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SEISMIC HAZARD ALONG A TAIPEI RAPID TRANSIT LINE

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ABSTRACT

An integrated approach is used to evaluate seismic hazards at four sites where underground stations are located along the Taipei Mass Rapid Transit (MRT) system Chung-Ho Line. In the establishment of recurrence relationships, historical data and instrumental records are taken. In the assessment of the seismic hazards, both the point source model and the fault-rupture model are used. In particular, in the shallow zones where earthquakes have the potential for long ruptures, the fault-rupture model is used; whereas, for the far-distance deep subduction zone, the point source model is used. Studies of different attenuation equations are also performed to provide some reasonable diversity in characterization of ground motion attenuation. In addition, the hazard-consistent magnitude and hazard-consistent distance corresponding to a specified annual probability of exceedance are determined to establish the ground motion of the probability-based scenario earthquake for evaluating soil liquefaction potential at the sites and seismic vulnerability of underground station structures.

KEYWORDS

Mass Rapid Transit system; recurrence; attenuation; fault-rupture ; seismic hazard; hazard-consistent

DESCRIPTION OF STATION SITES

The stations (Table 1) are located at the southern Taipei City, north of the Taiwan island. Taiwan is located in the Ryukyu-Taiwan-Philippine island arc chain, which rims the western border of the Pacific Ocean. The geologic, tectonic, and seismological information for the Taiwan area (except for the southern tip of the Taiwan Island) has been well investigated and quite available through the Institute of Earth Sciences (IES), Academia Sinica, the Taiwan Weather Bureau, and many researchers (Tsai et al., 1987; Loh et al., 1991a;b;c; Yeh et al., 1993).

The station sites lie in Taipei basin surrounding with hills and gravel terraces, located within the western province. The soil condition of the sites is typical of soft alluvial deposits. The beds are nearly flat-lying, and show no evidence of tectonic deformation. There are no active faults in the Taipei basin area.

Table 1. Site locations

Site	Station Name	N	E
1	Ting Hsi	2767593.014	301197.8459
2	Yung An Market	2766362.300	300744.7000
3	Ching An	2765459.851	300172.4734
4	Nan Shih Chiao	2764974.719	300531.7991

SOURCE MODELING

To describe the potential future activity for a region, a seismic hazard analysis employs three general source types: (1) point source, (2) line source, and (3) area source (Cornell, 1968). Moreover, a fault-rupture model (Der Kiureghian and Ang, 1977) was developed to model three types of source zones (line and area sources): (1) well-defined fault lines, denoted as type I, (2) areas of known fault direction, denoted as type II, and (3) areas of unknown direction, denoted as type III. Recently, a bounded model (for types II and III) was created to avoid the overlapping of two faults with different rupture characteristics (Loh et al. 1991a).
In general, the fault-rupture model is used for shallow seismic zones. Otherwise the point source model is used. Due to the limited information about the active faults in Taiwan (particularly in the northern Taiwan), Type III and point source are considered to model the seismic source. The former models the shallow-zone earthquakes (focal depth $\geq$ 35 km) while the latter models the deep-subduction-zone earthquakes.
The seismicity catalogs show that Taiwan's seismicity pattern is non-uniform and should be divided into several sub seismic zones. By referring to current researches (Loh et al, 1991b;c), this study adopts two zoning schemes for the Taiwan area; namely, scheme A for shallow zone and scheme B for deep zone (see Fig.1). More precisely, the seismic source for scheme A considers the fault-rupture model while that for scheme B takes the point source instead.

RECURRENCE RELATIONSHIP

The recurrence number of earthquakes in a source zone is described by the following equation (Gutenberg and Richter, 1944):

$$N(m) = e^{\alpha-\beta m} \text{ or } \log N = a - b\, m,\ a = \alpha / \ln 10 \text{ and } b = \beta / \ln 10 \tag{1}$$

where "m" is the magnitude; "N" is the cumulative number of events with magnitude greater than m; "a" is the log of the number of earthquakes expected to occur during the specified period of time; and "b" is the slope of the recurrence line. For engineering applications, the recurrence relationship is usually limited by a minimum magnitude m_l as well as a maximum magnitude m_u. Considering m_l(assuming 5.0, Yeh and Loh, 1993) in a source zone, the probability of the occurrence of an earthquake with its magnitude < m_l is

$$f(m) = 1 - N(m)/N_l = 1- e^{-\beta(m-m_l)} \tag{2}$$

where N_l is the total number of events with magnitudes $\geq m_l$ and $N_l = e^{\alpha-\beta(m-m_l)}$. Considering m_u, on the other hand, f(m) should be equal to 1 when m is equal to m_u. However, it is not satisfactory within the above equation. Thus, f(m) is redefined as

$$F(m) = f(m)/f(m_u) = 1-e^{-\beta(m-m_l)} / 1-e^{-\beta(m_u-m_l)} \tag{3}$$

Therefore, as a result of considering both m_u and m_l, N(m) is redefined as

$$N(m) = N_l[1-F(m)] \tag{4}$$

The data base (starting from 1900) of earthquakes with magnitudes $\geq$ 5 for the previously mentioned two types of seismic zones is a combination of historical data and instrumental data. The instrumental data have been reported regularly since two systems of strong-motion instruments (SMA-1 and SMART-1) were installed in Taiwan in 1972. Therefore, only those of data recorded after 1973 are used to determine the b values while the whole data base is used to determine the a values. However, because the time periods of data base to determine the a and b values are different each other in one equation, a hybrid procedure is required. That is to estimate the occurrence rate at a specified magnitude level, then to make the magnitude occurrence line (namely, log N) passing through that particular occurrence rate with the appropriate b value which has been determined previously with a shorter time period. By doing so for each sub seismic zone within a region of 200 km radius around the first site (Ting Hsi Station), the resulting a and b values for each zoning scheme are shown in Fig. 1.

ATTENUATION OF GROUND MOTION

The peak ground is attenuated as the epicentral distance increases. Three functional forms (Kanai's, Joyner and Boore's, and Cambell's) with coefficients suggested by Loh et al. (1991b) are taken for the attenuation relationships in Taiwan.

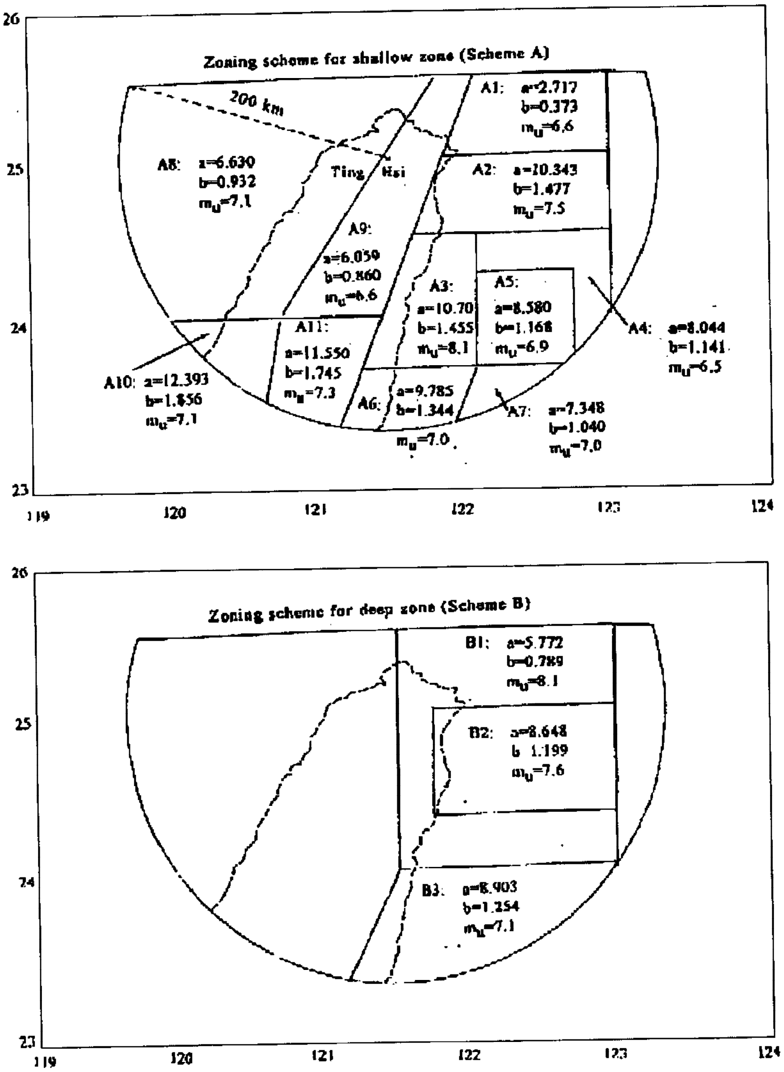

Fig. 1. The determined values of parameters (a, b, & m_u) used for seismic hazard analysis

$$A = 1.128 \exp(0.728\, M)(R + 32)^{-1.743} \tag{5}$$

$$\log A = -1.334 + 0.276M - \log(R^2 + 12)^{1/2} \tag{6}$$

$$A = 0.0073\exp(1.024M)[R + 0.0395\exp(0.92M)]^{-1.065} \quad (7)$$

where A is peak ground acceleration; R is source-site distance; and M is local magnitude (commonly used for engineering purposes). It needs to be pointed out that Loh et al. (1991b) also reported a range of 0.5-0.6 of the logarithmic standard deviations $\sigma\ln A$ of peak ground accelerations.

RUPTURE LENGTH-MAGNITUDE RELATIONSHIP

The rupture length-magnitude relationships for Taiwan were established during the seismic hazard assessment of Taiwan Power Company's nuclear power plants No.1, No.2, and No.3. This study adopts the rupture length-magnitude relationship used in plants No.1 and No. 3.

$$L = \exp(1.006M_L - 3.232) \quad (8)$$

ANNUAL PROBABILITY OF EXCEEDANCE

The occurrence of earthquakes in a seismic zone is usually assumed to follow a Poisson process. It is commonly believed that the Poisson model is reasonable for a region where data base is not sufficient enough to estimate an average recurrence rate (Cornell, 1968). According to the Poisson model, the probability that a ground motion parameter "A" exceeds a specified value "a" in a time period "t" is given by

$$P(A>a) = 1 - e^{-v(A>a)t} \quad (9)$$

where v(A>a) is the annual mean number of events that A exceeds a at the site. The annual mean number of events is obtained by summing the contribution from all sources, that is

$$v(A>a) = \sum v_k(A>a) \quad (10)$$

where $v_k(A>a)$ is the annual mean number of A > a events in source k, and can be expressed as

$$v_k(A>a) = \sum_i \sum_j v_k(m_i)p_k(A>a|m_{i.},r_j)p_k(r_j|m_i) \quad (11)$$

where $v_k(m_i)$ is the annual mean recurrence rate of magnitude m_i earthquakes in source k; $P_k(r_j|m_i)$ is the probability that r_j is the closest distance from the rupture surface to the site (or simply epicentral distance) given the occurrence of an earthquake of magnitude m_i in source k; and $P(A>a|m_i,r_j)$ is the probability that the ground motion exceeds the specified level "a" given an earthquake of magnitude m_i at a distance of r_j. The above equation should be rewritten if m_l and m_u (as defined in eq.3) are considered specifically. If range of magnitude between m_l and m_u is divided into small increment Δm, $v_k(m_i)$ corresponding to the increment Δm can be determined (from eqs.3 & 4) as $N(m)-N(m+\Delta m)$; namely,

$$v_k(m_i) = N_l \frac{\beta e^{-\beta(m-m_l)}}{1-e^{-\beta(m_u-m_l)}}\Delta m \quad (12)$$

If the epicentral distance is divided into small increment Δr_j, $P_k(r_j|m_i)$ corresponding to Δr_j (by assuming that r_j is independent to m_i) can be determined as

$$P_k(r_j|m_i) = A_j/A_t \quad (13)$$

where A_t is the area of source zone and A_j is the area of source zone between $r_j - \Delta r_j/2$ and $r_j + \Delta r_j/2$. If a deterministic approach is considered, then $P(A>a|m_i,r_j) = 1$(yes) or 0(no) depending on the A value determined from the attenuation equations (eqs. 5-7). For a probabilistic approach to include uncertainty in the amplitude of ground motion in the analysis, the A value is usually assumed to be lognormally distributed and $P(A>a|m_i,r_j)$ should be re-determined as

$$P(A > a|m_i, r_j) = 1 - \Phi\left\{\frac{\ln(a) - [\ln\hat{A}|m_i, r_j]}{[\beta_A|m_i, r_j]}\right\} \qquad (14)$$

where $\Phi\{\}$ is the cumulative distribution function of a standard normal variable; $\hat{A}|m_i, r_j]$ is the median value of A caused by an earthquake m_i at the epicentral distance r_j; and $\beta_A|m_i, r_j]$ (assuming 0.55 in the analysis) is the logarithmic standard deviation of A.

SEISMIC HAZARD CURVES

The seismic hazard analysis takes the same seismic source but the three different attenuation equations (eqs.5-7) into consideration respectively. As a result, the seismic hazard curve which is a plot of annual probability of exceedance "p" versus peak ground acceleration "g" can be determined for each form of attenuation. To include uncertainties of attenuation, the A values determined from the three attenuation equations are taken as median values with the same logarithmic standard deviation, 0.55. For the first site (specified in Table 1), the hazard curves corresponding to those attenuation equations are shown in Fig.2. As indicated in the figure, with respect to the same level of p value, the Kanai's form makes the largest g value and the other two forms result the close g values. In the mean time, all the three forms seem to estimate the quite similar g values and their differences become a little larger when the p value is very small (say 10^{-5}). For the other three sites, the resulting hazard curves show the nearly same results (about 2% difference).

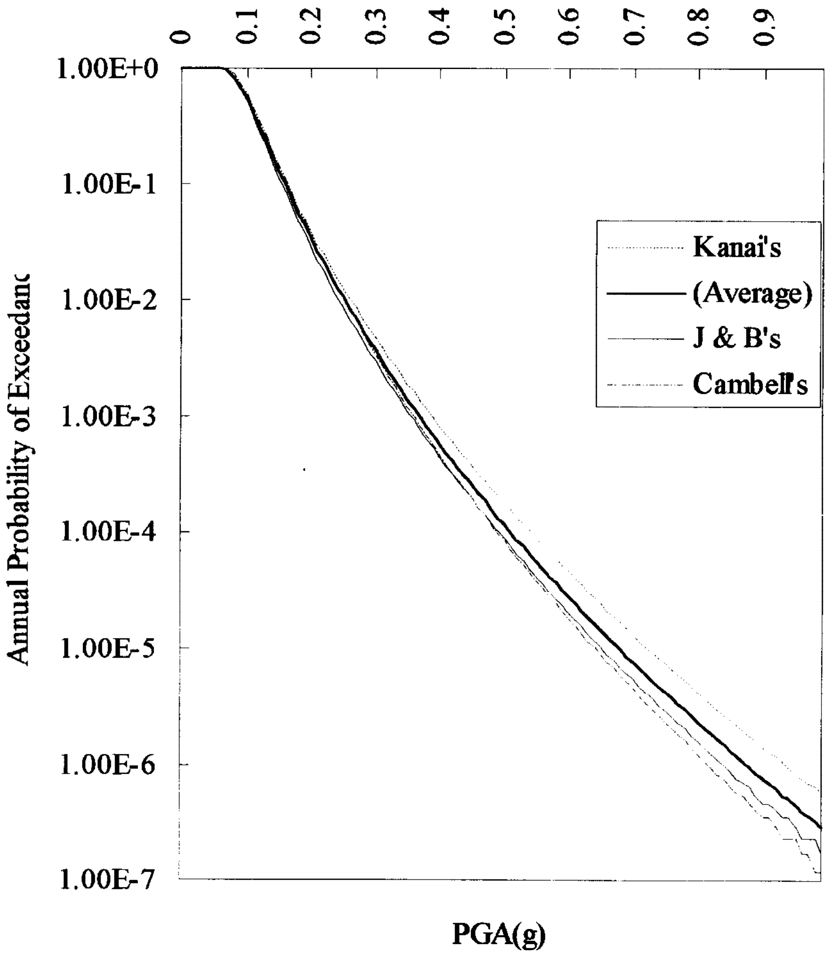

Fig. 2. The seismic hazard curves for the first site(Ting Hsi Station)

HAZARD-CONSISTENT MAGNITUDES AND DISTANCES

The hazard-consistent magnitudes and hazard-consistent distances with respect to different levels of annual probability of exceedance are calculated by using the method proposed by Ishikawa and Kameda (1991).The hazard-consistent-magnitude $\overline{m}$ and hazard-consistent distance $\overline{r}$ are defined as the conditional mean values given the A value exceeding the level corresponding to a specified probability of exceedance a(p).

$$\overline{m}(p) = E[m|A > a(p)]$$
$$= \frac{\sum_{i}\sum_{j} m_i P(A > a(p)|m_i, r_j) P(r_j) P(m_i)}{\sum_{i}\sum_{j} P(A > a(p)|m_i, r_j) P(r_j) P(m_i)} \qquad (15)$$

and

$$\overline{r}(p) = E[r|A > a(p)]$$
$$= \frac{\sum_{i}\sum_{j} r_i P(A > a(p)|m_i, r_j) P(r_j) P(m_i)}{\sum_{i}\sum_{j} P(A > a(p)|m_i, r_j) P(r_j) P(m_i)} \qquad (16)$$

For the first site (Ting Hsi Station), the hazard-consistent magnitudes and distances corresponding to the three attenuation equations are shown in Figs.3, 4 & 5, respectively. As indicated in the figures, with respect to the same level of p value, the Kanai's form makes the largest mean magnetite as well as the smallest mean distance. This observation is consistent with the previous one found in the hazard curves and it seems to be quite reasonable since the Kanai's form makes the largest g value which is a result of large mean magnetite and short mean distance. By specifying a designated annual probability of exceedance, the corresponding values of the hazard-consistent magnitudes and distances may proceed to establish the ground motion of the probability-based scenario earthquake for evaluating soil liquefaction potential at the sites and seismic vulnerability of underground station structures.

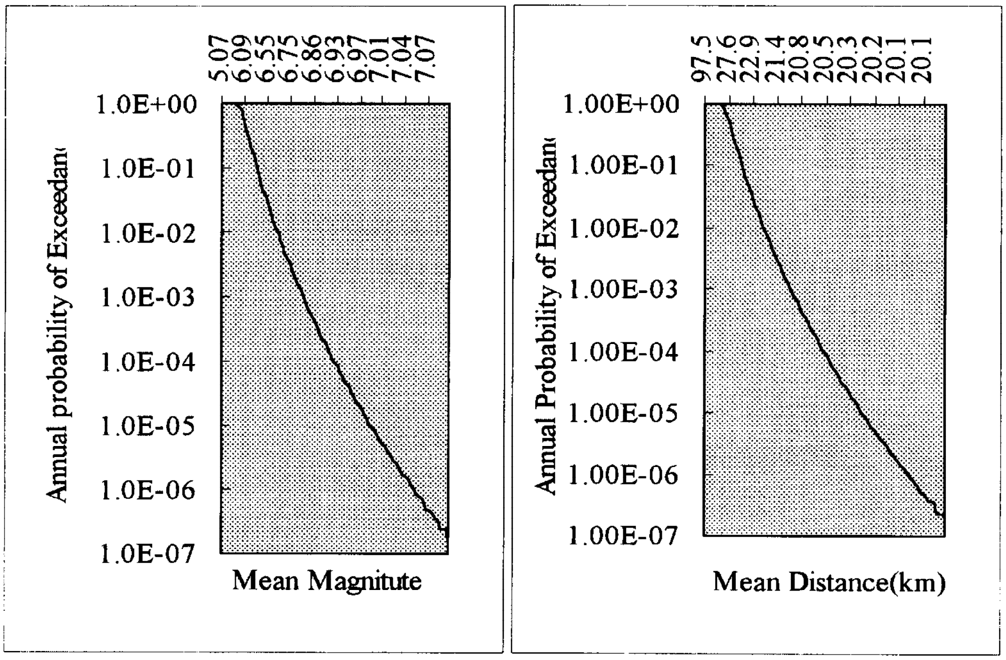

Fig.3. Hazard-consistent magnitudes and distances for the first site(J & B's)

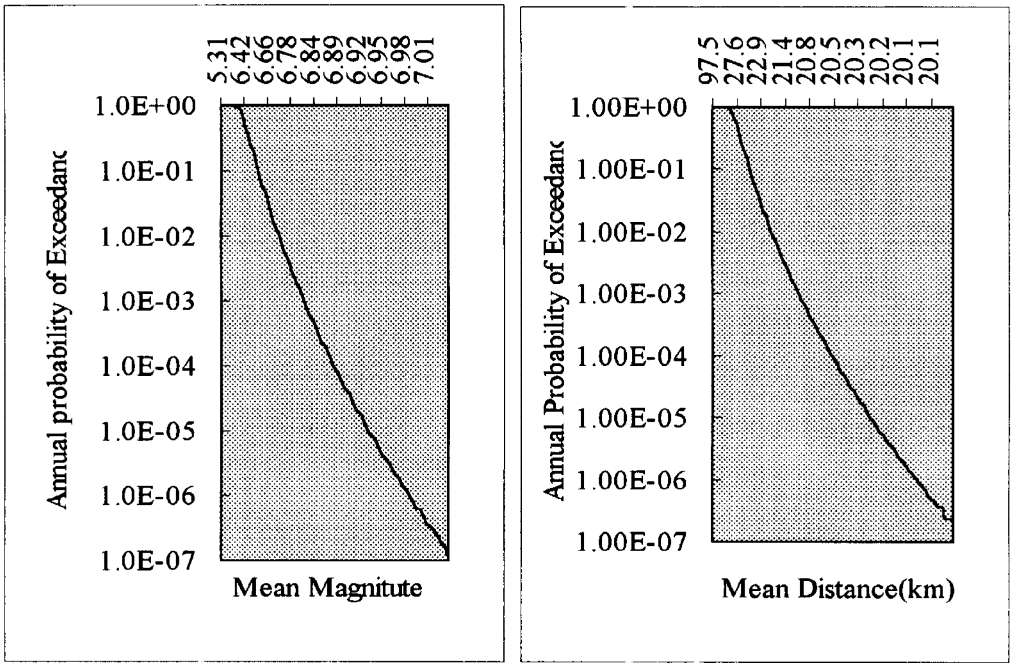

Fig. 4. **Hazard-consistent magnitudes and distances for the first site(Cambell's)**

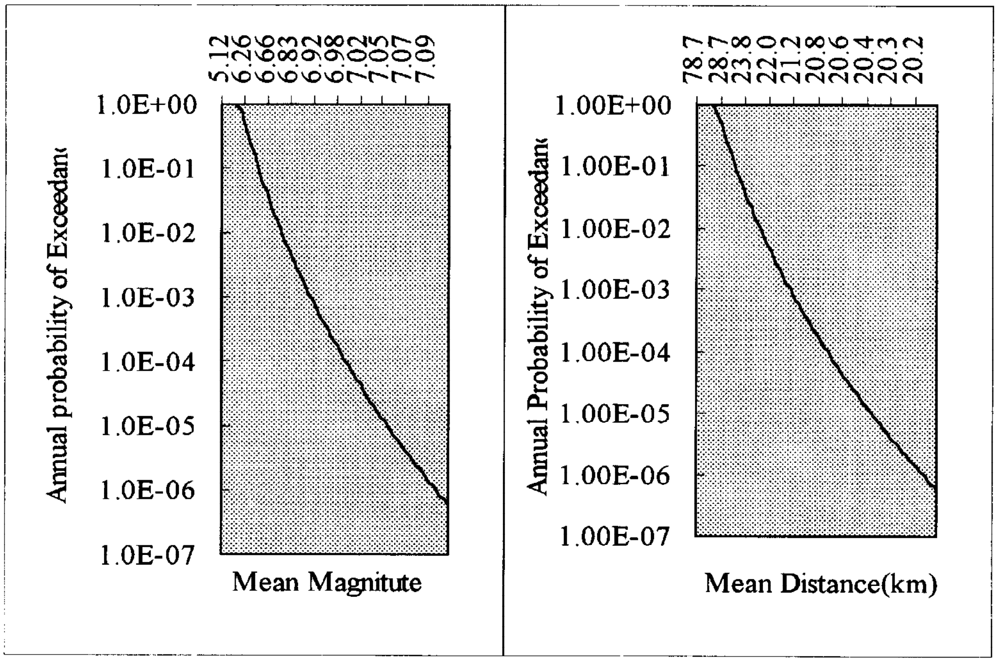

Fig.5. **Hazard-consistent magnitudes and distances for the first site(Kanai 's)**

CONCLUSIONS

A probabilistic analysis is performed to evaluate the seismic hazards at four sites where the MRT system Chung-Ho Line crosses the south part of the Taipei Metropolitan Area. The results are expressed as hazard curves, hazard-consistent magnitudes and distances by considering the three different attenuation equations. (a) Taking an earthquake having a mean return period of 475 years (annual probability of exceedance = $2x10^{-3}$) as a designated earthquake, the average PGA is around 0.33g. (b) All the four sites under investigation are located within the MRT Chung-Ho line with a distance of 6,440m. The final analyses indicate that the PGA values resulting from the other three sites differ the one resulting from the first site only about 2 %. The only small amount of difference is because those sites are closely located. (c) The probabilistic seismic hazard analysis is very sensitive to the the logarithmic standard deviation σlnA of peak ground accelerations used in the probabilistic model of ground motion attenuation. For example, the average PGA at the 475-year level will increase from 0.33g to 0.38g if the $\sigma \ln A$ is taken as 0.6 instead of 0.55. Therefore, the effect of uncertainties caused by attenuation is quite significant in the probabilistic model of seismic hazard analysis. (d) The hazard-consistent magnitude tends to increase as the probability of exceedance decreases, whereas the hazard-consistent distance decreases as the probability of exceedance decreases.

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