INFLUENCE OF LOCAL SOIL CONDITIONS ON GROUND RESPONSE: SITE AMPLIFICATION IN SHARJAH, UNITED ARAB EMIRATES

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Abstract

Site amplification increases the intensity of ground shaking that can occur due to local geological conditions. It does not depend only on the magnitude of the earthquake and the distance from the epicenter, but mainly on local soil properties that can vary considerably due to local geological conditions that act as a filter, thereby affecting the seismic waves that come from the bedrock all the way to the ground surface. Good design of a seismic resistant structure requires an estimation of the ground amplification intensity during earthquakes.

This research study was part of a comprehensive seismic risk assessment puzzle put together by the Hazards and Engineering Risk Management Research Group for the city of Sharjah, United Arab Emirates, to help engineers and others in assessing and managing seismic risk—as it defines soil conditions—and its effects on ground motion traveling to buildings through soil. The authors carried out a local site-specific ground-response analysis using SHAKE2000, a one-dimensional ground-response modeling software covering the city of Sharjah. Soil data were collected from over 387 boreholes in order to develop local site amplification-potential maps in the area. Site effects were then integrated in the Geographic Information System (GIS) platform for combined hazard-assessment presentations. The Emirates of Sharjah is zoned indicating regions of different amplification potential and regions of high vulnerability to seismic hazard. In addition, spectral acceleration maps at various frequencies were developed for future planning purposes as well as for risk analysis of structural damage due to earthquakes.

Introduction

The most important seismological aspect of earthquake hazard mitigation is the prediction of the strong ground motion likely at a particular site. Nevertheless, the aspects of earthquake prediction that still receive the most publicity are the prediction of the place, size and time of the earthquake. Of course, prediction of the region where earthquakes are likely to occur has long been achieved by seismicity studies using earthquake observatories, useful probability estimates of long-term hazards which can be inferred from geological measurements of the slip rate of faults, regional strain changes, etc.

The path of the seismic waves in the upper geological formation strongly influences their characteristics, thus producing varying effects on the ground surface motion [1], [2]. The ground motion parameters at a particular site are influenced by the source, travel path and site characteristics. The influence of local soil conditions on the ground response has been recognized for many years and its significance was felt during the 1985 Mexican, 1989 San Francisco, U.S.A., and 1995 Los Angeles, U.S.A., earthquakes. In addition, Istanbul, Turkey, has also experienced many strong earthquakes throughout its history and suffered extensive damage. According to Ince [3], the data pertaining to the damage sustained by historical artifacts and structures from past earthquakes were examined along with the soil amplification of the region. It was found that soil amplification and partial liquefaction contributed to the damage of historical artifacts and structures.

Seismic events were once thought to pose little danger to United Arab Emirates (UAE) communities. However, recent earthquakes and scientific evidence suggest that the risk is much higher than previously thought. The al-Masafi earthquake of 2002 had a magnitude of 5.2, and the successive earth tremors that followed are strong evidence of the active seismicity of the area. Currently, no reliable scientific means exist to predict earthquakes. Therefore, identifying seismic potential locations, adopting strong policies and implementing measures and utilizing other mitigation techniques are essential to reducing risk from seismic hazards in any community. Sharjah is becoming one of the main Emirates of UAE, having the third largest population and active business centers. For this, creating multiple maps that identify seismic risk areas can help Sharjah's planners, policy makers, building code officials and engineers understand which areas should have minimal development to reduce the impact of earthquakes.

Over a period of two years, the authors collected and analyzed data from over 387 boreholes in the Sharjah Municipality as well as others from different locations in the city. Many of the samples were collected from project sites where soil was used as backfill materials. The selections were based on the soil used for projects such as sub-base, sub-grade, below sub-grade, below foundation, below slab on grade and general filling.

In this study, a numerical analysis for the one-dimensional response of soil columns was carried out using SHAKE2000, a software package which has been previously used and found to be valuable [4]. It uses an equivalent linear, total stress analysis procedure to compute the response of a 1-D, horizontally layered viscoelastic system subjected to vertically propagating shear waves. Further, it uses the exact continuum solution to the wave equation adapted for use with transient motions through the Fast Fourier Transform algorithm.

This study aimed to perform analyses on the influence of local soil conditions on ground response during earthquakes at various locations in the Emirate of Sharjah, UAE. The specific objectives of this study were: (1) to contribute to a comprehensive seismic risk assessment study of the city of Sharjah; (2) to estimate the amplification potential and prepare maps indicating zones of high vulnerability to seismic hazard; (3) to obtain spectral acceleration maps used for seismic hazard risk assessment of the area; and, (4) to integrate the site effects in GIS for combined hazard assessment.

Geology and Seismicity of the Area

UAE has a mountain belt along the eastern coast on the Gulf of Oman, about one fifth of which is desert. The western part of the UAE is facing the subduction boundary across the Arabian Gulf opposite the Strait of Hormuz, one of the most seismically active zones in the world. The city of Sharjah faces the Zagros folded belt, one of the most active faults in the world. The main city lies on the Arabian Gulf and other parts of the Emirate lie on the Gulf of Oman. It is located in the geological window between altitudes 25° 25' N and 25° 14' N and 55° 45' E and 55° 20' E.

It has been generally accepted that the UAE has little or no earthquake activity. However, the country is not as safe from earthquake disasters as often assumed. In March, 2002, and according to Jamal and A-Homoud [5], an earthquake magnitude of 5 shocked the al-Masafi area, northeast of UAE, with its epicenter at a depth of 16 km. The strong motions recorded on December 10th, 2002, and April 25th, 2003, represent sufficient evidence of the existence of considerable seismic activity in the UAE.

According to UNESCO [6] and Malkawi et al. [7], the seismic activity in the area is attributed to the following:

1. Major faults of unknown activity levels have been mapped as transecting the UAE.
2. The horn formed by the territory of the UAE penetrates into the plate boundary of collision between the Arabian Peninsula and Asia, thus accumulating stresses.
3. The Zagros Mountain is a folded belt that extends for about 1,500 km in the northwest-southeast direction along the western part of Iran and the northeastern part of Iraq from Oman in the southeast to the Turkish borders in the northwest. The occurrences of earthquake events in the Zagros province define a zone, about 200 km wide, which runs parallel to the folded belt. The majority of the earthquakes occur in the crustal part of the Arabian plate that underlies the Zagros folded belt because it is one of the most active faults in the world. For example, a recent study of the historical seismicity of Iraq shows that most of the moderate to large historical events occurred in eastern Iraq along the Zagros folded belt.
4. The Makran subduction zone, the area where Oman Gulf subducts under the Eurasian plate, is an oceanic crust, which extends eastward to the Owen Fracture zone along the Indian plate boundary. This oceanic crust descends below the continental crust along the Makran subduction trench. This zone is capable of producing very strong earthquakes. For instance, the maximum regionally observed earthquake on November 27th, 1945, had a magnitude of 8.2 at about 750 km from the UAE.

Ground Response Analysis

Data Collection and General Classification

Soil borehole logs from over 387 sites covering most parts of the Emirates of Sharjah were utilized in this study. Boreholes selected were those with overburden thickness varying from 1 to 30 meters, representing typical geological features in Sharjah. The exact GPS locations for all boreholes were obtained from the Sharjah Directorate of Town Planning and Surveying, as shown in Figure 1.

Shear Wave Velocity

Due to a lack of availability of actual published shear wave velocities for the area under study, the following empirical model was used by Lyisan [8]:

$$V_s = 51.5\ N^{0.516} \qquad (1)$$

where: N = uncorrected SPT
V_s = shear wave velocity, m/s

Figure 1. Borehole Locations in the City of Sharjah

Attenuation Relationship

The attenuation relationship is an equation that describes how the ground motion changes with magnitude and source-site distance. Joyner and Boore [9] developed a highly generalized attenuation equation based on worldwide data, which were generated in two forms for earthquake magnitudes between 5.0 and 7.0:

$$\log PGA = 0.49 + 0.23(M-6) + \log r - 0.0027 \qquad (2)$$

$$\log PGV(cm/s) = 2.17 + 0.49(M-6) - \log r + 0.0026r \qquad (3)$$

where
PGA = peak ground acceleration at bedrock
PGV = peak ground velocity at bedrock
M = magnitude of earthquake
d = shortest plan distance between fault and site (km)
r = hypo-central distance

$$r = \left(8^2 + d^2\right)^{0.5} \qquad (2)$$

$$r = \left(4^2 + d^2\right)^{0.5} \qquad (3)$$

Atkinson and Boore [10] developed the following model for PGA using all available worldwide data and for all ranges of ground motion levels:

$$\ln a = c_1 + c_2 m + c_3 r + c_4 \ln r + c_5 p \qquad (4)$$

where c_1 = - 2.682, c_2 = 0.980; c_3 = 0.000580; c_4 = -1.522; and, c_5 = 0.518.

Equation (4) was used to obtain PGA at rock level after attenuation in the city of Sharjah [7], [11]. Figure 2 shows the grids of the PGA map for 50 years with a 10% probability of earthquake occurrence. The values obtained at bedrock for the city of Sharjah range from 0.06g to 0.09g.

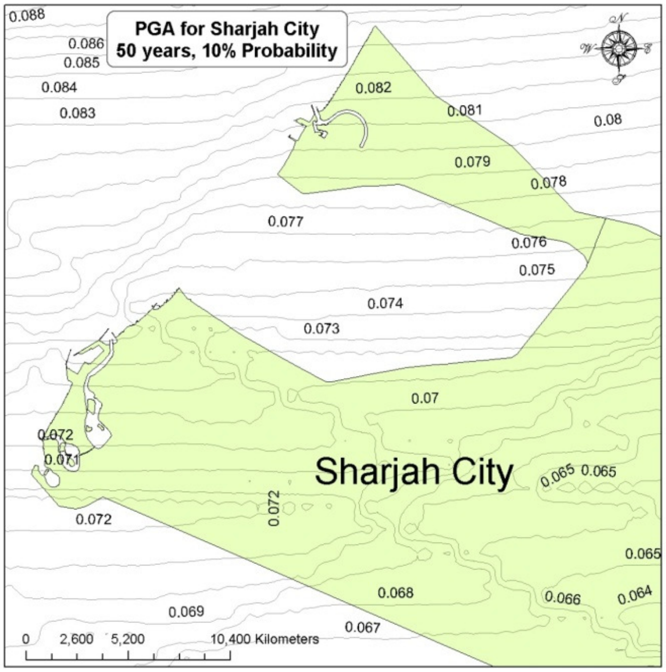

Figure 2. Seismic Hazard Map for the City of Sharjah for 50 Years and a Probability of 10% [7], [11]

Estimation of Ground Motion Signal at Bedrock

The input ground motion considered for this study was the Chalfant Valley (July 21st, 1986, at 14:42) with an earthquake magnitude of 6.2 as recorded by Long Valley Dam (L Abut) station. The reason for selecting this ground motion was based on two factors: the magnitude of the most effective earthquakes that originated from southern Iran and affected our study area was between 6.0 and 6.5, and the peak ground acceleration for the city of Sharjah over the last 50 years and with a 10% probability was between 0.06g and 0.09g. Chalfant Valley's PGA falls within the same range.

Results and Discussions

Microzonation of Ground Shaking

An equivalent linear one-dimensional ground response analysis using SHAKE2000 was followed for all borehole sites in the city of Sharjah in order to find the following parameters: peak ground acceleration, site amplification factor, peak spectral acceleration, frequency of peak acceleration, and the spectral acceleration at particular frequency zones. These factors are important for building a risk analysis. Maps showing the variation of these parameters in Sharjah were developed using GIS.

Peak Ground Acceleration at Rock and Surface

The values of the PGA at rock level for all locations were plotted following UNESCO [6] and Joyner and Boore [9] in order to obtain the PGA map shown in Figure 2. The values obtained at bedrock for the city of Sharjah ranged from 0.06g to 0.09g and were amplified based on the soil profile at different locations. From the SHAKE2000 analysis, the acceleration-time histories at various depths for all locations were found to obtain the peak acceleration value at the surface. These values, ranging from 0.04g to 0.3g, were plotted in order to obtain the Peak Ground Acceleration (PGA) map at ground surface, as shown in Figure 3. The map shows irregularly distributed peak acceleration values due to variation in the soil profile at various locations.

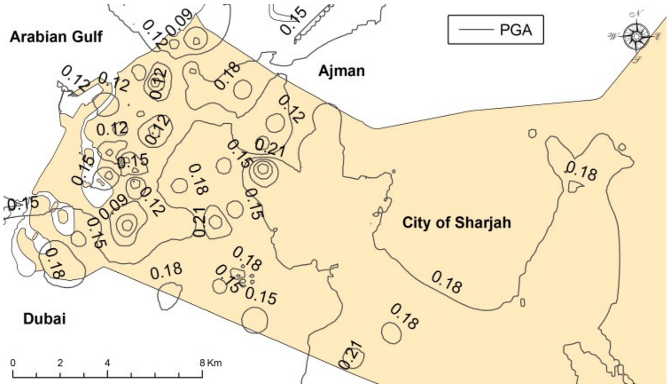

Figure 3. Peak Ground Acceleration Map at Surface Level

Site Amplification Factor

Amplification of ground motion is the increase in the intensity of ground shaking that can occur due to geological conditions. To estimate the amplification of the ground surface, it was necessary to estimate how many times the PGA at bedrock amplified on its way to the ground surface. The Site Amplification Factor refers to the ratio between the PGA at bedrock obtained from the ground acceleration-time history for each borehole and the PGA at the surface as an output from the ground response analysis. Results indicated that the amplification factors ranged from 1.2 to 3.0 for the city of Sharjah. Based on these factors, the city of Sharjah was divided into four main zones, as shown in Figure 4. Lower amplification values indicate smaller amplification potential and, hence, a lower seismic hazard.

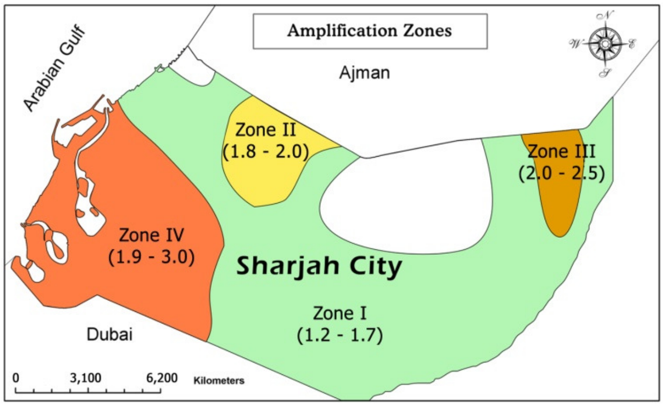

Figure 4. Site Amplification Factor Zonation Map for the City of Sharjah

As shown in Figure 4, most of the study area falls under zone I, which exhibits a relatively low amplification potential ranging from 1.2 to 1.7. The soil profile indicates that 70% of the soil column is dense to very dense, while 15% at a shallow 4-meter depth is loose. Table 1 shows typical soil profiles for zones I through IV. In zone II, a relatively small part of the city falls under this zone, with an amplification potential of 1.8 to 2.5. The soil profile indicates that 60% of the soil column is dense to very dense, while 15% of a shallow 4-meter depth is loose. In zone III, the amplification factor increased from 2.0 to 2.5. This is due to the soil column consisting of more loose to medium-dense soil, thus giving it more of a chance to trap the signal between soil particles with low shear wave velocity. Zone IV has an amplification factor of 1.9 to 3.0, which is slightly higher than previous zones. This zone contains less than 35% of dense to very dense sand, and more than 30% of loose sand, as shown in Table 1. It is worth mentioning that this region of the city contains high-rise buildings with a very dense population, indicating more risk potential.

Response Spectra at Surface

Distribution of Spectral Acceleration for Specific Frequency

At surface level, the estimate of the frequency at peak spectral acceleration is important for calculating the resonance effect from coinciding with the structure's natural frequency causing a negative impact on the safety of buildings. Therefore, the spectral acceleration of different frequencies—0.5 Hz, 2 Hz, 5 Hz, and 10 Hz—was calculated at each borehole and represents tall and high-rise, 3-4 story, 2-story, and 1-story buildings, respectively. A peak spectral acceleration (PSA) map for the city of Sharjah is shown in Figure 5. The PSA values vary from 0.14 to 1.4 and are divided into three main zones, as shown in Table 2.

Table l. Representative Soil Profiles for Zones I - IV

Depth, m	**Zone I**	Depth, m	**Zone II**		
	Soil Type	Avg. SV		Soil Type	Avg. SV
0 - 4.5	Loose Sand	160	0 - 4.5	Loose Sand	158
4.5 – 8.5	Medium Dense Sand	202	4.5 – 10.5	Medium Dense Sand	217
8.5 - 30	Dense to very Dense Sand	284	10.5 - 30	Dense to very Dense Sand	304
Depth, m	**Zone III**	Depth, m	**Zone IV**		
	Soil Type	Avg. SV		Soil Type	Avg. SV
0 - 7.5	Loose Sand	146	0 - 10.5	Loose Sand	128
7.5 – 20.5	Medium Dense Sand	261	10.5 – 18.5	Medium Dense Sand	234
20.5 - 30	Dense to very Dense Sand	302	18.5 - 30	Dense to very Dense Sand	308

Table 2. Zonation Based on PSA

Zone	PSA
I	0.14 -0.60
II	0.60 – 0.80
III	0.80 – 1.40

Figure 6 illustrates the spectral acceleration at 0.5 Hz, which relates to tall and high-rise buildings commonly found in the western part of the city of Sharjah. The acceleration values vary from 0.04g to 0.07g with an average value of 0.05g. This average value is on the lower end of the amplification range and considered relatively low from a seismic hazard point of view.

Figure 7 illustrates the spectral acceleration at 2 Hz frequency. The acceleration values vary from 0.06g to 0.5g with an average of 0.28g. The higher range is found in two areas, one around the coastal region, while the other is in the middle part of the city. A small part was also found near the northern border of the city of Sharjah.

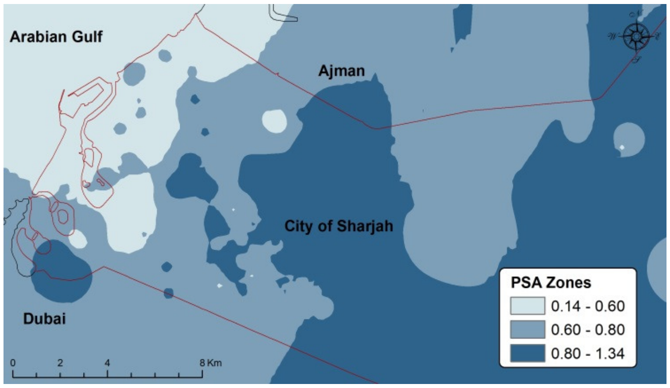

Figure 5. Peak Spectral Acceleration Zonation Map for the City of Sharjah

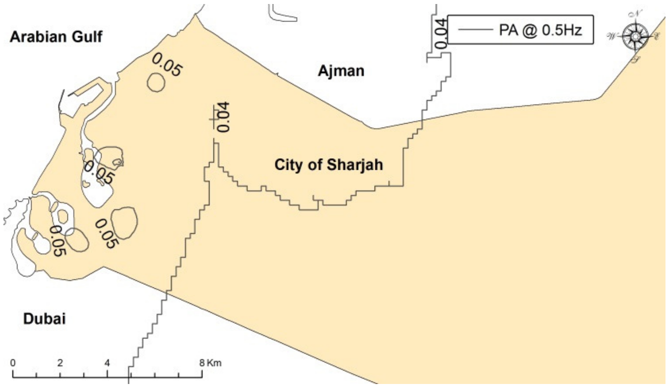

Figure 6. Spectral Acceleration Map of the City of Sharjah at 0.5 Hz

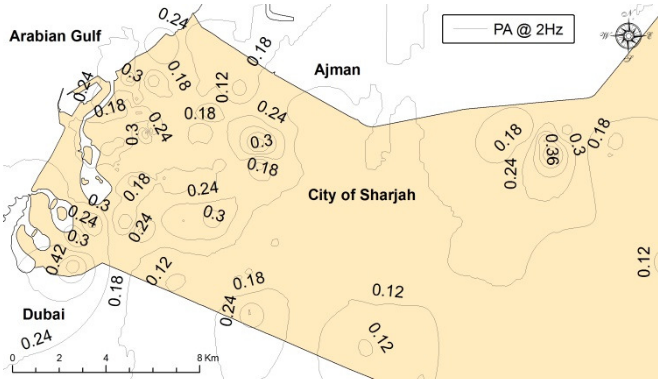

Figure 7. Spectral Acceleration Map of the City of Sharjah at 2 Hz

Figure 8 shows the spectral acceleration at 5 Hz, which relates to 2-story buildings. The acceleration values vary from 0.05g to 0.9g with an average value of 0.48g. Most of the areas that have high spectral acceleration in this frequency range are residential areas with 1- or 2-story buildings, which might be cause for concern during an earthquake.

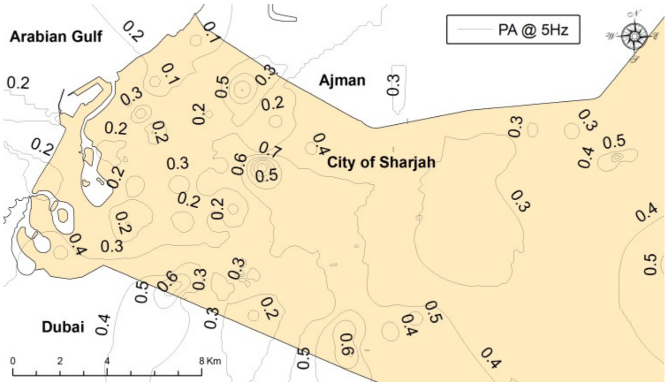

Figure 8. Spectral Acceleration Map of the City of Sharjah at 5 Hz

Figure 9 shows the spectral acceleration at 10 Hz. The acceleration values vary from 0.06g to 0.55g, with an average value of 0.3g. The distribution pattern of accelerations in this frequency range was similar to the one at a frequency of 5 Hz, in terms of building heights. In areas with high spectral acceleration under this frequency, 1-story buildings can be at high risk to life and property.

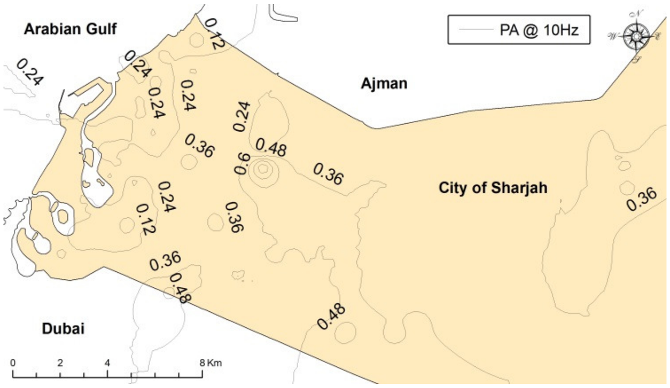

Figure 9. Spectral Acceleration Map of the City of Sharjah at 10 Hz

Distribution of Frequency at PSA

Figure 10 shows the frequency distribution at which maximum amplification is likely to take place. The map indicates three different zones of frequencies. First, the frequency range of 2.0 Hz to 5.0 Hz, where most of the city is under and site amplification might take place. This frequency range corresponds to 2- to 4-story buildings. In the city of Sharjah, these types of buildings are dominant and most likely affected by the presumed earthquake scenario presented in this study. Second, the frequency zone that is at a relatively lower risk ranges between 1.75 Hz to 2.5 Hz, which corresponds to 4- to 5-story buildings. Third, tall and high-rise buildings at a frequency of 1 Hz or less are considered outside the range for the peak spectral acceleration.

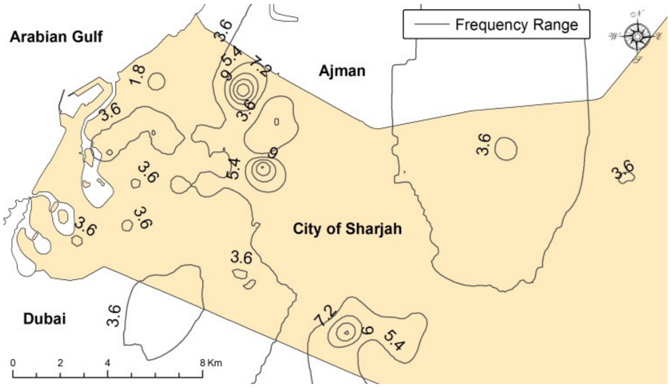

Figure 10. Frequency Range of Peak Ground Acceleration for the City of Sharjah (in Hz)

Conclusion

This study looked at a local site-specific ground response analysis, which is an important step in estimating the effects of earthquakes. The analysis used a one-dimensional ground response, modeled using SHAKE2000. Soil data from 387 boreholes were collected in order to develop local site amplification potential maps for the city of Sharjah. Furthermore, the researchers utilized a Geographical Information System (GIS) to create amplification potential and surface response spectra maps at various locations in Sharjah. These maps show zones of high vulnerability earthquake risk that can be used for earthquake-resistant design of structures.

The city of Sharjah was divided into four zones, according to the amplification factor, which ranged from 1.2 to 3.0. In Zone IV, a high amplification factor was found near the west region of the city, while the rest of the city lies in Zone I with amplification factors of 1.2 to 1.7. Response spectra at the ground surface obtained for all borehole sites showed a wide range of spectral acceleration at different frequencies. The range for spectral acceleration at 0.5 Hz was between 0.04g to 0.07g; at 2 Hz, it was in the range of 0.06g to 0.5g; at 5 Hz, it was in the range of 0.05g to 0.9g; at 10 Hz, it was in the range of 0.06g to 0.55g.

Most of the city lies in the frequency range of 2.0 Hz to 5.0 Hz, where site amplification will take place. This frequency range corresponds to 2- to 4-story buildings. In the city of Sharjah, these types of buildings are dominant and most likely affected by the presumed earthquake scenario presented in this study.

The reader is cautioned that the results presented in this paper were based on a limited soil sample. Prior to implementation in the field, further analysis using more soil data covering the entire city would need to be conducted. Finally, this work can be further improved by utilizing the dynamic properties of soil in this type of analysis.

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