CONSIDERATION OF EARTHQUAKES IN THE DESIGN OF THE MACAU TOWER

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SUMMARY

Macau Tower, a 338 m tall communication and observation tower currently under construction, is designed to remain essentially undamaged when subject to normal design level earthquake motions and to provide a high level of confidence of satisfactory performance during the Maximum Credible Earthquake (MCE).

To assess the appropriate design loads for seismic resistance, a site specific hazard study has been undertaken. The seismicity model used was derived from information obtained from Pu and Xiaohua (1997) and Pun and Ambraseys (1992). The attenuation-with-distance relationship used is that derived by Boore et al (1994). Information on soil conditions were obtained from the borehole logs prepared for the project geotechnical investigation.

Results of the assessment are presented in the form of estimated recurrence of peak ground acceleration, 5% damped hazard spectra for various return periods and response spectra estimated for the Maximum Credible Earthquake (MCE).

An additional analysis, utilising an unpublished (at the time) seismicity model derived by Wong *et al.* (1998) was also performed. The predicted seismic hazard at the site obtained using this model is higher than obtained using the Pun and Ambraseys model. It was, however, considered inappropriate at the time of our assessment to use the results of that study until such time as the model was published and subject to technical scrutiny.

The effect on the Tower of the design earthquake, and even MCE, motions is less than that resulting from severe wind i.e., typhoon with 1000 year return period).

INTRODUCTION

Macau is located in a region of a relatively low seismicity, approximately 60 km to the west of the seismically active ‘Earthquake Belt of the Pacific’. However, the Macau Tower, by virtue of its long natural period in the range of 6 - 7 seconds, also has the potential to be excited by large distant earthquakes.

The assessment of the seismic hazard at the site has included a probabilistic hazard analysis and an assessment of the Maximum Credible Earthquake (MCE) for the project.

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Figure 1: Macau Tower – an artist's impression

PROBABILISTIC SEISMIC HAZARD ANALYSIS

A hazard analysis requires two main inputs: a seismicity model, which defines the expected future occurrence of earthquakes in the region around the site; and appropriate attenuation relationships defining the expected variation in shaking with distance away from an earthquake epicentre. These two aspects are combined in the hazard analysis to provide statistical predictions of likely future occurrences of seismic shaking. It is also necessary to access the soil conditions at the site so that an appropriate attenuation relationship can be chosen.

TECTONICS AND SEISMICITY OF THE REGION

Macau is located in the southeastern part of Eurasian Plate, which is bordered by the Pacific Plate and the Philippine Sea Plate in the east and by the Indian Plate in the southwest. Seismic zoning of China, governed by the plate and fault block movements, includes 13 provinces and belts (Pu and Xiaouhua, 1997). Macau, which is very close to Hong Kong, is in the souteastern coastal tectonic block margin seismic province. This province belongs to an interplate region with moderate to strong seismicity. However, the narrower region around Hong Kong and Macau has low to moderate seismicity.

Faults in the Macau area have predominantly northeast and northwest direction. The nortwest orientated Laniau-Sanmen Island fault separates Macau block from the Hong Kong-Kowloon block to the east.

SEISMICITY MODEL

The seismicity within a particular seismic source region can be expressed in terms of the Guttenberg-Richter equation:

$$\log N = a - bM, \quad M \le M_{max} \qquad (1)$$

where: N = Frequency of occurrence of earthquakes of magnitude greater than or equal to M

M_{max} = Magnitude of the largest earthquake believed possible in the region considered

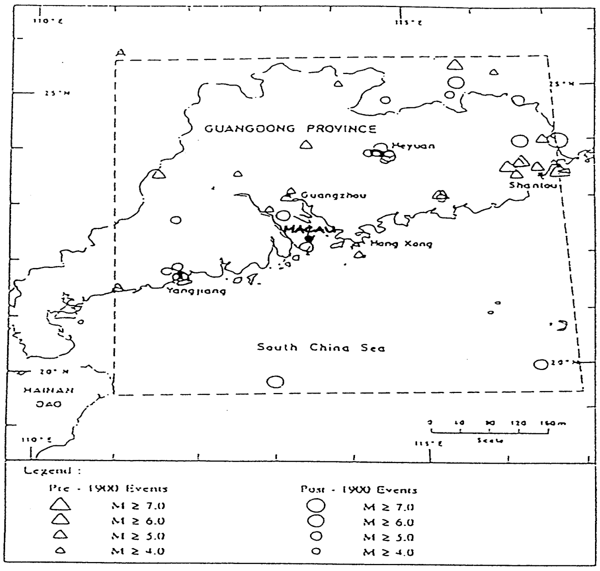
a and b are constants

Pun and Ambraseys (1992) define a uniform activity rate for the recurrence of earthquakes of various surface wave magnitudes, M_s, for a 660 x 660 km area around Hong Kong. This seismic model, shown in Figure 2, was considered appropriate for our study for the following reasons:

- the area investigated spreads well beyond Macau i.e., it is large enough to cover the region of interest, and

- the model was the result of, to the best of our knowledge, the most comprehensive study of the seismicity in this region, available at the time of performing the seismic hazard study.

Figure 2: Location of the Study Area and Earthquake Epicentres within the Area (Pun and Ambraseys, 1992)



One of the main references Pun and Ambraseys used in their 1992 study was the five-volume catalogue of Chinese earthquakes entitled *Compilation of Historical Materials on Chinese Earthquakes* and published in the period 1983 to 1986. This catalogue summarises information on historical and recent earthquakes including those for the Guangdong Province, which is in close proximity to Hong Kong and Macau. The first documented earthquake in this Province occurred in 288 A.D.

Information from the above document was combined with those from numerous other references (refer to Pun and Ambraseys, 1992). To eliminate discrepancies between different documents all data were critically examined and, where possible, magnitudes were re-calculated from raw data. Events and their associated magnitudes M_s (surface wave magnitudes) used in the derivation of the seismicity model are listed in Table 1 of Pun and Ambraseys (1992).

The authors made several adjustments before the final values for the constants a and b in formula (1) were calculated. Firstly, events that occurred prior to 16th century were discarded from the assessment. It is generally considered that the list of the events prior to about 1500 A.D. in this part of the world is unlikely to be complete. Also, of all listed events that occurred after 1500 A.D. only major events ($M \geq 6$) were taken into account in the analysis. It is considered reasonable to expect that historical records of small magnitude events, even after the 16th century, are incomplete. This is even more likely for those which occurred offshore, as their effects would have attenuated markedly by the time they reached the coast (Wong et al, 1998).

Therefore, the Pun and Ambraseys (1992) model is controlled by the large magnitude records since 16th century and small magnitude records (4.5 to 5.5) since 1900. The resulting recurrence relationship is:

$$\log N = -2.87 - 0.75 \times M_S \qquad (2)$$

where: N = Frequency of occurrence of earthquakes of magnitude greater than or equal to M_s per year per km^2

For this project the above relationship was modified to allow use of moment magnitude, as discussed later, and rearranged into its final form:

$$N = 0.01 \times (10^{1.1(4-M_w)} - 10^{1.1(M_w - M_{\max})}) \qquad (3)$$

where: N = Frequency of occurrence of earthquakes of magnitude greater than or equal to M per year per 1000 km^2

M_w = Moment magnitude

MAXIMUM MAGNITUDE

A hazard analysis requires an estimate to be made of the maximum magnitude event M_{max} for the region. This can be assessed from the tectonic setting of the region and/or from past seismicity. A sensitivity study performed by Pun and Ambraseys (1992) adopting M_{max} values of 6 to 8 showed the predicted Peak Ground Acceleration (PGA) is insensitive to the assumed value. This was also confirmed in our study. The sensitivity of predicted hazard response values, especially for longer structural periods, is, however, greater.

The area around Macau and Hong Kong is divided by Pu and Xiaohua (1997) into several zones each with an associated M_{max}. These values range from Richter magnitude 6.5, in the vicinity of the Macau, to 7.5 further to the south. In this study we have conservatively set M_{max} to 7.5.

ATTENUATION MODEL

It appears that no strong motion records for any earthquake within the region are available and, therefore, no local attenuation relationships have been developed. Pun and Ambraseys (1992) used an attenuation model derived by Joyner and Boore in 1981 to estimate recurrence of peak ground acceleration in Hong Kong. This model was developed from data obtained from western American shallow events similar to those in south China and was, therefore, considered appropriate for this part of the world.

The Joyner and Boore (1981) model uses moment magnitude (M_w) as a measure for earthquake energy. Pun and Ambraseys modified this relationship for use with M_s (surface wave magnitude) to be consistent with their seismicity model.

Most of the earthquake sources within the Macau region are also likely to be of shallow interplate tectonic type. It would have been possible to use the above attenuation model in our assessment. We have, however, decided to use the latest model derived by Boore et al (1994). The Boore et al (1994) attenuation relationship also uses moment magnitude, but rather than adjusting the attenuation relationship, the seismicity model was modified using the correlation relationship between M_s and M_w provided by Ambraseys (1990).

The Boore et al (1994) attenuation model predicts attenuation of structural response for structural periods of up to 2 seconds. The expected first mode period for the Tower is in the order of 6 - 7 seconds. For this study the expected response values for periods longer than one second were assessed by extrapolation - multiplying the value for the structural period of one second by the factor of 1/T, where T is the structural period in seconds. This is equivalent to making an assumption of constant response velocity beyond a period of 1.0 second.

SUBSOIL CONDITIONS

Boore et al have introduced, in their 1994 attenuation model, a classification of sites, in terms of site soil condition, which depends on the average shear wave velocity as shown in Table 1:

Table 1: Classification of sites (Boore et al, 1994)

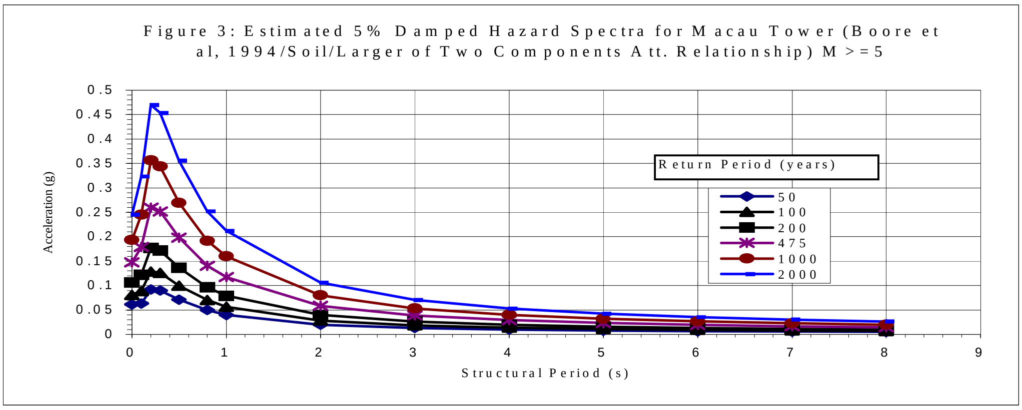
Site Class	Average Shear Wave Velocity (m/s)
A	> 750
B	360 - 750
C	180 - 360
D	< 360

Based on available information on site geology we have assessed that the tower site can be categorised as a class C site.

RESULTS

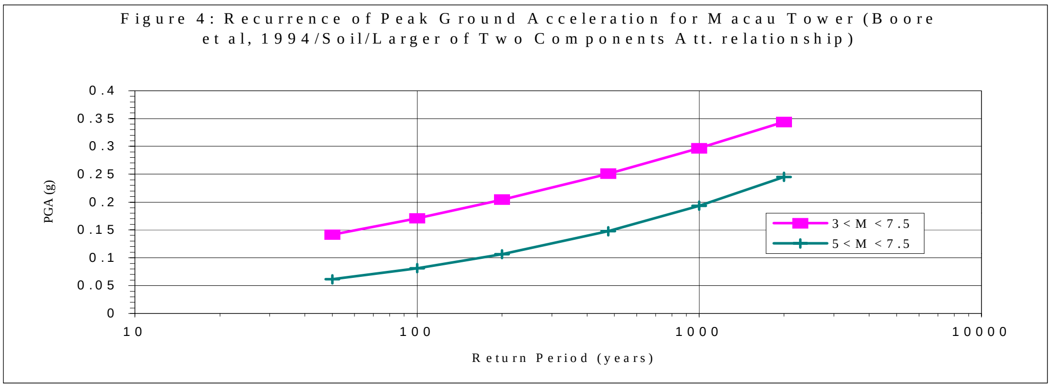
Hazard Spectra

The 5% damped hazard spectra for various return periods are shown in Figure 3. These have been estimated including the contribution of all earthquakes of magnitudes greater than or equal to 5.0. Earthquakes with magnitudes less than 5 are considered to be of insufficient duration to severely damage the tower.



Peak Ground Acceleration

The estimated recurrence graphs of peak ground acceleration, including the contribution of all earthquakes of magnitude greater than or equal to 5 and greater than or equal to 3 (to allow for the assessment of susceptibility to liquefaction), are shown in Figure 4.



Maximum Credible Earthquake (MCE)

The largest earthquake believed possible in a region (i.e., M_{max}) can, but need not necessarily, be chosen as the MCE for a certain project. For this project we have taken the magnitude of the MCE to be equal to M_{max}.

The magnitude and the location of the MCE was assessed from the available data (Pu and Xiaohua, 1997 and Pun and Ambraseys, 1992). Two possible scenarios were considered:

1. A Richter magnitude 6.5 event approximately 20 km from the site. The estimated return period for this event, as calculated from the adopted recurrence relationship, is about 40000 years.

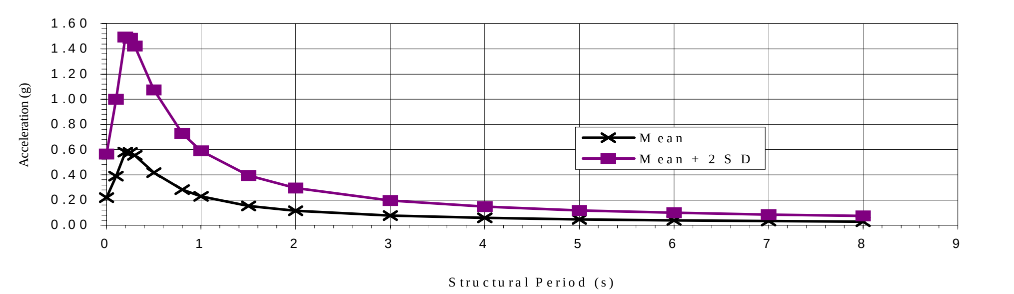
2. A Richter magnitude 7.5 event approximately 60 km South-east of the site with an estimated return period in excess of 100,000 years.

It is considered possible for an earthquake of magnitude 6.5 to occur say within 10 km from the tower (Pun and Ambraseys, 1992), but the estimated return period for such an event is so large that it is deemed statistically insignificant during the design life of the tower.

The spectral accelerations at the site from the first scenario (1 above), obtained using Boore et al (1994) attenuation relationship, are assessed to be more severe. This event was, therefore, chosen as the MCE for the design of the tower.

Acceleration spectra (5% damped) expected to result from the chosen MCE are shown in Figure 5. The two curves (mean and mean + two standard deviations), shown in Figure 5, represent expected levels of spectral acceleration with 50% and 2.5% probability of exceedance respectively.

Figure 5: Estimated 5% Damped Spectra for a Magnitude 6.5 Earthquake at an Epicentral Distance of 20 km (MCE for Macau Tower) (Boore et al, 1994/Soil/Larger of Two Components Att. Relationship)



ADDITIONAL ANALYSES

Adopted Seismicity Model

In order to verify our seismic model we have performed additional hazard analyses using unmodified Joyner and Boore 1981 attenuation relationship (larger of two components) for ‘Soil’ subsoil conditions and seismic model (recurrence relationship) adjusted for use of M_S, and Joyner and Boore 1981 attenuation relationship as modified by Pun and Ambraseys (1992) and the seismic model as originally derived in the same reference. This is effectively a repetition of the work undertaken by Pun and Ambraseys in 1992. All earthquakes of Richter magnitude greater than or equal to 3 were included in this assessment.

Results of the above additional analyses show that, although some variation in the results exist, they appear to be sufficiently similar to confirm consistency with the methodology given in Pun and Ambraseys (1992).

Choice of M_{max}

To investigate the sensitivity of the results (recurrence of PGA and response hazard spectra) to the choice of the maximum magnitude (M_{max}) adopted in the hazard analysis, we have performed additional analysis with the M_{max} set to 6.5 (Macau zone in Pu and Xiaohua (1997)) as compared to the value of 7.5 generally used in this study. The results of this analysis confirmed that this parameter does not have a significant effect on the assessed recurrence of PGA, as reported by Pun and Ambraseys (1992). A difference in the predicted hazard response values, especially for the longer structural periods, becomes more evident but is considered to be within the accepted accuracy for this type of analysis.

Wong et al Seismicity Model

An additional analysis, utilising Wong *at al.* (1998) seismicity model was performed.

Wong *et al.* (1998) show results of their assessment of the seismicity of the Hong Kong region. This appears to be much higher than assessed in previous studies (Pun and Ambraseys, 1992). A comparison of the recurrence parameters, as derived by Wong et al (1998) and those assessed by Pun and Ambraseys, and used in our seismic hazard analysis for the Macau Tower, are shown in Table 2:

Table 2: Comparison of recurrence parameters – Wong et al vs Pun and Ambraseys

Parameters in the Guttenberg – Richter equation	Wong *et al.* (1998) as modified to be used in this study (M_s converted to M_w)	Pun & Ambraseys (1992) as modified to be used in this study (M_s converted to M_w)
a4 (/year/1000 km2)	0.023	0.01
b	1.0	1.1

We have performed an additional hazard analysis utilising recurrence parameters assessed by Wong *et al.* in order to investigate the effects of their proposed seismicity model on the seismic hazard for the Macau tower. Results of this analysis are shown in Figures 6 and 7.

Figure 6: Recurrence of Peak Ground Acceleration for Macau Tower (Boore et al, 1994/Soil/Larger of Two Components Att. relationship) Wong et al. vs Pun & Ambraseys Recurrence Relationships

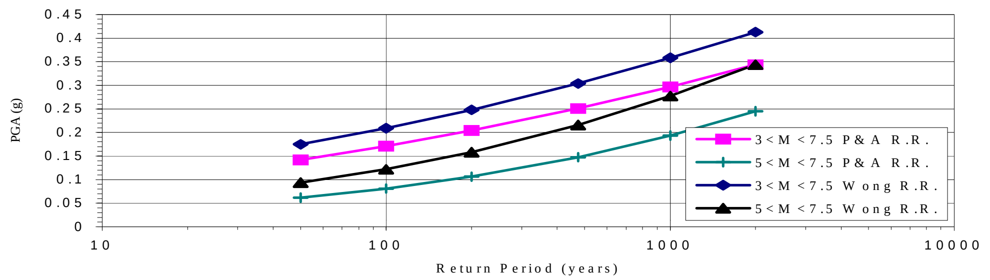
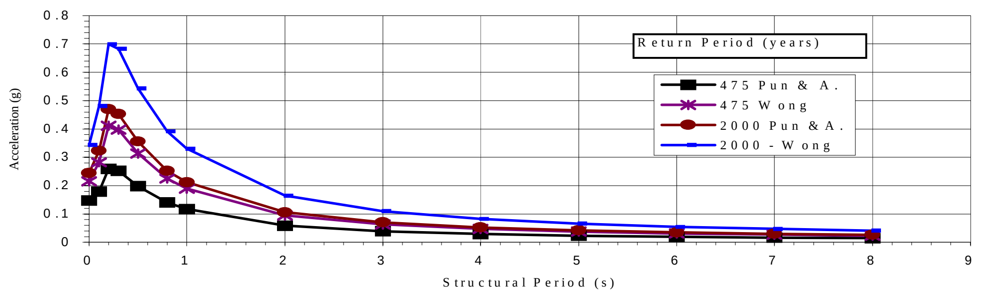


Figure 7: Estimated 5% Damped Hazard Spectra for Macau Tower (Boore et al, 1994/Soil/Larger of Two Components Att. Relationship) M>=5, Modified Wong et al. vs Pun and Ambraseys Recurrence Relationships



It is apparent, from Figures 6 and 7, that the predicted levels of earthquake shaking (PGA and response hazard spectra) at the site are much higher than estimated utilising the Pun and Ambraseys (1992) seismicity model.

We believe that the Wong et al (1998) seismicity model deals with several issues which are not adequately addressed by Pun and Ambraseys, and therefore it should lead to a more realistic estimate of the seismicity of the region. However, at the time our hazard assessment for the Macau Tower was completed, this model was still in preparation. It was considered inappropriate at the time to use the results of that study until such time as the model was published and subject to technical scrutiny.

SEISMIC DESIGN PHILOSOPHY

The Tower has been designed for the following seismic criteria:

- Serviceability Limit State – 50 year return period earthquake. The concrete is to remain uncracked.

- Ultimate Limit State – 1,000 year return period earthquake shaking. The Tower is designed to remain essentially undamaged (albeit with some cracking).

The Tower has also been checked for adequacy during the Maximum Credible Earthquake. In particular the stability of the raking concrete legs and the capacity of the coupling beams has been investigated

CONCLUSIONS

The Macau region is an area of low to moderate seismicity. This was confirmed by our site specific seismic hazard study, irrespective of which seismic model was used (Pun and Ambraseys or Wong et al). Although the influence of the design level earthquake motions is generally less than the forces generated by severe winds (seismic loads were critical for the design of the mast and upper sections of the shaft), the effects of eccentricity and the resulting torsion and shear forces are expected to be higher for earthquake than for wind.

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