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Stochastic Attenuation Modelling: Saudi Arabian Case Study

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ABSTRACT

Conventional ground motion prediction relationships employed for seismic hazard assessment are typically developed from an empirical or semi-empirical modelling approach. The *Component Attenuation Modelling* (CAM) methodology which has been developed at the University of Melbourne for about a decade is based on stochastic simulation of the seismological model (which was originally developed from data recorded in *Western* and *Eastern North America*). CAM has been adapted to predicting ground motions for both *interplate* and *intraplate* regions around the world including Australia, South China, Sumatra, Singapore, Indo-China, India and Iran. In all these studies, simulations from the model were shown to be consistent with observations from instrumental and Intensity records obtained locally. The application of CAM to ground motion prediction for the Saudi Arabian region is described in this study. Original features of CAM includes incorporating shear wave velocity information of the earth crusts into the evaluation of parameters which characterise path modification behaviour. Accelerograms were first generated on bedrock using CAM. Modifications of ground motions by the soil sediments were then included into the model. Importantly, the effects the depth of the sediments and the shear wave velocity properties of the bedrock have upon soil modification behaviour have been taken into account. Design response spectra have been developed for numerous nominated cities with Saudi Arabia using this approach.

Keywords: attenuation, stochastic, seismic hazard, site amplification, Arabian Shield.

1. INTRODUCTION

Accurate seismic hazard assessments require an abundant and reliable database of ground motion records that are representative of regional and local conditions. However, in many regions of low to moderate seismicity, such a requirement is not fulfilled. The alternative approach of theoretical, semi-empirical or stochastic modelling can be employed. Stochastic models in regions of low seismicity are preferred because of their capability in capturing both local and regional conditions and their potential effects on the transmission of seismic waves. Stochastic attenuation models are typically expressed in the frequency domain (in the form of the Fourier amplitude spectrum) to generate a large number of synthetic accelerograms of pre-determined frequency contents for given earthquake scenarios. Stochastic simulation procedures have been applied in some of the western coastal cities of Saudi Arabia: *Haql, Al Wajh, Yanbu, Jeddah* and *Jizan* for modelling seismic hazard which have incorporated the effects of attenuation in rock as well as site amplification. Importantly, response spectra calculated from accelerograms simulated using the stochastic methodology have been found to be very consistent with response spectrum models stipulated by current codes of practices.

2. OVERVIEW OF SAUDI ARABIA SEISMICITY

The seismicity of Saudi Arabia has been classified as low to moderate. Regions with close proximity to the Dead Sea, the Gulf of Aqaba, the Red Sea and the Gulf of Aden are considered most critical. The biggest part of the Arabian plate belongs to the Kingdom of Saudi Arabia. According to Al-Haddad et al. (1994), tectonic boundaries are delineated as shown in Fig. 1. The Arabian-Persian Plates from the north collide along the Zagros Mountains. The Makran zone on the eastern side is where the subduction of the Arabian plate is located. The Owen fracture region and the Gulf of Aden and the Red Sea Axial troughs are all located in the southeast and the southwest of the country, respectively. The collision zone of the Arabian-Turkish Plates is located alongside the Tauras Mountains.

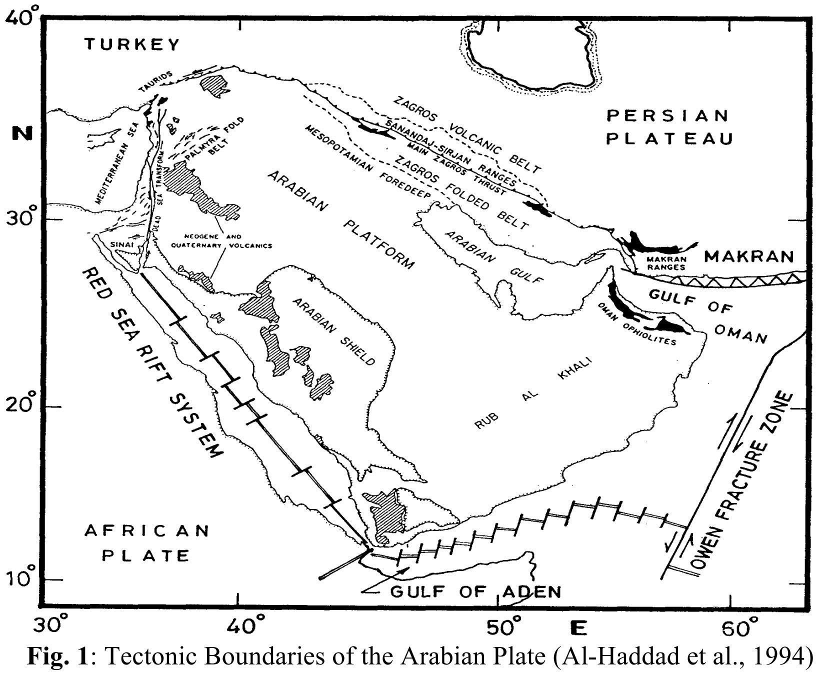

Fig. 1: Tectonic Boundaries of the Arabian Plate (Al-Haddad et al., 1994).

3. STOCHASTIC ATTENUATION MODELLING FOR SAUDI ARABIA ON ROCK SITES

The scarcity of observed and instrumental strong motion data around the globe, particularly in intraplate regions, is the main cause of uncertainties surrounding the estimates of earthquake ground shaking and the associated seismic hazard. Numerous studies and investigations have been conducted in the well-monitored regions of *Western North America* (WNA) and *Eastern North America* (ENA). The developed modeling procedure involves estimating the generation of seismic waves from the source of the earthquake, the transmission of the generated waves through long distances, and their upward propagation through the sedimentary layers up onto the ground surface.

3.1. DESCRIPTION OF SEISMOLOGICAL MODEL

Fourier amplitude spectrum Ax(f) has been commonly adopted by researchers (Brune, 1970; Boore, 1983; Boore and Atkinson, 1987; Hanks and McGuire, 1981; Atkinson, 1993; Atkinson and Boore, 1995; 1998; Atkinson and Silva, 1997, cited in Lam et al., 2000) to represent the seismological model. Traditionally, Ax (f) is function of both regional and local factors as shown in equation 1.

$$Ax(f) = S(f) \times G \times An(f) \times P(f) \times V(f) \qquad (1)$$

where S(f) is the regional source factor, G is the regional geometric attenuation factor, An(f) is the regional anelastic whole path attenuation factor, P (f) is the local upper crust attenuation factor and V (f) is the local upper crust amplification factor.

3.1.1. SOURCE FACTOR S(f)

A Fourier displacement amplitude model representing seismic waves radiated from the source of the earthquake was initially proposed by Brune (in the 1970's) and subsequently developed by Atkinson (1993). The latest form of the model featuring two corner frequencies is defined by equation 2.

$$S(f) = CM_O\left\{(1-\varepsilon)S_A + \varepsilon S_B\right\} \qquad (2)$$

$$S_A = \frac{1}{1+(f/f_A)^2}\ ;\ S_B = \frac{1}{1+(f/f_B)^2}\ ;\ C = \frac{R_P F V}{4\pi\rho\beta^3} \qquad (3,4,5)$$

where C is the midcrust scaling factor, M_O is the seismic moment (dyne-cm), R_P is wave radiation factor, F is the surface amplification factor, V is the factor partitioning energy in the two orthogonal directions, ρ is the rock density at the rupture depth (tonnes/m^3) and β is the shear wave velocity of the rock at the rupture depth (km/sec).

3.1.2. GEOMETRICAL ATTENUATION FACTOR (G)

The geometrical attenuation factor which is concerned with modelling the geometrical spread of energy can be expressed in the following form:

$$G = \frac{R_0}{R^n} \tag{6}$$

where R_0 is the reference distance (and is typically assumed to be 1 km), R is the source-to-site distance and n is a factor which is dependent on the value of R. The Geometrical attenuation factor can be estimated using equations (7.1-7.3) as function of the crustal thickness (D):

$$G = \frac{R_0}{R} \qquad (R \leq 1.5D) \tag{7.1}$$

$$G = \frac{R_0}{1.5D} \qquad (1.5D \leq R \leq 2.5D) \tag{7.2}$$

$$G = \frac{R_0}{1.5D}\sqrt{\frac{2.5D}{R}} \qquad (\ R \geq 2.5D\ ) \tag{7.3}$$

3.1.3. ANELASTIC WHOLE PATH ATTENUATION FACTOR An(f)

Energy dissipation of seismic shear waves along the wave transmission path through a long distance is often accounted for by the anelastic whole path attenuation factor An(f) which can be calculated using equation 8.

$$An(f) = e^{-\pi \times f \times R / Q\beta} \quad \text{(Boore and Atkinson, 1987)} \tag{8}$$

where Q is the wave transmission quality factor as defined by equation 9. It is clear from equation 8 that the shear wave amplitude attenuation is mainly affected by both the number of cycles along the wave travel path and the Quality factor for rock.

$$Q = Q_O (f/f_O)^n \tag{9}$$

where Q_o is the wave transmission factor at frequency of 1 Hz and f_o is the unit frequency.

3.1.4. UPPER CRUST ATTENUATION FACTOR P(f)

The effect of attenuation mechanisms in the upper part of the earth crust can be taken into account by the upper crust attenuation factor, $P(f)$ as defined by equation 10 (which is of the form similar to equation 8).

$$P(f) = e^{-\pi f \kappa} \tag{10}$$

where κ (pronounced as *kappa*), measured in seconds, is used in place of factor $R/\beta Q$ which forms part of the anelastic whole path attenuation factor $An(f)$. The upper crust attenuation factor is particularly relevant when dealing with modifications in the young sedimentary rock layers close to the earth surface. Abercrombie (1997) revealed that around 50–90% of the anelastic attenuation took place in the upper 300–3000 m of the earth crust in California (categorized as a young generic rock region). Atkinson and Boore (1998) proposed the following expression to account for such modification effects for the Californian crust:

$$\kappa = 0.0106M - 0.012 \tag{11}$$

ENA (categorized as a hard rock region), on the other hand, has a much lower κ value which can be conservatively assumed to be equal to zero.

3.1.5. UPPER CRUST AMPLIFICATION FACTOR V(f)

Young sedimentary rocks in the upper part of the earth's crust possess a very low shear wave velocity profile in comparison with the deeper sedimentary/metamorphic or crystalline rock layers. Consequently, shear waves are amplified when propagating through these rock layers up onto the earth surface. Amplification of seismic waves can be estimated using the conservation of energy principles. Boore and Joyner (1997) proposed a simple relationship as defined by equation 12 to account for the upper crustal amplification effects.

$$V = \sqrt{\frac{\rho_A V_A}{\rho_B V_B}} \tag{12}$$

where ρ_A and V_A is the density and shear wave velocity of rock at the depth of the source, and ρ_B and V_B is the density and shear wave velocity over a specific depth measured from the top of the crust.

4. ESTIMATED VALUES OF EARTH PARAMERES FOR THE WESTERN COAST CITIES OF SAUDI ARABIA

4.1. CRUSTAL STRUCTURE OF THE ARABIAN PLATE

The Arabian Peninsula is divided into two main provinces. The first province is the interior stable province which includes the *Arabian Shield* (comprising the Precambrian gneiss and metamorphosed sedimentary and volcanic rocks) in the west and the *Arabian Platform* (comprising the Phanerozoic sediments with Proterozoic basement rocks) in the east (Powers et al., 1966). The second province is represented by the interior platform and the sedimentary basins (Mokhtar and Al Saeed, 1994). The crustal thickness of the *shield* ranges between 35 and 45 km with an average value of 39 km (Al-Damegh et al., 2005). Mokhtar and Al Saeed (1994) modelled the shield crust by two layers with each layer being 20 km thick, and with a density of 2.72g/cm^3 and 2.87 g/cm^3 for the top and bottom layer, respectively.

According to Al-Damegh et al. (2005), the *Arabian Platform* crust is thicker than the *Shield* and with thickness ranging from 41 to 53 km in the southeastern part of the platform. Another crustal model proposed by Mokhtar and Al Saeed (1994) identified three layers in the make up of the crust. The first layer is about 3 to 5 km thick and with a density of 2.31g/cm^3; whereas the other two layers are each 20 km thick and with a density of 2.31g/cm^3 and 2.66 g/cm^3, respectively.

In the Red Sea region, both the oceanic and attenuated crust exist (Makris and Rhim, 1991). The crustal thickness decreases towards the Red Sea and the Gulf of Aqaba with a thickness of 23 km and 25 km, respectively. In this study an average crustal thickness value of 25 km has been assumed for the five coastal cities that are being studied.

4.2. ROCK TRANSMISSION QUALITY FACTOR (Q)

According to Pasyanos et al. (2009), there is a remarkable variation in the value of Q for distinct parts of the Arabian Peninsula and its neighboring regions. For instance, the Arabian Shield was assumed to possess a high value of Q (> 800). The northern part of the Arabian Platform has a slightly lower value of Q (300 – 400) whereas the rest of the platform has the value of Q in the range 400 – 600. Coastal strips along the Red Sea / Gulf of Aden as well as along the Zagros Mountains has much lower Q values (200 – 300).

The η factor in equation 9 is mostly unknown. One solution is to attempt to match the Q values obtained for the designated regions with the ones obtained from well-known, widely accepted relationships for other regions worldwide and to pick the corresponding η factor to represent the unknown ones. Incidentally, all the 5 cities being considered herein are situated in the coastal strip alongside the Red Sea and Gulf of Aqaba; hence, in accordance with Pasyanos et al. (2009), these cities should have the value of Q in the range 200 – 300. Given that the estimated range is consistent with that of California (where $Q = Q_O f^{\eta}; Q = 204 f^{0.56}$), hence, the value of η is estimated to be close to 0.56.

4.3. SHEAR WAVE VELOCITY PROFILE (SWV)

Most of the available literature regarding the shear wave velocity (SWV) profile for the different provinces within Saudi Arabia has been derived from deep seismic refraction surveys. However, information obtained from such surveys is not useful to constrain SWV profiles in the upper part (top 4 km) of the earth crust. For every city selected to be included in this study the SWV profile was inferred from information of the average SWV value in the top 30 m of the earth crust and that from deep seismic refraction survey studies. In addition, the SWV model developed for *WNA* was used as reference.

Data obtained from geotechnical investigations by Al Haddad et al. (2001) for the city of *Haql*, *Al Wajh*, *Yanbu*, *Jeddah* and *Jizan* were used to model SWV profiles at shallow depths. “Site 5” in the city of *Haql* was chosen to be representative of the near-surface SWV conditions for the eight other sites given that its V_{30} value is consistent with the value that has been averaged across those sites. Similarly, sites 1, 4, 2 and 4 were chosen to represent the top 30 m conditions of *Al Wajh*, *Yanbu*, *Jeddah* and *Jizan*, respectively. The most suitable model to represent the SWV profile from the seismological studies was chosen from Rodgers et al. (1999) (Fig. 2). The *Aqaba* model was chosen for the city of

Haql and the *Shield* model for the city of *Al Wajh*, *Yanbu*, *Jeddah* and *Jizan*. In summary, the suggested SWV profiles for the top 4 km of the earth crust's for the five cities are presented in Fig. 3.

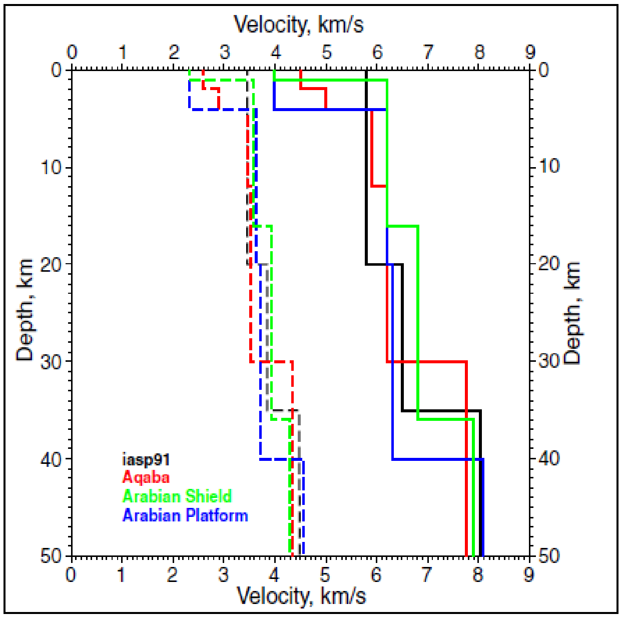

Fig. 2: S and P Seismic Shear Profile Dashed and Solid, Respectively (Rodgers et al., 1999).

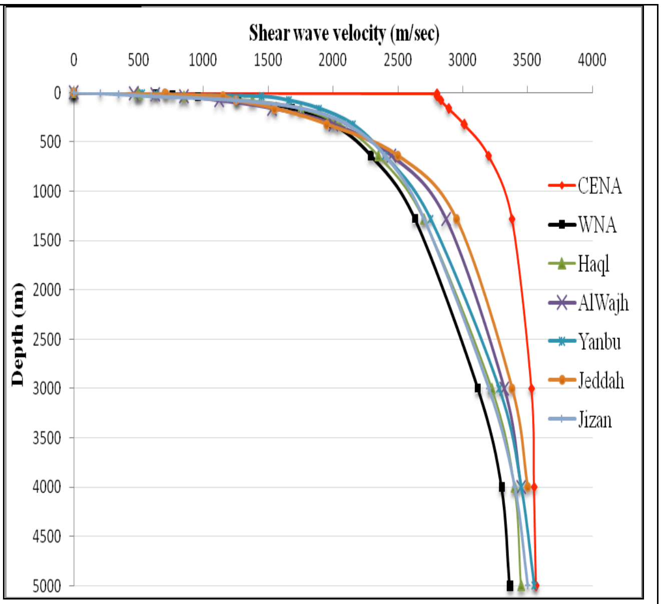

Fig. 3: Interpolated SWV Profile for the Western Coast Cities.

4.4. KAPPA VALUE (κ)

Direct measurement of the *kappa* value has not been mentioned in the reviewed literature conducted within the Saudi Arabian region. Alternatively, empirical relationships which correlate the value of *kappa* against that of a SWV parameter has been utilised for modelling purposes. Chandler *et al.* (2006) proposed an empirical relationship from global data that correlate *kappa* against the average SWV value for the top 30 m (V_{30}) of the earth crust as shown in equations 13; and in Table 1.

$$\kappa = \frac{0.057}{V_{s.0.03}^{0.8}} - 0.02 \qquad (3\text{ km/sec} \geq V_{s,0.03} \geq 0.5\text{ km/sec}) \qquad (13)$$

Table 1: Kappa Value for the Five Cities.

City	Haql	Al Wajh	Yanbu	Jeddah	Jizan
$V_{0.03}$ (km/sec)	0.450	0.537	0.566	0.662	0.284
κ	0.088	0.074	0.070	0.059	0.136

5. SYNTHETIC ACCELEROGRAMS DERIVATION

The pre-defined seismological model of the Fourier amplitude spectrum can be utilised and combined with randomly selected phase angles in a stochastic procedure to simulate the earthquake ground motion accelerograms e.g Fig 4. The generation of synthetic accelerograms were implemented using program, "GENQKE", which was developed at the University of Melbourne (Lam, 1999).

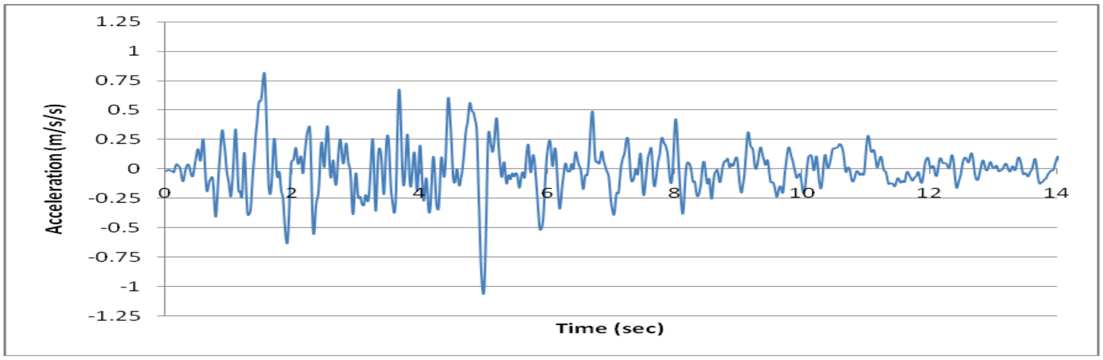

Fig. 4: An Example of Accelerogram Generated From M7R50 for Haql.

6. ACCELERATION RESPONSE SPECTRUM ON ROCK SITES

Elastic response spectrum of a rock site for 5% damping has been constructed by the use of program "Etamac" which accepts acceleration time-histories of the ground as input. Earthquake scenarios with moment magnitude ranging between 5 to 7 and site to source distance ranging between 10 to 70 km were considered. Response spectrum stipulated by the Saudi Building Code (SBC 301) for design purposes was found to be consistent with the response spectrums simulated/calculated by the authors based on 1 or 2 earthquake scenarios considered for each city. These SBC 301 compatible (best match) earthquake scenarios are shown in Table 2. The corresponding RSA diagrams are shown in Fig. 5.

For natural periods exceeding the peak acceleration limits for *Haql*, the M6R10 scenario curve is shown to diverge until it becomes around one-third of the SBC 301 model, whereas the other spectra are shown to match with natural periods exceeding 1 sec for *Al-Wajh*; the two scenario curves are shown to diverge for around one-third to two-thirds of the SBC 301 model. For *Jeddah*, for natural periods exceeding the limits of peak acceleration, the M6.5R30 scenario curve is shown to diverge for around half the level stipulated by the SBC 301 model whereas the other curves are generally consistent with the model.

Table 2: Summary of the Recommended Scenarios, *PGA* and RSA_{MAX} for the Five Cities.

City	Best matched scenarios		*PGA* (m/s/s)	RSA_{MAX} (m/s/s)
Haql	M6R10	M7R20	2.30	5.70
Al-Wajh	M6R30	M6.5R50	0.7	1.77
Yanbu	M6.5R70	---	0.5	1.28
Jeddah	M6.5R30	M7R50	0.78	1.96
Jizan	M6.5R70	---	1.10	2.80

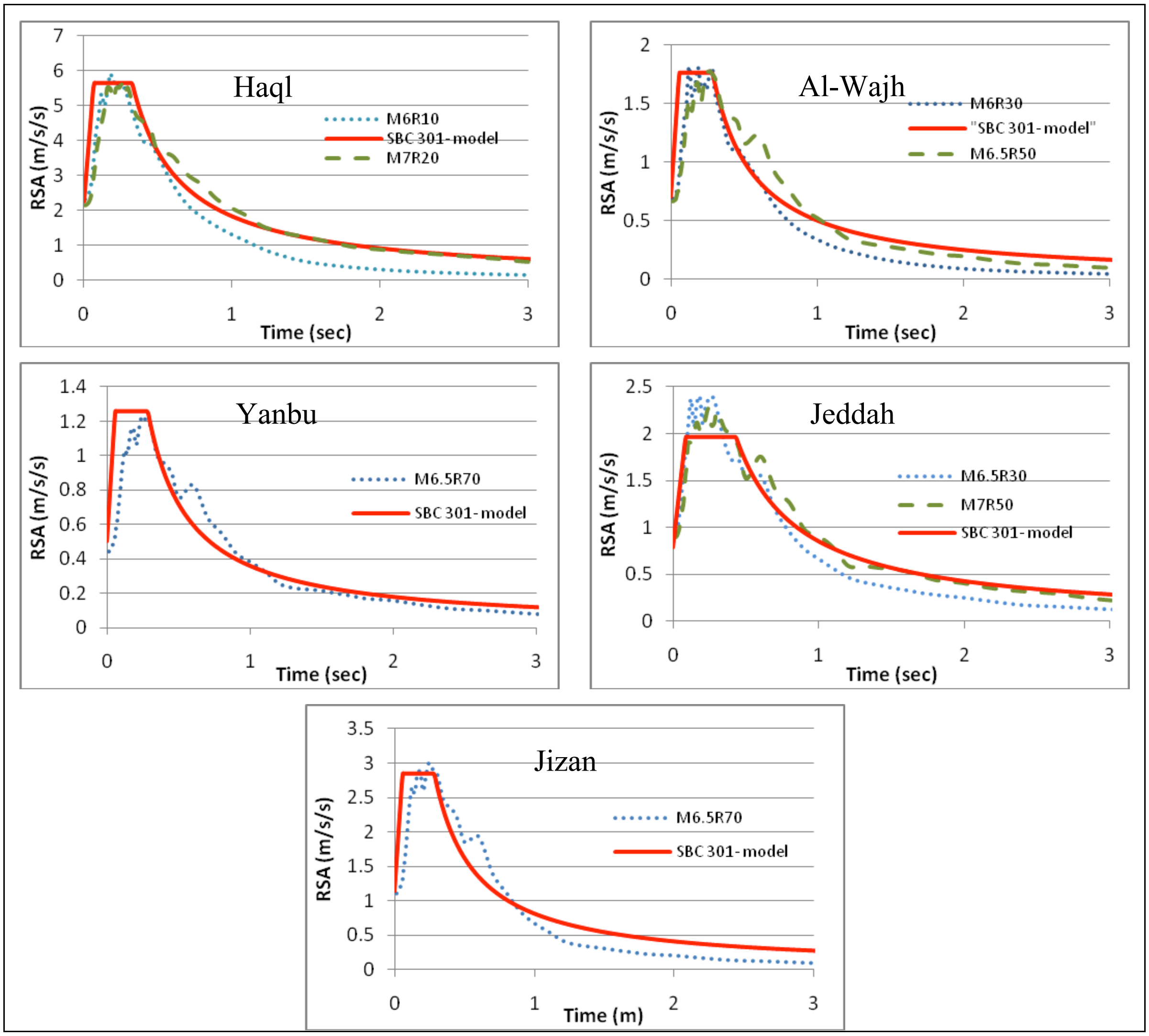

Fig. 5: Comparing the Code vs. the Stochastically Derived RSA Diagrams for the 5 Cities on Rock Sites.

7. ACCELERATION RESPONSE SPECTRUM ON SOIL SITES

The afore-mentioned stochastic simulation on rock sites for the five cities have been extended for evaluating the site amplification coefficients using program SHAKE. Thickness of the soil layers, SWV profile for each of the soil layers, depth to bedrock and the corresponding SWV value are the controlling parameters. Hence, the conventional approach of representing the top 30 meter of the soil layers by the corresponding SWV value was applied. In addition, the bedrock layers have also been modelled down to a depth where the SWV value reaches 3000 m/s as shown in Fig. 6.

The soil amplification effect on seismic waves as derived numerically in Fig. 7 has shown significant deviation from the suggested amplification effect in the SBC 301 code. At short natural periods, peak amplification from the numerical calculation resulted in a higher amplification effect than the code with percentages ranging from 67 % to 113 % for the city of *Haql*, *Al Wajh*, *Yanbu* and *Jeddah*. Similarly, the code model exceeds the amplification effect by the numerical approach at percentage values ranging from 40 % to 117 % for the same cities at long natural periods (at 3 seconds).

Although the afore-mentioned four cities possess similar characteristics in terms of the average SWV for the top 30 m (450 – 635 m/sec) and the site classification (Class C, very dense soil and soft rock), there are a great deal of uncertainties surrounding the estimates of the response spectrum. The *Jizan* model, on the other hand, showed a higher degree of discrepancy with the code model because of vulnerability of its soil to high potential of liquefaction at V_{30} = 284 m/sec. Furthermore, the code model for *Jizan* which is based only on the average SWV for the top 30 m of the soil layers (Class D, stiff soil), is not sufficient to model the potential risks of liquefaction.

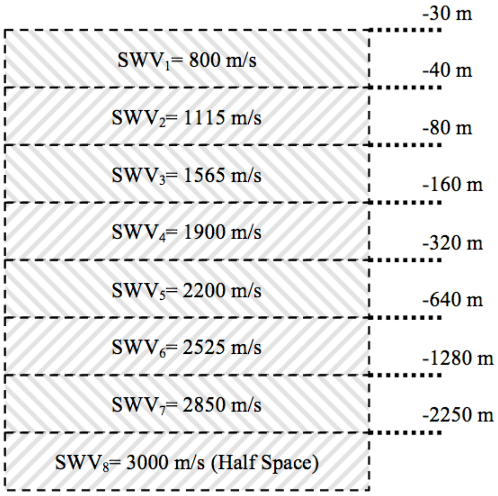

Fig. 6: The Rock Depth Modelling Stipulated in SHAKE (e.g., Haql).

Generally, discrepancies observed between the modelled site amplification effects and that stipulated by the code could well be understood given that the code model is based on averaging SWV value in the top 30 m of the soil layers irrespective of the actual depth to bedrock (and its SWV properties). Another source of discrepancies between the codes and results generated from this study can be attributed to uncertainties associated with parameters used for input into SHAKE, as well as uncertainties surrounding ground motions simulated for the calibrated earthquake scenarios.

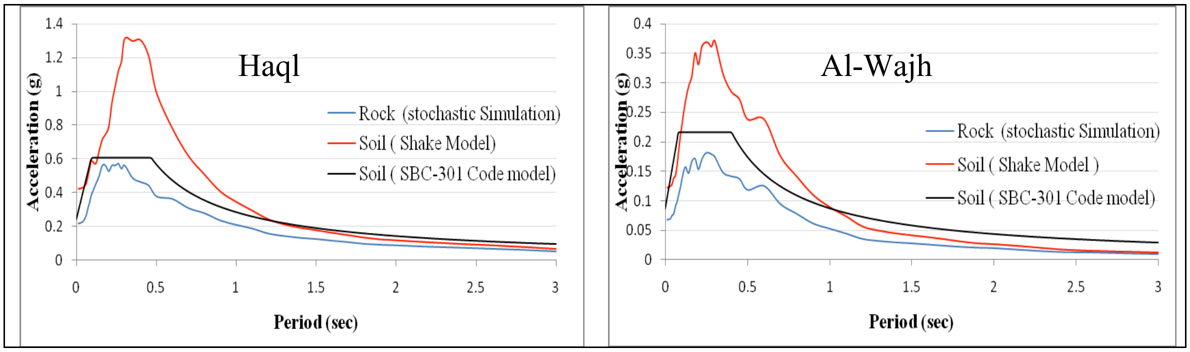

Fig. 7: Comparing the Code vs. the Stochastically Derived RSA Diagrams for the 5 Cities on Soil Sites.

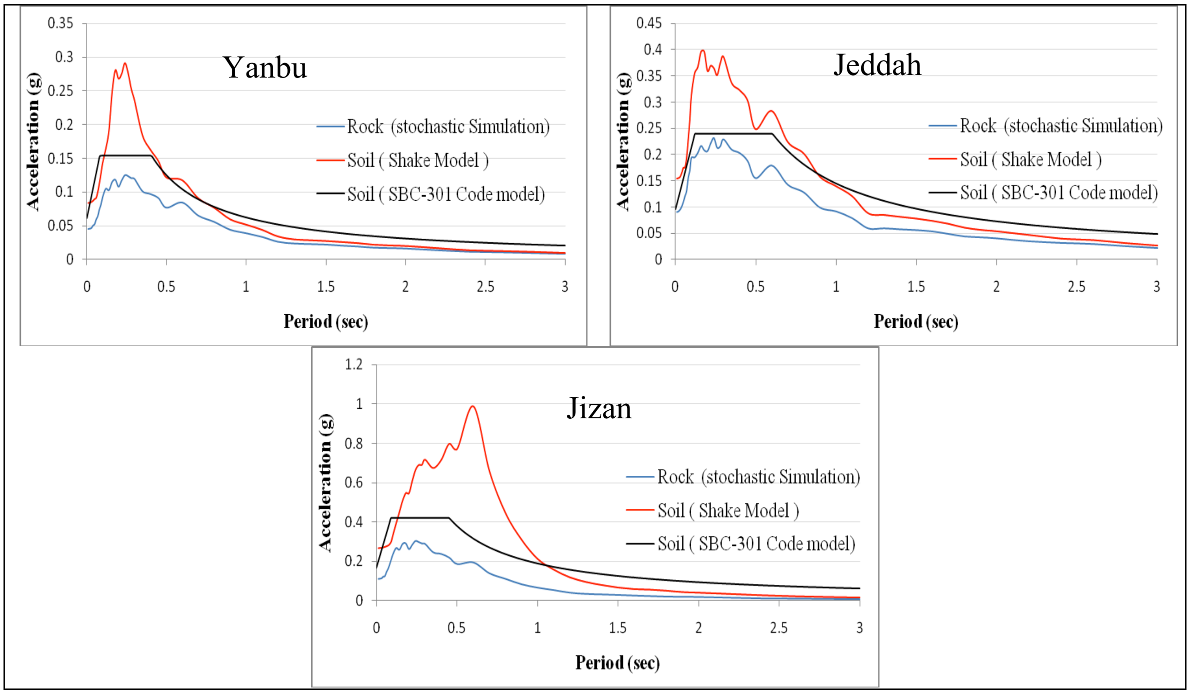

Fig. 7: Continued.

8. CONCLUSION

- Simulating earthquake response spectra on rock sites using the stochastic modeling approach requires good knowledge of the key parameters in the area of earth science. Knowledge of parameters such as the transmission Quality factor (Q) and the upper crustal attenuation parameter (*Kappa*) are often lacking. SWV profiles have been modeled by mathematical interpolation techniques based on results obtained from borehole tests and deep seismic refraction surveys.
- Stochastic simulation of the seismological model were utilised to simulate ground motion on rock sites for the city of *Haql*, *Al Wajh*, *Yanbu*, *Jeddah* and *Jizan*. Response spectra simulated from this study for certain earthquake scenarios were found to match with those stipulated by the Saudi Building code. The calibrated scenarios are namely M6R10 or M7R20, M6R30 or M6.5R50, M6.5R70, M6.5R30 or M7R50, and M6.5R70 respectively.
- A comparison of the response spectrum as derived numerically with the SBC 301 code model showed significant variation between the two models in the prediction of soil amplification effects. Typically, the code model underestimates amplifications at short periods but overestimate at long periods. Recommendations for modifications of the code model can be made once representative parameter values characterizing local and regional conditions have been identified.

9. REFERENCES

- Al -Damegh, K, Sandvol, E, & Barazangi, M 2005, ‘Crustal structure of the Arabian plate: New constraints from the analysis of telesismic receiver functions’, *Earth and Planetary Science letters*, vol. 231, pp.177-196.

- Al-Haddad, M, Al-Refeai, T & Al-Amri, A 2001 , 'Geotechnical Investigation for Earthquake Resistant Design in the Kingdom, Phase I, Western Coast', Final Report, King Abdulaziz City for Science and Technology, (KACST- Grant No. AR-14-77), Riyadh.
- Al-Haddad, M, Siddiqi, G.H, Al-Zaid, R, Arafah, A, Necioglu, A & Turkelli, N.A 1994, 'Basis for Evaluation of Seismic Hazard and Design Criteria for Saudi Arabia', *Earthquake Spectra*, vol.10, no.2, pp. 231-58.
- Atkinson, G 1993, 'Earthquake source spectra in eastern North America ', *Bull. Seism. Soc.Am.* vol. 83, pp.1778 –1789.
- Atkinson, G. M. & Boore, D. M. 1998, 'Evaluation of models for earthquake source
- spectra in eastern North America', *Bull. Seism. Soc. Am*. vol. 88, pp. 917-934.
- Boore, D.M & Atkinson, G 1987, 'Stochastic Prediction of ground motion and spectral response parameters at hard-rock sites in eastern North America ', *Bull. Seism. Soc.Am.* vol. 73, pp. 1865 –1894.
- Boore, D. B., Joyner, W. B. and Fumal, T. E. 1997, 'Equations for estimating horizontal response spectra and peak acceleration for western North American earthquakes: A summary of recent work', *Seism. Res. Lett*. vol. 68, pp. 128-153.
- Chandler, A, Lam, N. & Tsang, H 2006b, 'Near surface attenuation modelling based on rock shear – wave velocity profile', *Soil Dynamics and Earthquake Engineering*, vol.26,no.11, pp. 1004-1014.
- Lam, N. 1999, ' Program "GENQKE" User's Guide: Program for generating synthetic earthquake accelerograms based on stochastic simulations of seismological models', Department of Civil and Environmental Engineering, The University of Melbourne, Australia.
- Lam, N., Wilson, J & Hutchinson, G. 2000b, 'Generation of synthetic earthquake accelerograms using seismological modelling: a review ', *Journal of Earthquake Engineering*, vol.4, no.3, pp. 321-354.
- Makris, J. and Rhim, R. 1991, 'Shear-controlled evolution Red Sea: pull-apart model', *Tectonophysics 198 (199*1), pp. 441–466.
- Mokhtar, T & Al- Saeed, M 1994, 'Shear wave velocity structures of the Arabian Peninsula', *Tectonophysics*, vol. 230, pp.105-125.
- Pasyanos M, Matzel E, Walter W & Rodgers A 2009, 'Broad-band Lg attenuation modelling in the Middle East', *Geophys. J. Int*., vol. 177, pp. 1166-1176.
- Powers, R, Ramirez, L, Redmond, C & Elberg, E 1966, 'Geology of the Arabian Peninsula – Sedimentary Geology of Saudi Arabia ', *U.S.Geol.Surv., Prof*, .Pap.560-D, 147pp.
- Rodgers A, Walter W, Mellors R, Al-Amri AMS, Zhang YS 1999, 'Lithospheric structure of the Arabian Shield and Platform from complete regional waveform modeling and surface wave group velocities', *Geophys J Int,* vol. 138, pp. 871-878.
- Saudi Building Code (SBC – 301) 2007,'Loads and Forces Requirements', Saudi Building Code National Committee, Riyadh, KSA.
- Schnabel, PB, Lysmer, J and Seed, H, 1972, 'A Computer Program for Earthquake Response Analysis of Horizontally Layered sites', Earthquake Engineering Research Centre report: EERC 72-12, University of California at Berkeley, USA.