Seismic Loading Requirements for Singapore Buildings

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ABSTRACT

In this paper, the potential ground motion in terms of the peak ground accelerations (PGAs) due to long-distance Sumatra earthquakes is investigated for Singapore, following the probabilistic seismic hazard assessment approach. The case investigated differs from a conventional one, in that few attenuation equations for long-distance major earthquakes are readily available. The attenuation relationships developed for other regions of the world are thus reviewed. It is found that the existing attenuation equations, when extrapolated to distant major earthquakes, tend to underestimate the PGAs. By comparing with the PGAs recorded over long distances at stations of the Japanese Meteorological Agency for major earthquakes in Japan, an attenuation equation is chosen for this study. With the chosen attenuation equation, the probability of PGAs exceeding selected levels for various exposure periods of time is then computed. The results show that at Singapore there is a 10% probability in 50 years for the PGA at rock sites to exceed 1.1% g. In view of the results and the associated uncertainties, a base shear coefficient of 1.5% is being recommended as the tentative seismic loading in Singapore. The tentative seismic loading reflects the design value of the notional horizontal load, equal to 1.5% of the characteristic building weight as specified in the BS codes, which usually governs the design of most buildings in Singapore.

Key words *: seismic loading, peak ground acceleration, building code*

1. Introduction

Under some circumstances, distant earthquakes, occurring several hundred kilometres away, are capable of causing considerable damage. The Michoacan earthqake of 1985 is a good example. The earthquake caused serious damage in some areas of Mexico City, 300 to 450 km from the epicentre, because the incoming earthquake waves were re-amplified by the soft soil on the ground surface. This may be a peculiar case, but obviously soft-soil effects are to some extent present in many places. For example, in February 1994, some buildings in the ensely populated areas of Singapore responded to an earthquake of magnitude *(Ms)* 7.0 which occurred near Liwa in southern sumatra more than 700 km away (Fig. 1). Hundreds of people were woken up and rushed out of their flats in panic. In May 1994, tremors from an earthquake near Siberut Island, 570 km away, which measured only 6.2 on the Richter scale, were felt in Singapore. The shaking of some buildings again caused panic and some office workers rushed out of their offices. These incidents were reported in the local newspapers. In both incidents, the buildings that responded to the remote earthquakes were located in the southeastern part of the island, where they are underlain by the Quaternary deposits, namely the Kallang Formation. Buildings in other areas of Singapore had no apparent response. It appears that the Quaternary deposits amplified the incoming earthquake waves in both incidents. The Siberut Island earthquake caused tremors in Kuala Lumpur, Malaysia, as well. In October 1995, even

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stronger and more extensive tremors were caused in Singapore by a magnitude 7.0 earthquake occurring 450 km away. This earthquake also generated ground tremors in Kuala Lumpur and in the southern state of Johor in Malaysia. It therefore seems reasonable to postulate that larger and closer earthquakes might result in higher ground motions.

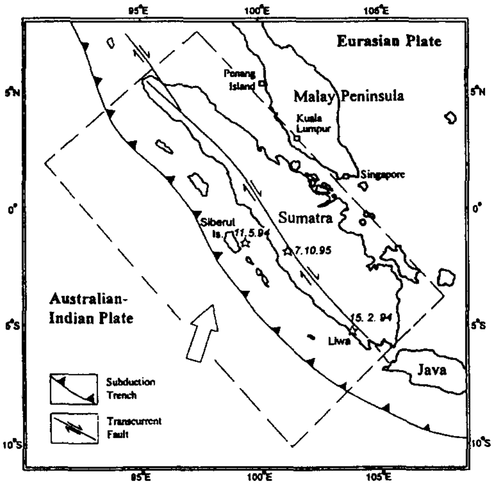

Fig. 1 Seismotectonic map of Sumatra region

It is thus appropriate to investigate the magnitude of the likely ground motion for highly built-up cities on th Malay Peninsula under such circumstances. However, there are many difficulties in doing so, the biggest of which is the lack of strong motion data recorded on the Peninsula. The Malay Peninsula is of very low seismicity. Historically, earthquakes have never caused real problems in western Malaysia. Hence little effort has been mode so far to investigate the probability of significant ground motions in this region. This is understandable since the nearest earthquake belt, comprising the Sumatra subduction zone and the Sumatra Fault, is more than 300 km away. Borrowing the existing attenuation relationships developed for other regions is also problematic, as they are typically developed for sites with epicentral distances less than 100 km, or at most 200 km. Hence, this investigation has to resort to some special treatments.

The location of Singapore is taken as (1.5° N, 103.5° E) off the southern tip of the Malay Peninsula. As mentioned earlier, site conditions could affect ground motions significantly. Therefore in this study only the ground motions at rock or stiff soil sites will be investigated. The ground motion at a soft-soil site may then be estimated separately on the basis of a given soil profile and bedrock motion.

2. Probabilistic approach to earthquake hazard analysis

There are generally two approaches to earthquake hazard analysis: one is deterministic and the other is probabilistic. In the first approach, an event with a certain magnitude at a certain distance is chosen as the design earthquake. Buildings are then required to be designed against the ground motions caused by this design earthquake. The deterministic approach is straight forward and easy for the public and policy makers to understand, but the choice of design earthquake is difficult. In the probabilistic approach, buildings are required to withstand a ground motion that has a certain probability of being exceeded within an exposure time period. For example, in the Uniform Building Code,(17) the minimum ground motion is taken as one that has a 10% probability of being exceeded in 50 years. It recognises the possibilities of stronger ground motion and accepts the risk. The probabilistic approach tells how much risk one is taking when designing a building against a certain level of ground motion. This exploits the trade-off between being safe and being economical. The probabilistic approach also incorporates the uncertainties in seismic activity and ground motion attenuation. However, it is more difficulty, for the public to understand how the results have been obtained. Despite the difficulty the probabilistic approach is chosen for this study.

In the probabilistic approach, a ground motion value i is selected, and the probability of ground motion I exceeding the value i for any earthquake can be calculated as follows:

$$F_I(i) = \int_{M_{\min}}^{M_{Max}} \int_r P[I \geq i \backslash m, r] f(m) h(r) dr dm \tag{1}$$

where $P[I \geq i \backslash m, r]$ is the probability of I greater than i given a magnitude m and distance r; *f(m)* is the probability density function for an earthquake of magnitude m to occur; *h(r)* is the probability density function of an earthquake occurring at distance r; $M_{\min}$ is the minimum magnitude of earthquake in the sample; and $M_{\max}$ is the maximum magnitude of earthquake possible for the area under study.

Given an exposure time t, if N earthquakes are expected per year in the region, the probability of ground motion I being exceeded in t years will be (Lomnitz(14))

$$P_E = 1 - e^{-F_{I(i)Nt}} \tag{2}$$

Hence the probabilistic method of earthquake hazard analysis consists of the following four steps:

1. Identifying the seismic source areas;
2. Determining seismicity statistics, i.e. the probability density functions for magnitude and epicentral distance, *f(m)* and *h(r)*;
3. Defining an attenuation law (i.e., $P[I \geq i \backslash m, r]$);
4. Computing probabilities of exceeding a given ground motion at a particular site for a given exposure time, using equations (1) and (2).

3. Seismotectonics of Sumatra

Sumatra is located adjacent to the Eurasian (Sunda land) active margin. The Indo-Australian Plate subducts below the Eurasian Plate along this are at a rate of about 67 mm year (Demets et al(6)). The displacement between the two plates is partly accommodated by sudden movements, which cause numerous earthquakes. Very large earthquakes can be generated along the interface between the two plates. The earthquake in 1833 had an estimated moment magnitude (Mw) between 8.7 and 8.8, and was believed to have caused a 500 km long rupture along the interface extending from the southern island of Enggano to the Batu Islands (Newcomb and McCann(16)). (On the oceanic side of the trench, bending of the oceanic lithosphere prior to subduction also generates large earthquakes, and on the land side a dextral strike-slip fault, the great Sumatra Fault, constitutes yet another source of numerous earthquakes (Katili and Hehuwat(12)). The Sumatra or Semangko Fault is more than 1,500 km long and runs the entire length of Sumatra, coinciding with the Barisan Mountain belt. The fault is about 350 km away from the major cities along the west coast of the Malay Peninsula. An earthquake on the Sumatra Fault on 17 May 1892 caused widespread tremors in Singapore. Most earthquakes in Sumatra are shallow to intermediate in depth; deep events are very unusual.

4. Earthquake data and their processing

The earthquake data for the following study were study were taken from the Earthquake Data Base System (EDBS) managed by the National Earthquake Infor- mation Center (NEIC), United States Geological Survey (USGS). EDBS is a collation of 54 worldwide of or regional catalogues, some of which are directly relevant to this investigation (NEIC(15)). The area selected for temporal distribution study is shown in Fig. 1 enclosed by dashed lines.

The PDE catalogue has been used for cataloguing earthquakes since the beginning of 1964. It contains earthquakes located by the USGS NEIC and its predecessors. Records which have both the surface wave magnitude (M_s) and the body wave magnitude (m_b) are used to establish a relationship between M_s and m_b through regression. There are 256 records of this type, and the result of the regression gave

$$M_s = 1.45 m_b - 2.59 \tag{3}$$

with a coefficient of correlation of 0.780.

Using the empirical relationship obtained for M_s and mb, the M_s values were calculated for those records initially having m_b only. This way a surface wave magnitude catalogue has been constructed for earthquakes from the beginning of 1964 to the end of February 1994. The frequencies of these earthquakes are shown in Fig. 2(a).

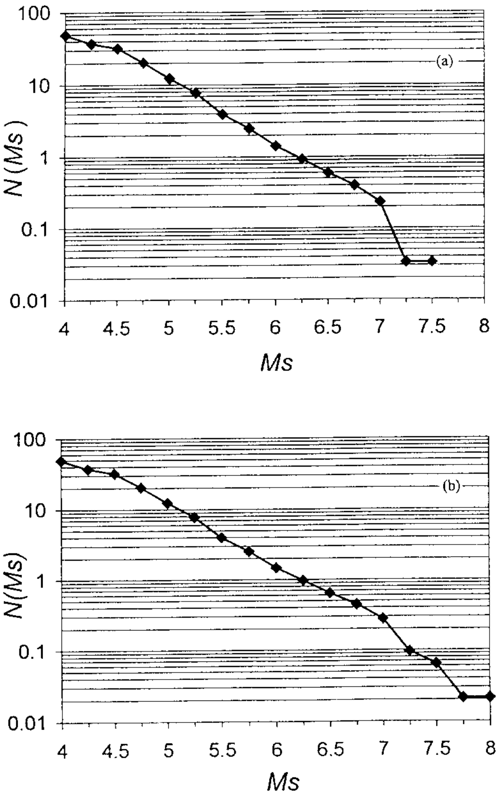

Fig. 2 Magnitude and frequency of recorded Sumatra earthquakes: (a) 1964.1.1 to 1994.2.28, and (b) 1900.1.1 to 1994.2.28

It can be seen from Fig. 2(a) that the frequency and magnitude of the earthquakes follow a log-linear relation, as described by the well-known formula of Gutenberg and

Richter,(10) for earthquakes with M_s between 4.5 and 7. The change in the trend in the range of $M_s < 4.5$ may be attributed to the limited accuracy of the network, while the sudden change of the trend in the range of $M_s < 7$ is due to the sparseness of large earthquakes, whereby 30 years is not a long enough period for the representative frequency of large earthquakes ($M_s < 7.0$), for which a longer time span is needed, to be exhibited. As a result, it was necessary to use other catalogues, which cover a longer time span than PDE but do not contain the smaller earthquakes. These are the ABE, BDA, and ISSN catalogues. These have been combined to give a single catalogue assumed to be complete for earthquakes occurring between 1900 and 1964 with surface wave magnitudes equal to or greater than 7.0. Finally, the magnitudes and frequencies of Sumatra earthquakes were determined. These are displayed in Fig. 2(b).

In the proposed equation, m should always be of the same type of magnitude (e.g. as in M_s). However, this was not possible for this study, since Ms tends to saturate for earthquakes with $M_s > 8.1$. For very large earthquakes, M_w is thus the only appropriate measurement. In the following, it is assumed that the magnitude m is as in M_s if m < 8.1 and otherwise as in M_w. In view of the limited accuracy of earthquake observations, this treatment appears acceptable, especially for the Sumatra region.

5. Magnitude-frequency relationship of Sumatra earthquakes

In this section, the magnitude-frequency relationship in the form of the probability density function $f(m)$ will be computed for Sumatra. The magnitude-frequency relationship is typically in the form of the Gutenberg and Richter formula, where there is no limit to earthquake size. In reality, however, there exists a limit to the size of earthquakes physically possible. Another problem is that different earthquake catalogues are not of the same quality, and this inhomogeneity should be incorporated. There have been several suggestions for a better description of the magnitude-frequency relationship. Dong, et. al.(7) proposed that the probability density function $f(m)$ should be

$$f(m) = \frac{\lambda e^{-\lambda m}}{e^{-\lambda M_{\min}} - e^{-\lambda M_{\max}}} \quad (M_{\min} \leq m \leq M_{\max}) \qquad (5)$$

where $M_{\max}$ is the maximum possible earth- quake for the region studied; $M_{\min}$ is the minimum magnitude of the given sample; and the minimum biased estimate of λ can be obtained from the following equation:

$$\frac{1}{\lambda} + \frac{M_{\min} e^{-\lambda M_{\min}} - M_{\max} e^{-\lambda M_{\max}}}{e^{-\lambda M_{\min}} - e^{-\lambda M_{\max}}} = \overline{M} \qquad (6)$$

in which $\overline{M}$ is the average magnitude in the sample. Equation (5) is required in equation (1) for calculating the probability of exceeding a specified value of ground motion.

The number of earthquakes with magnitude equal to or greater than 4.5 is 31.9 per year in Sumatra, i.e, $M_{\min} = 4.5$ and $N(M_{\min}) = 31.9$. The maximum possible earthquake was assumed to be 8.75, i.e. $M_{\max} = 8.75$, since an earthquake of magnitude 8.7 to 8.8 is believed to have occurred in Sumatra. The average magnitude of the sample is 4.976, i.e.

$\overline{M}$ = 4.976. Substituting the foregoing values into equation (6), λ = 2.10 was obtained.

6. Probability density function *h(r)* of earthquake qccurrences at various distances

The probability density function *h(r)* is determined using past earthquake distributions. The radial distance *r* refers to Singapore location (1.5° N, 103.5° E) off the southern tip of the Malay Peninsula. The probability density function *h(r)* was estimated using earthquake data from 1964 to November 1994, assuming that future earthquakes (m > 4.5) have the same spatial distribution as those occurring during that time interval. The surrounding source area was divided into concentric rings of 10-km width. The total number of earthquakes within 600 km of Singapore was 244. The probability density function *h(r)* for Singapore is displayed in Fig. 3. It was calculated by dividing the number of earthquakes within each of the 10-km-width rings by the number of earthquakes.

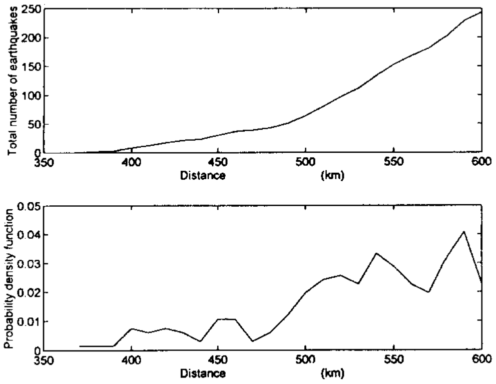

Fig. 3 Probability density *H(r)* of earthquakes occurring at distance *r* from Singapore

7. Attenuation of earthquake ground motion

The strength of earthquake ground motions can be measured by the peak ground acceleration (PGA), peak ground velocity, response spectrum, etc. When describing the attenuation of earthquake strong ground motion, PGA is by far the most widely used, although some researchers have found that PGA alone is insufficient to represent the damage potential of ground motion. In this paper, PGA is used because of the abundance of available attenuation equations in term of PGA. Some of the existing attenuation equations of PGA are reviewed briefly in the following.

(A) Joyner and Boore(11) gave the following attenuation equation for the western part of north America:

$$\log a = -1.02 + 0.249M - \log r - 0.00255r + 0.26$$
$$r = (d^2 + 7.3^2)^{1/2} \qquad (7)$$

in which a is the horizontal PGA in g (the gravitational acceleration), M is in moment magnitude, and d is the closest distance (in km) to the surface projection of the fault rupture. This is the most wellknown known attenuation equation. It applies to both hard and soft sites.

(B) Kawashima, et. al.(13) investigated the peak ground motions based on data from Japan and recommended the following formula:

$$\log a = \log(987.4) + 0.216M - 1.218 \log(\triangle + 30) \qquad (8)$$

where a is the horiziontal PGA (in *gal*) on rock or firm soil, M is in Japanese Meteorlogical Agency (JMA) magnitude, and D is the epicentral distance (in km). The formula for PGA in soft soil appears to be peculiar and is not reproduced here.

(C) Fukushima and Tanaka[9] derived and empirical attenuation formula based on data from Japan

$$\log a = 0.41M - \log\left(R + 0.032 \times 10^{0.41M}\right) - 0.0034R + 1.30 \tag{9}$$

where a is the mean of the peak accelerations of two horizontal components (in *gal*), M is in surface-wave magnitude, and R is the shortest distance between

(E) Recently, Dahle, et. al.[5] gave the following attenuation model for Central America:

$$\ln A = -1.579 + 0.554M - 0.560 \ln R - 0.00302R + 0.326S \tag{11}$$

where $R = \sqrt{r^2 + 36}$, in which A is the PGA (in m/s^2); M is the moment magnitude; r is the hypocentral distance (in km); and coefficient S equals 1 for soil sites and 0 for rock sites. The standard deviation is 0.75 for this empirical formula.

Though there are many other attenuation equations, the five formulae mentioned above are considered to be most relevant to

Japanese Meteorological Agency (JMA). Some of these were located at epicentral distances of over 1,000 km. Among the available accelerograms, 13 sets were recorded at stations with epicentral distances of between 200 km and 800 km. The PGAs, together with the attenuation curves of the equations reviewed above, are plotted in Fig. 4(a) for rock or rock or hard sites.

As can be seen in Fig. 4(a), the equations of Joyner and Boore(11) and Fukushima and Tanaka(9) both undersetimate the PGA in this distance range. The equations of Kawashima, et. al.(13) and Dahle, et. al.(5) predict PGAs at the high end of the scale. The formula of Bufaliza(2) predicts the PGA reasonably well in this distance range for this earthquake, though it also understimates for soft soil sites.

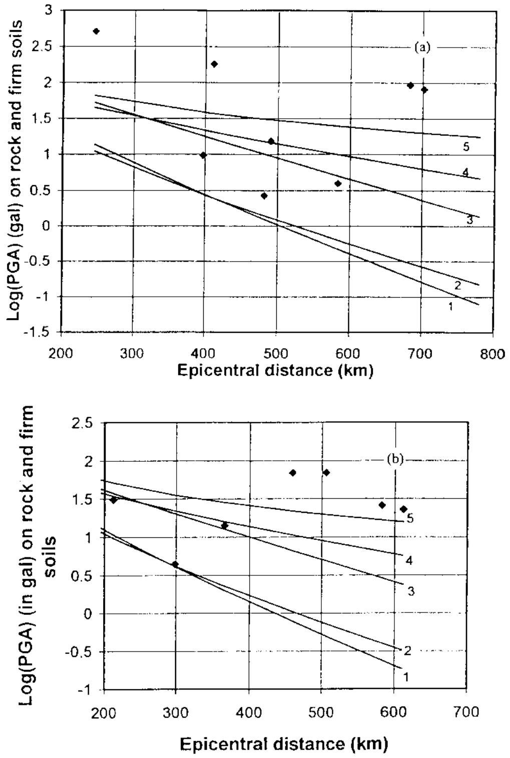

Fig. 4 Peak ground acceleration as predicted and measured and measured at rock or stiff soil sites for (a) Hokkaido Toho-Oki earthquake of October 4, 1994, and (b) Kushiro-Oki earthquake of 1993. Dots are measurements, and curves are values predicted using the equations of authors: 1. Fukushima and Tanaka (1990); 2. Joyner and Boore (1981); 3. Bufaliza (1984); 4. Dahle, et. al. (1995); 5. Kawashima, et. al. (1986)

It should also be stated that "distance" is defined differently in differently attenuation equations. For the purpose of comparison over long distances, it is reasonable and necessary, for the sake of simplicity, to treat all distances as the epicentral distance, so that the curves may be plotted on the same diagram.

7.2 Kushiro-Oki earthquake (15 January 1993)

Similar observations can be made by comparing the predicted and the recorded PGAs for the Kushiro-Oki earthquake of 15 January 1993. The earthquake has a moment magnitude of 7.5, and its epicentre was located at 145.5° E and 42.9° N. Fig. 4(b) shows the comparisons between the predictions and the recordings for rock or stiff soil sites. The findings are similar to those derived for the Hokkaido Toho-Oki case, and again the equation of Bufaliza(2) gives the more reasonable predictions.

Similar observations, that existing attenuation equations tend to underestimate ground motions when extrapolated to a long distances have been made by other investigators. For example, Cramer and Darragh(4) studied the stronge motion recordings for the Landers (Mw = 7.3) and Big Bear (Mw = 6.2), California, earthquakes of 1992 and found that for distances greater than 70 km, attenuation of the ground motion as a direct function of distance is less than that predicted by contemporary attenuation relationships. Campbell and Bozorgnia(3) also studied the strong motion recordings of the 1992 Landers earthquake and reported that for distances greater than 60 km contemporary attenuation relationships underpredict strong motion by a factor of 2 to 3.

It follows from the above observations that for the present study the attenuation equation of Bufaliza(2) seems to be the most appropriate for predicting the peak ground acceleration at the distances generated by major earthquakes in Sumatra. The standard deviation of the attenuation equation affects the prediction results significantly. A standard deviation of 0.21 is adopted, which is similar to the value given by Fukushima and Tanaka(9) and is probably the smallest of all. The probability of the PGA exceeding a given value I due to an earthquake with magnitude M at distance r can then be calculated, assuming a normal distribution. Using a smaller standard deviation results in a lower predicted value for the probability of exceeding the PGA.

8. Peak ground acceleration estimation

All elements $f(m)$, $h(r)$, and $P[I \geq i\backslash m, r]$ that are required by equation (1) for the probabilistic seismic hazard assessment have been defined. The magnitude-frequency relationship as represented by $f(m)$ is assumed to be true everywhere in the area of study. However, the maximum magnitude possible varies spatially. The upper limit for integration in the magnitude domain thus depends on the distance r. In this study, the upper limit of magnitude for integration is assumed on the basis of past acceleration at rock or stiff soil sites in Singapore by different levels are presented below.

For Singapore, the values of $M_{\max}$ are 7.0 from 370 km to 400 km, 7.5 from 400 to 430 km, and 8.2 beyond 430 km. The upper limit $M_{\max}$ used for the integration at various distances from Singapore is shown in Fig. 5.

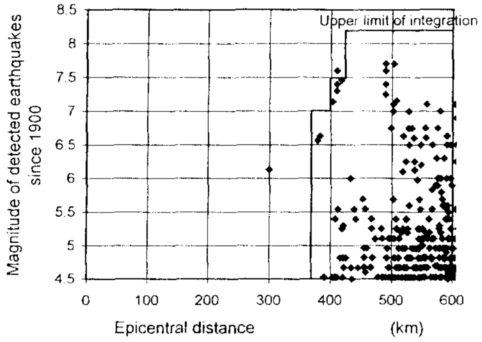

Fig. 5 The upper limit of intergration in the magnitude domain at different distances from Singapore

Fig. 6 shows the probability of the PGA exceeding 0.5% to 1.4% of the gravitational acceleration at rock sites for different exposure periods. In 50 years, the probability of PGA exceeding 1.1% g is about 10%, and that of exceeding 1.5% g is negligible. In other words, the PGA on rock or stiff soils in Singapore due to Sumatra earthquakes has a 10% probability of exceeding 1.1% g in 50 years. The contributions to the probability of exceeding 1.1% g made by earthquakes of different magnitudes and different distances are presented in Fig. 7.

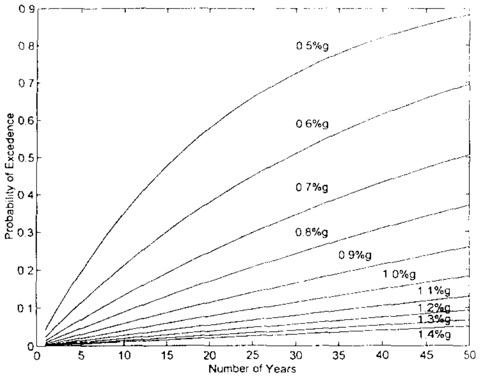

Fig. 6 Probability of exceeding the PGA at rock or stiff soil sites of Singapore within the given years of exposure

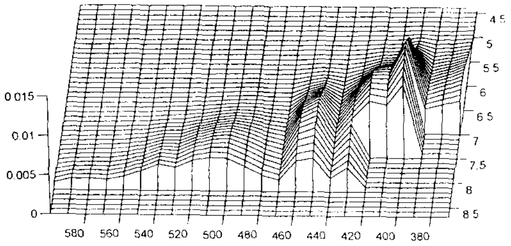

Fig. 7 Disaggregation of the probability of the PGA exceeding 1.1% g at Singapore in terms of earthquake magnitudes and epicentral distances

9. Discussion

The choice of an attenuation relationship is a critical step in the hazard assessment process. Some people believe that the September 1985 Mexico City earthquake is an abnormal event (a double event, to be more specific), and that the bedrock motion in that case was probably at the upper limit of what can be generated at that distance by an earthquake of that size. However, the attenuation equation of Bufaliza(2) was established before the 1985 event, and its derivation could not have been affected by this abnormal event. Generally, the choice of attenuation equation, the treatment of seismicity probability density functions $f(m)$ and $h(r)$, and the limiting values of the integration to obtain $M_{\max}$ are perhaps more on the conservative side in this study. For comparison, a probabilistic seismic hazard assessment for Singapore was conducted in the same way, except that the attenuation equation is taken from Dahle, et. al.(5) instead of from Bufaliza.(2) The predicted ground motion using the new attenuation equation is a few times higher. In fact, the PGA at a rock site in Singapore that has a 10% probability of being exceeded in 50 years becomes nearly 4% g using the attenuation equation of Dahle, et. al.(5)

The probability of ground motion at Singapore contributed by other earthquake sources have not been included here. Firstly, it is possible to have earthquakes with magnitudes larger than 8.2, the value of $M_{\max}$ used in equation (1). Fortunately, these great events are expected to be rather distant, and their contribution would probably be small. Secondly, the pattern of the spatial distribution of earthquakes is based on that from 1964 to 1994. If the reference time span had been longer, earthquakes is based on that from 1964 to 1994. If the reference time span had been longer, earthquakes taken into account would have occurred closer to the chosen location, as can be seen in Fig. 5. These events were not only rare but also not well determined. Thirdly, no allowance has been made for local earthquakes, i.e. only Sumatra earthquakes have been taken into consideration.

In view of the above results and associated uncertainties, a base shear coefficient of 1.5%

is being recommended as the tentative seismic loading in Singapore. The recommended level of the tentative seismic loading reflects the design value of the notional horizontal load, specified in the BS codes (BSI(1)) as equal to 1.5% of the charcteristic building weight, which usually governs the design of most buildings in Singapore.

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