the desired intensities for fragility analysis.

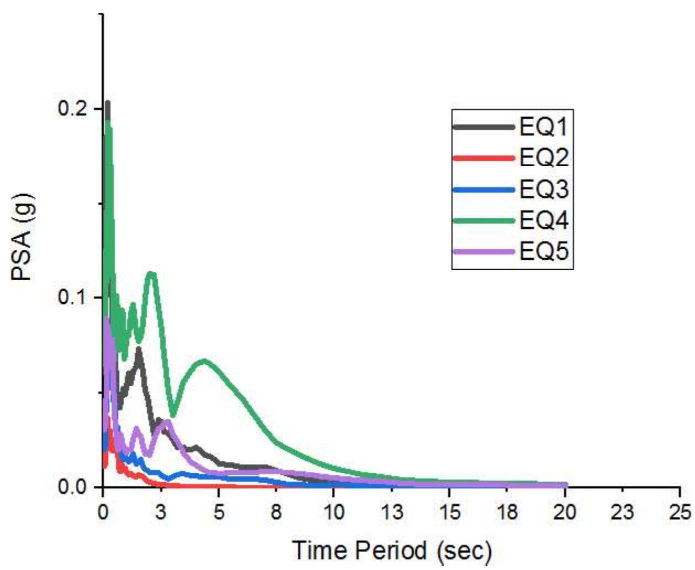


Fig.16. Spectral Acceleration V/S Time Plot For The Selected 10 Earthquake Events

For time history analysis, accelerograms of selected five earthquake records are used. The normalized accelerograms are further scaled for PGA of 0.1g to 0.5g. Therefore a total of 25 earthquake events have been used for the analysis. Through the time history analysis, maximum deck displacements have been recorded for each earthquake as shown in figure 18. A response matrix of 5 × 5 as shown in Table 4 has been obtained. The analytical fragility curves have been derived which are generally expressed as lognormal cumulative distribution functions (lognormal CDF) as a common practice.

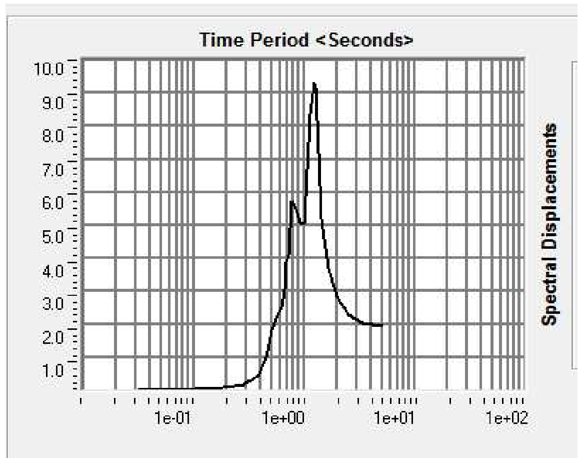


Fig. 17. Time History analysis output in SAP2000

4.4 Defining damage states

Damage bounds are stated in terms of displacements. For this, moment curvature plots for grid C piles are derived (Figure 13) using section designer module of SAP2000. As per PIANC [2], the moment curvature derived for grid C piles can be idealized to get damage bounds as shown in Fig. 19, where Øy is the curvature at pile yield moment and Øu at ultimate moment. Øs is the curvature at maximum moment in the pile. For a given axial force and moment, corresponding curvature is derived by interpolation of given moment curvature plots. The axial forces and corresponding moments along with curvatures for different limit states are shown in Table 2. Calculation of displacement bounds require plastic hinge length of pile i.e. Lp and plastic rotation capacity of plastic hinge i.e. Ɵp, as given in PIANC [2]. PIANC [2] also recommends decreasing the stirrup spacing (pitch) of piles to enhance the capacity of the wharf. Based on these, damage bounds are derived for stirrup spacing 250mm, 175mm and 75mm respectively as shown in Table 3.

Table 2. Axial force in grid C pile and corresponding moments and curvature

Damage state	Axial force (kN)	Moment (kN-m)	Curvature (1/m)
Yield	2310	3897	1.89 x 10-5
Serviceable	2586	4157	2.39 x 10-4
Ultimate	3459	4876	5.42 x 10-3

Table 3. Displacement bounds (mm) for different pitch

Pitch (mm)	Damage state-I	Damage state -II	Damage state -III
250	102.29	444.54	786.79
125	103.21	531.90	971
75	105.42	632.87	1024

Table 4. Response matrix of the structure for different scaled ground motions

Earthquake Event/PGA	0.1g	0.2g	0.3g	0.4g	0.5g
EQ1	0.032	0.053	0.088	0.091	0.15
EQ2	0.045	0.062	0.07	0.087	0.98
EQ3	0.072	0.081	0.083	0.099	0.109
EQ4	0.035	0.047	0.051	0.075	0.139
EQ5	0.069	0.076	0.092	0.105	0.22

5 Conclusions

In the present study, dynamic site characterization and time history analysis of pile supported wharf structure has been carried out in the study area. From the results of PSHA, the hazard parameters a= 2.409 and 0.69 found a good match with the hazard parameters of south India from other researchers. Hazard curves and response spectra will be further helpful in synthetic ground motion generation as well as seismic design of huge infrastructure projects. From the ground response analysis it is evident that the city is prone to higher acceleration than the peak acceleration specified by IS code [3]. Peak ground acceleration values at surface level ranges from 0.08-0.14g whereas the at bedrock level varies with in a range of 0.08-0.11g. Amplification factors range from 1.0 -1.6. Locations present in extreme Southern part of the city have shown higher response due to the presence of tidal flats with marine clays. North-East and Northern part of the city have shown lesser PGA due to presence of rock outcrops.

From the analysis of microtremor recordings, the peak frequency and amplitude have been estimated. The frequency values are ranging from 0.31-10.1Hz. Frequency values of 4.0Hz. To 10.0 Hz are observed in most of the locations in Central and northern parts of the area under study delineating gravel and rock with pebbles. These locations were classified as T-I (Type-I). Few sites in west and southern parts of the city are identified with predominant frequency ranging between 2.0-4.0Hz and classified as T-II (Type-II) sites. Clayey and silty sands are predominantly found in these locations. Lower frequencies of < 2.0Hz. are observed at locations in eastern and central parts of Vishakhapatnam due to the presence of soft marine clayey deposits with higher amplification phenomenon classified as T-III (Type-III).

The fundamental time period of the wharf structure according to IS: 1893 -2016 estimated using the empirical expression, Ta = 0.075 h0.75 comes out to be Ta = 0.913 sec whereas from the dynamic mode shape analysis, time period comes out to be 0.063 sec. Hence variation of time period greatly over estimates the seismic forces. It is revealed that the variation in PGA for DBE, at the selected site, as per ASCE7-05 (0.19g) [25] and IS: 1893-2016 (0.05g) [3], is nearly 52 % , which demands the need for revision in the available standards. A site specific spectrum is vital for seismic design of port structures and other special and important structures to obtain actual ground motions instead of referring default Indian spectra which are underestimating. Soil structure interaction provides better awareness of the behavior and performance of pile supported wharf. Dynamic modal time period of pile supported wharf should be considered instead of referring formula from Indian standard. The results from the present study help in evaluating the socio economic impact of the damage to wharves and other prominent structures during a natural hazard event.

References

1. Wikipedia (accessed 2019) 2011 Tōhoku earthquake and tsunami, https://en.wikipedia.org/wiki/2011_Tōhoku_earthquake_and_tsunami.
2. PIANC (2001) Seismic Design Guidelines for Port Structures, International Navigation Association, A.A. Balkema Publishers, Rotterdam, Netherlands.
3. IS 1893-2016. Criteria for earthquake resistant design of structures: Part 1 -General provisions and buildings, Bureau of Indian Standards, BIS, New Delhi.2016.
4. Putti, S.P., Devarakonda, N.S. & Towhata, I. Nat Hazards (2019). https://doi.org/10.1007/s11069-019-03658-5
5. Putti, S.P. & Satyam, N. Innov. Infrastruct. Solut. (2018) 3:12. https://doi.org/10.1007/s41062-017-0113-4
6. Lee, V.W. and Trifunac, M.D., 1985. Torsional accelerograms. International Journal of Soil Dynamics and Earthquake Engineering, 4(3), pp.132-139.
7. Kayal, J.R., 2008. Microearthquake seismology and seismotectonics of South Asia. Springer Science & Business Media.
8. Kijko A, Sellevoll M. A (1992). Estimation of earthquake hazard parameters from incomplete data files Part II. Incorporation of magnitude heterogeneity. Bull. Seism. Soc. America, Vol. 82 (1), 120-134.
9. Kaila K.L., Gaur, V.K. andNarainHari. Quantitative seismicity maps of India. Bull Seismol. Soc. Am.1972, 62:1119–1131.
10. Jaiswal K. and R. Sinha. Probabilistic seismic-hazard estimation for peninsular India. Bulletin of the Seismological Society of America.2007, 97, 318–330.
11. Ram, A and Rathore, H. S., 1970. On frequency magnitude & energy significant Indian earthquakes, Pure and Applied Geophysics. 79, 26-32.
12. T. G. Sitharam,P. Anbazhagan. Seismic Hazard Analysis for the Bangalore Region, Natural hazards.2007, 261–278.
13. Kanth, S.R. and Iyengar, R.N., 2006. Seismic hazard estimation for Mumbai city. Current Science, pp.1486-1494.
14. Schnabel P.B., Lysmer J. & Seed H.B., 1972. SHAKE: A computer program for earthquake response analysis of horizontal layered sites. Earthquake Engineering Research Centre, University of California, Berkeley, CA, USA, Report No EERC 72-12.
15. Youssef M.A.H., 2009. DEEPSOIL, http://www.geoengineer.org/software/applications-deepsoil.html.
16. Nakamura, Y. (1989). A method for dynamic characteristics estimation of subsurface using microtremor on the ground surface. Tokyo: Railway Technical Research Institute/Tetsudo Gijutsu Kenkyujo.
17. Diagourtas, D., Tzanis, A., & Makropoulos, K. (2002). Comparative Study of Microtremor Analysis Methods. Proc. of Earthquake Microzoning, 2463-2479.
18. Ch´avez-Garc´ıa F. J., & Cuenca, J. (1996). Site effects in Mexico city urban zone, A complementary study; J. Soil Dyn. Earthq. Eng., 15, 141–146.

19. Ch´avez-Garc´ıa F. J., & Tejeda-J´ acome, J. (2010) Site response in Tecoman, Colima, Mexico – II Determination of subsoil structure and comparison with observations; J. Soil Dyn. Earthq. Eng. 30(8), 717–723.
20. Surve, G., & Mohan, G. (2010). Site response studies in Mumbai using (H/V) Nakamura technique. Natural Hazards, 54(3), 783–795.
21. Putti, S.P., Satyam, N. Evaluation of Site Effects Using HVSR Microtremor Measurements in Vishakhapatnam (India). Earth Syst Environ 4, 439–454 (2020). https://doi.org/10.1007/s41748-020-00158-6
22. Rao, K. S., and D. Neelima Satyam. "Liquefaction studies for seismic microzonation of Delhi region." Current science(2007): 646-654.
23. ATC-40 (1996) Seismic Evaluation and Retrofit of Concrete Buildings - volume 1, Redwood City, California.
24. National Disaster Management Authority (NDMA) (2011) Development of Probabilistic Seismic Hazard Map of India, Appendix II – Application of the PSHA Results, Govt. Of India, New Delhi.
25. American Society for Civil Engineers (ASCE) (2006) ASCE 7-05 Minimum Design Loads for Buildings and Other Structures, Reston, Virginia.
26. Pacific Earthquake Engineering Research Center (PEER) (2010) PEER Ground Motion Database, California [online] http://ngawest2.berkeley.edu/spectras (accessed April 2013)..