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DEVELOPMENT OF SEISMIC HAZARD MAPS FOR CHENNAI CITY, INDIA

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ABSTRACT

Chennai, the fourth largest metropolitan city of India, located on the Coromandel Coast of Bay of Bengal is upgraded from Zone II to Zone III along with other places indicating its vulnerability to ground shaking. However, the modification of seismic zonation was done without carrying out detailed seismological and geotechnical investigations in this region. Strong tremors have been felt in the city during Pondicherry earthquake of Magnitude, M_w 5.5 on 25th September 2001 centered 100 km from Chennai and Sumatra Earthquake of Magnitude, M_w 9.1 on 26th December 2004. A number of multi-storied buildings at various regions of the city have undergone large oscillations due to the amplification of the ground. Therefore, the present study focuses mainly as a comprehensive preliminary study to provide important inputs needed in seismic hazard zonation. The development of seismic hazard maps for the selected regions of the Chennai city is underway.

A large number of borehole data collected from reliable sources were integrated into a spatial database in GIS environment. Scanned toposheets of 1:50,000 scale were used for the creation of base map. Toposheets were digitized onscreen with several layers and this serves as a base map for further studies. It is intended to create a subsurface profile using the base map by incorporating the geotechnical data, variation of soil properties with depth and seismotectonics data. Idealized soil profile for the area was obtained based on the generalization of individual borelog details. Design ground motion has been established by carrying out deterministic seismic hazard analysis. One dimensional ground response analysis was carried out by equivalent linear approach using SHAKE91. All the available data can be transformed to GIS format and the results can be evaluated to obtain the hazard level associated with each region. Results of amplification studies along with response spectral ordinates are used in the realistic seismic hazard zonation of the selected regions of the Chennai city in the form of PGA values. This paper is the pilot study to give an overview of the proposed methodology.

Keywords: Seismic hazard, GIS, Amplification, Shear wave velocity, Ground response, SHAKE91.

INTRODUCTION

India has witnessed destroying earthquakes in recent times. It is primarily the Bhuj earthquake in 2001 led to the modification of the seismic zonation of India. The total devastation caused by the 2001 Bhuj earthquake (M_w 7.6) brought sharply into focus the seismic hazard faced by India. The Bhuj earthquake, like the earthquakes of Koyna (1967; M_w 7.6), Latur (1993; M_w 6.1) and Jabalpur (1997; M_w 5.8) occurred in the “stable” Indian shield. Under such a seismotectonic scenario, evaluation of site dependent earthquake design parameters, particularly the peak ground acceleration becomes

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necessary. Also in such poorly studied and/or low-seismicity areas, strong motion data set is not available. Seismic zonal classification has categorized the Chennai region in Zone III with a Peak Ground Acceleration (PGA) of 0.16g. Chennai is situated on the flat eastern coastal plains (Coromandel Coast) i.e., the northeast corner of Tamil Nadu and located between 12.75° – 13.25° N and 80.0° – 80.5° E. Chennai is the India's fourth largest metropolitan city covering an area of 1,177 km². The estimated metropolitan population in 2006 is 7.0 million. For administrative purposes, Chennai is divided into five taluks. 1. Egmore-Nungambakam 2. Fort-Tondiarpet 3. Mambalam-Guindy 4. Mylapore-Triplicane 5. Perambur-Purasawalkkam. The Chennai metropolitan area covers three districts namely Chennai city and parts of the districts of Kanchipuram and Thiruvallur.

The main cause for site amplification in parts of Chennai city is the local geologic and soil conditions that amplify the bedrock motion. Amplification of seismic waves is usually taking place in the case of soft soil deposits, as waves travel from bedrock to the ground surface by transferring more seismic energy in the form of higher accelerations to the structures. The amplification of ground motion causes damage to structures, particularly when the resulting seismic wave frequency matches with one of the resonant frequencies of the structures more specifically the fundamental frequency. Development of seismic hazard maps requires accurate estimation of site amplification during the expected earthquake. Moreover, the Chennai city is highly populated with structures of all kinds, which need special attention in view of the revised zonation for their strengthening and seismic retrofit. The zonal values of PGA cannot assure with certainty what ground acceleration will be experienced by the structures located in the respective zones. It is the level of ground acceleration, coupled with site-specific effects, which actually buffet buildings due to the impact of an earthquake. In this paper, an attempt has been made to study the seismic response of selected areas of Chennai city in order to establish PGA values.

INDIAN PENINSULAR SHIELD

Lack of data has led to the erroneous belief that continent shields are seismically stable. Shield regions in general do not show evidence of major deformations since the Precambrian or Paleozoic era. However, evidences of uplift and subsidence along major fractures during later ages were noted.

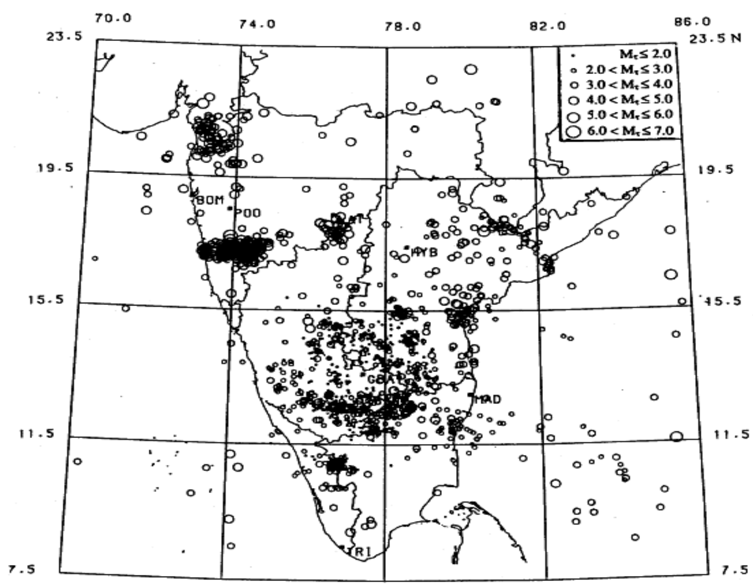

Figure 1. Seismicity of Peninsular India (Gangrade and Arora, 2000)

These movements represent the manifestations of the tectonic processes operative in the crust and upper mantle, which control the evolution of geotectonic and physiographic features in the dismemberment and progressive development of the continental land mass, and produce shallow earthquakes with strong ground motion responsible for damage on the surface.

There are reports of only three earthquakes of some consequences with a maximum intensity of VII on the Modified Mercalli Intensity scale in Peninsular India (10-26 N, 68-90 E) in the historical past (Chandra, 1977). These occurred at Mahabaleshwar (1764), Bellary (1843) and Coimbatore (1900). Apart from these three events, there have been a few earthquakes of intensities IV and V on the MMI scale. It is only in recent decades that the occurrence of some earthquakes with magnitude (m_b) of 5 and a couple of earthquakes with m_b 6 has caused concern which led to the study of peninsular seismicity in greater detail. Earthquake catalog data for Peninsular India after Jaiswal and Sinha (2005) show about 9 earthquakes of Moment magnitude greater than 6.0. Typical seismicity of Peninsular India based mainly on Gauribidanur seismic array (GBA) detections of regional earthquakes spanning two decades (1978–1997) is shown in Figure 1.

METHODOLOGY

Seismic hazard analysis is the quantitative estimation of ground-shaking hazards at a particular site based on the identification of all possible sources of seismic activity, estimation of their associated seismicity and prediction of the probable consequent ground motions. Two basic methodologies used for the purpose are the deterministic (DSHA) and the probabilistic seismic hazard analysis (PSHA) approaches. In the deterministic approach, the strong-motion parameters are estimated for the maximum credible earthquake, assumed to occur at the closest possible distance from the site of interest, without considering the likelihood of its occurrence during a specified exposure period. On the other hand, the probabilistic approach integrates the effects of all the earthquakes expected to occur at different locations during a specified life period, with the associated uncertainties and randomness taken into account. The present paper discusses about the deterministic approach of seismic hazard analyses. The outcome of deterministic seismic hazard analysis was used to carry out the seismic site response analysis using the wave propagation program SHAKE 91. The toposheets of the study area were digitized in a GIS environment to serve as a base map. The Geotechnical borehole data when mapped along with the outcomes of the ground response analysis in the base map, the final seismic hazard map is obtained. The flow chart showing the various steps involved in the development of hazard map is given in Figure 2.

GEOLOGY OF CHENNAI CITY

The geology of Chennai comprises of mostly clay, shale and sandstone. The city is classified into three regions based on geology: sandy areas, clayey areas and hard-rock areas. Sandy areas are found along the river banks and coasts. Igneous/metamorphic rocks are found towards south; marine sediments containing clay-silt sands, Charnockite rocks are found in the eastern, northern and western parts, and are composed of alluvium, sedimentary rocks. Clayey regions cover most of the city. The thickness of soil formation ranges from a few meters in the southern part to as much as 50 m in the northern and central parts.

The area within 300 km radius of the site has different geological and tectonic settings. The site area is situated over the Archaean Khondolite –Charnockite-Granite gneissic, which is covered by beach sand. In the west, the area comprises Karnataka craton of Archaean-Proterozoic peninsular granitic gneiss. The Palar basin constitutes Permo-carboniferous Gondwana sediments bounded by faults. In the north is the Late Precambrian Cuddapah basin. While in the south lies the Cauvery basin comprising late Jurassic-Cretaceous-Paleocene and Mio-Pliocene sediments. The area being the coastal one, large tracts are affected by lateritization and also deltic environment is seen. The geological formations at beach sands are Quaternary and recent periods. A major part of the area is built up with a flat topography having on elevation of 20m-30m in the west to sea level in the east. Four cycles of erosion have been identified and the landforms constitute assemblage of fluvial estuarine and marine deposits. Soil distribution in Chennai is tabulated in Table 1.

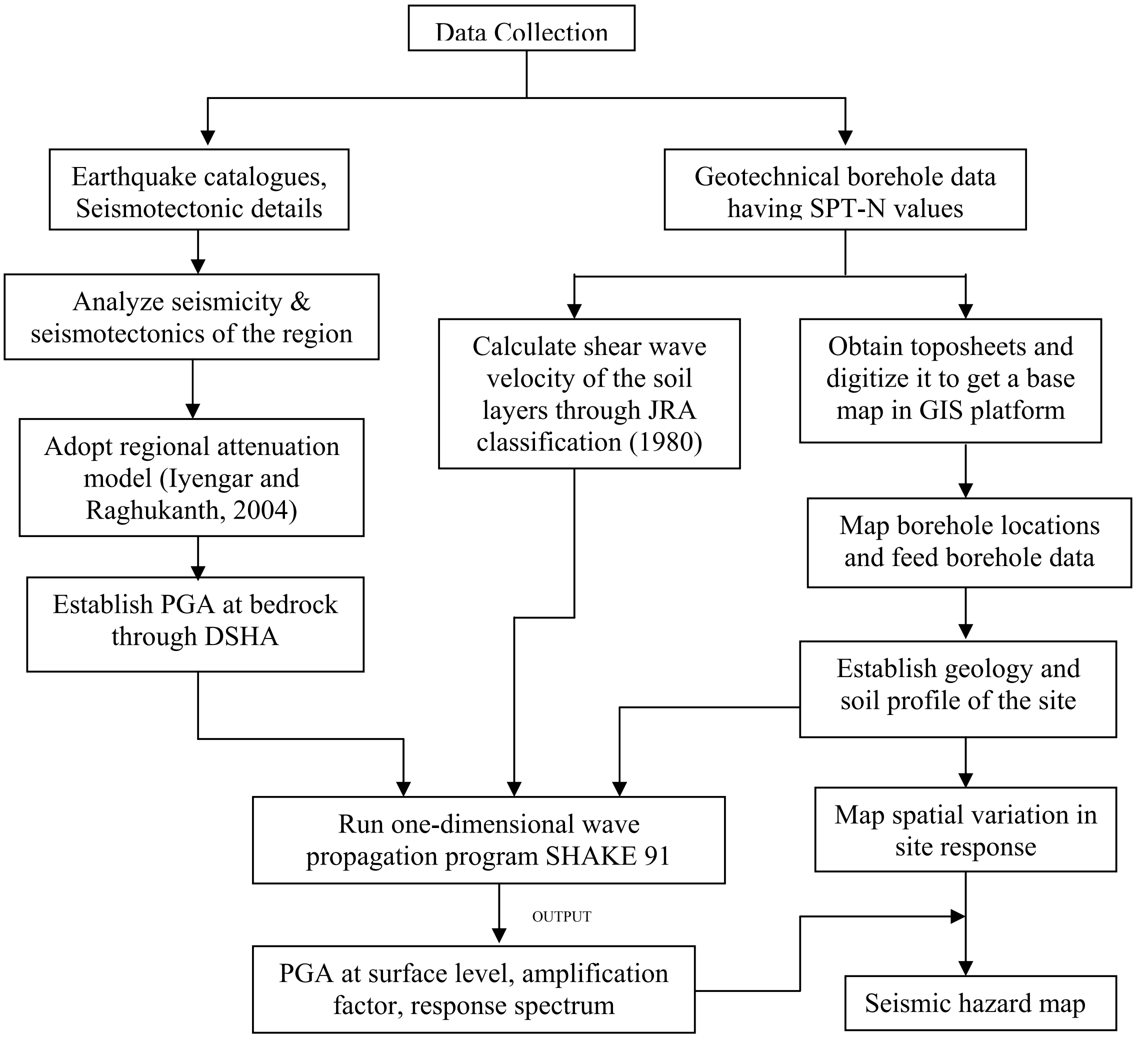

Figure 2. Flow Chat for the Development of Seismic Hazard Map

Table 1. Soil Distribution in Chennai

Soil classification	Distribution (%)
Alluvial/ sandy soil	2
Red sandy and red loamy soil	54.7
Red sandy to brown clayey soil	34
Brown clayey soil	9.3

SEISMICITY AND SEISMOTECTONICS OF THE REGION

The Indian seismicity is characterized by a relatively high frequency of great earthquakes and a relatively low frequency of moderate earthquakes. Seismological data that comprises about hundred years of information related to the seismicity of the region, frontal fault system including important structural and seismotectonic features of the region were collected from the latest Seismotectonic Atlas of India. The Seismotectonic map combines the fault map with geological features of the area under consideration. It shows the main tectonic features in relation to the seismicity.

Regions with pronounced variation in thickness show higher seismicity as compared to the parts with more or less uniform thickness. Historical earthquake information obtained from NEIC, USA show around 65 earthquakes that have occurred within 300 km from Chennai since 1800 A.D. onwards as given in Table 2. Recorded earthquakes of magnitude 6 were found accompanied by rumbling noise and had shallow focal depths. The seismological details gathered for establishing ground motion parameters for the Prototype Fast Breeder Reactor (PFBR) building site at Kalpakkam located 60 km from Chennai city were used in this study (Ghosh, 1994). Earthquake data taken from the global sources are presented in Table 3.

Table 2. List of Earthquakes within 300 km from Chennai (NEIC, USA)

Sr. No	Year	No. of earthquakes	Magnitude
1	1800-1850	9 (1)	3.7 – 4.3 (5)
2	1851-1900	21	3 – 4.3 (5.7)
3	1901-1950	1	5
4	1951-2000	32	3 – 5.8

Table 3. Summary of Earthquake Events
(Events with M > 2 considered)

Sr. No.	Magnitude range	Global data	GBA Data
		No. of events	No. of events
1	2.0 – 2.5	1	109
2	2.5 – 3.0	3	110
3	3.0 – 3.5	5	103
4	3.5 – 4.0	14	54
5	4.0 – 4.5	19	35
6	4.5 – 5.0	2	4
7	5.0 – 5.5	6	2
8	5.5 – 6.0	2	0
9	6.0 – 6.5	1	0

Figure 3 encircles the faults and lineaments observed within 100 km radius from Chennai, which includes Kalpakkam region also. The known faults and shear zones of the peninsular shield closely follow the pattern of major rivers. Following are the faults clearly observed: Muttukadu fault; Kaliveli fault; Palar river fault; Cheyyar river – Tambaram fault; Damal – Kilcheri lineament; Ponnaiyar – Cuddalore lineament and Kollidam fault. And out of these, the Palar fault located at a distance of 68km from the Chennai city was identified as a future seismic source for the city.

Recently, 2001 Bhuj earthquake measuring Mw 7.6 and Pondicherry earthquake measuring Mw 5.6 and 2004 Sumatra earthquake measuring Mw 9.1 shook many parts of Chennai. This led to the differential amplification of the seismic waves around Chennai. The seismological studies carried out for the design of new reactor building at Kalpakkam has been adopted in our study. In view of the above, the bedrock motion parameters for the present study were estimated considering the Palar fault as the causative fault with a moment magnitude of 6.5.

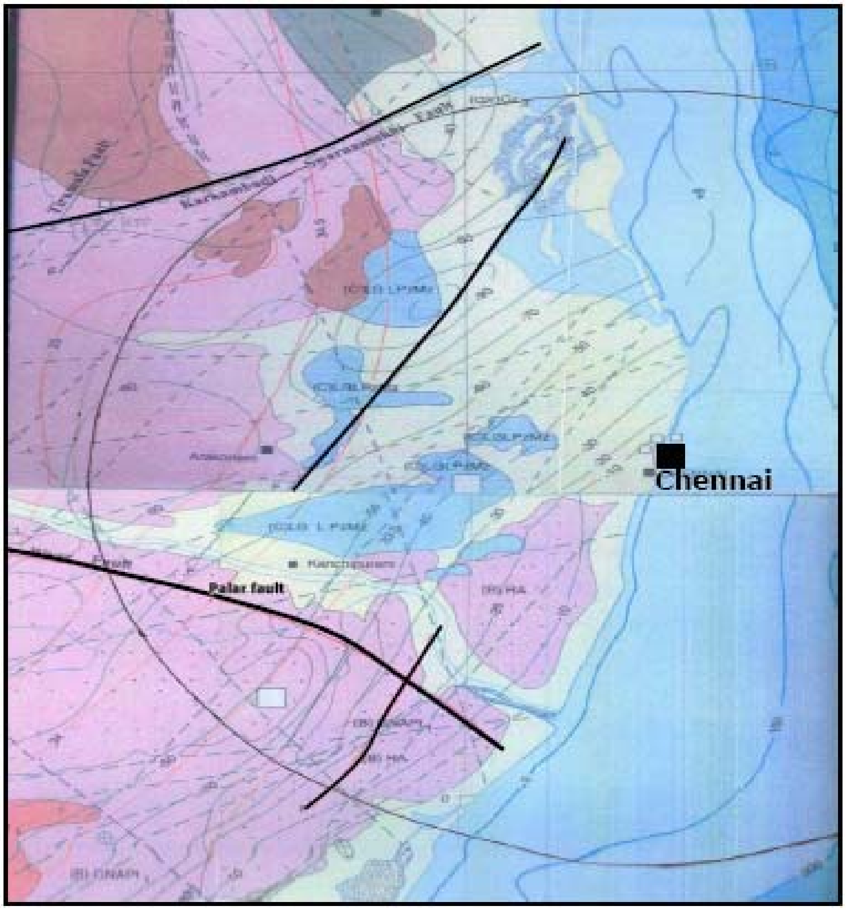

Figure 3. Seismotectonic Map of Chennai City

BASE MAP PREPARATION

Toposheets of scale 1:50,000 obtained from Survey of India were used for the creation of base map. The scanned toposheets were digitized onscreen with several layers including administrative boundaries, highways, railroads, water bodies, and land marks as shown in Figure 4. A large number of borehole data collected from reputed agencies were used to create subsurface profile in GIS environment for selected regions of the Chennai city. Over the last four decades Geographical Information Systems (GIS) have emerged as the predominant medium for graphic representation of geospatial data, including geotechnical, geologic and hydrologic information. GIS due to its advanced virtues of creating multibase and integrated spatial databases, is used to create this extensive borehole database. The database thus created will be used for seismic hazard mapping. The GIS software, ARC/INFO was used for creation of base map of the city (Figure 4). Typical borehole locations for the one of the regions of the Chennai city are also shown in figure. It is intended to compile all the available data relevant to local geology, subsurface layering and geotechnical characteristics and implement as coverages in the GIS thus generating a complete subsurface profile.

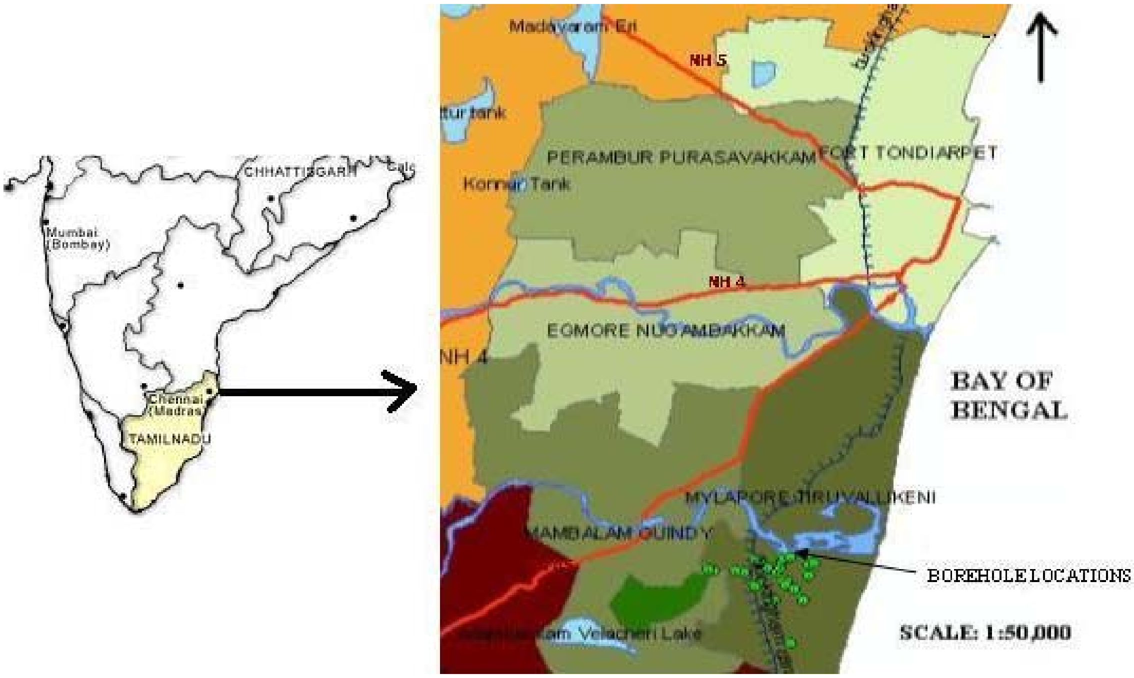

Figure 4. Base Map of Chennai City

DETERMINISTIC SEISIMC HAZARD ANALYSIS

One of the key parameters engineers look for is the PGA at the chosen site for the design basis event. But very limited recorded data is available about ground motion in the peninsular India for engineers to rely upon. Under such circumstances, Iyengar and Raghukanth (2004) have adopted the seismological model for synthetic generation of PGA values following Boore (1983). A two-step stratified regression analysis originally proposed by Joyner and Boore (1981) was carried out on the generated synthetic data to obtain the parameters of the attenuation equation. The proposed attenuation relationship for Peninsular India by Iyengar and Raghukanth (2004) is given below.

$$\ln\left(PGA/g\right)=C_1+C_2\left(M-6\right)+C_3\left(M-6\right)^2-\ln\left(R\right)-C_4\,R+\ln\varepsilon \quad (1)$$

where C_1 = 1.6858; C_2 = 0.9241; C_3 = –0.0760; C_4 = 0.0057 and σ (*ln* ε) = 0.4648.

For the design moment magnitude of 6.5, peak horizontal acceleration for bedrock was calculated using this attenuation relationship. The estimated peak ground acceleration (PGA) obtained was 0.134g. This is the possible seismic hazard of the region in terms of Peak Ground Acceleration (PGA) by the deterministic seismic hazard analysis.

SEISMIC SITE RESPONSE ANALYSIS

The local soil conditions impose significant effects on the acceleration amplitude and frequency characteristics of ground motion during an earthquake. It has also been identified that the geometry of soil profile, geotechnical and dynamic properties of soil and characteristics of the base rock motion are the three essential components of the seismic site response analysis.

One dimensional ground response analysis was carried out by the equivalent linear approach using the wave propagation program SHAKE 91. The analysis is performed to determine the extent to which shallow sediments contribute to anomalous response. Iterative procedure of the program is used to account for the non-linear behavior of soils. The main program input parameters are: (1) acceleration time history, (2) soil parameters, and (3) variation of soil shear modulus and damping with strain level. The bedrock motion, which is a candidate ground motion typical of regional seismicity of the Chennai city, is evaluated by seismological models and is expressed in terms of peak ground accelerations including the bracketed duration. The time history of the bedrock motion of the Loma Prieta earthquake was modified with respect to the estimated ground motion parameters of the study area and the same was used as an input motion (Figure 5). The SPT N-values obtained in the field were corrected for various factors: overburden pressure, hammer energy, bore hole diameter, rod length and fines content.

Shear wave velocity, Vs was estimated from the corrected SPT-N values using the following equations (JRA, 1980):

$$V_s\left(\text{m/sec}\right) = 100\,N^{1/3} \quad \left(\text{For Clay}\right) \tag{2}$$

$$V_s\left(\text{m/sec}\right) = 80\,N^{1/3} \quad \left(\text{For Sand}\right) \tag{3}$$

Modulus reduction curves depend on plasticity for cohesive soils and on density for cohesionless soils. The standard modulus reduction and damping curves proposed by Sun et al. (1988) for clay and Seed and Idriss (1970, 1990) for sand were used in the site-specific ground response analysis.

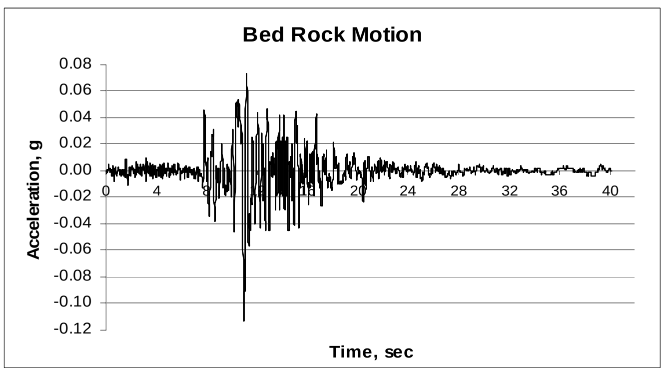

Figure 5. Input Time History

Table 4 presents the soil profiles for Region 1 (Guindy), Region 2 (Santhome), Region 3 (Tiruvottiyur) and Region 4 (Velachery) respectively. It can be observed that Guindy and Velachery have bedrock at shallow depth compared to the other two regions. Tiruvottiyur and Santhome are situated along the coast and comprise of predominantly sandy layers. Thus among Guindy, Velachery, Santhome and Tiruvottiyur regions, the first two regions may be grouped under hard rock sites and the latter two under soil sites.

Figure 6 gives the acceleration time history at the surface level for the above regions. Regions 3 and 4 show higher surface acceleration when compared to the hard rock areas. Site amplification can be expressed in terms of amplification rating, i.e., amplification factor, with respect to bedrock motion. It is the ratio of Fourier amplitude at the surface level to the Fourier amplitude at the bedrock level. This ratio can be used to assess the amplification hazard at the selected regions. Figure 7 shows the plots of amplitude ratios against frequency for the selected regions. It can be observed from the figure that both the hard rock regions show similar behavior. The amplification of which is found to occur at higher frequencies (greater than 7.5 Hz) and consist of two peaks. Alternatively, amplification at the soil sites occurs at a frequency of less than 3 Hz. The peaks narrow down and die out subsequently unlike hard rock regions which exhibit wide spread peaks. Figure 7 reveals that the amplification of ground motion occurs mainly due to the presence of surficial soil deposits. The figure also indicates the occurrence of de-amplification in the higher frequencies. Hence, a certain type of flexible structures can be subjected to additional lateral forces due to earthquake excitation.

Table 4(a). Soil Profile Description for Region 1

Region 1 – GUINDY			
Depth, m	Soil type	SPT-N Value	V_s, m/s
0-1.5	Fill	10	215
1.5-2.3	Sandy clay	13	235
2.3-3.0	Medium sand	19	213
3-6.90	Stiff clay	26	296
6.9-8.4	Clayey sand	42	278
8.4-9.5	Weathered disintegrated rock	>100	900
9.5	Weathered rock	>100	1000

Table 4(b). Soil Profile Description for Region 2

Region 2 – SANTHOME			
Depth, m	Soil type	SPT-N Value	V_s, m/s
0-1.4	Dirty sand	4	159
1.4-3.0	Clayey Sand	1	80
3.0-11.0	Sand	18	210
11.0-17.0	Silty Sand	29	246
17.0-18.8	Clayey cemented	65	402
18.8-21.8	Sandy clay	75	422
21.8-23.8	Silty Sand	90	359
23.8-24.7	Dirty sand	>100	900
24.7	Weathered disintegrated rock	>100	1000

Table 4(c). Soil Profile Description for Region 3

Region 3 – TIRUVOTTIYUR			
Depth, m	Soil type	SPT-N Value	V_s, m/s
0.0-4.0	Soft clay	1	100
4.0-5.0	Soft to medium stiff clay	6	182
5.0-5.8	Silty clay	15	247
5.8-8.0	Medium sand	16	202
8.0-9.5	Silty clay	9	208
9.5-10.2	Medium sand	24	231
10.2-13.0	Fine sand	35	262
13.0-15.0	Silty very fine sand/ sandy silty with clay	48	363
15.0-19.0	Clayey sand / sandy clay	24	288
19.0-20.0	Stiff clay	50	336
20.0-22.0	Weathered disintegrated rock	>100	900
22.0	Weathered rock	>100	1000

Table 4(d). Soil Profile Description for Region 4

Region 4 – VELACHERY			
Depth, m	Soil type	SPT-N Value	V_s, m/s
0-2.0	Sandy clay	16	252
2.0-3.3	Medium to dense sand	12	183
3.3-4.4	Fine to medium sand	9	166
4.4-5.3	Clayey sandy silt	51	297
5.3-9.5	Clayey silty sand	90	359
9.5	Weathered disintegrated rock	>100	900

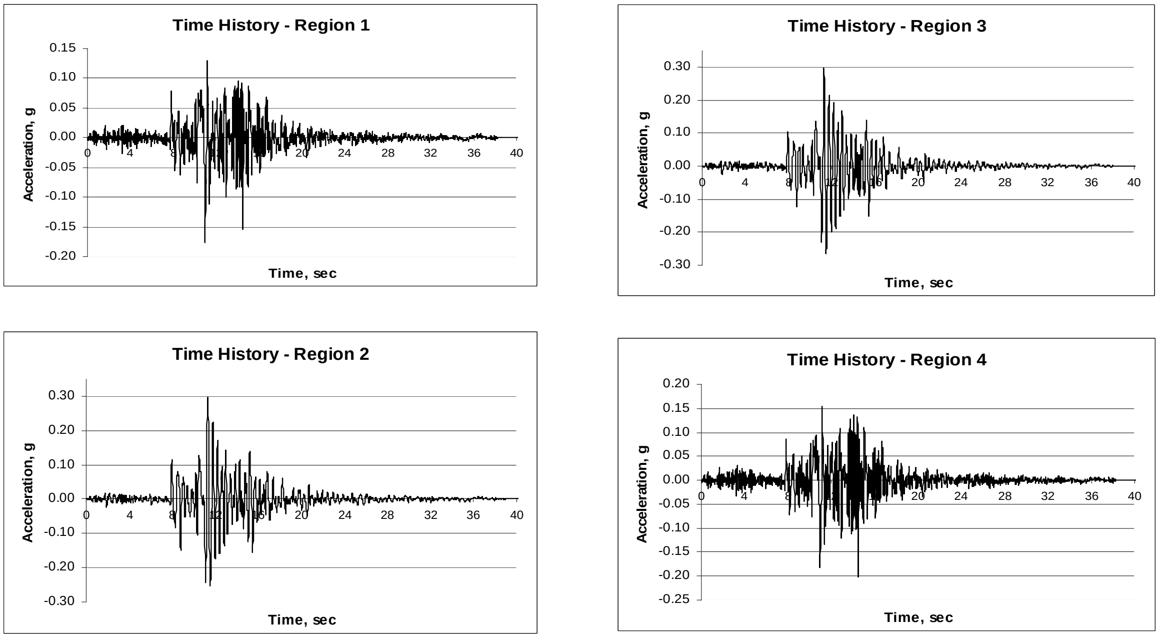

Figure 6. Acceleration Time History at Ground Surface for all Regions

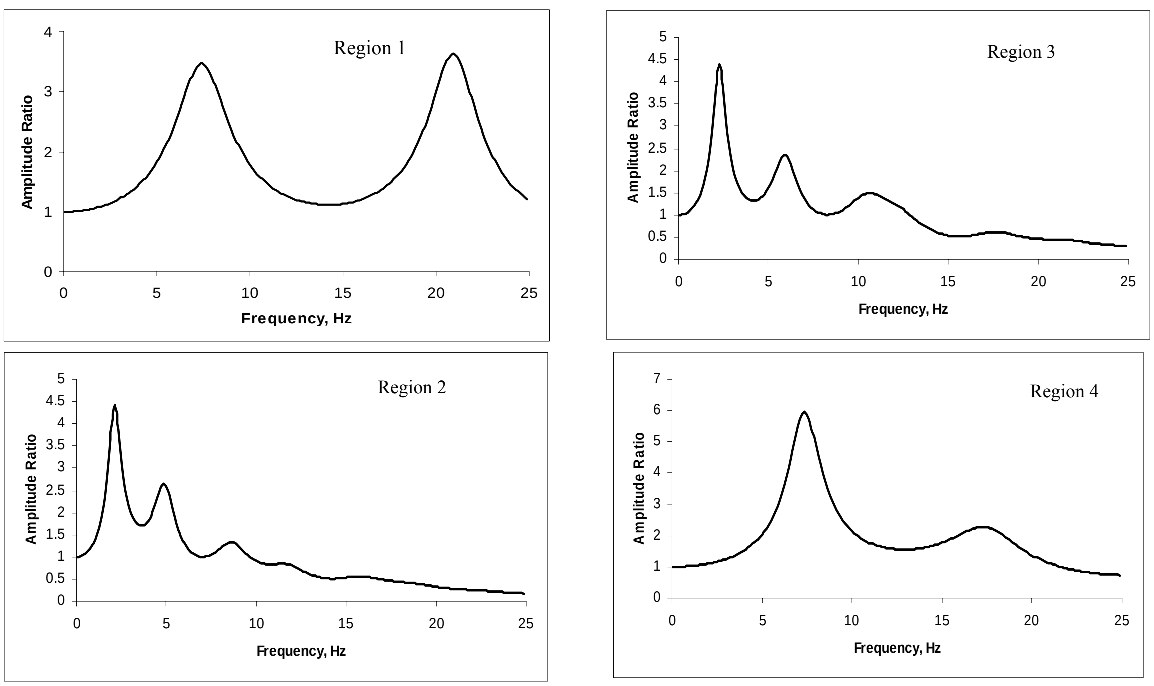

Figure 7. Plots of Amplitude Ratios for the All Regions

Response spectra for 5% damping are obtained for each of the regions and are given in Figure 8. It is noted from the figure that hard rock areas amplifies at periods less than 0.15 seconds and soil sites above 0.4 seconds. Finally, the computed PGA values can be contoured to produce an iso-acceleration map. Thus, the seismic hazard map can be prepared, on which the seismic zonations can be determined. The final hazard map also provides the user the peak ground acceleration for the given coordinates.

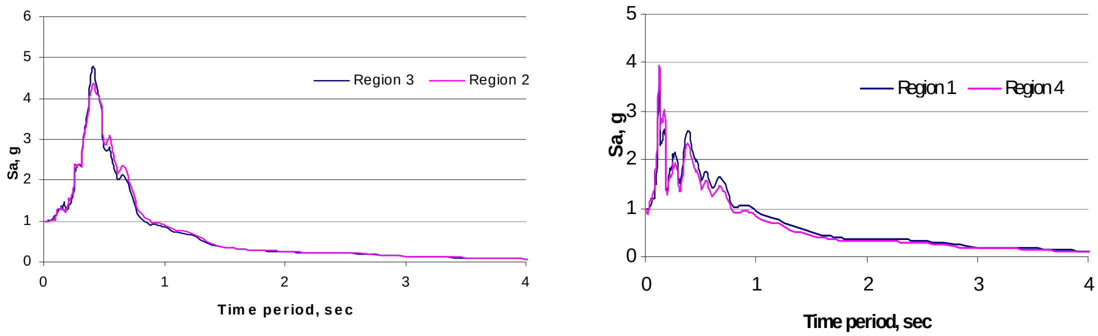

Figure 8. Response Spectra for the All Regions

CONCLUSIONS

Seismic response analysis has been carried out using the soil profiles and time history of bedrock motion modified in accordance with the regional conditions to project acceleration response spectra and illustrate amplitude of local variation attributable to the shallow sediments. Based on the preliminary seismological and geotechnical studies carried out for Chennai city, the following conclusions are drawn. The ground response studies carried out at a few selected regions of the Chennai city indicated the occurrence of amplification only in the low range of frequencies (below 2 Hz) for soil sites and 5-10 Hz for rocky sites. It was found that at higher frequencies, the ground surface acceleration is much less compared to the bedrock acceleration. This is attributed to the de-amplification of the bedrock motion. It is noted that the seismic site response is affected mainly by the soil properties of the surficial soil deposits and not as significantly by the bedrock motion.

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