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Application of Seismic Risk Analysis and Earthquake Simulation Methods to the Western Region in Saudi Arabia

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ABSTRACT. This paper presents a series of applications of existing methods of seismic risk analysis and earthquake simulation to four major cities in the Western Region of Saudi Arabia.

Seismic risk maps available in literature, in the form of isointensity and isoacceleration graphs for the region, are first used to obtain design spectra for the four cities of Jizan, Jeddah, Makkah and Yanbu. Earthquake generation procedures are then applied to obtain the time history for ground acceleration, velocity and displacement.

It is believed that the artificial earthquakes generated in this work reasonably reflect the geological and seismic nature of the region and due to the complete lack of any recorded accelerograms, these artificial earthquakes could be of great value for the detailed analysis and design of earthquake-resistant structures in the region.

1. Introduction

Because of its geographical location, overlooking the Red Sea as shown in Fig. 1, the Western Region of Saudi Arabia is considered to be a moderately active seismic zone. Seismic events in the region that have been reported in literature include a significant earthquake, with a magnitude of 6.25, that occurred in 1941 at about 30 km to the east of Jizan city[1]. Seismic events also include a sequence of earthquakes which occurred in 1967 along the Red Sea rift system at a distance of about 150 km to the south west of Jeddah[2]. Recently, El-Isa *et al.* [3] reported that about 500 local earthquakes with magnitudes less than 4.85, occurred in the Gulf of Aqaba area during the period from January 21 to April 20, 1983.

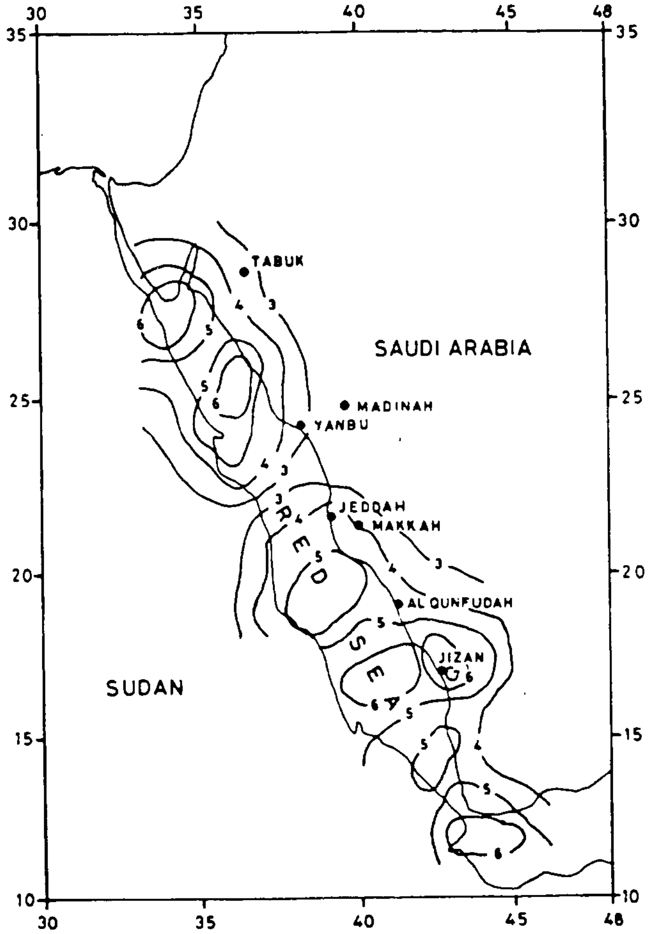

FIG. 1. Isointensity map, return period = 100 year[7].

Merghelani[4] has also reported that a high level of microearthquake activity was detected near the border of the Red Sea and near the transition from oceanic to continental crust.

In seismic design, the design response spectra constitute the traditional means of specifying ground motion[5]. However, those design spectra, in some cases and especially for structures of high importance, provide less reliable results and time history analysis is needed.

The limitation and pausity of recorded accelerograms, together with the need to use time history dynamic analysis have motivated the development of earthquake simulation capabilities. The simulation should be based on realistic models that indeed reflect the general characteristics of the location in terms of seismic as well as geographical and geological characteristics.

It is the main objective of this work to use an existing stochastic model[6-8] and seismic risk maps[6] to generate artificial ground acceleration time histories for the Western Region of Saudi Arabia. It is important to mention here that no real earthquake records; neither in terms of recorded time-histories nor peak ground accelerations have been available for the region.

In the next section the previous work on the seismicity of the Western Region of Saudi Arabia is briefly discussed. This is followed by a brief description of some available methods for generating artificial ground acceleration time histories based on available design spectra. The application of these methods on four major cities in the Western Region of Saudi Arabia and the resulting data are then discussed. Finally the main conclusions of this work are reported.

2. Previous Work on Seismicity in Saudi Arabia

Since the earthquake simulation applications presented in this paper based on the intensity maps prepared by Ali[6-7] in a previous study; it is reasonable to define the basic concepts and to briefly state the specific relationships used for the intensity calculations. This section is devoted for this purpose.

2.1 Magnitude-Frequency Relationship

In the study made by Ali[6-7], the recorded data of 192 seismic events were sorted and assigned to fourteen various sources. The magnitude-frequency relationship for each source was then obtained by linear regression using the familiar Richter's law :

$$\log N = a - bM \qquad (1)$$

where N is the number of occurrence per unit time greater than the magnitude M. The unit time was taken as 80 years[6]. The range of M magnitudes used in Eq. (1) was 5 to 7.33

2.2 Attenuation Model

Several attenuation models based on empirical formulation and observation have been proposed in literature[8-13]. However, Ali[6] adopted the following attenuation model proposed by Cornell[8] :

$$I\,(M,\,R) = C_1 + C_2\,m - C_3 \ln\,(r + r_o) \qquad (2)$$

where the values of C_1 , C_2 , C_3 and r_o are set to be :

C_1 = 8

C_2 = 1.5

C_3 = 2.5

r_o = 20

In Eq. (2), I is the mean value of the distribution of modified Mercalli intensity, r is the epicentral distance in kilometers, and m is the earthquake size in surface wave magnitude.

The adaption of Cornell's attenuation model, which has been developed for firm ground in Southern California, in Ali's study may be questionable. However, due to the apparent difficulty of the total lack of real records, attenuation models that relate peak ground acceleration or velocity to the magnitude and distance[15-16] could not be established. It seems that Ali[6] has adapted Cornell's model following a similar study made by Teikari *et al.*[17] for northern Iraq, a nearby region, in which a similar attenuation model was used.

2.3 Probabilistic Model

The probabilistic model used by Ali[6] was based on the total probability :

$$P\,[I > i] = \int\int P\ [I > i \mid m,\ r \mid f_M\,(m)\,f_R\,(r)\ dm\ dr \tag{3}$$

where P indicates probability, I is the event whose probability is sought, and M and R are continuous independent random variables which influence I. For more details the interested reader is referred to reference[6].

Once the risk associated with an intensity level i at a site has been calculated for the occurrence of one earthquake of arbitrary magnitude and location in a source, the annual expected number of events from that source which cause intensity i or greater, is obtained by multiplying the single event risk by the expected number of events during one year. The total expected number of events causing intensity $I > i$ at the site is obtained by summing the expected number from each source. Risks are then calculated assuming that earthquakes occur as Poisson's arrivals, that is :

$$\text{Risk} = 1 - \exp\,(-\ \text{total expected number}) \tag{4}$$

Ali[6] used a computer program developed by McGuire[18] for his seismic risk analysis.

The results were presented in the form of isointensity maps that correspond to some selected return periods and represent 10 percent chance of exceeding. In the present study, the seismic risk map that corresponds to a return period of 100 year and future exposure time of 10 years, Fig. 1, is chosen as the basis for the application of earthquake simulation. From this map, the intensities at the four cities of Jizan, Jeddah, Makkah and Yanbu, are found to be 6.95, 4.33, 3.7 and 3.25 respectively, with 0.01 risk per year.

2.4 Isoacceleration Maps

Since isointensity maps have limited direct use in seismic design; design accelerations have to be determined based on the corresponding intensity levels. Ali[7] used the method proposed by Krinitzsky and Chang[19] to establish isoacceleration maps corresponding to the selected return periods. The justification given by Ali[7] for his choice of Krinitzsky and Chang's method is that most of the epicenters of reported earthquakes in the Western Region of Saudi Arabia exist in the Red Sea[2-4, 6] and hence it seems appropriate to use the far field curves. Since there is a wide scatter in the data used to establish these curves, Ali selected the 100% curve for the determination of accelerations based on safety and conservatism criteria. Figure 2 shows the isoacceleration map for a return period of 100 years and 10% chance of exceeding[7]. The peak ground acceleration for Jizan is 0.24g, for Jeddah is 0.09g for Makkah is 0.05g, and for Yanbu is 0.03g.

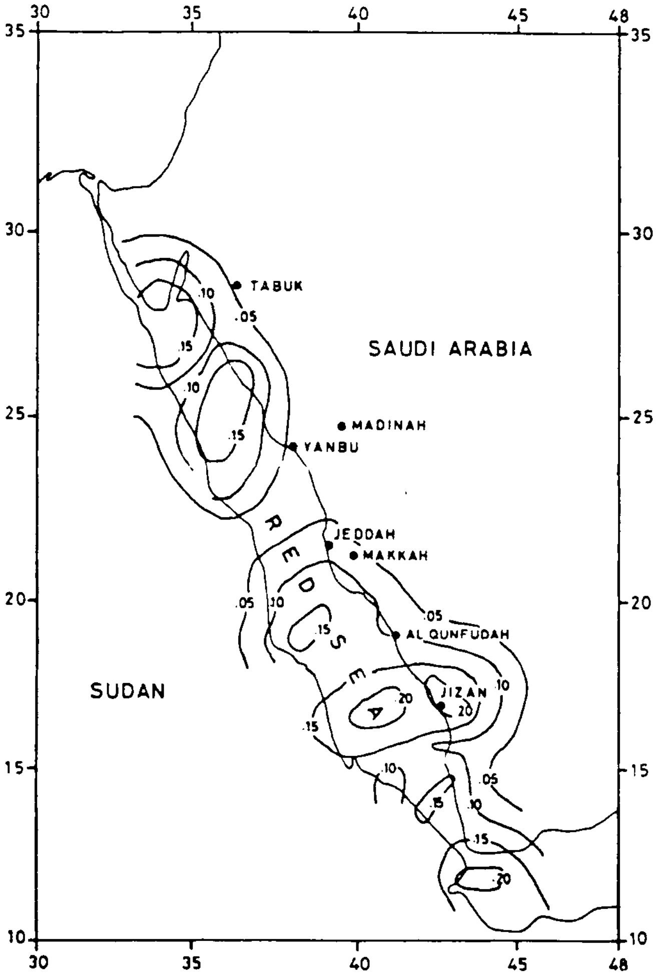

FIG. 2. Isoacceleration map, return period = 100 year[7].

3. Earthquake Simulation Methods

There are several methodologies proposed in literature for earthquake simulation[5, 20-24]. However for the specific purpose of this study the method developed by

Gasparini and Vanmarcke[20] is adopted.

3.1 Design Response Spectra

The Newmark method[25-27], for the construction of response spectra, is employed in the present study to get the design response spectra for the four cities under consideration using the peak ground accelerations obtained before. It should be mentioned here that Newmark's procedure involves the scaling of standard spectra shapes, obtained by normalyzing the response spectra of recorded ground motions, to the design values of the ground motion parameters. Hence the method assumes that motions of different intensities are similar in same respect. Despite this fact, it has been resorted to this method due to the complete lack of real records. Other methods such as that reported by McGuire[15] can be only used if recorded data is available. The calculated design response spectra are shown in Fig. 7 (a-d) as dashed lines.

3.2 Review of the Generation Procedure

A brief description of the generation method developed by Gasparini and Vanmarcke is now given, while more details can be obtained from reference[20]. The method is based on the fact that any periodic function can be expanded into a series of sinusoidal waves.

$$\ddot{z}(t) = \sum_{n} A_n \sin(\omega_n t + \Theta_n) \qquad (5)$$

in which $\ddot{z}$ is the base acceleration, A_n is the amplitude, ω_n *and* Θ_n are the frequency and phase angle of the nth contributing sinusoid respectively. The algorithm uses random number generator to produce strings of phase angles with uniform likelihood in the range between 0 and 2 π.

The amplitudes A_n are reflected to the (one-sided) spectral density function $G(\omega_n)$ in the following way :

$$G(\omega_n) = \frac{A_n}{2} \qquad (6)$$

Since the total power may be expressed as :

$$\Sigma A_n^2/2 = \Sigma G(\omega_n) \cdot \Delta\omega \qquad (7)$$

then, for large number of sinusoids, the total power will become the area under the continuous curve $G(\omega)$, such as :

$$\Sigma A_n^2/2 = \int_o^\infty G(\omega)\, d\omega \qquad (8)$$

The method establishes a relationship between the response spectrum (SV) and the spectral-density function $G(\omega)$ of ground motion at a site. The relationship is not unique, though; it depends on the chosen strong motion duration, on the exceedance probability level assigned, and on the damping level involved[20].

The power of motion calculated by Eq. (5) does not vary with time. To simulate the transient nature of real earthquakes, the steady state motions are multiplied by a deterministic function $I(t)$. There are several patterns in which the deterministic envelope $I(t)$ can be expressed. These involve trapezoidal, exponential and compound shapes[20].

The artificial motion $\ddot{z}(t)$ then becomes :

$$\ddot{z}(t) = I(t) \sum_{n} A_n \sin(\omega_n t + \Theta_n) \tag{9}$$

The resulting motion is stationary in frequency content with a peak acceleration close to the target peak acceleration. The response spectra corresponding to the motion are then calculated using the method reported by Nigam and Jennings[28] which is based on exact solution of the differential equation of motion. To smooth the calculated spectra and to improve the match, iteration is implemented in the generation procedure. This is done by modifying the spectral density function as follows :

$$G(\omega)_{i+1} = G(\omega)_i \, [SV(\omega) / SV_{ti}(\omega)]^2 \tag{10}$$

where $SV(\omega)$ is the calculated velocity spectra and $SV_{ti}(\omega)$ is the target velocity spectra for the control frequency in the ith cycle. The procedure may not converge at all control frequencies, because the response at a control frequency is dependent on the spectral density function value for that frequency as well as values at other frequencies close to the frequency of interest.

3.3 Base Line Correction

There are many significant contributions in literature to the general problem of base-line correction and double integration of digitized accelerograms[29-31]. The parabolic base line correction[29] has been used for the present study. The correction considers the duration of motion in calculating the constant coefficients in the parabolic equation[29] :

$$\ddot{z}_2(t) = \ddot{z}_1(t) + a_1 + a_2 t + a_3 t^2 \tag{11}$$

where $\ddot{z}_2(t)$ is the corrected accelerogram and $\ddot{z}_1(t)$ is the ground acceleration before correction.

3.4 Strong Motion Duration

Due to lack of recorded accelerograms for the region under consideration, the duration of the strong phase of the simulated motion could not be established in a rational manner. However, it should be as short as possible if it is not specified from the seismo-tectonic conditions governing site seismicity[5], bearing in mind that it should at least allow the steady state structural response to be achieved. A minimum strong motion duration of 6 seconds (coupled with a built-up duration of 4 seconds) is recommended for nuclear power plant[32]. In general, the duration tends to decrease with increasing intensity level and increases with the increase of the epicentral distance for a specified intensity level[31]. The total duration of the simulated motions in the present study has been established based on the following formula proposed by

Esteva and Rosenblueth[33] :

$$T = 0.02\, e^{0.74M} + 0.3\, R \tag{12}$$

where M is the earthquake magnitude and R is the epicentral distance. The modulation enveloped of the simulated motions may be expressed as :

$$I(t) = \begin{cases} 56.25\, \frac{t}{T} & 0 \le t \le \frac{2}{15}\, T \\ 1.0 & \frac{2}{15}\, T \le t \le \frac{T}{2} \\ \exp\left[-2.976\left(\frac{t}{T} - \frac{1}{2}\right)\right] & \frac{T}{2} \le t \le T \end{cases} \tag{13}$$

such envelope has been widely used for probabilistic response of structures due to artificial earthquakes[34-35].

4. Applications to the Western Region in Saudi Arabia

4.1 Simulated Motion Parameters

The application of earthquake simulation procedures on the four major cities of Jizan, Jeddah, Makkah and Yanbu in the Western Region of Saudi Arabia starts by defining a set of parameters on which the process is based. These parameters are given in Table 1. The epicentral distances are established based on the assumption that epicenters are located along the axial trough of the Red Sea[6]. The corresponding magnitudes are established from the attenuation relation given by Eq. (2). The total duration for each case is determined by Eq. (12). The modulation time envelope described by Eq. (13) is used for each case with a total duration corresponding to that case.

TABLE 1. Input parameters of the simulated motions.

Variable \ Motion	Jizan	Jeddah	Makkah	Yanbu
Intensity (mm)	6.95	4.33	3.7	3.25
Epicentral distance (R km)	175	110	155	125
Magnitude (M)	8.08	5.67	5.74	5.13
Total duration (T sec)	60	35	50	40
Cutoff period (sec)	7	7	7	7

A rough estimation of the cutoff periods for the motions may be based on the response spectra of the filtered motion for short earthquakes and on the frequency content of the ground velocity and displacement for large earthquakes[20]. However, as mentioned before, since no recorded events are available, the proposed cutoff periods are chosen arbitrarily, but expected to give acceptable results.

4.2 Time Histories and Response Spectra

The calculated time histories of ground acceleration, velocity, and displacement are shown in Fig. 3-6 for Jizan, Jeddah, Makkah and Yanbu respectively. The velocity and displacement time histories have been obtained by integrating and simulated acceleration time history after applying the base line correction. The maximum values of these ground motions are given in Table 2. The frequency content is reflected on the simulated motions since all the design spectra have wide frequency range.

TABLE 2. Output parameters of the simulated motions.

Output parameter \ Motion	Jizan	Jeddah	Makkah	Yanbu
Max. displacement (cm)	14.30	6.60	4.30	1.70
Max. velocity (cm / sec)	33.30	13.80	5.10	3.40
Max. acceleration (g)	0.24	0.09	0.05	0.03
Spectral intensity (cm) (5% damping)	60.33	24.00	13.17	7.69

The corresponding response spectra for 2, 5 and 10% damping are shown in Fig. 7. The calculated spectra have been obtained for 200 values of natural periods. It can be noticed that for almost all the spectra, the agreement between the design target spectra (5% damping) and the calculated spectra is quite reasonable for all ranges of period values with excellent agreement for short period range of 0.1 to 3.5 second. The effect of the cutoff period is clearly reflected on the simulated motions where rapid decrease in the response spectra of all motions is noticeable for periods greater than seven seconds.

Table 2 gives also the spectral intensity (SI), defined as :

$$SI_{5\%} = \int_{0.1}^{2.5} SV(5\%, T_n)\, d\, T_n \tag{14}$$

for all calculated spectra. Figure 8 shows the energy input per unit mass spectra of the simulated motions for 0, 2, 5, and 10% fraction of critical damping.

The damage potential in terms of the mean-square integral which is defined as :

$$DP = \int_0^T \ddot{z}^2(t)\, dt \tag{15}$$

is a reasonable measure of the intensity of a ground motion[36]. The mean-square integral is shown in Fig. 9 for the generated motions. Applying the criteria of the strong motion duration as defined by Trifunac and Brady in references[36-37]; it is found from Fig. 9 that Jizan has a duration of 38.54 seconds and Jeddah has 22.3 seconds. From

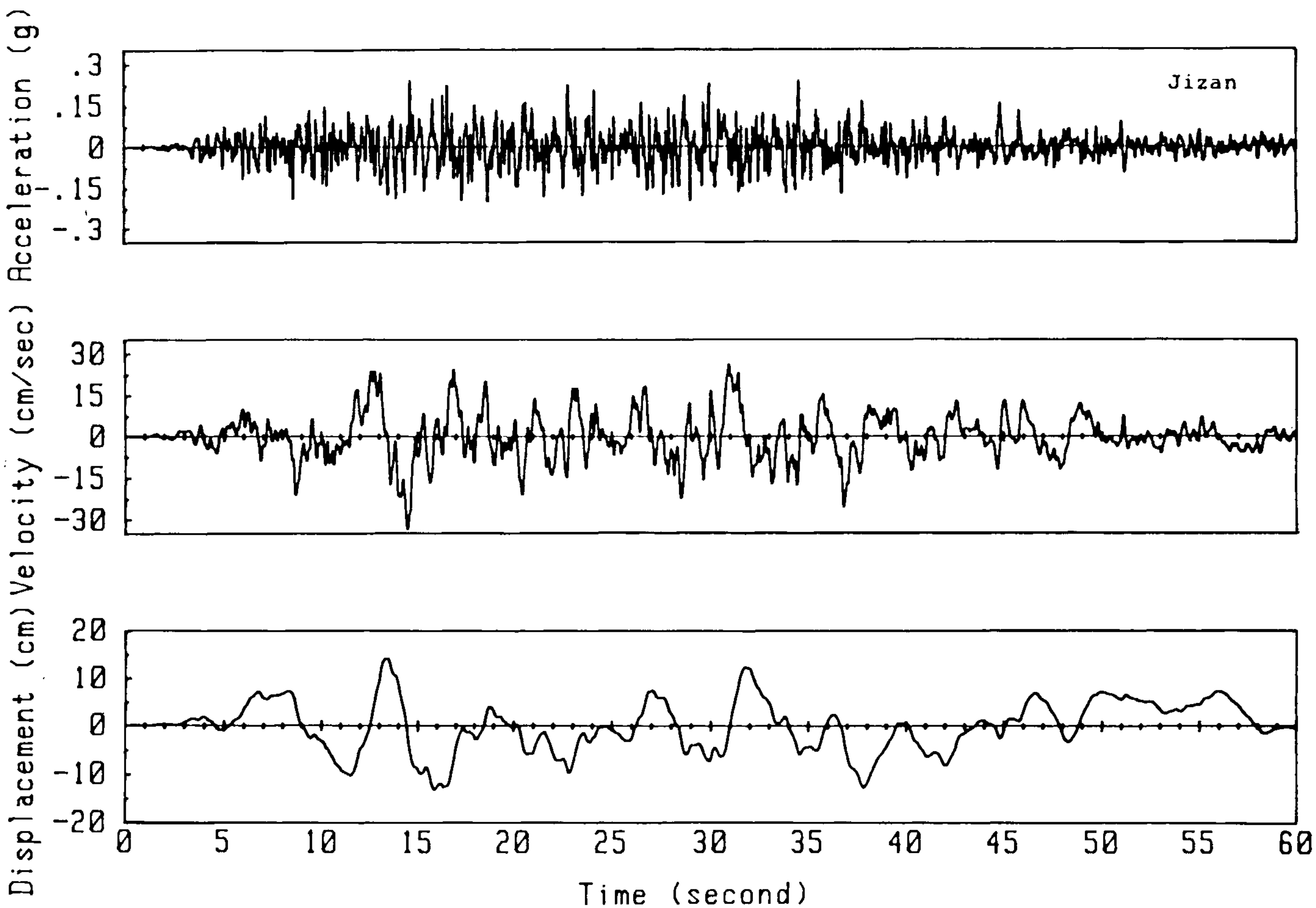

FIG. 3. Time history of ground motion for Jizan.

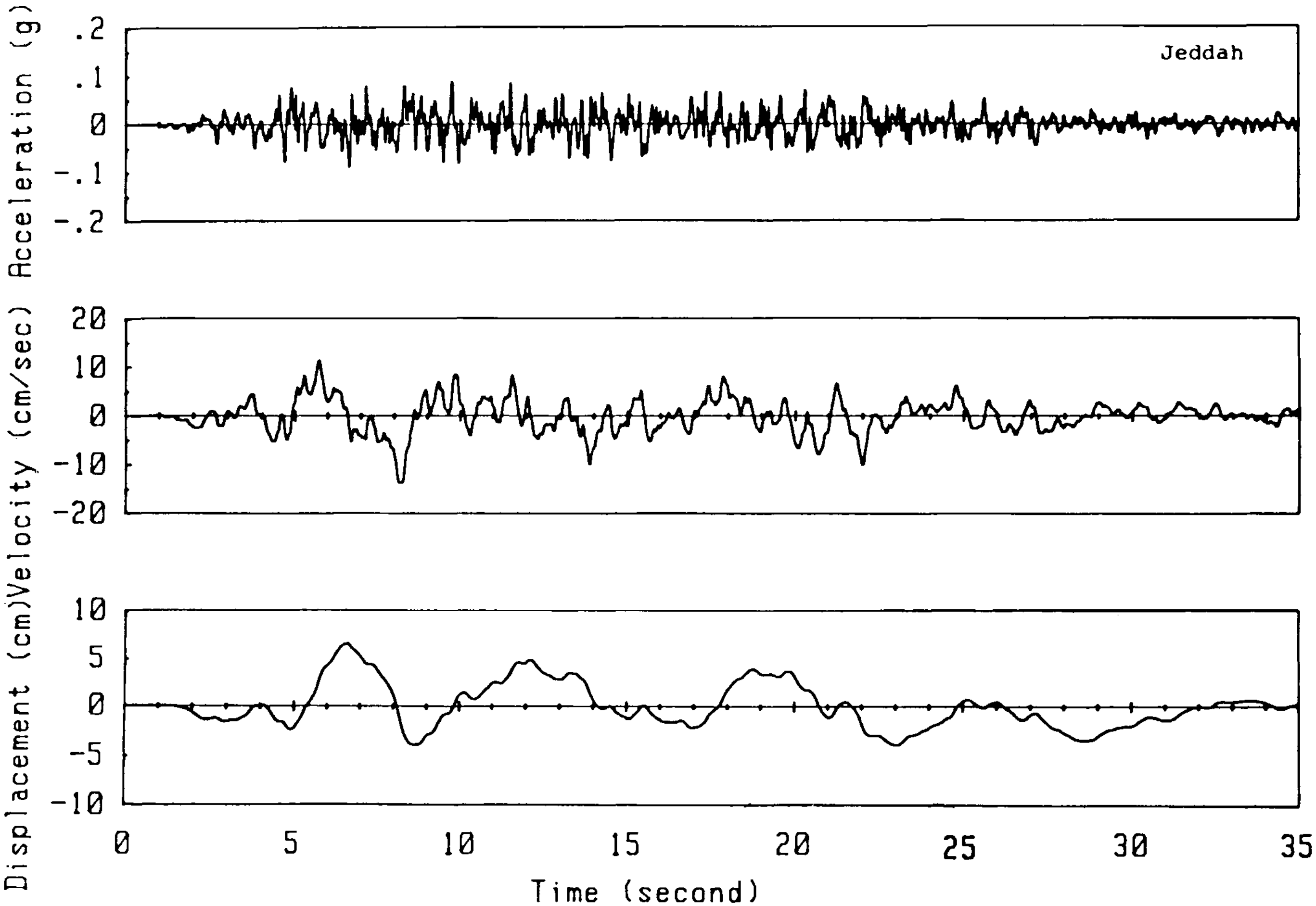

FIG. 4. Time history of ground motion for Jeddah.

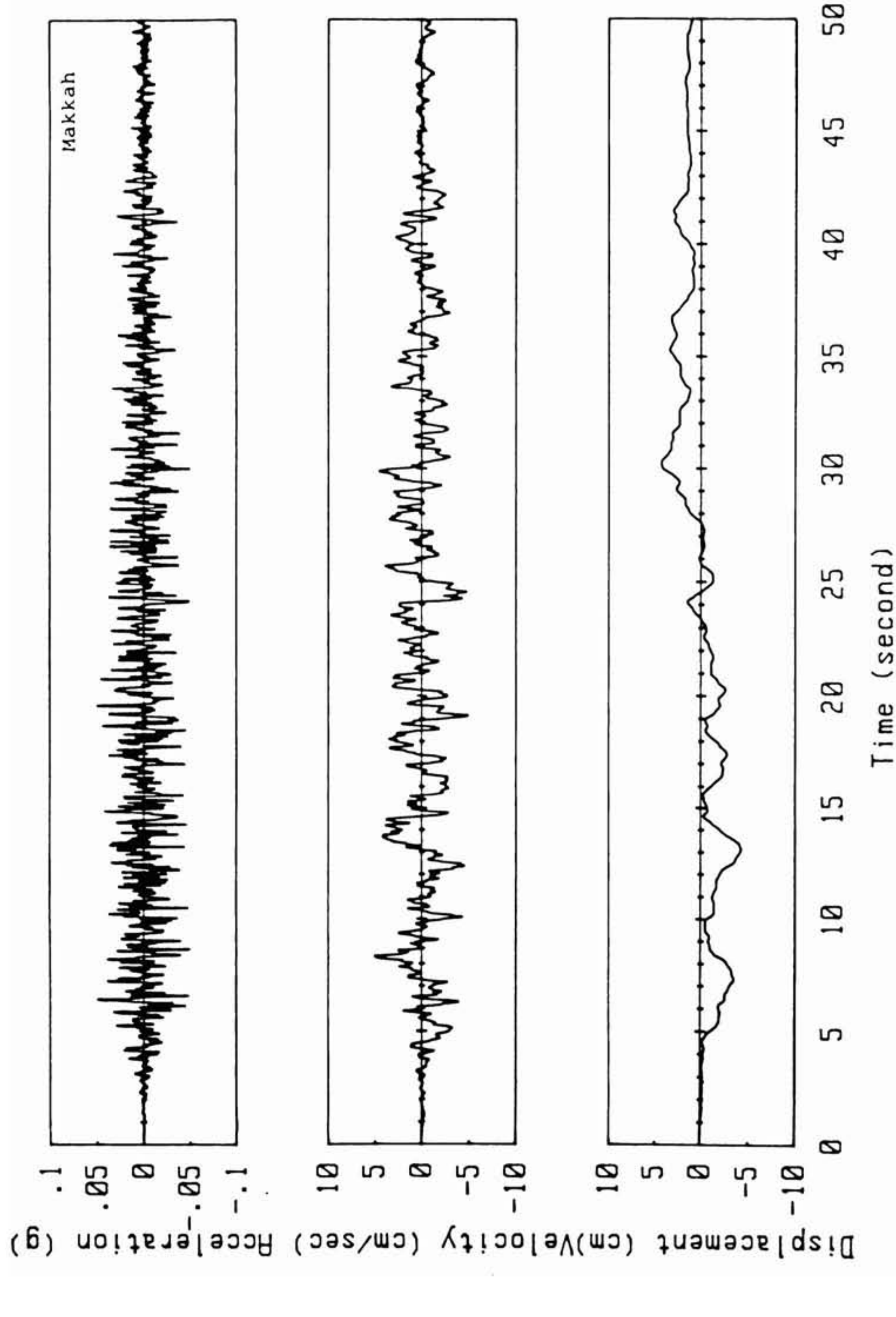

FIG. 5. Time history for ground motion for Makkah.

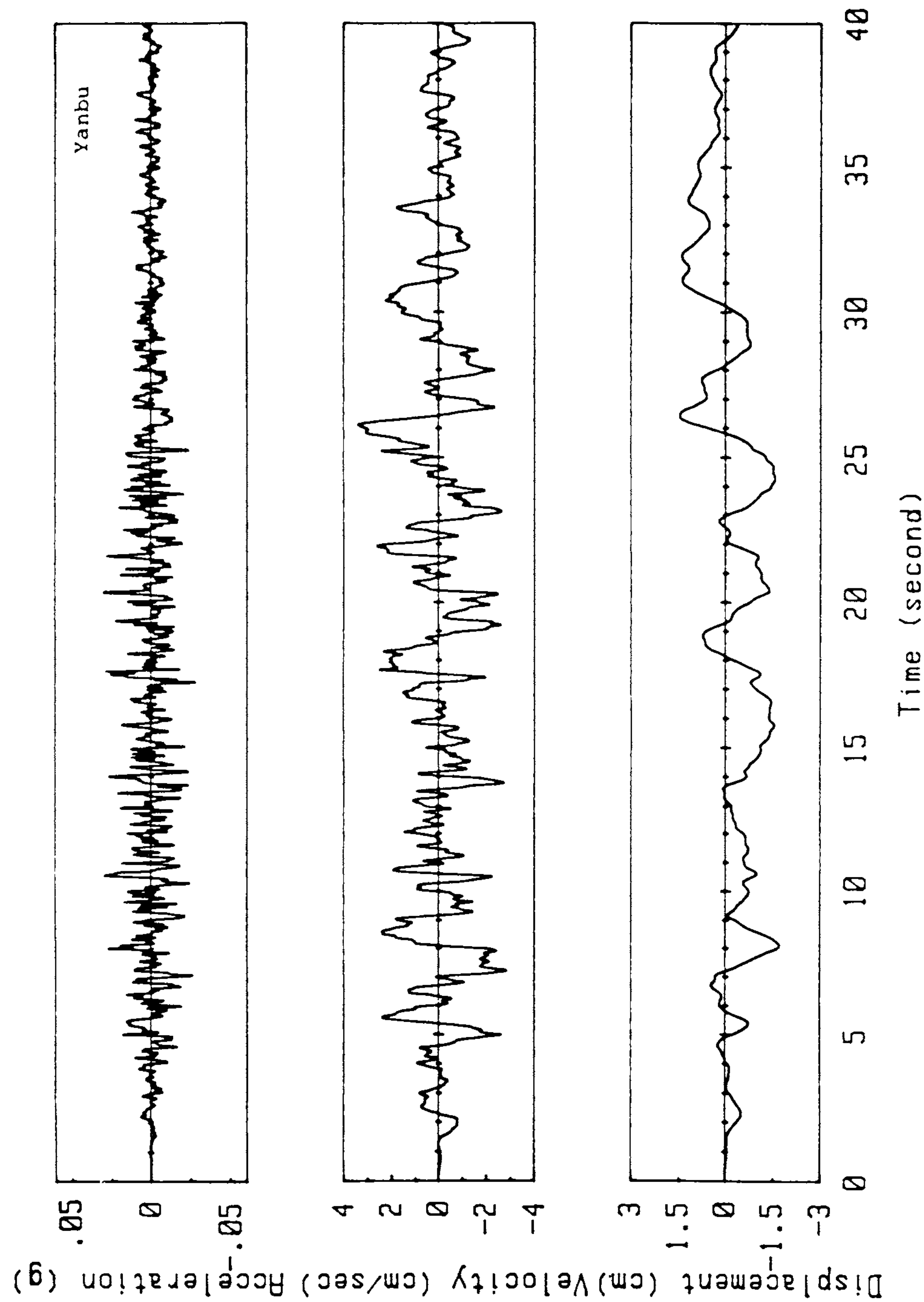

FIG. 6. Time history of ground motion for Yanbu.

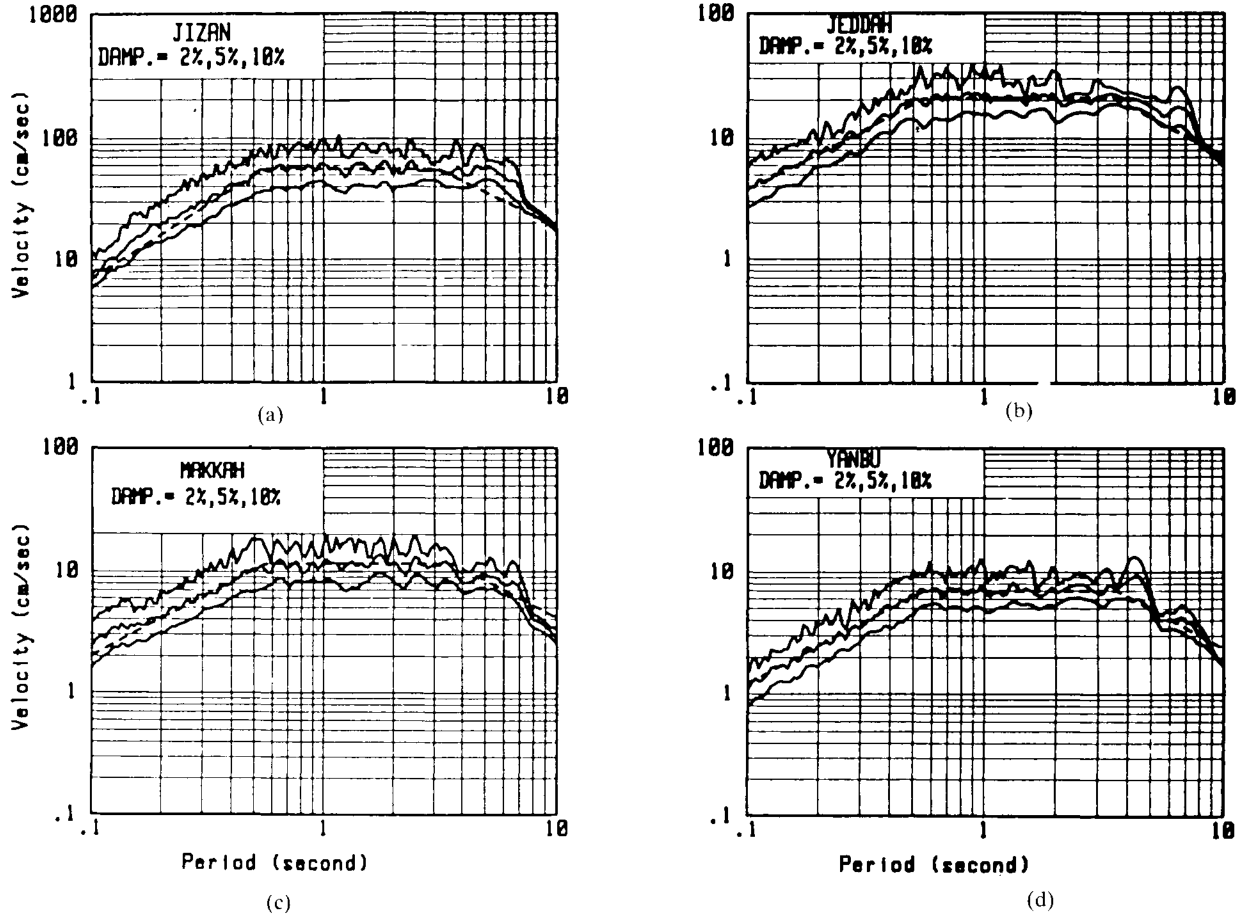

FIG. 7. Response spectra: (a) Jizan, (b) Jeddah, (c) Makkah, (d) Yanbu.

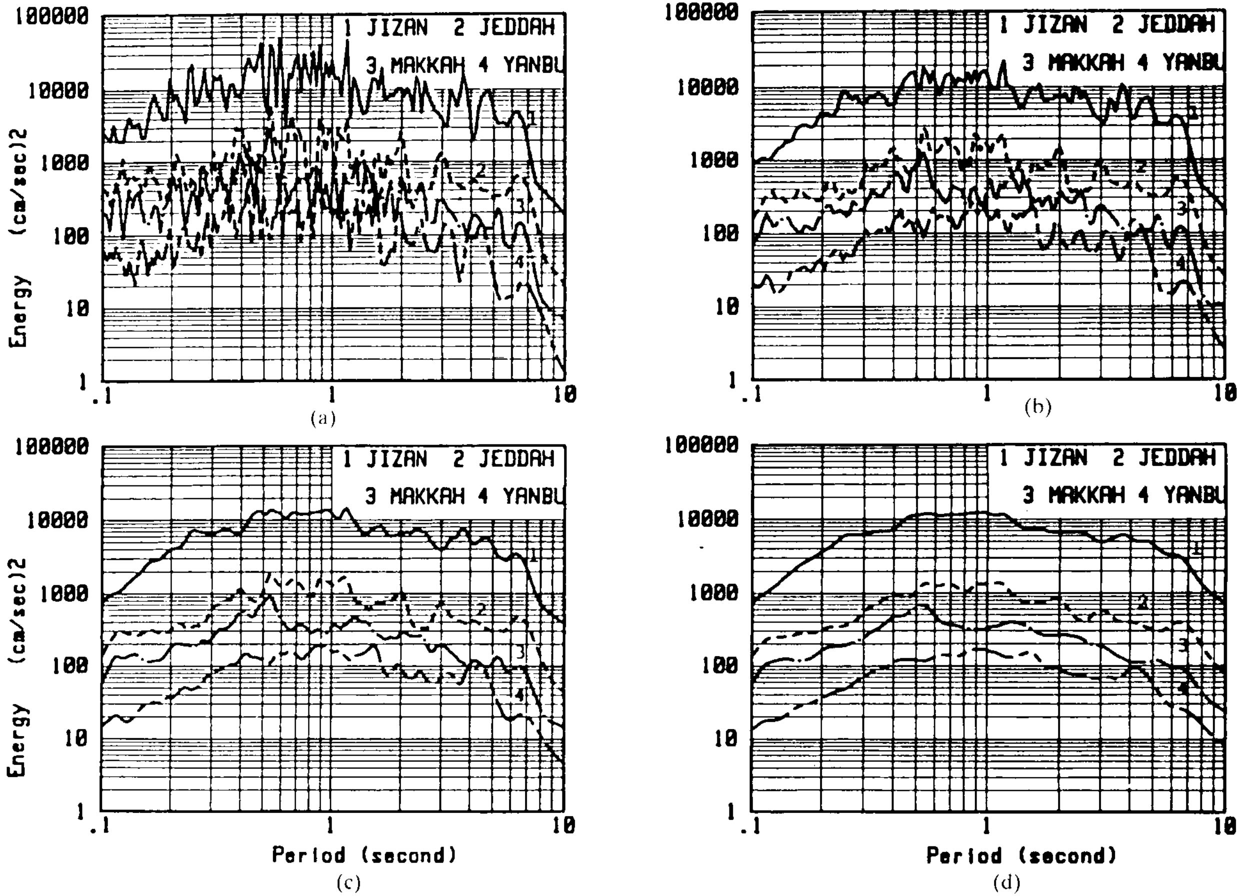

FIG. 8. Energy input per unit mass spectra: (a) 0% damping, (b) 2% damping, (c) 5% damping, (d) 10% damping.

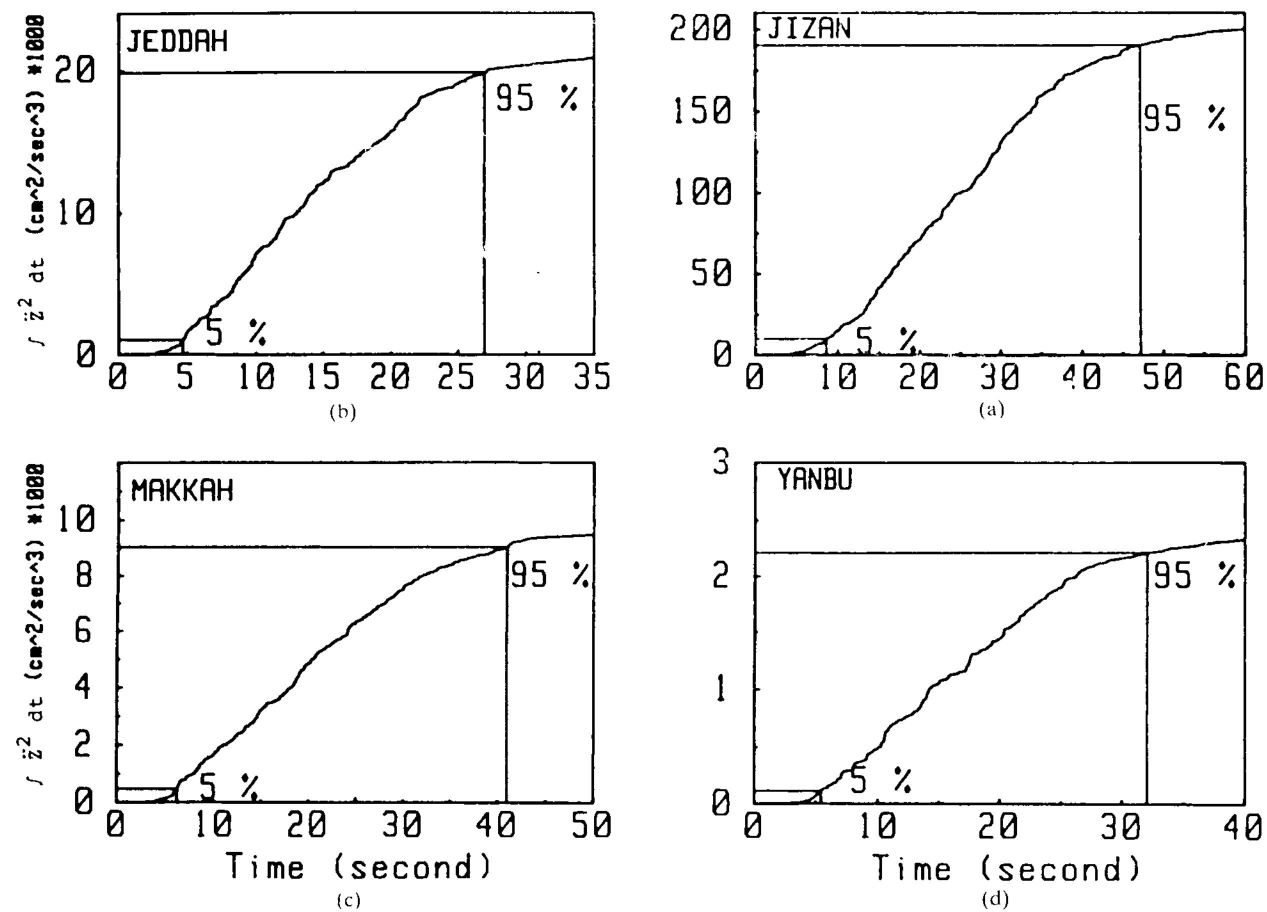

FIG. 9. Mean-square acceleration integral: a) Jizan, (b) Jeddah, (c) Makkah, (d) Yanbu.

the same figure, the durations for Makkah and Yanbu are 34.7 and 26.6 seconds respectively.

Another parameter that characterizes strong ground motion is the root-mean-square (RMS) acceleration which is defined as[37] :

$$\text{RMS} = \left[\frac{1}{T} \int_0^T \ddot{z}^2 (t) \, dt \right]^{1/2} \tag{16}$$

The cumulative RMS function (CRF) is a continuous representation of the RMS as a function of time. To determine the CRF, the RMS is calculated at every time increment of the acceleration record. The CRF provides a clear picture of the times at which pulses or groups of pulses of energy arrive[37]. Figure 10 shows the CRF for the simulated motions with the trend of real motions provides a reasonable representation of the simulated motions as an input for future seismic design.

The generated accelerograms enable a more reliable time history integration to be performed for the determination of seismic building response in the region. However, as pointed out by Vanmarcke[38], "a design response spectrum is developed to cover different possible ground motions (*e.g.*, caused by large distant earthquakes or close moderate earthquakes) each with its own frequency content and expected duration. The common practice of generating simulated motions for use in design based on a single spectral density function appears to be justified only if one earthquake source accounts for nearly all of the total site seismic risk, or if the local geology is principally responsible for shaping the frequency content of the ground motion. Otherwise, it is necessary to reexamine the data on seismicity and attenuation to determine the relative likelihood of occurrence of the various types of site ground motion and frequency content. These issues need considerable further study.

5. Conclusion

Applications of available procedures of transforming design ground acceleration and design spectra, obtained by seismic risk analysis, into time history accelerograms have been presented in this paper. This involves generating artificial earthquake reocords for the four major cities of Jizan, Jeddah, Makkah and Yanbu in the Western Region of Saudi Arabia with computed spectra that match certain prescribed target spectra with a specified damping. The target design spectra for each city has been calculated using the corresponding peak ground acceleration for the city, obtained from seismic risk maps available in literature for the region.

The artificial earthquakes obtained in this work reasonably reflect the geological and seismic nature of the Western Region in Saudi Arabia and provide better approach for the analysis and design of structures that are required to have reliable resistivity for seismic forces.

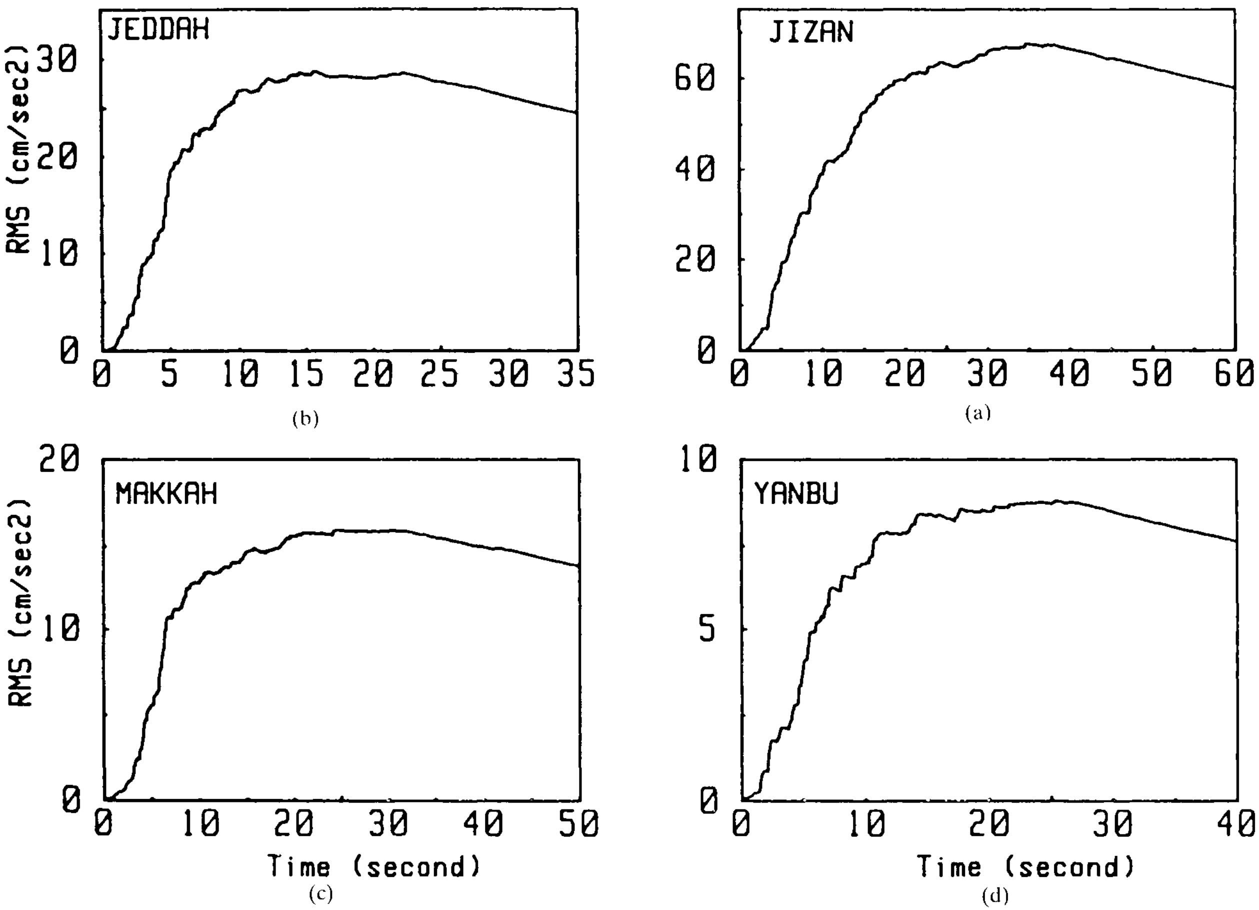

FIG. 10. Root-mean-square acceleration integral: a) Jizan, b) Jeddah, c) Makkah, d) Yanbu.

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تطبيــقات لطرق تحليل الخــطر الزلزالي ومحاكاة الزلازل في المنطقــة الغربيــة بالمملكة العربية السعودية

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المستخلص . تقـدم ورقـة البحث سلسلة لتـطبيقات طرق موجودة عن تحليل الخطر للزلـزال ومحـاكـاة الـزلازل بالنسبة لأربع مدن رئيسة في المنطقة الغربية بالمملكة العربية السعودية . وقد استخدمت خرائط الخطر الزلزالي المتوافرة بمراجع سابقة على هيئة أشكال تمثـل خطوطًـا متساوية الشدة وخطوطًا متساوية العجلة للمنطقة ، وذلك للحصول على أطياف التصميم لمدن جيزان ، جـدة ، مكة المكرمة وينبع . وقد تم تطبيق خطوات لتوليد زلازل اصطناعية تشمل علاقة زمنية بالنسبة للعجلة الأرضية ، والسرعة الأرضية والمسافة .

ويعتقد أن هذه الزلازل الاصطناعية تعكس بطريقة معقولة الطبيعة الجيولوجية والزلزالية للمنـطقـة . ونتيجة لعدم توافر أي معلومات مسجلة عن شكل تعجيل بالنسبة لزلازل سابقـة ، فإن هذه الـزلازل المصطنعة يمكن أن تكون ذات قيمة عالية لتحليل مُفصَّل وتصميم منشآت مقاومة للزلازل في المنطقة .