0179

INVESTIGATION ON ATTENUATION CHARACTERISTICS OF STRONG GROUND MOTIONS IN CHINA AND HONG KONG

Y L WONG[1] And John X ZHAO[2]

SUMMARY

We present qualitative evidence that strong-motion attenuation characteristics in China are significantly different from those of typical intraplate regions such as Eastern North America. We use a very limited amount of strong motion data to calibrate four recently developed attenuation models and we find that an attenuation model by Crouse & McQuire (1996), derived from Californian data, could possibly capture the main attenuation characteristics of the Tangshan earthquake and aftershocks. In the absence of published spectral attenuation models developed for China, we recommend the Crouse & McQuire model as a possible basis for seismic hazard study in Hong Kong and possibly for China as well. Our supporting evidence includes coda and S-wave Q factors, preliminary results of kappa values, stress drop and areas enclosed by the isoseismal of Modified Mercalli intensity V. The values of the parameters are all close to those from California.

INTRODUCTION

Many seismologists consider china to be an intraplate region (butler et al. 1979). On this basis a response spectrum attenuation model that is considered possibly suitable for china has been derived from a combination of a limited number of records from the 1976 tangshan earthquake and aftershocks and intraplate earthquakes from other parts of the world (dahle et al 1990). The model predicts a similar level of ground shaking to that predicted by the toro et al (1997) model for the central and eastern north america (ena) if applicable site conditions are considered to be the same for both models. Intraplate earthquakes are expected to produce a much higher level of ground shaking than interplate earthquakes at moderate to large distances because of the low attenuation rates observed for a stable continental environment such as ena.

Only a limited number of strong motion records are available for Chinese earthquakes, and most are from the 1976 Tangshan earthquake and aftershocks. Modified Meccarli Intensity (MMI) records, however, are abundant and reasonably reliable intensity attenuation models have been established for different parts of China. Strong motion attenuation models have also been established in China by modifying attenuation models derived from Californian strong motion data, based on comparisons of intensity attenuation models for China and for California (Huo et al 1992). The following two aspects of this methodology need to be examined carefully before engineering communities in Hong Kong can have full confidence in the models derived by this method.

To derive a useful attenuation model for seismic hazard analysis for engineering structures, reliable MMI data for intensity VI and greater have to be utilized. However, intensity is a damage index at MM VI or above and the amount of damage to structures during an earthquake depends on building materials, workmanship and structure configuration. In China, construction practice, structural configuration for residential houses and building materials changed little in more than a few hundred years before the middle of this century and changed significantly only in cities in the last 50 years or so. Those in US are, however, very different from those in China and the uncertainties associated with

[1] *Dept of Civil and Structural Eng, The Hong Kong Polytechnic University, Hong Kong, Email: ceylwong@inet.polyu.edu.hk*
[2] *Institute of Geological & Nuclear Sciences, Gracefield, Lower Hutt, New Zealand, Email: j.zhao@gns.cri.nz*

1) attenuation models based on comparisons of MMI attenuation may be quite high, even though great care has been taken by Chinese seismologists in determining consistent MMI scales.

2) The correlation between strong motion parameters, such as peak ground acceleration (PGA), and intensity is only moderate and so uncertainty in an attenuation function derived from an MMI-PGA correlation would be considerable. The correlation between MMI and response spectra at moderately long and long periods (for example > 0.5s) would be even worse than that for PGA, because high MMI data are usually inferred from the amount of damage to brittle and stiff structures and low MMI data are inferred from felt reports. Human perception is likely to be most sensitive to high frequency components of ground motions.

The biggest question for earthquakes in China is whether source and attenuation characteristics are similar to those of California or to those of ENA, because the level of ground shaking predicted by models for these two different tectonic regions can be very different at source distances of 100km or more. In the present study, we compare a very limited number of strong motion records obtained in the Tangshan earthquake and aftershocks with a number of recently developed attenuation models for both plate boundary and intraplate regions. We also compare the Q factors (anelastic attenuation factor for the earth's crust), kappa value (the high-frequency decay factor of acceleration Fourier spectra) and some existing attenuation models derived for California, ENA and China, so that qualitative guidance on the attenuation characteristics for China can be obtained. We further compare the areas enclosed by the MM V isoseismal in ENA and China. Finally we recommend suitable response spectrum attenuation models for the Hong Kong region.

STRONG MOTION DATA SET

We carefully selected 45 strong motion records from the Tangshan earthquake and aftershocks recorded by analogue instruments, and 65 more recent digital strong motion records from the same area. The records were obtained from CDs issued by the US National data center and the data was originally from the Harbin Institute of Engineering Mechanics (IEM) which manages a major strong motion network in China. We have reprocessed all records and ensured that the records were essentially free from noise by examining Fourier spectrum and displacement plots (Zhao 1999). As a result, the maximum usable periods for most records were found to be much shorter than those recommended in the data files from the CDs and only a small number of the records could be used at a spectral period of 2.0s. We carried out site classification for all stations by carefully examining published site soil profiles, with invaluable assistance from Professor Peng of IEM (per. comm. 1999), according to the classification scheme used by Crouse & McQuire (1996). The records were mostly from stiff and intermediate soil sites.

Uncertainties in earthquake magnitudes can be very large for small earthquakes recorded only by a near-source array of digital strong-motion instruments. Peng et al (1985) reported that the local magnitudes determined for those events with $M_L>3.8$ were based on the records from a soil-site station and that profound site effects would be expected. Peng et al (1985) deducted 0.5 of a unit of magnitude for those events in order to eliminate the bias with magnitudes in their PGA attenuation modelling. However, the magnitudes for those events in the CDs and the other catalogues published in China are not always consistent with the recommendation of Peng et al. We did not use the digital records to calibrate existing attenuation models, because we also found significantly large and consistent bias of those records with respect to all the models we calibrated. For the other earthquakes, we adopted the surface-wave magnitudes reported in the International Seismological Center (ISC) catalogue determined by a number of organizations, and moment magnitudes M_w reported in the Harvard catalogue. We adopted M_L as the best estimate of M_w for two events (M_L = 5.4 and 5.6) for which M_w was not available. We used the focal depths reported by IEM. Some of the depths were found to be significantly different from those reported in the ISC catalogue but we do not expect the depth uncertainties to have a great effect on the results of our study because most stations are 30 km or more away from source. For one event in our data set, focal depth was not reported by IEM and the focal depth reported in the ISC catalogue was far too large compared with that indicated by P- and S-wave travel time difference in a high quality record obtained at an epicentral distance of 19km. We therefore used a focal depth of 12km for this event.

We would also expect a considerable uncertainty in earthquake location, and indeed the differences in epicentral distances calculated from the locations reported by Chinese seismologists and by ISC are typically about 20km. We found that the locations reported by China for the Tangshan aftershocks were consistent with the P- and S-wave separations for a small number of records from analogue instruments that recorded the first arrival of P-waves. We therefore adopted the source locations reported in China for all aftershocks and used the hypocentral distance as source distance. We calculated the source distances for the Tangshan earthquake according to a seismological model by Liu (1985).

Our final dataset contained 35 components from 7 earthquakes with Ms=5.5-7.8.

ATTENUATION MODELS

The objective of our study was to determine whether the attenuation characteristics in China are similar to those of plate boundary regions or to those of intraplate regions. We used a number of existing models for comparison purposes. The first was the Abrahamson & Silva (1997) model for crustal earthquakes in California and a few overseas events. It is valid for moment magnitudes of 4.4-7.4 and closest distances to fault rupture of 0.1-220km. It has two site classes, i.e. rock and soil based on Geomatrix site classification methods.

We also selected the model of Crouse and McQuire (1996). Their model uses surface-wave magnitudes, which are the magnitudes most used for attenuation studies in China. The model has four site classes from A to D corresponding to B to E in the NEHRP seismic provisions.

We compared the records from the Tangshan event and aftershocks with the attenuation model derived from world-wide intraplate earthquakes by Dahle et al (1990). A small number of rock site records from the Tangshan earthquake and aftershocks were included in their data set. Their model is for rock sites only and there was no clear definition of site conditions in terms of shear-wave velocity. From our assessment of the sites in China included in Dahle et al model, the model seems to be intended for all rock sites, including soft rock sites. The model is for the larger of the two horizontal components and so we divided the predicted results by a factor of 1.13 so that both horizontal components could be used to calibrate the model. Because the number of records from rock sites is very small, we also included records from soil sites in our present study. We calculated average spectral ratios for site classes B, C and D with respect to class A from Crouse & McQuire model by selecting M_s=5, 5.5 and 6.0 for PGA=0.05g, 5.5, 6.0 and 6.5 for PGA=0.1g and 6.0, 6.5 and 7.0 for PGA=0.15g, so that a reasonably wide range of magnitude and distance is covered.

We calibrated the model derived for ENA by Toro et al (1997) which was based on stochastic simulations. Their model is for hard rock sites with surface shear-wave velocities larger than 1600m/s, whereas the rock sites in our data set are all soft rock sites. We adopted the following approach to derive spectral ratios between soft rock and hard rock sites. Boore and Joyner (1997) presented site amplification factors for rock sites with average shear-wave velocity of 620m/s in the top 30m. The amplification factors have to be modified by a suitable kappa value (the decay rate of acceleration Fourier spectra at high frequencies) for rock sites. We selected a kappa value of 0.035s based on our preliminary results as described later in this paper. This approach, however, produced de-amplification at frequencies above about 9 Hz and this is not consistent with many attenuation modelling results for hard rock sites. We selected the average value at frequencies 3-6 Hz as the amplification factor for PGA at 0.1s period. The amplification effect for hard rock site presented by Boore and Joyner was not accounted for here and any possible amplification between the rock sites defined by Toro et al and those by Boore and Joyner was not accounted for either.

According to several published studies the Tangshan events are usually considered to be dominantly strike-slip, and so we have adopted a strike-slip mechanism for all attenuation models that have focal mechanism as a model parameter.

RESIDUALS ANALYSIS

The residuals of the selected records with respect to four attenuation models are shown in Figure 1. Because the number of records is very small, we present all the residuals for periods between 0.0 and 0.5s in one figure. Figure 1(a) shows that the residuals with respect to the Dahle et al model have a clear bias with source distance, although the mean residual is close to zero. The clear trend with distance suggests that the anelastic attenuation factor Q in the Tangshan area of China is larger than those derived by Dahle et al from intraplate records. Figure 1(b) shows that the model by Crouse & McQuire (1996) predicts the response spectra surprisingly well, without significant bias in the residual distribution. Figure 1(c) shows that the Toro et al (1997) model over-predicts the recorded ground motions and that the residual distribution with distance has no clear trend. Figure 1(d) shows that the Abrahamson & Silva (1997) model under-predicts the recorded strong motions within about 50km distance and over-predicts beyond about 160 km.

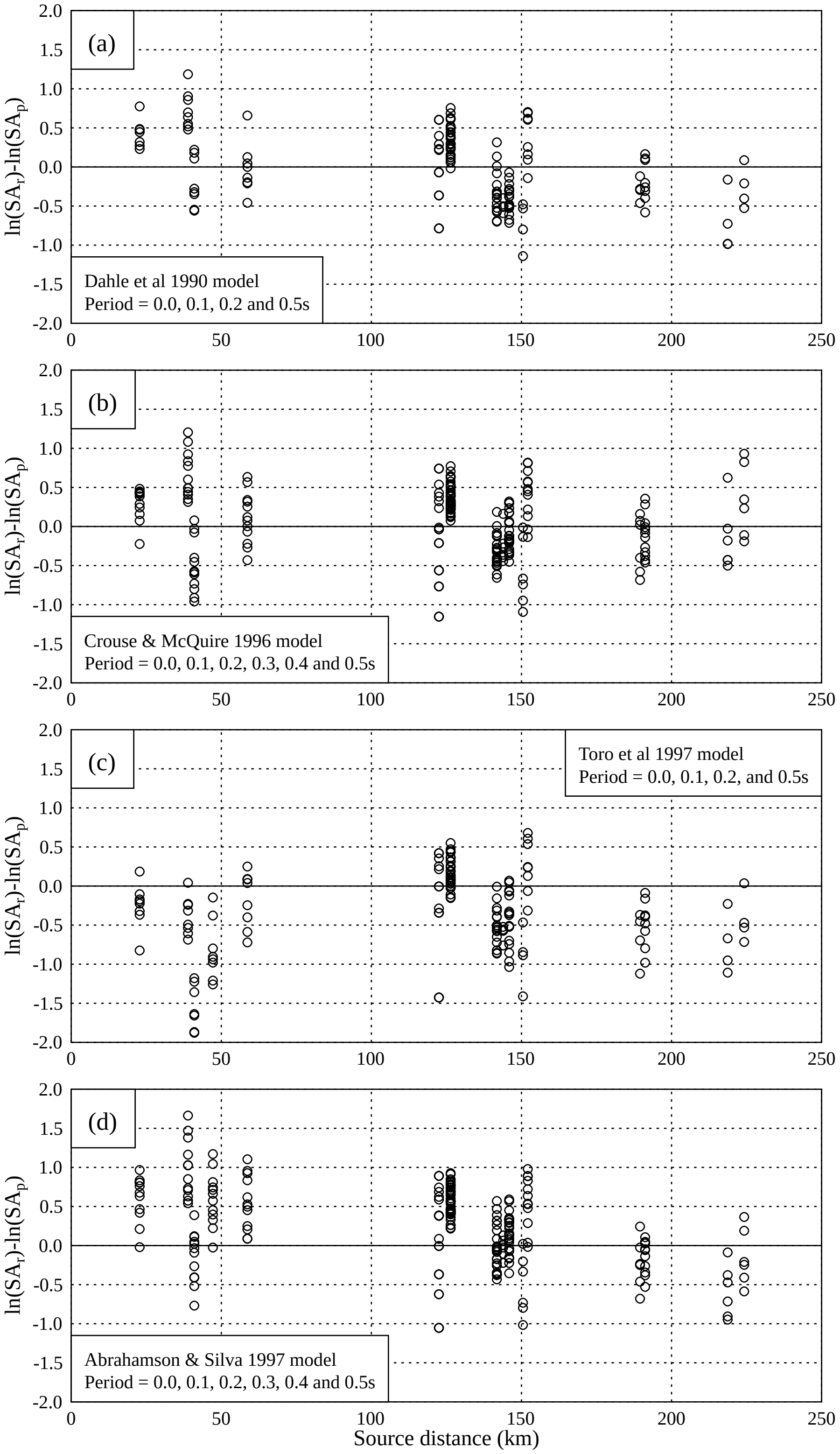

Figure 1 Residuals of strong motion data with respect to attenuation models calibrated (a) Dahle et al 1990 (b) Crouse & McQuire 1996 (c) Toro et al 1997 and (d) Abrahamson & Silva 1997.

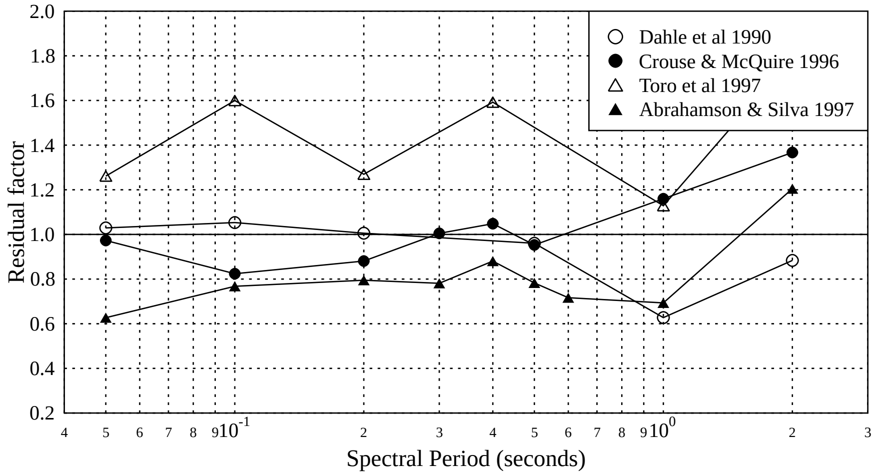

Figure 2 Residual factors of Tangshan earthquake data with respect to attenuation models

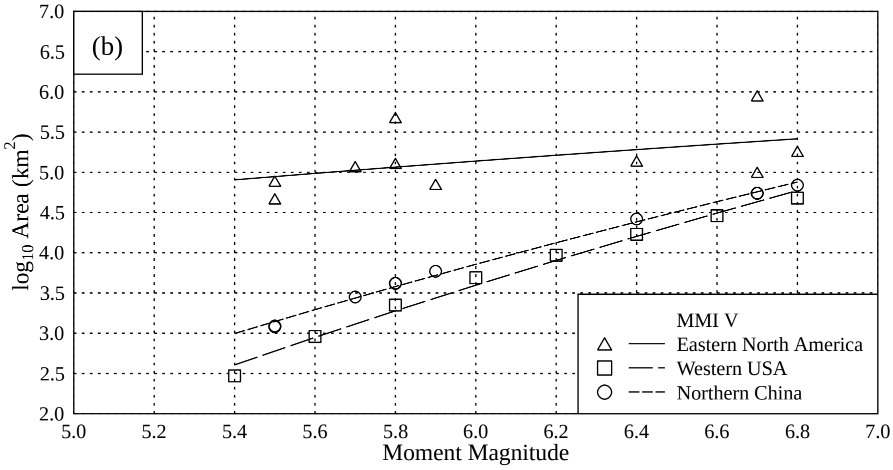

Figure 3 Comparison of area enclosed by MM V isoseismal in ENA, western USA and China

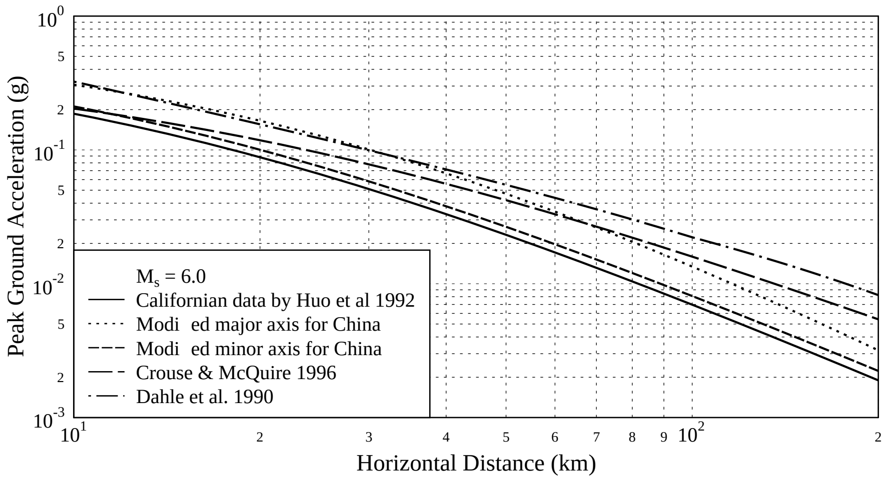

Figure 4 Comparison of attenuation models for peak ground accelerations

We do not present the residuals for spectral periods of 1.0 and 2.0 seconds for a number of reasons. In the present data set a small number of sites are deep soil sites which are likely to have first modal periods between 1.0 and 1.5s. At this period range, site resonance is likely to occur and the resonance effect will be clearly reflected in residual plots. However, attenuation models are usually derived from a large number of ground motion records and resonance effects would be diminished by the averaging procedure in a regression analysis. Residuals analyses at long periods for a small number of records would be likely to suggest large bias that would not exist when a large number of records are used. We also processed many records using a high-pass filter having a corner frequency of 0.5 Hz and therefore the spectra for those records would be under-estimated for spectral periods of 1.5-2.0 seconds.

Mean residual factors for the four models are presented in Figure 2. The mean residual factor is defined by the mean ratio of the predicted to the recorded response spectral values. Figure 2 shows that both the Dahle et al (1990) and the Crouse & McQuire (1996) models predict the recorded motions very well on average. The Abrahamson & Silva (1997) model under-predicts the recorded motions on average by 40% for PGA and about 20% for the other periods, and Toro et al (1997) model over-estimates the recorded motions on average by 40%.

The above analyses seem to produce conflicting results. Residuals analysis with respect to the Abrahamson & Silva (1997) and the Toro et al (1997) models suggests that the attenuation characteristic in China is between those of intra- and inter-plate regions, even when the Toro et al model is been modified by accounting for the high kappa value in China. However, both the Dahle et al (1990) and the Crouse & McQuire (1996) models predicted the recorded motions in China reasonably well. This discrepancy is likely to be largely caused by using different magnitudes, i.e., moment and surface wave magnitudes in the two sets of models. The uncertainty in magnitude estimates significantly affects the results of the residuals analysis as a relatively large number of records are from two large earthquakes. Using the moments derived by various researchers, moment magnitudes differing more than 0.4 units can be estimated for the same earthquake. Also, unfortunately, half of the strong motion data used in the present study are from a single event with M_s= 6.8 for which M_w= 6.4 is reported in the Harvard Catalogue. If M_w for this event is under-estimated or M_s is over-estimated by a significant amount, this will be directly reflected in the residuals distribution in Figures 1 and 2 for all models. Another possible uncertainty arises from the site conditions used in the Dahle et al model, as we cannot verify all site conditions (ie, hard vs soft rock). We found that a quite large number of Tangshan records used in the Dahle et al model possibly contained excessive noise, and we also suspect that some of these records contain only part of the complete ground motion time history. We therefore recommend the Crouse & McQuire (1996) model as a possible basis for seismic analysis in China and Hong Kong with further supporting evidence that the attenuation characteristics in China are close to those in California.

SUPPORTING EVIDENCE OF ATTENUATION CHARACTERISTICS IN CHINA

The first supporting evidence for our recommendation of the Crouse & McQuire (1996) model for China and Hong Kong is the area enclosed by the MM V isoseismal. Atkinson (1993) showed that the area enclosed by the MM II isoseismal correlates very well with high-frequency acceleration spectra (Fourier). MM intensity V is usually inferred from felt reports rather than amount of damage to structures and therefore the determination of MM V should be independent of factors such as building materials, workmanship and structural configuration. We expect that the area enclosed by the MM V isoseismal would be very similar in two regions with similar source and attenuation characteristics. To estimate the average area enclosed by MM V isoseismals, we used the MM intensity attenuation model developed by Huo et al (1992) for the northern part of China. We also used the MM Intensity model reported by Huo et al (1992) for the western USA to estimate the average area enclosed by MM V isoseismal. We converted M_w to M_s by using a model based on world-wide data (Ekstrom & Dziewonski 1988). The MM comparison, Figure 3, clearly shows that area enclosed by the MM V isoseismal in China is very similar to that for the western USA and significantly different from that of ENA (from Atkinson 1993). However, a direct comparison between the area estimated from MMI attenuation models and the observed data is not strictly valid for the following reasons. Attenuation models are usually derived by ordinary least squares regression analysis and intensity is usually taken as the dependent variable. For the present comparison distance should be taken as the dependent variable. It is well known that ordinary least squares methods produce two straight lines that cross each other, at the mean data point, at a considerable angle when the scatter of the data set is large. This is one possible reason why the straight line passing through the data shown in Figure 3 for ENA has considerably smaller slope than the lines passing through the data points of the enclosed area derived from the MMI attenuation model. The large difference between ENA and China in Figure 3 at magnitudes less than 6.4 is most likely caused by this discrepancy and the difference at the magnitude range of 6.4-6.6 is likely to be credible. The comparison between China and the western USA is, however, made on an equivalent basis. Another possible problem in the above comparison is that the MM V isoseismal is not available for moderately large or large earthquakes and extrapolation using an MM intensity attenuation model is therefore required. For this reason we did not attempt to compare the areas enclosed by isoseismals of MM IV or less because the extrapolations to such low intensities would be too great.

The second supporting evidence for our recommendation is the kappa value estimated for the records obtained in China. Our preliminary results show that the kappa values for the Tangshan earthquake and aftershocks vary between 0.02s and 0.07s for rock and soil sites and these are much larger than the typical values for ENA (less than 0.01s). The kappa values for the Tangshan event and aftershocks are similar to those derived for California (Anderson et al 1996).

The third supporting evidence is the Q factor at 1.0 Hz derived for China. Using intensity data, Chen and Nuttli (1984) obtained a Q factor of 544 for a region including Beijing and Tangshan and 592 for a region including Hong Kong. Later Chen et al (1984) estimated a coda Q value of 400-500 for the Beijing area. Jin and Aki (1988) estimated a coda Q value of 150-320 for the Beijing and Tangshan areas and 240-370 for the Hong Kong region. More recently, Zhang and Matsunami (1997) derived an S-wave Q factor of 67 using data obtained in a strong motion array in Tangshan in China. Even though the Chinese Q values estimated by different authors vary significantly depending on the data and the methods used, the values are closer to those of California (200-360, assuming geometric attenuation, Atkinson & Silva 1997) than to those of ENA (670-2000, assuming geometric attenuation, Atkinson & Mereu 1992).

The last supporting evidence is the stress drop estimated for the Tangshan earthquake and aftershocks. Many estimates of stress drop have been made for the events, and typically they vary from 6 to 45 bars. These values of stress drop are even smaller those estimated for Californian earthquakes (50-120 bars, Atkinson & Silva 1997) and much smaller than those estimated for the earthquakes in ENA (100-500 bars, Atkinson 1993).

Finally, in Figure 4, we compare the attenuation models derived by comparison of MMI attenuation models and MMI-PGA correlation and the two models derived directly from strong motion data. Figure 4 shows that the Crouse & McQuire (1996) model predicts significantly higher PGAs at all distances than the model developed by Hou et al (1992) from their Californian data set. The differences between these two models are most likely due to the size of data set with the data set of Crouse & McQuire being significantly larger than that used by Huo et al. Within about 70km of source the Crouse & McQuire model varies from the Huo et al models for minor axis to major axis. Beyond 70km, the Crouse & McQuire model predicts higher PGAs than the model by Huo et al. The Dahle et al (1990) model predicts similar PGAs to the Huo et al major axis model up to about 40km, but for moderate to large distances predicts much larger PGAs than all the other models. We attempted to make comparison only at magnitude 6.0 as this is likely to be the average magnitude for all the data sets from which these attenuation models were derived.

DISCUSSION AND CONCLUSIONS

Even though we recommend the Crouse & McQuire (1996) model as a possible basis for seismic hazard analysis in Hong Kong, there are many questions still unanswered. Our data shows that the model by Abrahamson & Silva (1997) under-estimates the recorded motions and the model by Toro et al (1997) significantly over-estimates the recorded motions of the Tangshan event and aftershocks. The amount of reliable strong motion data is, however, too small and we are forced to rely on seismological evidence for qualitative support. Our results certainly show that the attenuation characteristics in the northern part of China are significantly different from those in Eastern North America even though attenuation modelling there has a very large uncertainty. Our results suggest that many seismological parameters associated with attenuation functions, such as the Q factor, the kappa value and the stress drop, in China are close to those in California. We can also confirm that on average the area enclosed by the MMI V isoseismal in northern China is very similar to that in California. This similarity is, however, not enough to verify that both source and path parameters are similar. Further research is required to separate source, path and site effects so that detailed comparisons can be made.

In the absence of published and carefully calibrated spectral attenuation models for China, we recommend that the model developed by Crouse & McQuire 1996 (originally intended primarily for estimating site effects) be a possible candidate for seismic hazard analysis for Hong Kong. The model is calibrated in the present study by data from the northern part of China only, and so any differences in attenuation characteristics between the northern part of China and the Hong Kong region are not yet accounted for. However, the preliminary results of Chen & Nuttli (1984) and Jin & Aki (1988) suggested very similar values of Q factor for Beijing area and Hong Kong region.

ACKNOWLEDGEMENT

The work presented here is part of a large research project, in the Department of Civil and Structural Engineering of the Hong Kong Polytechnic University, funded by the university to investigate possible seismic effects on engineering structures in Hong Kong. A large number of our colleagues in Hong Kong, China and New Zealand have made significant contributions to this project. The authors wish to thank Dr. Qifeng Luo of Tongji University for his invaluable contribution, Professor Kezhong Peng of Harbin Institute of Engineering Mechanics and a large number seismologists from the China Seismological Bureau for their invaluable discussions. The authors also wish to thank Drs. K.T. Chau and E.S.S. Lam for their support and contribution to this project and Dr. Jim Cousins for review this manuscript. The support for Dr. John Zhao from Institute of Geological & Nuclear Sciences of New Zealand is gratefully acknowledged.

REFERENCES

1. Abrahamson, N.A. and Silva, W.J. (1997), "Empirical response spectra attenuation relations for shallow crustal earthquakes ", *Seism. Res. Let.*, **68**, pp 94-127.
2. Anderson, J.G., Lee, Y., Zeng, Y. and Day, S. (1996), "Control of strong motion by the upper 30 meters", *Bull. Seism. Soc. Am.,* **86**, pp1749-1759.
3. Atkinson, G. (1993), "Earthquake source spectra in Eastern North America", *Bull. Seism. Soc. Am.*,**83**, pp1178-1798.
4. Atkinson, G. and Mereu, R.F. (1992), "The shape of ground motion attenuation curves in southeastern Canada", *Bull. Seism. Soc. Am.*, **82**, pp2014-2031.
5. Atkinson, G. and Silva W. (1997), "An empirical study of earthquake source spectra for California earthquakes", *Bull. Seism. Soc. Am.,* **87**, pp97-113.
6. Boore, D.M. and Joyner, W.B. (1997), "Site amplifications for generic rock sites", *Bull. Seism. Soc. Am.,* **87**, pp327-341.
7. Butler, R., Stewart, G.S. and Kanamori, H. (1979), "The July 27, 1976 Tangshan, China earthquake – a complex sequence of intraplate events", *Bull. Seism. Soc. Am.*, **83**, pp 1178-1798.
8. Chen, P. and Nuttli, O.W. (1984), "Estimates of magnitudes and short-period wave attenuation of Chinese earthquakes from Modified Mercalli intensity data", *Bull. Seism. Soc. Am.*, **74**, pp957-986.
9. Chen, P., Nuttli, O.W., Ye, W. and Qin, J. (1984), "Estimates of short-period Q values and seismic moments from coda wave for earthquakes of the Beijing and Yuan-nan regions of China", *Bull. Seism. Soc. Am.,* **74**, pp1189-1207.
10. Crouse, C.B. and McQuire J.W. (1996), "Site response studies for purpose of revising NEHRP seismic provisions", Earthquake Spectra, **12**, pp407-439
11 Dahle, A., Bungum, H. and Kvamme, L.B. (1990), "Attenuation models inferred from intraplate earthquake recordings", *Earthquake Engineering and Structural Dynamics*, **19**, pp. 1125-1141.
12 Ekstrom, G. and Dziewonski, A.M. (1988) "Evidence of bias in estimations of earthquake size", *Nature*, **332**, pp319-323
13. Huo, J.Y., Hu, Y.X. and Feng, Q.M. (1992), "Study on estimation of ground motion from seismic intensity", *Earthquake Engineering and Engineering Vibration*, **12**(3), pp 1-15 (in Chinese).
14. Jin, A. and Aki, K. (1988), "Spatial and temporal correlation between coda Q and seismicity in China", *Bull. Seism. Soc. Am.,* **78**, pp741-769.
15. Liu, F. (1985), "Tangshan earthquake", Seismological Press, Beijing
16. Peng, K., Xie, L., Li, S., Boore, D.M., Iwan, W.D. and Teng, T.L. (1985) "The near-source strong-motion accelerograms recorded by an experimental array in Tangshan, China", *Physics of the Earth and Planetary Interiors*, **38**, pp 92-109.
17. Toro, G.R., Abrahamson, N.A. and Schneider J.F. (1997), "Model of strong motions from earthquakes in central and eastern north America: best estimates and uncertainties", *Seism. Res. Let.*, **68**, pp41-57.
18. Zhang, W. and Matsunami, K. (1997), "A comparison of site-amplifications estimated from different methods using a strong motion observation array in Tangshan, China", *Proceedings of International Symposium on Natural Disaster Prediction and Mitigation,* Dec. 1-5, 1997, Kyoto, Japan, pp91-106
19. Zhao, J.X. (1999), "Development of attenuation models from JMA strong motion data", *GNS Client Report 1999/25*, Prepared for Dr. Paul Somerville of the Woodward-Clyde Federal Services.