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ORIGINAL PAPER

Seismic hazard assessment for Yanbu metropolitan area, western Saudi Arabia

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Abstract The stochastic method is used to predict ground motions for Yanbu metropolitan area which has been affected by several earthquakes with the maximum magnitude of 6.8 in 1121 AD. The stochastic method has been used for simulating the time domain history for the peak ground acceleration (PGA), peak ground velocity (PGV), and peak ground displacement (PGD) at Yanbu metropolitan area. In addition, the response spectra at 3, 5, and 10 % of the damped pseudo-spectral acceleration (PSA) have been calculated at Al-Majd Sporting Club, Al-Maktabah, and Al-Shate Secondary School sites within the Yanbu metropolitan area. The results show that the values of PGA range from 137 to 388 cm/s^2, PGV values vary from 8.96 to 25.5 cm/s, and PGD values range from 6.7 to 20.9 cm. The values of pseudo-spectral acceleration and predominant period are 974.53 cm/s^2 (with 5 % damping) at 0.14 s for Al-Majd Sporting Club, 487.06 cm/s^2 at 0.19 s for Al-Maktabah site, and 700.83 cm/s^2 at 0.14 s for Al-Shate Secondary School. It is cleared that the values of ground motion parameters are amplified due to the presence of thick sections of very soft to soft sediments to more than six times those of the hard rocks. Furthermore, the estimated predominant periods from this study are correlated well with that of multichannel analysis of surface wave (MASW) approach. These results should be taken into account during design and construction of civil engineering structures within the Yanbu metropolitan area.

Keywords Yanbu · Stochastic · Synthetic data · Frequency · Seismic hazard

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Introduction

Yanbu metropolitan area is one of the important Saudi cities which represents one of the marine ports along the eastern coast of the Red Sea (Fig. 1). This city is affected by the present-day geodynamic processes acting in the Red Sea region. The resulting structures either normal or transform faults run parallel to and/or across the Red Sea. Some of these faults extend inland over tens or hundreds of kilometers (Al Shanti 1966; Pallister 1984). The relative movements along such faults can cause large and damaging earthquakes. The collected information (Poirier and Taher 1980; Merghelani 1981; Ambraseys and Milville 1983; Ambraseys et al. 1994) revealed that Yanbu area has a significant level of earthquake activity which should be assessed.

Recently, the Yanbu metropolitan area has been stroked by an earthquake with moment magnitude of (M_w 5.7) from Harrat Lunayyir about 130 km northeast of Yanbu metropolitan area. The macroseismic intensity ranged from IV to V (Modified Mercalli Intensity scale). In addition, the surface soil heterogeneities act as another factor for seismic hazard threats, due to the above mentioned reasons. Therefore, it is of utmost importance to study and to evaluate the seismic hazard potentialities for Yanbu metropolitan area.

The stochastic method is a simple and powerful method for simulating ground motions to combine parametric or functional descriptions of the ground motion's amplitude spectrum with a random phase spectrum modified such that the motion

Fig. 1 Location map for the study area

is distributed over duration related to the earthquake magnitude and to the distance from the source. It is particularly useful for simulating the higher-frequency ground motions, and it is widely used to predict ground motions for regions of the world, in which recordings of motion from potentially damaging earthquakes are not available. One of the essential characteristics of the method is that it distills what is known about the various factors affecting ground motions (source, path, and site) into simple functional forms.

Geology and tectonics

The Yanbu metropolitan area lies in the eastern edge of the Red Sea rift basin which is covered by Cenozoic basaltic flows and eolian sand deposits. The narrow coastal strip is composed of Tertiary–Quaternary marine and continental coastal plain sediments (Fig. 2). The marine Quaternary deposits are represented mainly by reefal terraces, which lie several meters above sea level. Sand and mud constitute the lower zones of sharms intermixed with contemporaneous alluvial materials. The continental Quaternary deposits are represented by (1) a sandy mantle covering a wide area, which has a composite origin incorporating fluviatile and eolian transport; (2) gravelly or sandy spreads dissected by very close drainage; and (3) gravel spreads related to the degradation of the older terraces (Pellaton 1979).

Structurally, the Red Sea is a graben along the crest of an anticline, which formed in the Arabian-African Shield. A zone of 1–2 km wide that is composed of high and tensional faults concealed by coastal sediments lies at the foot of the escarpments. On the seaward side of this zone, the basement has been step-faulted downward in blocks and lies beneath the shelf area at depths of 2–3 km below sea level (Chapman 1978). Two sets of faults seem to have controlled the development of the Red Sea. These were the NW–SE trending main line of faults, which are associated with step faulting and the WNW–ESE major fault trend in the Precambrian basement, which caused many irregularities in the coastline.

The occurrence of earthquakes and active volcanisms with the axial trough indicates the present-day rifting (Fairhead and Girdler 1970; El-Isa and Al-Shanti 1989; Al-Amri 1995). Depending on the tectonics of the Red Sea–western Arabia region, there are many NE trending transform faults along the Red Sea rift system (Whiteman 1976). This is confirmed by the marine and land magnetic studies, where some of these transform faults extend inland and displace prominent upper Cenozoic structural features (Blank 1977). The west-central part of the shield and in an area of approximately 600 km along the Red Sea coast, extending from Al-Lith to Yanbu

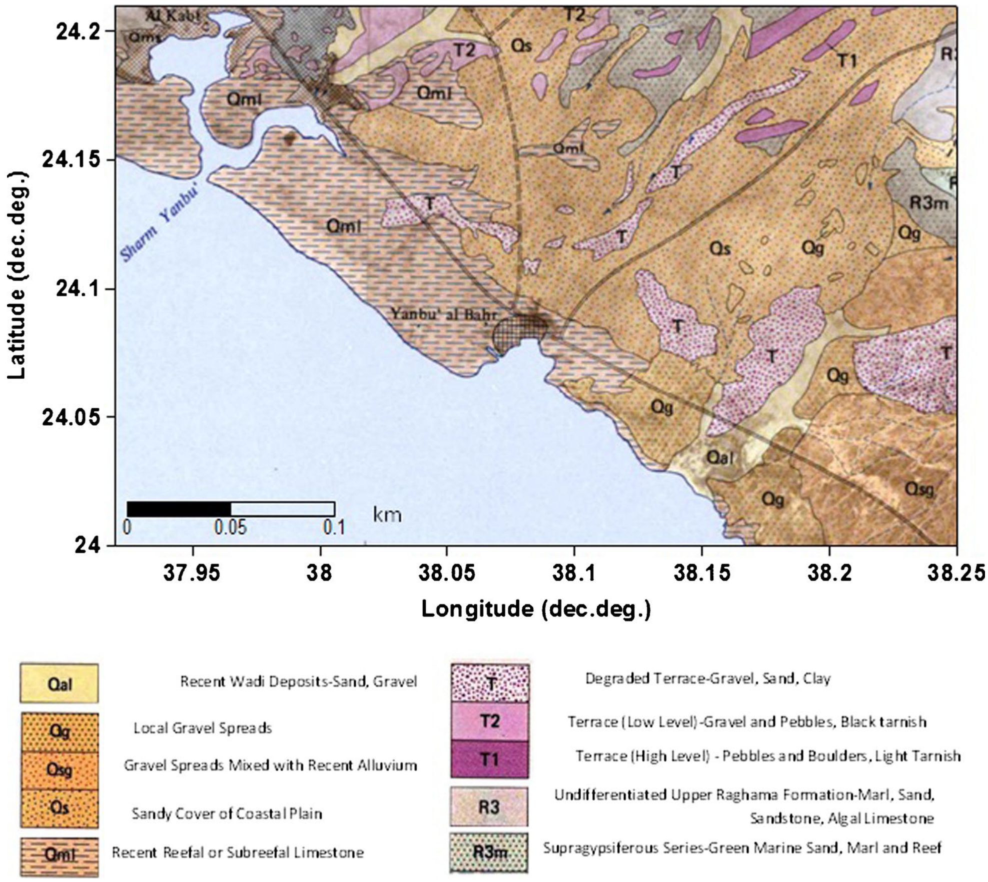

Fig. 2 Geologic map for Yanbu (after Alyousef et al. 2014)

and 150 km inland, the tectonic trends, as well as the lithostratigraphic belts, attain a NE direction. This forms the second major tectonic trend in the shield. The offshore continuation of such faults is confirmed from the magnetic and seismic data (Coleman 1977; Hall 1979). Two major Tertiary tectonic trends prevail in the region of the Red Sea and western Arabia; there are the NW and NE faults. The NE trending faults in the Red Sea region could be considered of two categories: faults controlled by older Precambrian ones and reactivated during Tertiary, or newly formed transverse faults related to the opening of the Red Sea and ocean floor spreading. The clustering of NE trending faults in the central Red Sea and west-central Saudi Arabia is related most probably to the reactivation movements along the pre-existing Precambrian faults. NW faults are responsible for rifting and opening of the Red Sea. They form the structural basins along the coastal zones, where shallow marine Tertiary clastics were deposited.

Seismicity of Yanbu area

The earthquake data (1900 to Dec. 2013) are collected from Ambraseys et al. (1994), International Seismological Center (ISC), and King Saud University (KSU) catalogs to conduct the most recent seismicity map for Yanbu area (Fig. 3). It is cleared that most of the earthquakes occurred along the main and axial trough of the Red Sea. However, the seismicity is not uniformly distributed but occurs in clusters on the ridge crests, or near transform faults of the rift axis. Other low significant activities appear inland of the Arabian Shield (Al-Amri 2004), which may be related to intrusive mechanism, normal fault movements associated with the down dropping of blocks, or movements along undetected transform faults.

Yanbu was violently stroked in 1121 AD, where a damaging earthquake was originated from the main Red Sea trough (lat. 23.5 N, long. 37° E) with magnitude M_s=6.8 (Ambraseys et al. 1994). It was strongly felt over a wide area, where damaging effects were reported to relatively long-period structures located about 330 km apart (e.g., Mecca and Al-Madinah). Ambraseys (1988) indicated that, strong ground shaking has been felt in the city of Al-Madinah Al-Monawarah due to the occurrence of the 1256 event with experienced ground shaking. This inland seismicity may be related to continuing of the Red Sea transform faults into land (El-Isa and Al-Shanti 1989).

Recently, Yanbu metropolitan area was stroked by a moderate earthquake (M_w=5.7) on May 19th, 2009 that occurred at Harrat Lunayyir, about 120 km north of Yanbu metropolitan area (Al-Amri and Fnais 2009). The Macroseismic intensity survey demonstrated that the seismic intensity ranges from IV

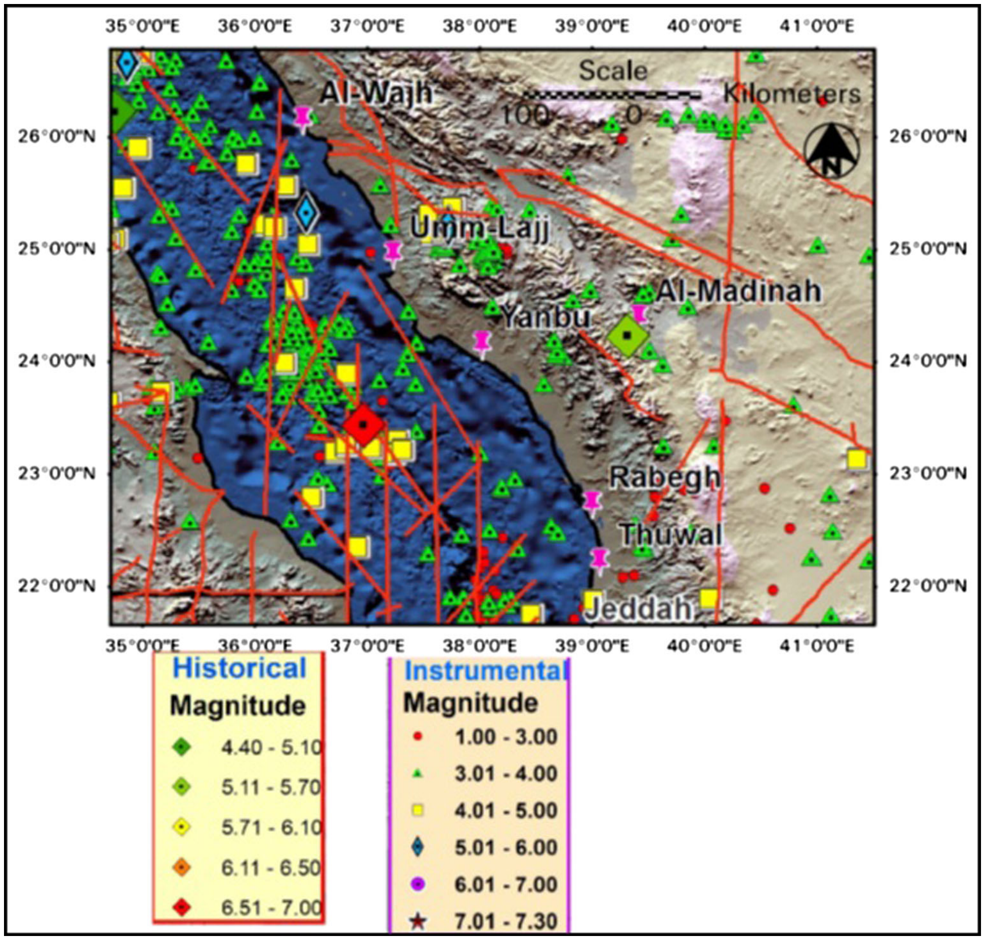

Fig. 3 Seismicity of Yanbu metropolitan area from 184 to 2012

to V (Modified Mercalli Intensity scale, MMI) at Yanbu metropolitan area. This earthquake followed by a huge number of aftershocks shows two adjacent clusters, one aligned NW–SE while the other nearly oriented NE–SW. These trends are correlated well with the direction of transform faults crossing the Red Sea and offsetting the median trench and NW–SE spreading axis of the Red Sea.

Seismic source zones modeling

Identification of seismic source zones has been achieved through the integration between earthquake epicentral distribution and the main structural and tectonic trends controlling the studied area. According to the geological and structural setting and its relation with the earthquakes that occurred in the Yanbu area, it is indicated that the Yanbu area is affected by six source zones (Fig. 4) as follows:

1. Western Al-Wajah source zone
2. Northwestern Yanbu source zone
3. Western Yanbu source zone
4. Southwestern Yanbu source zone
5. Thewal-Rabegh source zone
6. Yanbu-Umlajj source zone

Frequency–magnitude relationship

Gutenberg and Richter (G-R formula) or the recurrence relation used in this study for seismic hazard assessment (Gutenberg and Richter, 1954) is given by

$$\mathbf{Log\ N = a–bM}$$

where N is the number of earthquakes having magnitude greater than M, M is the earthquake magnitude, and a and b are constants depending on the source area and have physical meaning. The a and b values have been calculated for each source region based on events extracted from the catalog (Fig. 5 and Table 1).

According to Table 1, there are great variations in b values that reflect the great material heterogeneities and stress level accumulations in the identified source zones (Mogi 1962; Scholz 1968; Wyss 1973).

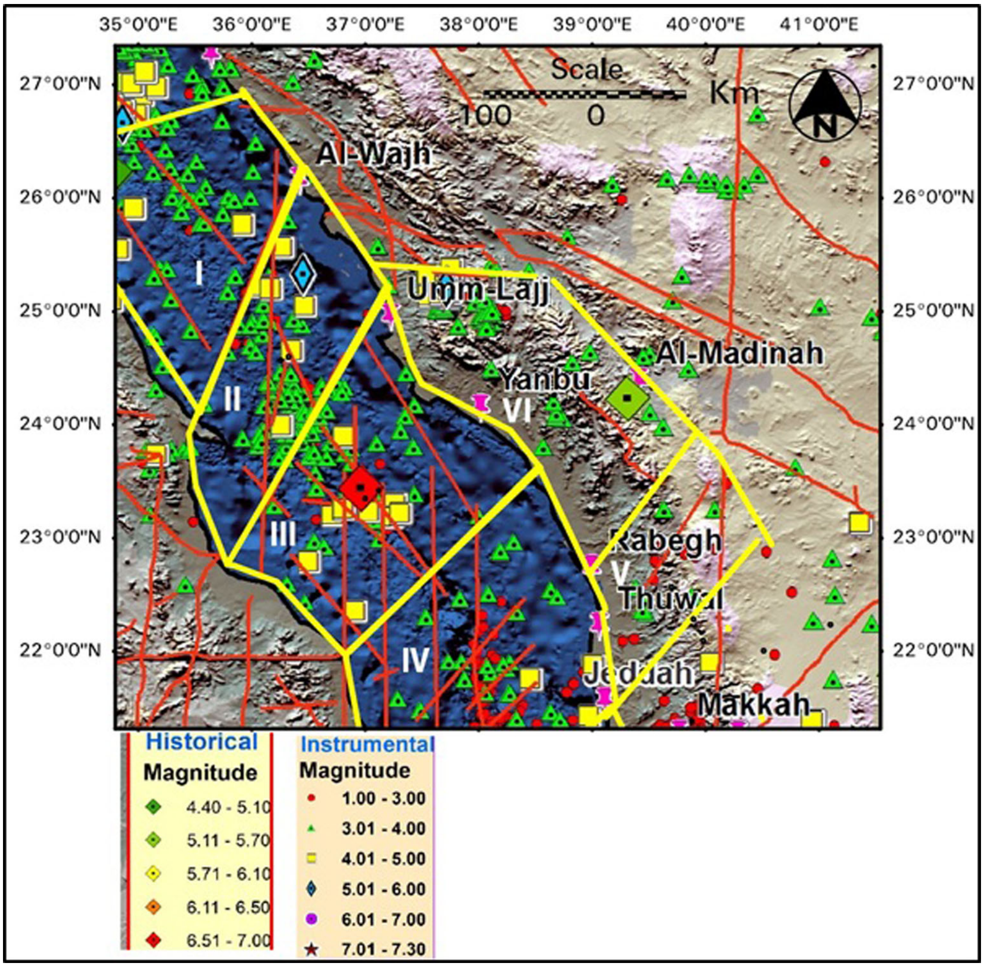

Fig. 4 Identifying the seismic source zones affecting Yanbu metropolitan area

Generation of synthetic earthquake data

In regions lacking strong motion data, it is necessary to generate the synthetic strong motion data. The seismological model established by Boore (1983) is used for generation of synthetic acceleration-time response (as shown by Atkinson and Boore (1995) and Hwang and Huo (1997)). Boore (1983) gave the details for estimating the ground motion based on the Fourier amplitude spectrum of acceleration at bedrock. Boore (2003, 2005) broke the total spectrum of the motion at a site ($Y(M_0, R, f)$ into contributions from earthquake source (E), path (P), site (G), and instrument (I). By separating the spectrum into these components, the models based on the stochastic method can be easily modified to account for specific situations or for improved information about particular aspects of the model. The FORTRAN-based program for Strong Motion Simulation (SMSIM) version 2.0 by Boore (2003, 2005) has been used in this study for generation of synthetic time domain response for the peak ground acceleration (PGA), peak ground velocity (PGV), and peak ground displacement (PGD) at Yanbu metropolitan area. In addition, the response spectra at 3, 5, and 10 % of the damped pseudo-spectral acceleration (PSA) at various geological sequences in Yanbu Metropolitan area have been calculated. The motion spectrum and its components are expressed as:

$$Y(M_0, R, f) = E(M_0, f)P(R, f)G(f)I(f)$$

In the present study, the single corner frequency model has been used (Brune 1970), which is given as follows:

$$E(M_0, f) = C(2\pi f)^2 M_0 \Big/ [1 + (f/f_c)]$$

where $E(M_0, f)$ is the source spectral function, C is a scaling factor, and f_c is the corner frequency and function of $\beta_s(\Delta\sigma/M_0)$ where $\Delta\sigma$ is the stress drop and M_0 is the seismic moment, whereas the moment magnitude is used rather than the seismic moment as a more familiar measure of the earthquake size. The seismic moment is the best known measure of the size (Boore 2003, 2005). $E(M_0, f)$ in the above equation is the displacement source spectrum. The scaling factor is given as

$$C = (R_{\theta\phi}) V.F \Big/ (4\pi\rho\beta_s^3 R_0)$$

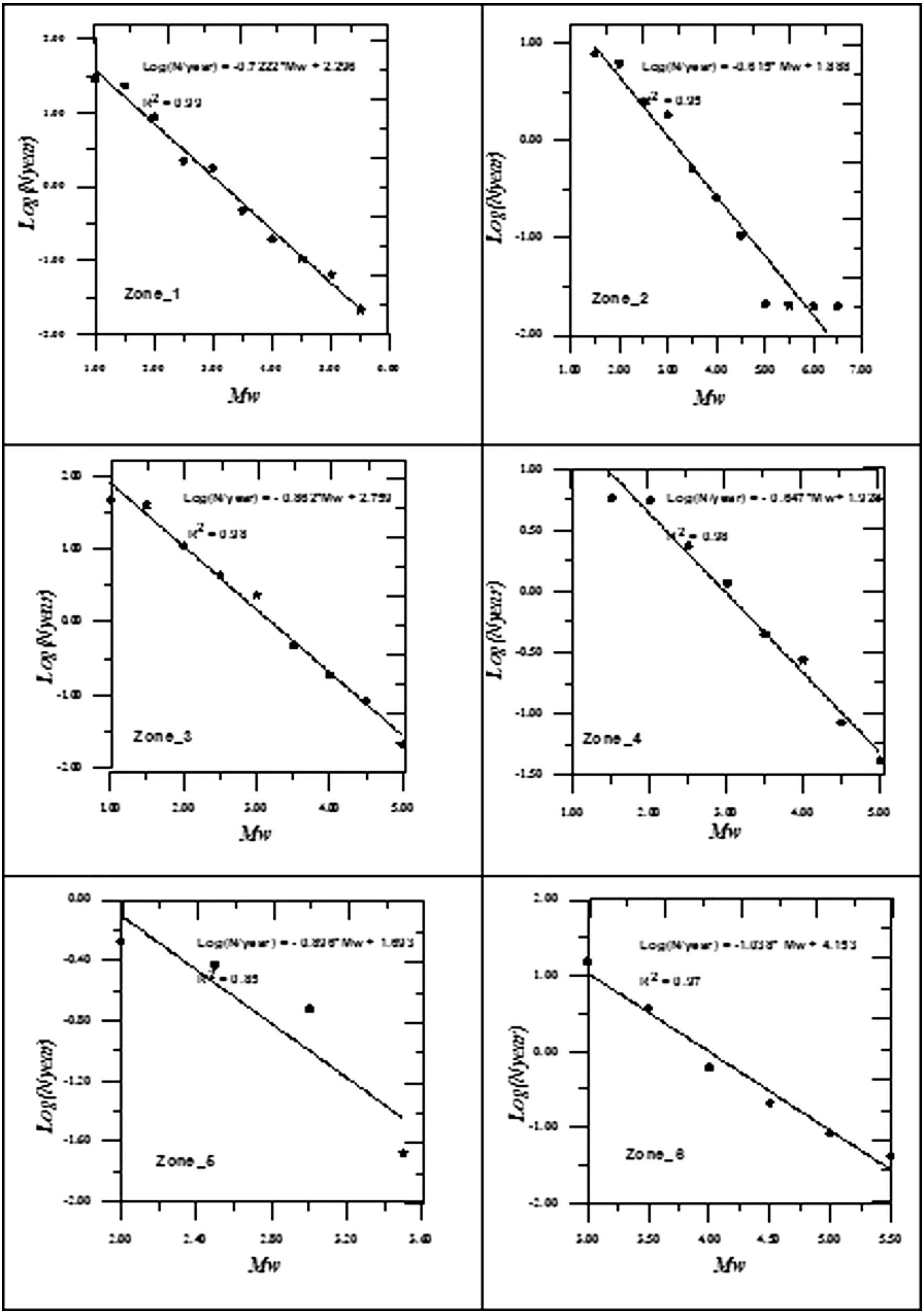

Fig. 5 Recurrence relations for source zones affecting Yanbu area

where $R_{\theta\varphi}$ is the radiation coefficient averaged over an appropriate range of azimuths and take-off angles, V represents the reduction factor that accounts for the partitioning of energy into two horizontal components, F

Table 1 Estimation of a and b values for the identified source zones

Source zone no.	a value	b value
I	2.296	0.7222
II	1.888	0.615
III	2.759	0.862
IV	1.928	0.467
V	1.693	0.896
VI	4.153	1.038

is the amplification due to free surface, ρ and β_s are the density and shear wave velocity in the vicinity of the source, and R_0 is a reference distance, usually set equal to 1 km. So, the scaling factor can be expressed as

$$C = \left(R_{\theta\phi}\right)\sqrt{2}\Big/\left(4\pi\rho{\beta_s}^3\right)$$

where $\sqrt{2}$ arises as the product of the free surface amplification and partitioning of energy in orthogonal directions. Here, the shear wave velocity (β_s) in the source region is taken as 3.58 km/s (Al-Amri et al. 2008). The effects of the path are represented by simple functions that account for geometrical spreading, attenuation (combining intrinsic and scattering attenuations), and the general increase of duration with distance due to the propagation and scattering. The path $P(R, f)$ is given by

$$P(R,f) = G\exp[-\pi f R/\beta_s Q(f)]$$

in which G refers to the geometric attenuation and the other term to the elastic attenuation. In this equation, $Q(f)$ is the quality factor of the region. The geometrical spreading G is given by a piecewise continuous series of straight lines, as

$$\left\{\begin{array}{ll} Ro/R & R \le R_1 \\ Z\left(R_1\right)\left(R_1/R\right)^{P1} & R_1 \le R \le R_2 \\ Z\left(R_n\right)\left(R_n/R\right)^{Pn} & R_n \le R \end{array}\right\}$$

where R is usually taken as the closest distance to the rupture surface rather than the hypocentral distance. The site effects $G(f)$ are classified into amplification $A(f)$ and diminution $D(f)$, as follows:

$$G(f) = A(f)D(f)$$

The attenuation or diminution operator $G(f)$ accounts for the path-independent loss of high frequency in the ground motions, at which a very rapid decay of spectral amplitudes for $f \geq f_{max}$, where f_{max} is controlled by some property of the source, such that radiation at higher frequencies is simply not excited or a site effect as suggested by Hanks (1982)). Some loss mechanism occurs locally at the site, itself, a mechanism capable of dissipating energy very rapidly, as a function of frequency greater than f_{max}, or by a combination of these effects. Simple multiplicative filter can account for the diminution of the high-frequency motions. Two filters are in common use: the first is f_{max} or the high-cut filter (Hanks 1982; Boore 1983), given by

$$D(f) = \left[1 + \left(f/f_{max}\right)^8\right]^{-1/2}$$

The second is κ_0 filter given by $D(f)=\exp(-\pi\kappa_0 f)$ where κ_0 is the spectral decay parameter. Both filters can be combined in any application, as described in the following equation:

$$D(f) = \exp(-\pi\kappa_0 f)\left[1 + \left(f\Big/f_{max}\right)^8\right]^{-1/2}$$

In this study, the parameters used for the source spectral function are R=1 km, Rs is the average shear wave radiation pattern (0.55), F is the free surface effect (2.0), V is the partition onto two horizontal components (0.707), ρ is the density at the source (2.7 gm/cm^3), and β_s is the shear wave velocity at the source (3.58 km/s). The three-segment geometrical spreading operator of Atkinson and Boore (1995) is used. R^{-1} geometrical spreading is assumed for a distance less than 70 km and $R^{0.0}$ for distances varied from 70 to 130 km, and $R^{-0.5}$ for greater distances. The attenuation of seismic waves (Q model) in the Arabian plate has been studied only by few investigators (Healy et al. (1982); Mokhtar (1987)); Mokhtar et al. (1988); Seber (1990); Badri (1991); Ghalib (1992); Seber and Mitchell (1992); Mokhtar and Al-Saeed (1994)).

Inversion of γ_R provided Q_β (shear wave quality factor) models indicating that Q_β increases from 30 in the upper 50 m to 150 at a depth of 0.5 km. The Q_β at depths greater than 0.5 km was determined from the amplitudes of the higher modes relative to the fundamental mode of the Rayleigh waves and was found to have a value between 400 and 700 for the frequency range 1.0–20 Hz. It was found that Q_β is very sensitive to lithological changes and to geological structures of the formations, as determined by the degree of faulting and the lineation present in the rocks. Empirical observations and theoretical simulations suggest that the path-dependent part of the duration can be represented by a connected series of straight-line segments with different slopes.

The function of Atkinson and Boore (1995) is used, where the path duration is modeled as trilinear, using the transition distances 70 and 130 km for consistency with the attenuation model. The slope is 0.16 for the distance ranging between 10 and 70 km, −0.03 for the distance ranging between 70 and 130 km, and 0.04 for the distance varying from 130 to 1000 km. The slope is assumed to be zero for distances less than 10 km. The amplification is relative to the surface motion that would exist, if the material, was replaced with uniform material whose velocity and density equal those at the source. According to Fnais et al. (2009) and Alyousef et al. (2014), the

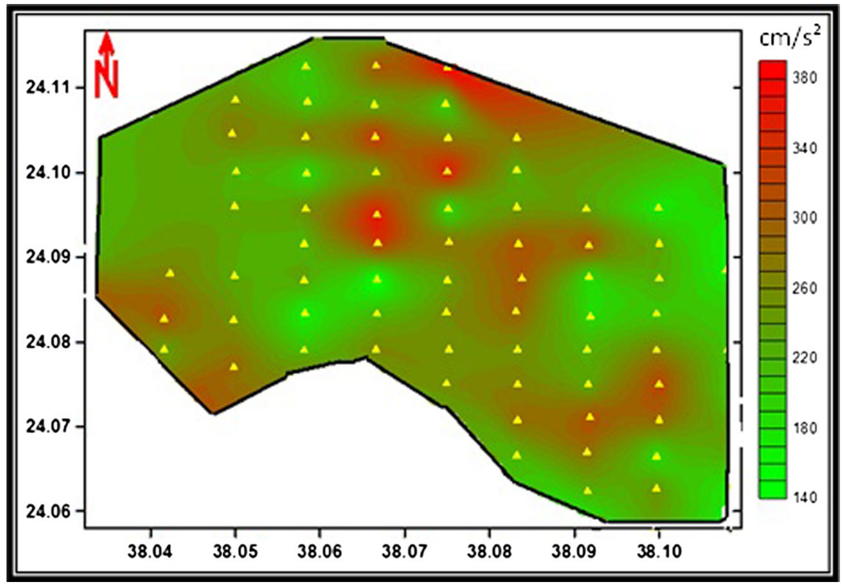

Fig. 6 PGA at Yanbu metropolitan area and measuring sites (*yellow triangle*)

amplification factor varies from 1 to 6.9 for a wide range of soft to very soft sediments at Yanbu metropolitan area. For this high cutoff filter, f_{max} is the high-frequency cutoff proposed by Hanks (1982). For a limited data set, a value of f_{max}=20 Hz is assumed, due to the absence of strong motion records (as Yanbu) suitable for such determination and to avoid the vital frequencies from engineering sense (up to 10 Hz).

Strong motion data have been simulated for the moment magnitude (M_w) of 7.3 at closest distance from 123 to 131 km. The obtained values of PGA (Fig. 6) range from 137 to 388 cm/s^2, PGV values (Fig. 7) vary from 8.96 to 25.5 cm/s, and PGD values (PGD) range from 6.7 to 20.9 cm (Fig. 8). Three sites (Figs. 9, 10, and 11 and Table 2) have been selected as representatives for the simulated ground motions throughout Yanbu metropolitan area.

It is noticed at the above mentioned figures that there are some sites characterized by higher values of PGA, PGV, and PGD. These local areas have very soft sediments (sabkha patches) and/or thick sections of soft sediments where the surface deposits vary from very soft to stiff sediments through the city.

Depending on the nature and depth of local soil deposits, the intensity of the seismic ground motions may be amplified and the frequency characteristics of the motions significantly

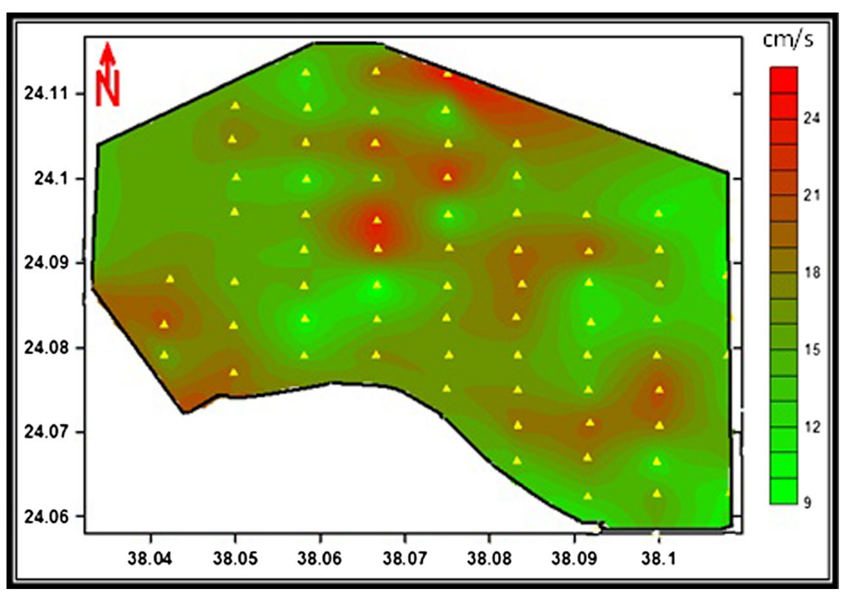

Fig. 7 PGV at Yanbu metropolitan area and measuring sites (*yellow triangle*)

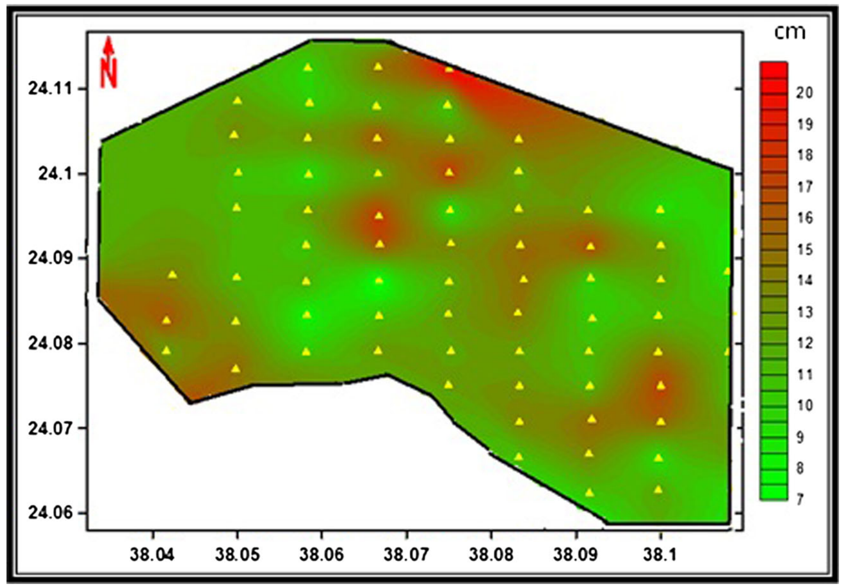

Fig. 8 PGD at Yanbu metropolitan area and measuring sites (*yellow triangle*)

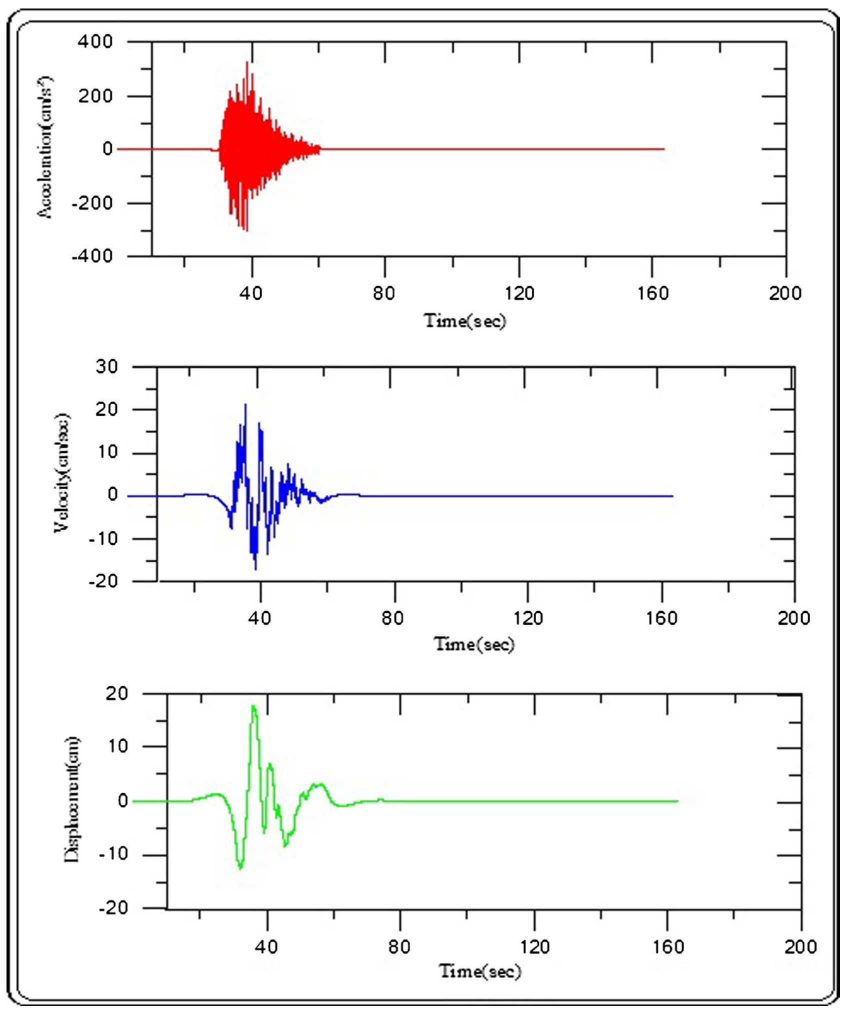

Fig. 9 Simulated ground motion parameters at Al-Majd Sporting Club

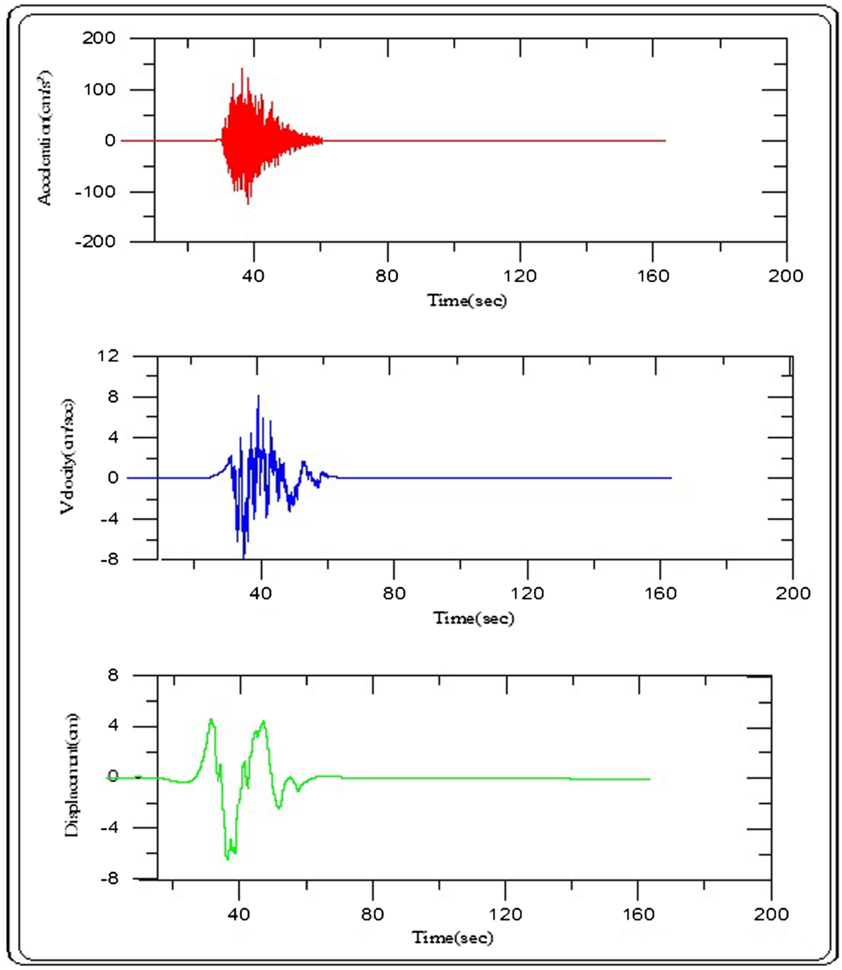

Fig. 10 Simulated ground motion parameters at Al-Maktaba Site

altered as the seismic waves propagate through the intervening soil media to the site. Previous studies (Thenhaus et al. 1986; Al-Haddad et al. 1994) indicated that the average value of PGA is about 100 cm/s^2 through area of study, but this value did not take the local site amplification factor into account. Recently and through the first microzoning study of the Yanbu metropolitan area (Fnais et al. 2009; Alyousef et al. 2014), it is illustrated that the presence of very soft to soft sediments may amplify the ground motion more than six times that of bedrocks.

Acceleration response spectra are important parameters in the earthquake engineering approach and designing of the earthquake resistance structures. Response spectra and dual function characterize the ground motion as a function of the predominant period where one of the most important tools in earthquake engineering is the site predominant period. The response spectra, calculated at 3, 5, and 10 % of the damped pseudo-spectral acceleration, are estimated (Table 2). Synthetic earthquake response spectra at the three sites through Yanbu metropolitan area have been calculated (Figs. 12, 13, and 14).

It clearly indicates that predominant period of the earthquake is 0.14 s at Al-Majd Sporting Club, 0.19 s at Al-Maktabah site, and 0.14 s at Al-Shate Secondary School. Based on earthquake engineering point of view, the estimation of predominant period for reinforced concrete (RC) buildings is very important, and the seismic response represents the idealized elastic response spectrum for a 5 % critically damped, single-degree-of-freedom oscillator subjected to the average ground motion implied by the building code. So, response spectra for 5 % damping is the appropriate value for RC building through Yanbu metropolitan area.

Results and conclusions

Yanbu metropolitan area lies within Red Sea tectonic environment and affected by destructive earthquakes through its history. It is surrounded by six of seismotectonic source zones, the western Yanbu source zone (M_w=7.3), which triggered the highest PGA, is the most vulnerable source for the Yanbu area. The simulated time history obtained, from Red Sea

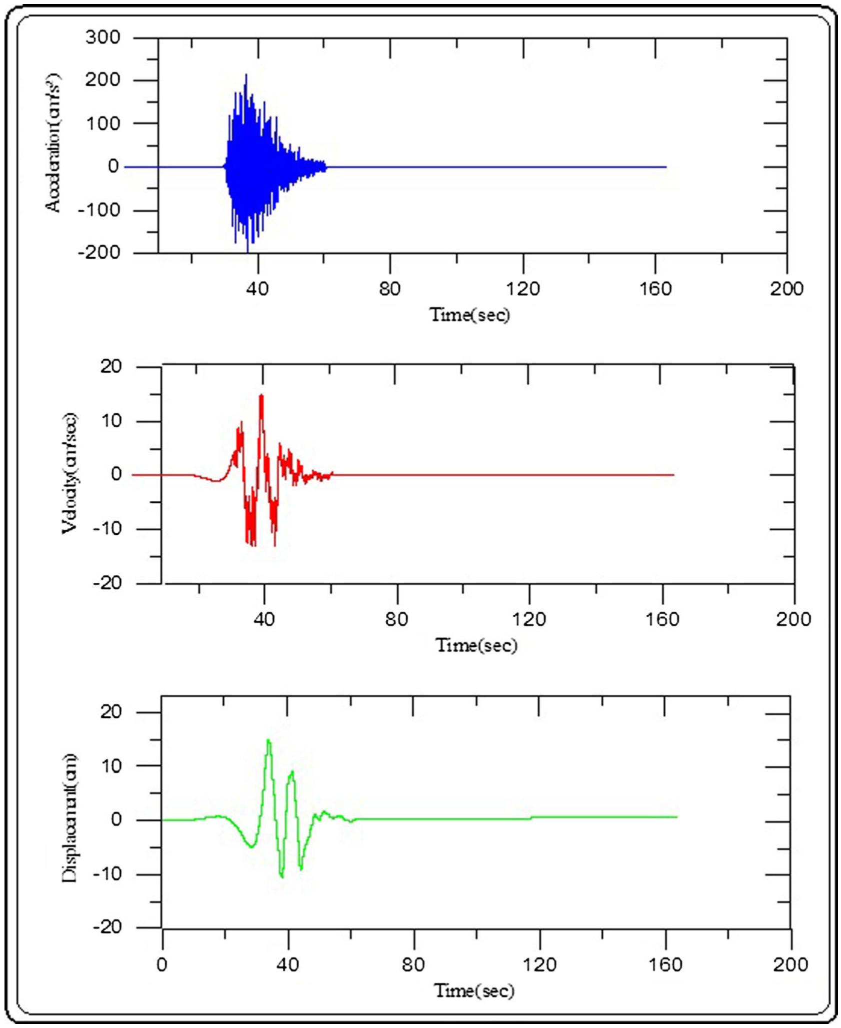

Fig. 11 Simulated ground motion parameters at Al-Shate Secondary School

seismotectonic source, for PGA ranges from 137 to 388 cm/s^2, PGV values from 8.96 to 25.5 cm/s, and PGD values lies in the range from 6.7 to 20.9 cm. The response spectra, calculated at 3, 5, and 10 % of the damped pseudo-acceleration, are estimated at three sites inside Yanbu metropolitan area.

It is indicated that the predominant period of the earthquake is 0.14 s and the peak spectral acceleration is 974.53 cm/s^2 (with 5 % damping) at Al-Majd Sporting Club, 0.19 s and the peak spectral acceleration is 487.06 cm/s^2 at Al-Maktabah site (with 5 % damping), and 0.14 s and the peak spectral acceleration is 700.83 cm/s^2 at Al-Shate Secondary School (with 5 % damping). The predominant periods have been checked with the values obtained by the available borehole data and shear wave velocity profiles obtained using the multichannel analysis of surface wave (MASW) technique in the area (Al-

Table 2 Simulated ground motions at the selected sites through Yanbu metropolitan area

Site name	Closest distance (Km)	Simulated time history			Pseudo-spectral acceleration (PSA)		
		PGA (cm/s^2)	PGV (cm/s)	PGD (cm)	3 % damp.	5 % damp.	10 % damp.
Al-Majd Sporting Club	128.992	324	21.10	17.40	1238.0	979.8	703.0
Al-Maktaba	126.768	137	8.96	6.70	526.2	415.8	296.9
Al-Shate Sec. School	123.432	233	15.40	12.30	884.9	703.1	505.6

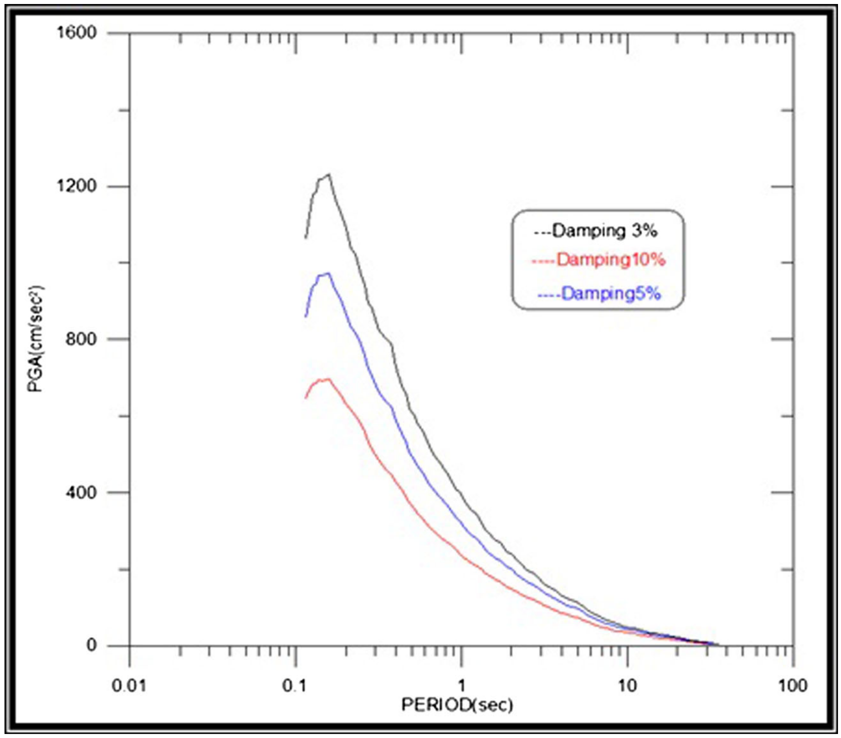

Fig. 12 Response spectra for site with at Al-Majd Sporting Club

Haddad et al. 2001) where the estimated acceleration response spectra are 0.15, 0.21, and 0.15 s at Al-Majd Sporting Club, Al-Maktabah site, and Al-Shate Secondary School, respectively.

Accordingly, it is concluded that the predominant period through this study, are correlated well with those of Al-Haddad et al. (2001). It is recommended that the results of this study must be taken into consideration for designing and

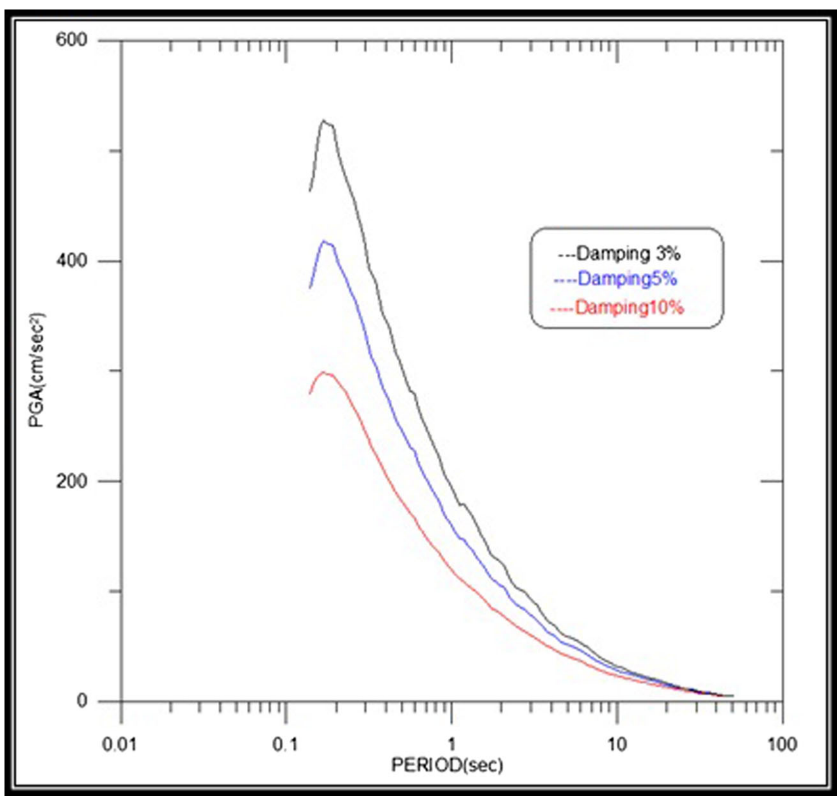

Fig. 13 Response spectra for site with at Al-Maktaba Site

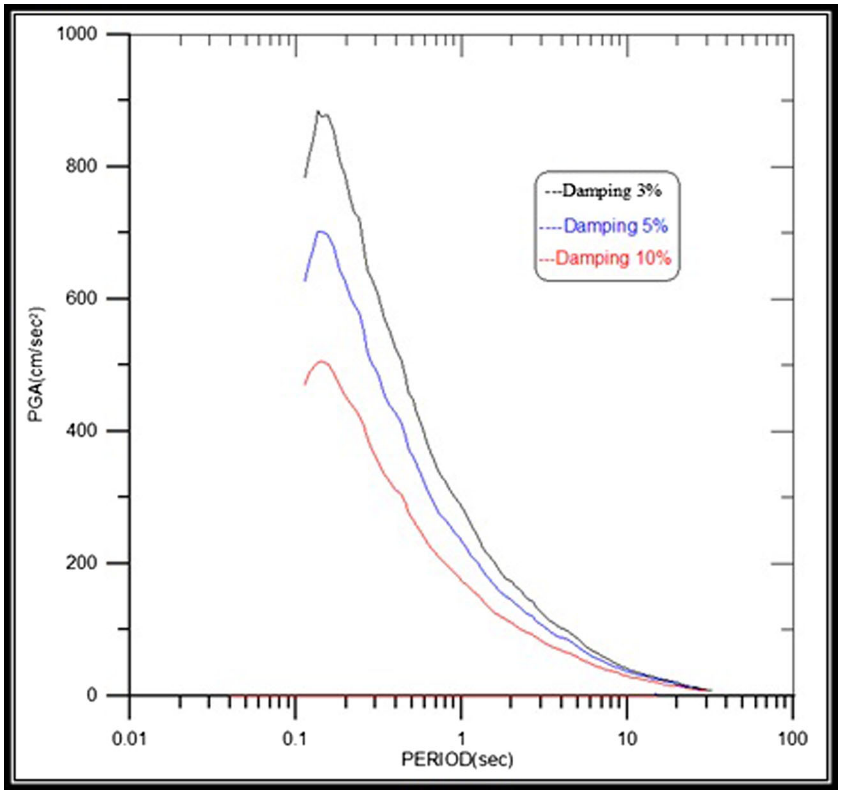

Fig. 14 Response spectra for site with at Al-Shate Secondary School

construction of the civil engineering structures in Yanbu metropolitan area.

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