Seismic Hazard Analysis of the Hong Kong Region

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ABSTRACT: *Based on regional seismicity records and seismotectonic conditions, this paper presents a probabilistic assessment of the seismic hazard for the Hong Kong region. The potential seismic source zones are identified and the resultant seismic ground motion parameters evaluated. The pertinent attenuation relations proposed by various authors are analyzed. Uncertainty analyses are also conducted. The main conclusion is that the peak acceleration on bedrock lies is in the range of 75-115gal for the Hong Kong region, corresponding to a 10% probability of exceedence in 50 years. The basic seismic intensity for the same probability of occurrence is rated as VII for the study area.*

Keywords: Earthquake; Seismic hazard; Probabilistic assessment; Peak ground acceleration; Seismic intensity

1. Introduction

The region of Hong Kong, comprising Hong Kong Island, Kowloon Peninsula and the New Territories, has a total land area of 1,092km^2. It also includes 235 outlying islands, the biggest of which is Lantau Island. At the time of the last census in 1996, Hong Kong has a population of more than 6.4 million. This makes Hong Kong one of the most densely populated areas in the world. At the same time, Hong Kong has developed into one of the most important financial and trading centers of the world, complete with a very busy container port. It is thus clear that if a sizeable earthquake were to occur in the region, the socio-economic impact could be significant.

Hong Kong is situated in an intraplate area of low to moderate seismicity [13]. Historical data indicate no records of Hong Kong ever being struck by an earthquake with a magnitude of 5 or above [1, 2, 3]. However, damages by infrequent large earthquakes in intraplate areas had occurred in the past [4]. As a result, the local authority, the Geotechnical Engineering Office (*GEO*) contracted the University of Hong Kong (*HKU*) and the Guangdong Seismological Bureau (*GSB*) in June 1995, to undertake a comprehensive seismic hazard analysis of the Hong Kong region [10]. The study included an in-depth analysis of seismicity records, field mapping and age dating of capable faults, seismic zoning and attenuation modelling, and the determination of ground motion parameters. This paper presents the major findings of the study.

2. Methodology Used

The probabilistic method of seismic hazard analysis developed by Cornell [5] was used in the present study. The method has also been used previously in compiling the seismic zoning map of China, with a scale of 1:4,000,000 [17].

Figure (1) illustrates the methodology and procedures used. In essence, the steps are as follows:

- ❖ Division of the broad seismic region of interest into various seismotectonic units, based on regional seismicity pattern, geophysical fields and seismotectonic settings. Each seismotectonic unit is characterized by its tectonic features and a relatively unified seismicity pattern. The seismotectonic units are thus taken as the basic statistical units.
- ❖ Statistical analysis of the magnitude-frequency relationship and the seismic activity trend for a return period of one hundred years, and evaluation of the annual mean occurrence rate of earthquakes for each statistical unit.
- ❖ Identification of the individual potential seismic source zones together with their upper bound magnitudes within each seismic belt, based on our knowledge of the tectonic indicators of seismogenic structures and the spatial seismicity pattern.
- ❖ Allocation of the annual mean occurrence rate of earthquakes within various magnitude intervals to each potential seismic source zone.
- ❖ Computation of the seismic hazard for each site

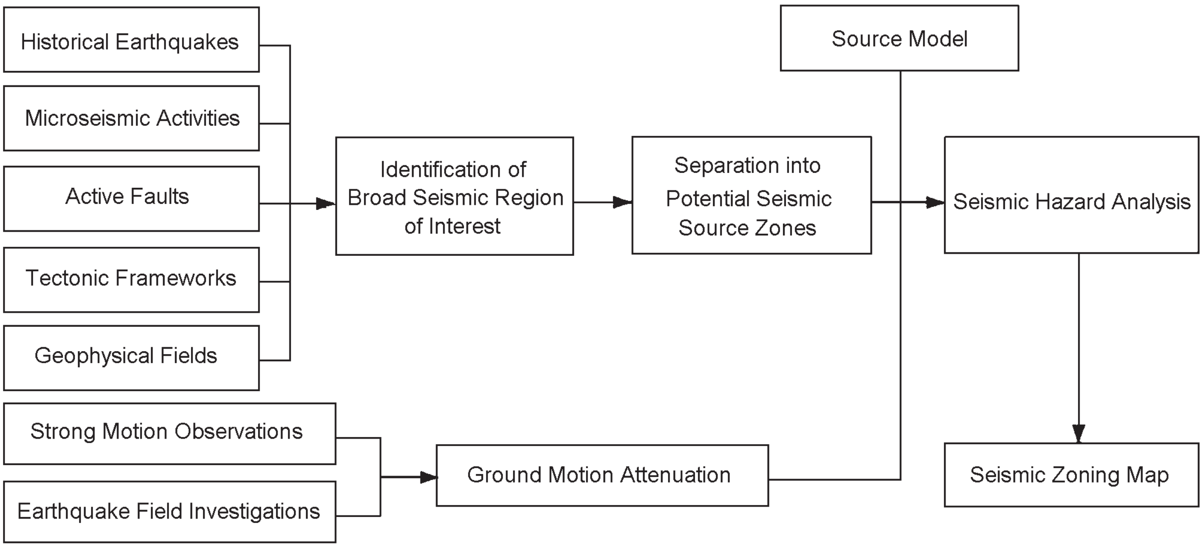

Figure 1. Working diagram for seismic zoning.

by using an elliptic or conjugate elliptic model. The regional differences in seismic attenuation and its anisotropy are taken into account in the computation.

- Compilation of the seismic intensity zoning map by synthesizing the calculated intensity values at each site for the given probability level and return period.

3. Seismicity and Seismic Zone

The region being studied forms part of the middle segment of the southeastern coastal seismic belt of China. A total of 119 earthquakes with surface-wave magnitude $M_S \geq 4.75$ have been recorded since 1067 [11,12]. They include 84 events with M_S between 4.75 and 5.25 (intensity *VI*); 21 events between 5.5 and 5.75 (intensity (*VII*); 7 events between 6 and 6.5 (intensity (*VIII*); 4 events between 6.75 and 7 (intensity *IX*) and 3 events between 7.3 and 7.5 (intensity *X*). Most of them occurred along the inland zone and the coastal zone, which also form the inner and outer zones respectively of the southeastern coastal seismic belt, Figure (2). The outer zone has been relatively more active than the inner zone. In the past few centuries, events of $M_S \geq 7$ and M_S 6 events had occurred only in the zone. A few M_S 6 events were also found in the inner zone though the largest event did not exceed M_S 6.75.

Seismicity in the southeastern coastal seismic belt of China is characterized by periodic alternate cycles of intense and low activity. Historical records of seismicity show that there have been two cycles of seismic activity since the year 1400. The first cycle occurred between 1400 and 1710, while the second cycle, which began in 1711, has yet to be completed. Each cycle lasts for approximately 320 years. Further analysis of the complete process of strain buildup and relief shows that each cycle comprises four stages of development. The first stage, or the strain buildup stage, with events of $M < 6$ only, lasts for 73 to 112 years. The second stage or the precursory relief stage, with the possible occurrence of events of $6 \leq M \leq 7$, lasts for 112 to 155 years. The third stage is the main relief stage, with events of $M \geq 7$, lasts for 4 to 6 years. The final stage is the residual relief stage, with the possible occurrence of M 6-6.75 events, lasts for 88 to 94 years. The seismic zone currently is at the residual relief stage of the second cycle, which is expected to last until the year 2015 approximately [13].

Since 1874, there have been six earthquakes with magnitude above M_S 6 within a distance of less than 350*km* from Hong Kong [10], Figure (3). In chronological orders, they are as follows:

- M 5.75 event, Dangan Islands, June 23, 1874
  Based on historical records of the felt area, the epicenter is believed to be located in the coastal waters to the east of the Dangan Islands. It is the major event that occurred most closely to Hong Kong among the six. The resulting intensity in Hong Kong was *VI.*
- M 5.5 event, Macau, August 12, 1905
  The epicenter was found to be located offshore of Macau. The earthquake was clearly felt in Hong Kong, but no damage was recorded.
- M 6 event, Honghai Bay, May 15, 1911
  The earthquake was located offshore at a distance of about 100*km* from Hong Kong, where the intensity was estimated to be *V*. To this date, earthquakes with magnitude M 2-3 are still frequently recorded in the area.
- M 7.3 event, Nan'ao, February 13, 1918
  The event is the largest earthquake in Southern China in the past century, with an epicentral intensity of *X*. Seismic motion was clearly felt in

Figure 2. The distribution of southeastern coastal seismic zone.

Figure 3. Epicenter distribution of historical earthquakes within a distance of less than 350km from Hong Kong.

Guangdong Province, even at locations that are more than 400*km* away from the epicenter. The intensity recorded in Hong Kong was *VI*.

- *M* 6.1 event, Heyuan, March 15, 1962
  This event is a reservoir-induced earthquake with an epicentral intensity of *VIII* [6]. It was clearly felt in Hong Kong with an intensity in the range of *IV-V*. To this date, there are a few hundreds events with a magnitude of less than *M* 5 recorded in the area around the reservoir every year.
- *M* 6.4 event, Yangjiang, July 26, 1969
  It is the largest on-land earthquake in Guangdong Province in the last century. The intensity in Hong Kong was reported to be about *IV*.

Besides the above, there was an *M* 7.3 earthquake epicentred at the southern end of the Taiwan Strait on September 16, 1994. But it was too far away (>450*km*) to make any impact on Hong Kong.

Thus, the maximum seismic intensity in Hong Kong in the last hundred years was no more than intensity *VI*.

A provincial seismograph network was established by the Guangdong Province in 1970. A total of 53 events with $M_L \geq 1.8$ were recorded within the Hong Kong region during the period 1972-1995. The frequency of recorded microseismicity has increased somewhat since 1990, although the change in magnitude has been rather small.

4. Seismicity Parameters

As indicated in Figure (1), it is the first step of the seismic hazard analysis to identify the seismic zone as well as to determine the seismicity parameters, which are the lower bound magnitude, background magnitude, *b*-value (regression coefficient in Eq. (1), as noted later in this section) and the average annual rates.

Hong Kong has had several historical earthquakes of magnitude 4, which has caused slight damage to buildings [7, 9, 10]. As a result, magnitude 4 has been selected as the lower bound magnitude in carrying out the calculations required for the seismic hazard analysis. The magnitude 4 has also been used as the lower bound magnitude in performing statistical analysis of the *b*-value and the average annual rates.

Background magnitude is the maximum magnitude of seismic events that can occur within any potential source zone. Background magnitudes are taken as 5 and 5.5 for the inner and outer zones respectively in Figure (2). In other words, any area in the inner and outer zones could experience an event of magnitude up to 5 and 5.5, respectively.

The *b* value is determined from the Gutterberg-Richter magnitude--frequency relationship

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

where, *M* is magnitude, *N* is cumulative frequency, and *a* and *b* are regression coefficients.

In this study, the Segment-Poisson process is adopted to model the time process of earthquake occurrence. The *b*-value reflects the proportional relationship between large and small earthquake frequencies in a seismic zone. It has a direct relation with the probability of future earthquake occurrence. Usually the values of *a* and *b* in the above equation are determined by referring to historical earthquakes that occurred during a specified period of time. Small to medium magnitude earthquakes were often omitted in historical records, leaving large magnitude earthquakes to account for a major portion of these records. This bias thus results in a lower *b*-value from a statistical analysis. Although modern seismic monitoring technology can now record a much more complete spectrum of seismic events, these instrumental records are available only for a relatively short period of time. Moreover, medium to large earthquakes formed a very limited portion of such recorded data. The bias in contemporary seismic data thus results in a higher *b*-value from the statistical analysis. In order to avoid such a bias in the data, the authors decided to adopt a statistical method, which calculates *b*-values for recorded events over different time periods and with different magnitudes, Figure (4).

The average annual occurrence rate refers to the number of earthquakes with $M \geq 4.0$ occurring every year in the inner zone or outer zone. This value has a substantial influence on the results of seismic hazard analysis. The statistical method adopted in the calculation of *b*-value is used again to determine the average annual occurrence rates in the outer and inner zones, which correspond to 1.151 and 0.873 events/year respectively, Figure (5).

A potential source zone (*PSZ*) represents an area in which destructive earthquakes can occur in the near future. It can be determined by synthesizing such relevant information as geological structures, geophysics, crustal deformation and seismic activity of a region. The two fundamental principles of potential source zoning can be described as follows:

- An area with frequent earthquakes in the past would probably continue to experience more earthquakes of similar magnitudes in the future.
- Areas with similar geological conditions would also have similar seismic activities.

In the process of identifying potential source zones with different magnitude values, it is also necessary to take into account the specific geological and structural conditions of a given region. In general, the maximum magnitude of historical earthquakes in this region as well as in the other area with the same tectonic pattern can be used as the upper bound magnitude of a potential source zone. Based on the above principles, more than one

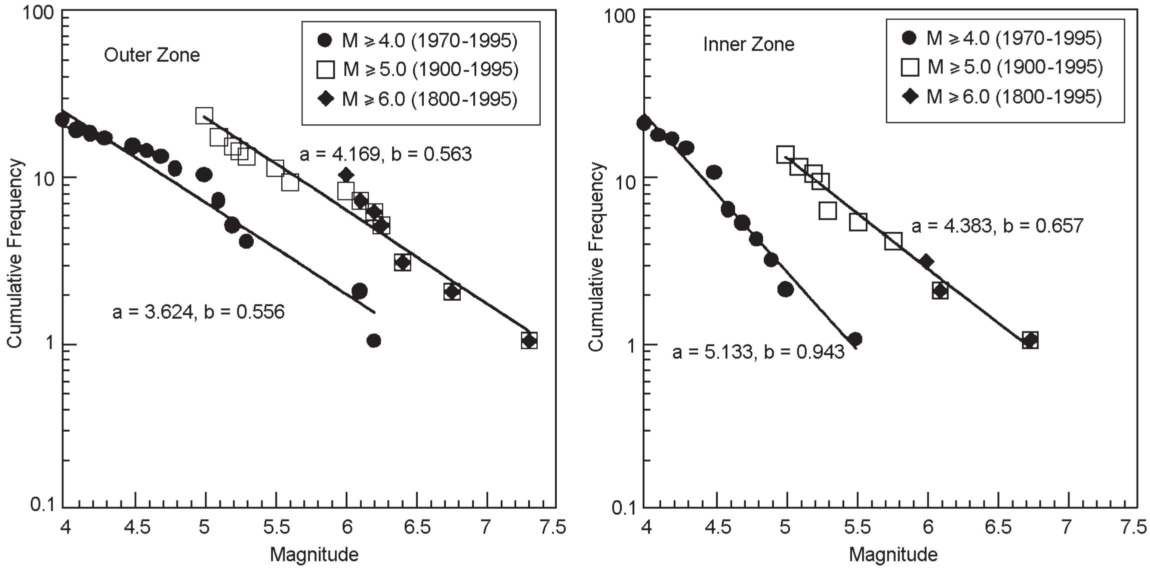

Figure 4. B-values for the southeastern coastal seismic belt.

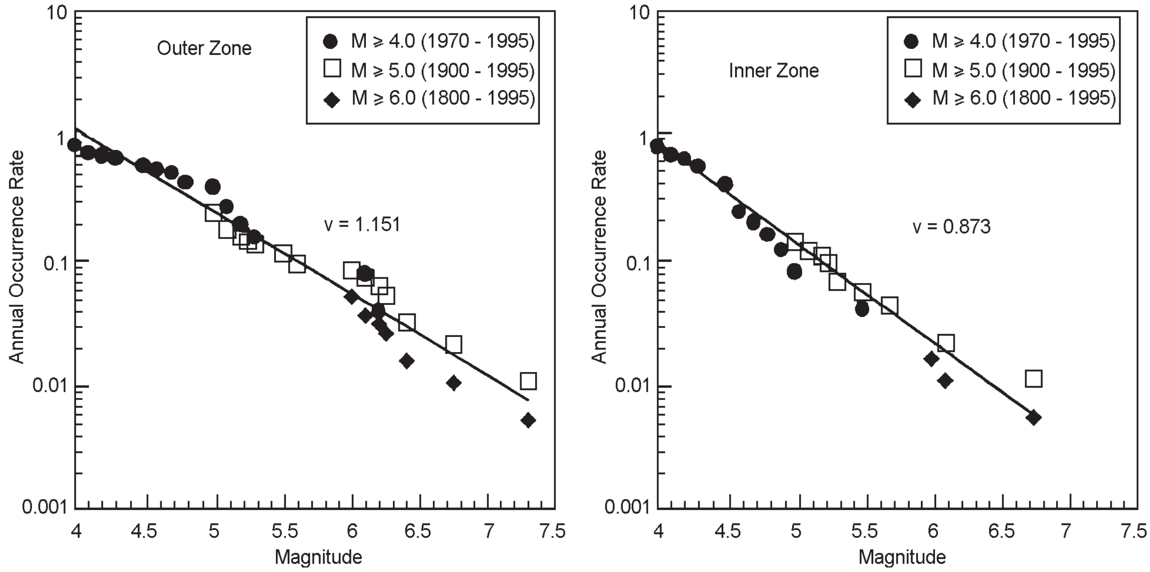

Figure 5. Annual occurrence rate for the southeastern coastal seismic belt of China.

hundred potential source zones have been identified in the southeastern coastal seismic belt of China [17]. The present investigation has adopted this zoning plan but with adjustments and modifications for the potential source zones in the Hong Kong region. The potential source zones of significant influence to Hong Kong are illustrated in Figure (6). They are zones in which destructive earthquakes with $M \geq 5.5$ could possibly occur. A similar zoning system has previously been used in compiling the seismic zoning map of China [17].

5. Ground Motion Attenuation Models

When an earthquake occurs, seismic waves radiate from the source outwards to the external region. The larger the distance from the source (where the seismic energy is being released), the smaller would be the amount of seismic energy and the amplitude of ground motion. This process is known as the attenuation of seismic ground motion. This process is known as the attenuation of seismic ground motion. Attenuation of ground motion is usually represented and modeled using statistical or empirical attenuation equations of seismic intensity and peak ground acceleration (*PGA*).

As few strong motion instruments have been installed in southern China, very limited ground motion records of strong earthquake events are available. It is therefore difficult to obtain the attenuation equations for *PGA* directly from the seismic records of strong earthquakes in the study area. There is, however, an abundance of ground acceleration data from the western USA. Huo et al [8], for example, has applied the attenuation equations of western USA to southern China, in his study of seismic ground

Figure 6. Delineation of potential source zones for Hong Kong and its surrounding region.

motions in southern China.

During the past decades, a number of researchers have investigated the historical earthquakes of southern China and obtained isoseismal maps accordingly [11, 12]. Based on such isoseismal maps, attenuation equations of seismic intensity can be obtained for the southern China region using either the circular or elliptical attenuation models.

Based on historical earthquake data from southern China [16] and the circular attenuation model, the authors have developed the following attenuation equation of seismic intensity for southern China [10]:

$$I = 4.1839 + 1.4372M - 1.6099 ln(R + 14)$$
$$\sigma_1 = 0.515 \qquad (2)$$

where

I = seismic intensity
M = surface wave magnitude
R = epicentral distance
$\sigma_1 =$ standard deviation

Similarly, using the elliptical attenuation model, the authors have obtained the following relations:

$$I_a = 4.85474 + 1.31271M - 1.49944\, ln\,(R + 15)$$
$$I_b = 3.20975 + 1.31271M - 1.24136\, ln\,(R + 7) \qquad (3)$$
$$\sigma_{I_a} = \sigma_{I_b} = 0.515$$

where

$I_a =$ seismic intensity along long axis of ellipse
$I_b =$ seismic intensity along short axis of ellipse
$\sigma_{I_a} =$ standard deviation for long axis ellipse
$\sigma_{I_b} =$ standard deviation for short axis of ellipse

Based on a statistical analysis of 16 representative isoseismal maps from southern China, Zhou et al [18] developed the following attenuation equation of seismic intensity for southern China:

$$I = 5.8520 + 1.4899M - 1.9986\, ln\,(R + 25)$$
$$\sigma_1 = 0.210 \qquad (4)$$

In a probabilistic analysis of seismic hazard for Hong Kong carried out by Pun and Ambraseys [14] and Pun [15], the following attenuation equation of PGA was developed, based on seismicity data from Hong Kong and the adjacent Guangdong Province of China:

$$log a = -0.789 + 0.2128M - log R - 0.00255R + 0.25P \qquad (5)$$

where

a = peak ground acceleration (PGA)
P = probability of exceedence of peak ground motion

By taking into account the saturation characteristics of near field ground motion in a high intensity region and using the elliptical attenuation model, Huo et al [8] obtained the following attenuation equation of bedrock *PGA* for southern China:

$$log_{10}a = -1.2629 + 1.4956M - 0.0513M^2 - 2.2252 \, log\left[D + R_0(M)\right]$$

Major axis: (6a)

$$R_0(M) = 0.3618 exp(0.6989M) \qquad \sigma_{log_{10}a} = 0.247$$

$$log_{10}a = -2.0301 + 1.4573M - 0.0501M^2 - 1.9731 \, log\left[D + R_0(M)\right]$$

Minor axis: (6b)

$$R_0(M) = 0.1201 exp(0.7654M) \qquad \sigma_{log_{10}a} = 0.247$$

where

D = epicentral distance

$R_0(M)$: saturation factor of distance

If $M_S = 5$, the different attenuation equations produce relatively similar attenuation curves, especially over short distances. If $M_S = 6$, the attenuation curves are still reasonably close to each other. If $M_S = 7$, the differences of the curves become more obvious. Hence, the larger the magnitude and the longer the epicentral distance, the larger would be the differences among the equations.

Eqs. (6a and 6b) have been established using the elliptical attenuation model to take into account the saturation characteristics of near field seismic motion in a high intensity region. As a result, they have been adopted in the present seismic hazard calculations for the Hong Kong region. In the process of calculating the bedrock *PGA*, the authors performed seismic hazard analysis for the Hong Kong region and 25 other neighboring zones using Eqs. (6a and 6b).

6. Seismic Hazard in Hong Kong Region

Figure (7) illustrates the isoseismal maps of bedrock peak *PGA* corresponding to a 10% probability of exceedence thus obtained for the Hong Kong region, for a return period of 50 years. The isoseismal curves are mainly oriented in the *EW* direction. The northern region has relatively lower values of bedrock *PGA* while the southern region has relatively higher values.

The northern sites of the region have *PGA* values of between 75 and 85*gal*, while Kowloon, Hong Kong Island and Lantau Island have values of between 90 and 105*gal*. The difference between the maximum and minimum values

Figure 7. Bedrock PGA contours for a 10% probability of exceedance in 50 years.

of *PGA* is about 40*gal*, which reflects that sites in the region do not have very significant differences in their *PGA* values.

Of all potential source zones considered, there are five that contributed more significantly to the bedrock *PGA* in Hong Kong. Take the Kowloon site at *N*22.31, *E*114.17 as an example. Bedrock *PGA* values for this site were derived mainly from those five potential seismic source zones, as shown in Table (1). Among the five zones, the Dangan Island potential source zone (99) made the largest contribution. However, for a *PGA* value of 20*gal*, the three potential source zones (23), (32) and (38) which are adjacent to Hong Kong collectively made a contribution in excess of 50% of the *PGA* value.

For a 10% probability of exceedence over 50 years, the corresponding value of bedrock PGA for the Kowloon site was 92.7*gal*. Figure (8) illustrates the variation of probability of exceedence for different return periods, at the Kowloon site. From this figure, *PGA* values can be obtained for return periods of 1, 20, 50, 100 years and for different probabilities of exceedence. The *PGA* values for different return periods and probabilities of exceedence at other sites in the Hong Kong region were basically similar to those for the Kowloon site.

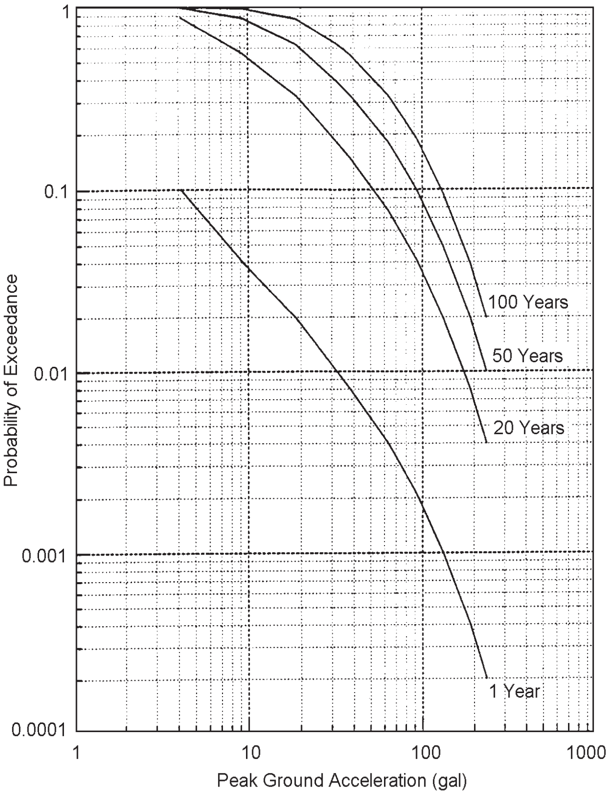

Figure 8. Curves of probabilities of exceedance in 1, 20, 50, 100 years at Kowloon site (114°10'E, 22°19'N).

The results of the seismic hazard analysis were found to be dependent on the values of the various input parameters used in computation. To a certain extent, these values were selected based on judgement, and are hence not completely reliable. Consequently, it was necessary to conduct a sensitivity analysis on the seismic hazard analysis results. Sensitivity analysis is one aspect of uncertainty analysis. The present investigation took into account the corrections for such uncertainties in the attenuation relations.

At present, there are no rigorous mathematical formulations to calculate the effects of uncertainty in seismic ground motion parameters on the seismic hazard analysis results. The present investigation adopted the sensitivity analysis technique to determine the effects of uncertainty. In such a sensitivity analysis, the numerical values of the seismic parameters are varied over a given range. These results of the seismic hazard analysis are then calculated based on the different values of the seismic parameters. By comparing the results of the parametric analysis, the effects of uncertainty in seismic parameters could be assessed.

From Table (1), it is obvious that there are five potential source zones which contribute substantially to the bedrock *PGA* at sites in the study region. They are Dangan Island (99), Lantau Island (38), Shenzhen (23) and Dapengwan (32) and Pearl River Mouth (48) respectively. These potential source zones together account for more than 98% of the peak *PGA* value of 75*gal* calculated. It would therefore be prudent to concentrate the sensitivity analysis on these five zones. In the sensitivity analysis, two values, i.e., 7.0 and 7.5, are assigned as the upper bound magnitude for the Dangan Island potential source zone. The other four zones also have two sets of values each as their upper bound magnitude. The increase in the upper bound magnitude of the important potential source zones by 0.5 unit results in an increase of less than 30*gal* in the *PGA*.

Table 1. Contributions to bedrock PGA values at Kowloon site from major potential source zones.

Zone No.		99	38	23	32	48
Potential Source Zone		Dangan Islandse	Lantaue	Shenzhen	Depengwan	Pearl River Mouth
Bedrock *PGA* Value	20gal	40.1%	16.5%	22.6%	13.2%	7.7%
	75gal	62.6%	14.2%	14.1%	8.0%	12%
	150gal	83.9%	13.6%	0	2.5%	0

The values of 0.80 and 0.56 were used as *b*-values for the inner and outer seismic zones, respectively. In order to determine their effect, the two *b*-values were increased or reduced by 0.05. It was observed that such variations of b-values have a limited effect on the seismic intensity but a considerable effect on the *PGA* calculated. The changes in the seismic intensity are about ±0.08 and those in the *PGA* are less than ±10*gal*.

The average annual occurrence rates were 1.05 and 1.38 (*events/year*) for the inner and outer seismic zones, respectively. An addition or reduction of 20% was made to these original values in the sensitivity analysis. The results indicate that the 20% variation in the average annual occurrence rate has a limited influence on the results of seismic hazard analysis.

The above calculations are based on the elliptical attenuation model. If the orientation of the major axis of the ellipse varies by plus 15^0 or minus 15^0, these variations would have a very limited influence on the results of seismic hazard analysis.

With the same potential source zones and the same seismological parameters as determined on this project, the probabilistic hazard analysis approach used in this study was applied in trial calculation to other parts of the Pearl River Delta region. The purpose of this trial calculation was to validate the suggested approach by comparing the present results with those obtained earlier by researchers of the Guangdong Seismological Bureau while compiling the Zoning Map of China, as mentioned earlier. The present results compare well with those obtained in such earlier studies for the Pearl River Delta region. The deduction therefore is that the values of seismic ground motion parameters and the attenuation equations of seismic intensity and *PGA* determined in this study are acceptable and that the results obtained are reasonable.

7. Conclusions

A comprehensive study of the available seismicity data and seismotectonic conditions in the Hong Kong region has been completed under the auspices of the local authority. It is concluded that the peak ground acceleration on bedrock in Hong Kong is in the range of 75-115*gal*, corresponding to 10% probability of exceedence in 50 years. The basic intensity is in the order of *VII*. This is consistent with much of the Pear1 River Delta, where the seismotectonic setting is generally similar. It should be noted that there are currently no seismic design code or requirements for buildings in Hong Kong. The potential impact of credible seismic motions on typical buildings and structures in Hong Kong is now being studied.

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