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# Ground Motion Modeling in the Near-Source Regime: A Barrier Model

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## ABSTRACT

**A method using the specific barrier model (Tsai, 1998) is adopted here to simulate ground motion accelerations for the purpose of seismic hazard analysis at sites near a dominant fault system. The technique incorporates the simulation of fault geometry and adopts an appropriate relationship between stress drop and seismic moment to estimate the number of cracks on the fault for the barrier model. Radiated direct shear waves are established following Boore's (1983) procedure. The simulated peak ground accelerations (PGA) are then calibrated by strong-motion data. Basically, the model is of uniform source, and the directivity of the source is ignored.**

**The results show that the calibrated PGA values are neither sensitive to the relationship between the stress drop and seismic moment and nor to that between the fault rupture length and magnitude. However, the calibrated PGA values may increase about 20 percent for sites near the fault when the cut-off frequency, $f_{max}$, is raised from 5 Hz to 10 Hz. The variability of the simulated ground motion is, in general, smaller than that of the empirical strong-motion data shown in the literature. This may be improved by adding randomness to the parameter of $f_{max}$ and uncertainties into the empirical relationships adopted in the model. The calibrated attenuation curves are used to judge which types of conventional attenuation equations are better at representing the attenuation of PGA's for sites near the fault, especially for large earthquake events. The results infer that, among the four attenuation equations in Tsai *et al.* (1987), the Joyner and Boore's form seems to be the most adequate one for ground motion estimates in the near-source regime in Taiwan.**

**(Key words: Ground motion, Seismic hazard, Near-source, Barrier)**

## 1. INTRODUCTION

Besides the modeling of the occurrence of earthquakes, the other affecting factor in probabilistic seismic hazard analysis (PSHA) lies in the estimation of ground motions. Conventional approaches for PSHA make use of empirical attenuation equations to estimate peak

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ground accelerations, velocities and/or spectral accelerations. As a general rule, empirical attenuation curves are better constrained in distance ranges with sufficient observations of strong-motion recordings. As a result, no matter what forms of attenuation equations (e.g., those of Joyner and Boore, 1988) are adopted, regression curves (using various attenuation forms) fitted to the data are quite similar in the well-constrained range, while they appear significantly different in the shorter distance range of up to 30 km from seismic sources. However, the degree of diversity in the prediction of ground motion at close distances to the fault can be reduced by adding more near-source data from the strong-motion observations. Nevertheless, for the PSHA at sites of interest, recordings at the near-source distance range are normally rare. Therefore, while data are not sufficient in a wide range of distances and earthquake magnitudes, a theoretical simulation of ground motion for sites at close distances to seismic sources becomes a better way to solve the problem.

Although a few methods have recently been made available, they may not be effective for the purposes of PSHA. Four of these are: (1) the simplified empirical Green's function model (Somerville *et al.*, 1991); (2) the asperity model (Tsai, 1992, 1997a); (3) the composite source model (Zeng *et al.*, 1994); and (4) the kinematic self-similar rupture model (Herrero and Bernard, 1994). Basically, these four models all involve specific descriptions of the spatial slip distribution for seismic scenarios. A kinematic slip description of the source equally advocates a heterogeneous depiction of that source. Tsai (1992) has shown that both heterogeneous and homogeneous sources can generate non-stationary direct shear waves at close distances to the fault. Thus, it is apparent that whether or not the source must be heterogeneous is not crucial for the purpose of PSHA.

Unlike the asperity model proposed by Tsai (1992, 1997a), the other models make use of either empirical or numerical Green's function for ground motion synthesis, which involves many more computations than does the asperity model. The model proposed by Tsai (1992, 1997a) produces, at least to some extent, the directivity effect of the rupturing source, a phenomenon which is not strongly supported by observations of high-frequency ground accelerations although this is commonly seen from low-frequency ground motions, namely, velocity and displacement.

Chin and Aki (1991) adopted the specific barrier model (Papageorgiou and Aki, 1983a) to simulate the ground accelerations recorded from the 1989 Loma Prieta earthquake. Their model, which ignores the directivity effect and simplifies the computation by skipping Green's function and the kinematic description of the seismic source, is very suitable for the theoretical simulation of ground motion in PSHA. The procedure they used, however, is not adequate in simulating ground motions induced by "future earthquakes" since the source power spectrum cannot be predetermined. For this reason, Tsai (1998) has recently proposed a modified procedure (using the specific barrier model) adapted from Chin and Aki (1991) and Papageorgiou and Aki (1983a) to implement the theoretical simulation of ground motion for the purpose of PSHA in the near-source region.

This paper, serving as a complement to Tsai's (1998), presents more details in the application of the proposed technique applied to the local strong-motion data collected in the Taiwan region. Various conventional attenuation equations from Tsai *et al.* (1987) are examined by comparing simulated attenuation curves using the specific barrier model. Thus, adequate types of attenuation forms are sorted out based on the simulated attenuation curves, which make for more reliable predictions of strong-motion accelerations in the near-source region of Taiwan. The proposed model (Tsai, 1998) limits its application to the near-source region, where direct shear waves dominate peak ground motions. It should be noted that the site condition considered is for rock only.

## 2. THE METHOD

Tsai's (1998) method is followed in this study. Figure 1 gives a summary of the procedure. Basically, the flow chart indicates that the procedure determines the adequate number of cracks in the specific barrier model given an earthquake magnitude $M$. Then, using Boore's (1983) stochastic method for ground motion modeling and incorporating the calculated corner frequency, the acceleration time history of the radiated shear waves is simulated from each crack on the fault. The acceleration spectrum $A_i(f)$ for crack $i$ is calculated following Boore (1983):

$$A_i(f) = \frac{0.85 M_{0_{\text{sub}i}}}{4\pi\rho\beta^3 R_i} \frac{(2\pi f)^2}{1+\left(\frac{f}{f_{0_{\text{sub}i}}}\right)^2} \frac{1}{\left[1+\left(\frac{f}{f_{\max}}\right)^8\right]^{1/2}} e^{-\pi f R_i / Q\beta}, \quad (1)$$

where $f$ is the frequency (Hz), $\rho$ the density, $R_i$ the distance from the $i$-th crack to the site (km), $Q$ the quality factor and $f_{\max}$ the cut-off frequency. The accelerogram for each crack is obtained by converting the above acceleration spectrum using the inverse fast Fourier transform with random phases. Finally, the total accelerogram is established by summing up the accelerograms produced by each crack on the basis of each arrival time at the site.

It is suggested that the relationship between $\Delta\sigma$ and $M_0$ (shown in Figure 1) follows Nuttli's (1983) form:

$$\log_{10}\Delta\sigma = a + b \log_{10} M_0, \quad (2)$$

where $a$ and $b$ are regression coefficients for analysis by the least-squares fit to the data available from the seismic source zones of interest. For instance, based on the data in Table 1 and with those of the Loma Prieta earthquake ignored, $a$ and $b$ of Equation (2) are found to be 0.2268 and 0.08496, respectively, while a correlation coefficient of 0.894 is obtained by a linear regression analysis.

To be consistent with the specific barrier model, it is assumed here that the cut-off frequency $f_{\max}$ is introduced by the source effect (Papageorgiou and Aki, 1983a; Aki and Papageorgiou, 1988; Aki, 1990). There are however opponents who advocate that $f_{\max}$ is a result of attenuation due to a low value of $Q$ for the crust in the vicinity of the site (e.g., Hanks, 1982; Anderson and Hough, 1984; Frankel, 1990). Originally, in Papageorgiou and Aki (1983b) and Chin and Aki (1991), $f_{\max}$ was obtained from the source spectrum of acceleration inversed

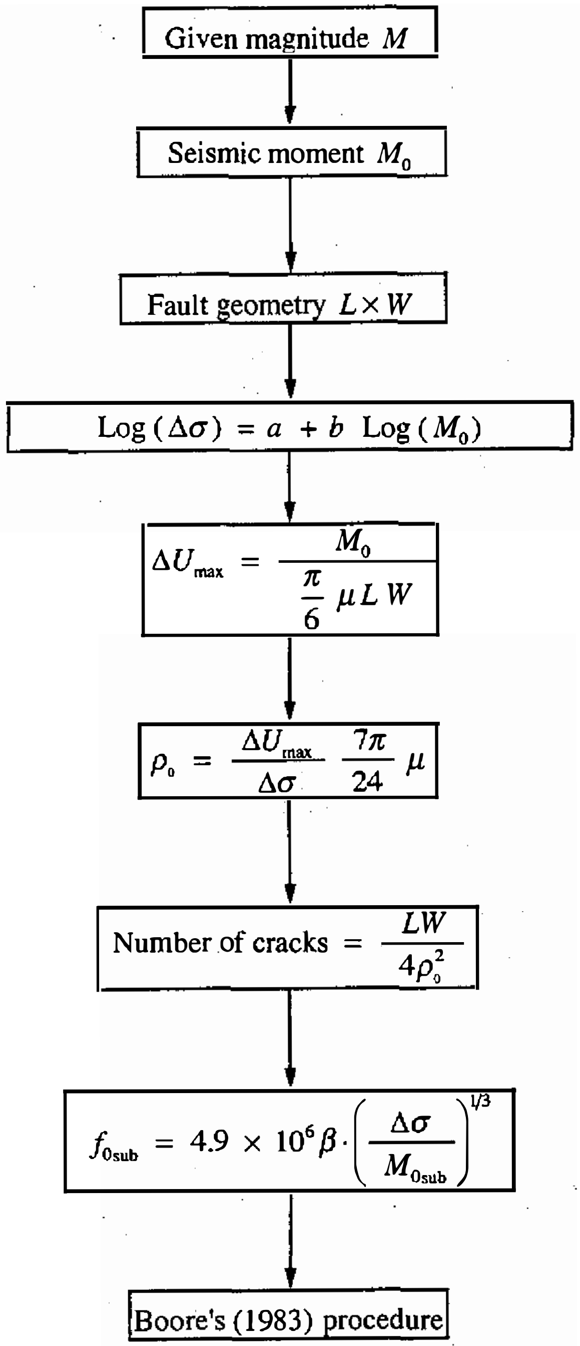



*Fig. 1.* The flow chart illustrates the modified procedure which adapts the specific barrier model and incorporates Boore's (1983) procedure for the synthesis of acceleration time history for sites in the near-source regime (after Tsai, 1998).

Table 1. Source parameters of six earthquake events occurring in California adopted from Papageorgiou and Aki (1983a) and Chin and Aki (1991).

| Event | $M_0$(dyne-cm) | $P_0$(cm²/sec³) | $\Delta\sigma$ (bars) |
|---|---|---|---|
| San Fernando 1971 | $1.2 \times 10^{26}$ | $8.5 \times 10^5$ | ≈ 300 |
| Kern County 1952 | $2.0 \times 10^{27}$ | $1.0 \times 10^6$ | ≈ 350 |
| Long Beach 1933 | $2.8 \times 10^{25}$ | $5.0 \times 10^5$ | ≈ 220 |
| Borrego Mtn. 1968 | $6.3 \times 10^{25}$ | $2.0 \times 10^5$ | 200 - 300 |
| Parkfield 1966 | $1.4 \times 10^{25}$ | $2.0 \times 10^5$ | 200 - 300 |
| Loma Prieta 1989 | $2.2 \times 10^{26}$ | $1.6 \times 10^5$ | 119 |

from the observations. As that treated in Tsai (1998), it is *a priori* designated for the seismic source and is identical for all cracks (subevents) on the fault.

## 3. APPLICATION TO A FAULT SYSTEM IN TAIWAN

The Tachienshan-Chukou fault system in southwestern Taiwan (Figure 2), long recognized as active (Bonilla, 1975, 1977), is assumed to be the seismic source for ground motion prediction at nearby sites. Another assumption made is that the seismic setting is capable of both rupturing an area with a maximum width of 17 km and length of 75 km and producing earthquakes with magnitudes of 7.0 or less. This fault system is taken to be the sole, dominant seismic source for nearby sites. Also assumed here is that the direct shear waves dominate the ground motion accelerations in the near-source regime.

It is believed that when an earthquake event takes place on the fault system, the ruptured area scales with the moment magnitude (or seismic moment) for its size and randomly takes its position on the fault system. An empirical equation which relates the fault rupture length to the magnitude is adopted following the results of Tsai *et al.* (1995) for the Taiwan area:

$$\log_{10} L = 0.4369M - 1.4036. \tag{3}$$

The seismic moment is directly calculated following Hanks and Kanamori's (1979) relation as follows:

$$\log_{10} M_0 = 1.5M + 16.1. \tag{4}$$

Tsai's (1992, 1997a) procedure for simulating earthquake fault geometry given a magnitude is followed in this study. Accordingly, a suitable fault width $W$ ($\leq$ 17 km) corresponding to the given $M$ and the calculated $L$ is obtained with the constraint that the seismic moment $M_0(= \mu\,\bar{u}\,WL)$ is preserved, where $\bar{u}$ is the average slip of the barrier model.

The shear modulus $\mu$ is taken as $3 \times 10^{11}$ dyne/cm². The sweeping ($V$) and spreading ($\upsilon$)

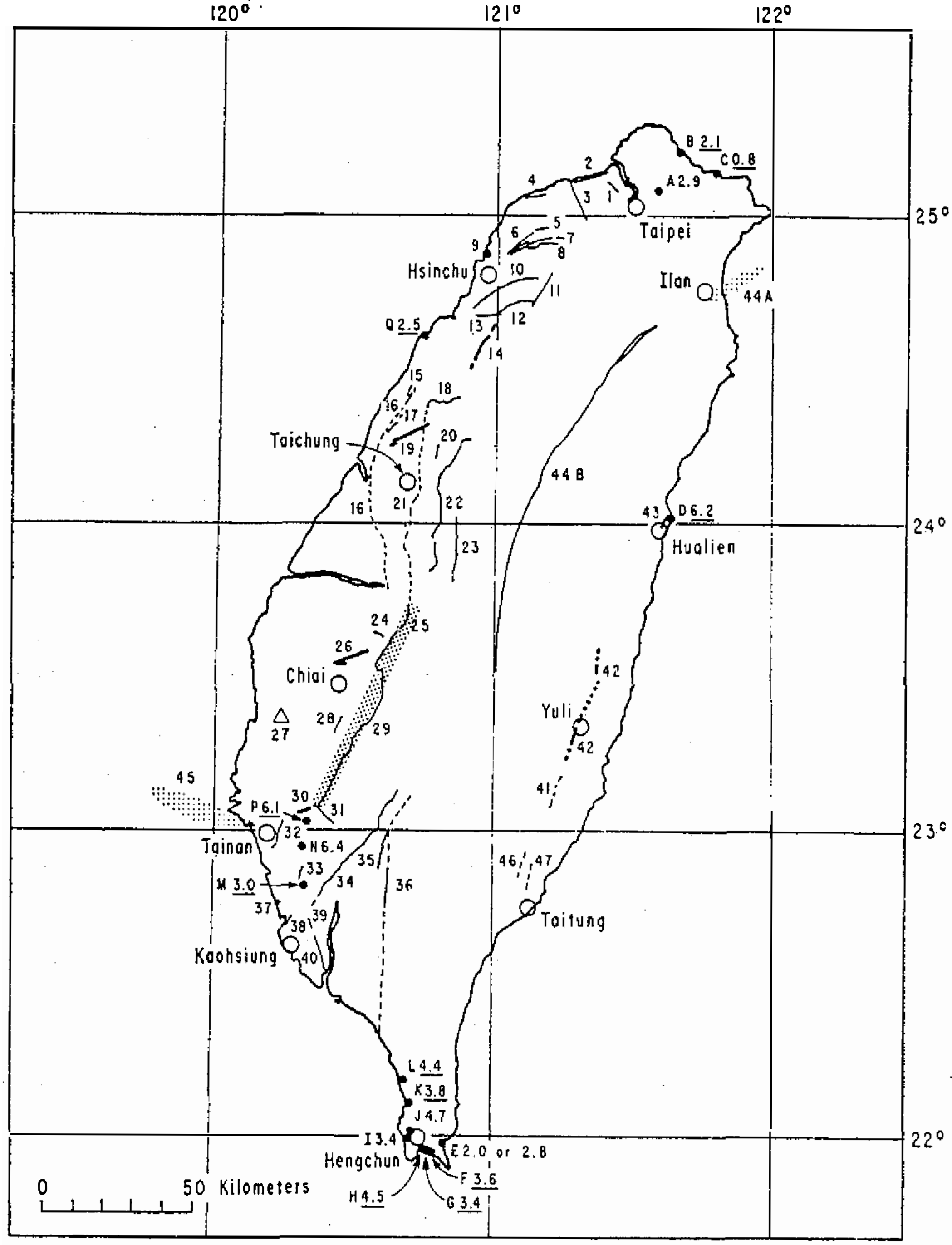



*Fig. 2.* The Tachienshan-Chukou fault system is highlighted by a long narrow shaded area as shown in the map and is denoted by the numbers 25 and 29. This map is reproduced and modified from Bonilla (1977).

velocities are both taken as equal to 2.78 k sec. $\beta$ and $\rho$ are 3.27 km/sec and 2.8 gm/cm$^3$ (Hwang and Kanamori, 1989), respectively. The P-wave velocity is set to equal $\sqrt{3}\beta$. The quality factor $Q$ is approximated at 300, and $f_{max}$ is assumed to be 5 Hz. Empirically obtained in an adoption from Tsai (1993) by regression analysis from the source parameters as listed in Table 1 with the local stress drop of the Loma Prieta earthquake changed to 250 bars, the coefficients $a$ and $b$ in Equation (2) are 0.4105 and 0.07747, respectively.

The peak ground accelerations induced by the Tachienshan-Chukou fault system at sites within 90 km of the fault are first simulated following the flow chart in Figure 1 with all the parameters given above. Then, the simulated attenuation curves using the barrier model are calibrated by strong-motion recordings available for rock sites on Taiwan. Because the direct shear waves registered at distant sites from the seismic source (say, out of the near-source regime) might not dominate the peak ground accelerations, the "source-to-site" distance in the range of 20 - 80 km for the strong-motion data is chosen for the purpose of calibration. The numerical simulation of PGA, using the specific barrier model proposed by Tsai (1998), is implemented by combining different locations of rupture planes, foci and sites for each pair of magnitude and distance.

## 4. RESULTS AND IMPLICATIONS FOR STRONG GROUND MOTIONS IN TAIWAN

Figure 3 shows the results of the theoretical simulations. On the bottom right in the plot, the (calibrated) median curves are shown together for magnitudes 5.0 to 7.0 with 0.5 increments. The others individually show the calibrated median curves for various magnitudes, strong-motion data (the PGA's of two horizontal components with magnitudes in the range of $M \pm 0.2$) and the uncalibrated median curves with the median $\pm$ one-standard-deviation curves. The distance, like that used by Joyner and Boore (1982), is the smallest distance from the site to the vertical projection of the fault system.

It is evident that the decay of the calibrated PGA curves with respect to distances for different magnitudes is rather consistent with the observations in the distance range of 20-80 km, although quite a broad dispersion is noted for the strong-motion data in the same distance range. Unexpectedly, the calibrated PGA's of $M$ 5.0 are larger than those of $M$ 5.5 for distances of less than about 4 km from the fault. Such discrepancy is not physically acceptable because the (ensemble) average of PGA's produced by larger earthquakes is expected to be higher than those produced by smaller ones. This may be due to either a flaw in the data used for calibration or inadequacies in simulating the geometry of the fault for small earthquake events of $M$ 5.0.

It also reveals that the calibrated curves do not increase smoothly in accordance with magnitude (see the plot on the bottom right in Figure 3). The increments of the PGA values from $M$ 6.5 to 7.0 are much larger than those from $M$ 6.0 to 6.5 as well as those from $M$ 5.5 to 6.0. This may be attributed to flaws in the strong-motion data used and/or the source characteristics of the Taiwan region.

As stated in Tsai (1998), the variability of the simulated PGA's is obviously smaller than those of the observational data shown in Figure 3. Tsai (1998) showed that the standard

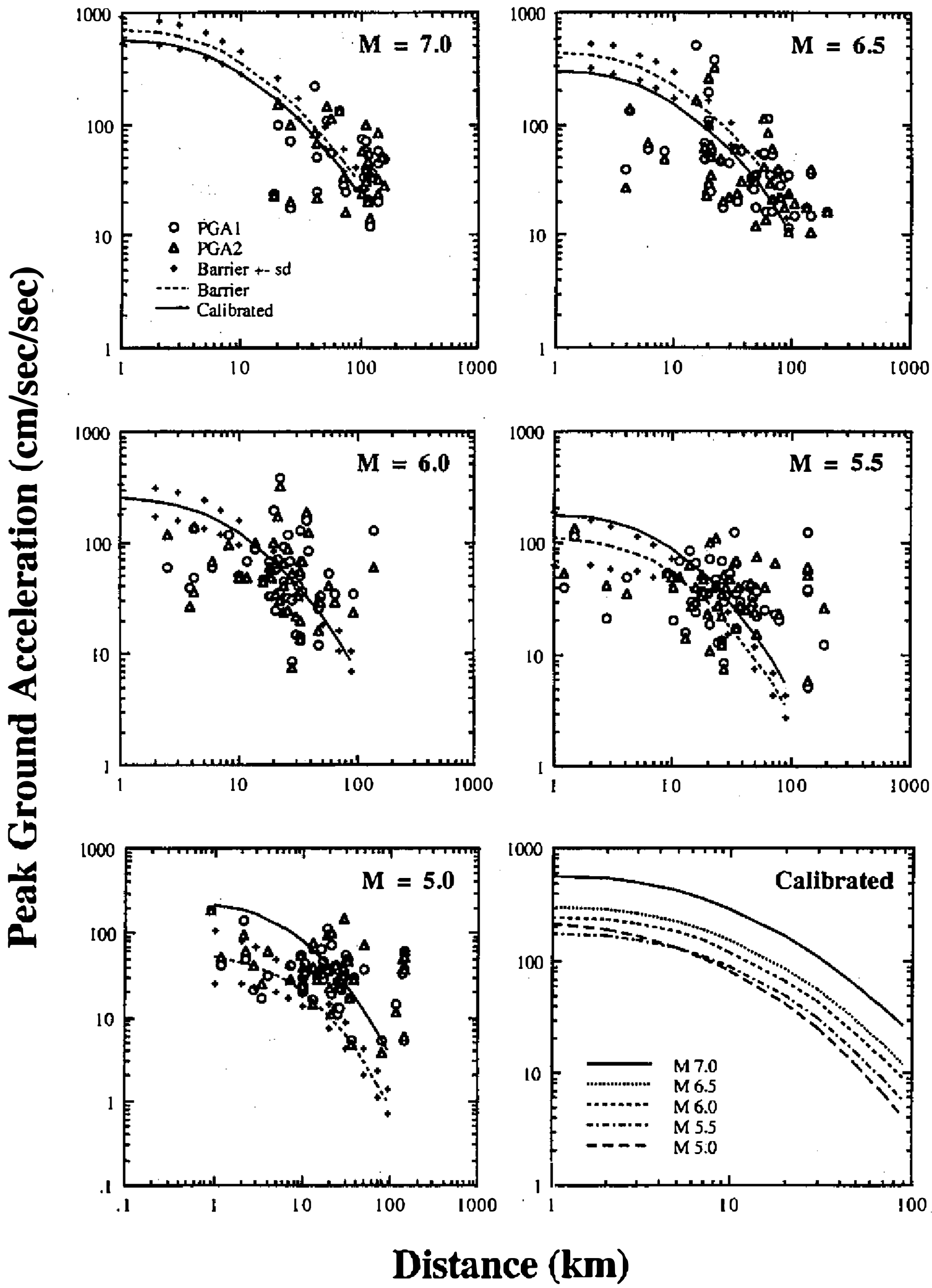



*Fig. 3.* The simulated and calibrated attenuation curves are shown together with the observed data. PGA1 and PGA2 denote the peak ground accelerations of two horizontal components of the recordings. Distances used for calibration are in the range of 20-80 km. The plot on the bottom right shows the calibrated median curves of the simulated results.

deviations of the natural logarithm of the simulated PGA ($\sigma_{\ln PGA}$) for $M$ of 6.0, 6.5 and 7.0 are approximately between 0.2 and 0.3 for distances of 1 km to 90 km. These values are lower than those shown in Tsai *et al.* (1987) where they range from 0.48 to 0.57 for the strong-motion data of Taiwan. They are also lower than those shown in Campbell (1985) and Joyner and Boore (1988) where they range from 0.3 to 0.7. A general trend reveals that the larger the distances, the smaller are the values for $\sigma_{\ln PGA}$. Tsai (1998) inferred that a smaller dispersion of the simulated PGA's may be a result of a number of simplifications in the model. For instance, a fixed value of $f_{\max}$ (5 Hz) for all sites in the simulation obviously contrasts with the real situations in which strong-motion data have been involved. In fact, the ground motion data are made up of recordings from various sites, source mechanisms and sizes. In addition, the specific barrier model is basically homogeneous in terms of stress drop, source geometry and moment release on the fault. At the same time, the observational data are produced by earthquake events of considerably more complicated source characteristics than those assumed for the proposed model.

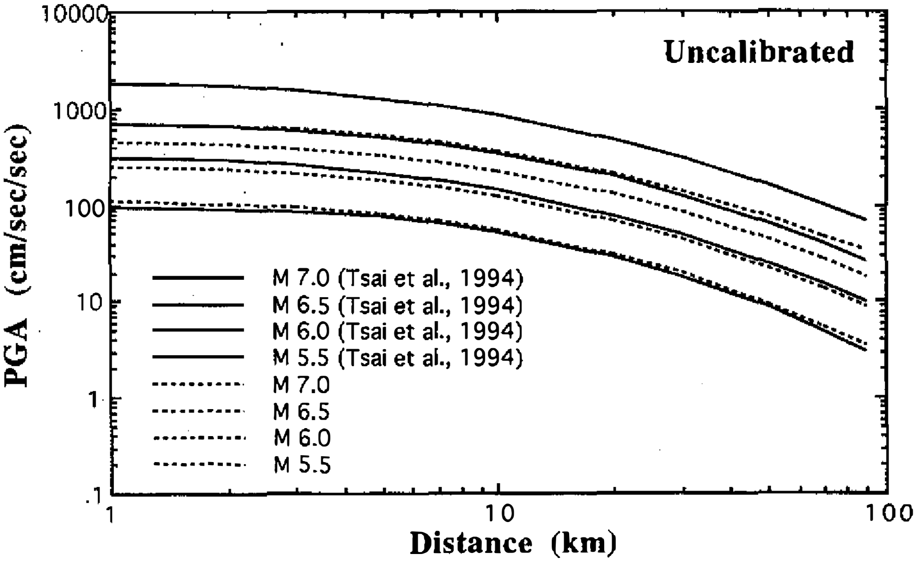
Tsai (1998) showed that a greater than 20 percent increase in PGA's in the near-source regime may be expected for sites with $f_{\max}$ raised from 5 Hz to 10 Hz. This implies that the determination of $f_{\max}$ is important when ground motion modeling is implemented for sites near a potentially large fault system. This is also consistent with the results of Tsai (1997a).

Another set of values -4.867 and 0.2925 are used for the coefficients $a$ and $b$ of Equation (2), respectively, to examine the sensibility of the relationship between $\Delta\sigma$ and $M_0$. They are adopted from Tsai *et al.* (1994) and Tsai (1997b) and were empirically obtained in those studies by regression analysis from the source parameters of seismic sources in the Taiwan region. [These two values are not used at the onset of this study because they might not be very representative for the seismic sources around the Taiwan region. The dependence of the stress drop on the seismic moment as revealed by 0.2925 (the coefficient $b$) seems too strong compared with 0.07747.]

Figure 4 shows the comparisons of the attenuation curves between the results of the two groups of coefficients: The upper plot shows the curves of the uncalibrated PGA values; the lower one shows those of the calibrated ones. It is apparent from the former that the specific barrier model is sensitive to the relationship between $\Delta\sigma$ and $M_0$ for large earthquake events. However, from the lower plot, after the PGA values are calibrated, Tsai's (1998) method is not sensitive to the relationship between $\Delta\sigma$ and $M_0$ except for large earthquakes (say, $M \leq 7.0$). In the case of large events, the difference in the calibrated PGA's is about 15 percent at sites within 10 km of the fault, whereas it is negligible at distant sites.

The effect of the relationship between rupture length and magnitude [Equation (3)] on the calibrated PGA's has been explored by Tsai *et al.* (1995). Their results show that the proposed procedure of Tsai (1998) is also not sensitive to the relationship of Equation (3), especially for large earthquake events. Consequently, the variability of the calibrated PGA induced by the uncertainty of Equation (3) should be ignored for wide ranges of both magnitudes and distances.

As concluded by Tsai (1997a, 1998), the main factors affecting the results of the theoretical modeling are the cut-off frequency ($f_{\max}$) and the strong-motion data used for calibration. If the randomness of $f_{\max}$ and the uncertainty of the relationships between both the stress



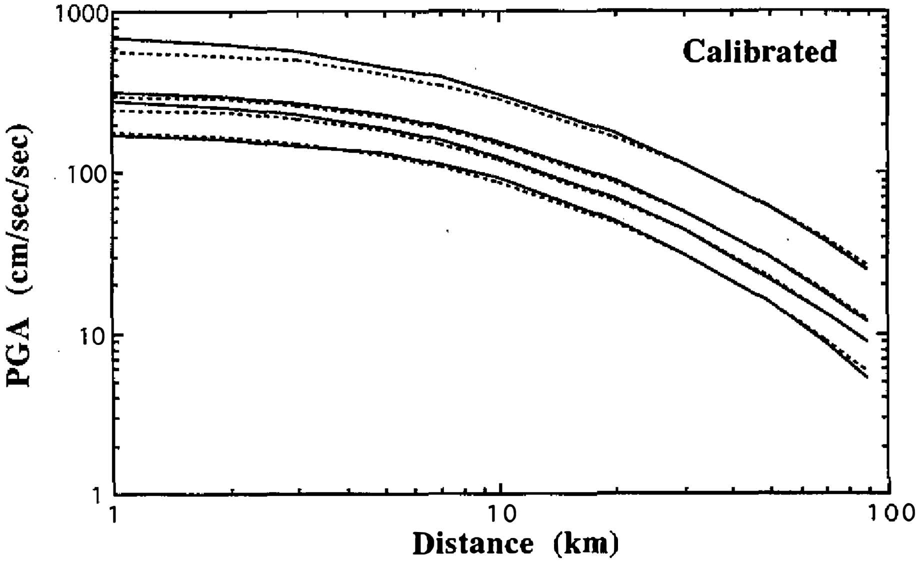




*Fig. 4.* Comparisons of the attenuation curves obtained by using two different relationships between $\Delta\sigma$ and $M_0$ [Equation (2)]. Solid lines represent the results using the relationship adopted from Tsai *et al.* (1994); the dashed lines represent those using the relationship obtained from Table 1 (with the local stress drop of the Loma Prieta earthquake changed to 256 bars), which shows a weaker dependence of the local stress drop on the seismic moment. The upper one shows the uncalibrated results, while the lower one shows the calibrated results. The lower plot indicates that Tsai's (1998) method is not sensitive to the $\Delta\sigma$ - $M_0$ relationship.

drop and the seismic moment as well as between the rupture length and the magnitude can be incorporated into the model, the overall variability of the calibrated PGA ($\sigma_{\ln PGA}$) will be more similar to that of the observational data empirically presented in the literature. The calibration of PGA values plays a vital role in the theoretical simulations. Thus, it is necessary to have "good" observational strong-motion data in order to have convincing calibrated attenuation curves in the near-source regime where empirical data are not sufficient for large earthquake events. These data, in general, have a longer return period of time than those of small earthquakes.

An advantage of using the modified procedure of the specific barrier model (Tsai, 1998) is that adequate types of attenuation forms can be sorted out by comparing the calibrated attenuation curves with those of the empirical ones of various types of forms. Figure 5 shows the four attenuation curves of 6.5 from Tsai *et al.* (1987), the simulated median curve (calibrated, see Figure 3) with the same magnitude using the specific barrier model and the observed ground motion data. The empirical attenuation curves are more diversified at close distances than at 20-80 km from the seismic sources. Note that the attenuation curves from Tsai *et al.* (1987) are obtained from a different data set from that adopted in this study. Thus, it is expected that these empirical curves deviate from the calibrated curves which are theoretically simulated. Despite the significant differences between the observed PGA data and the four attenuation curves, it may be inferred that based on the decay of PGA's with distances and the comparisons with the simulated median curve, the Kanai and the Joyner and Boore forms are more adequate than the other two. Figure 6 presents more comparisons with multiple magnitudes for the Kanai and the Joyner and Boore forms. It is inferred that, in general, the Joyner and Boore form is better than the Kanai form (*M* of 5.0 being ignored) if the simulated curves better reflect the attenuation of strong ground accelerations in the distance range where direct shear waves dominate the peak motions.

## 5. CONCLUSIONS AND SUGGESTIONS

A modified procedure using the specific barrier model (Tsai, 1998) to simulate the ground motion accelerations in the near-source regime from a solely dominant fault system in Taiwan has been followed in this study. The main parameter affecting the simulated PGA values is the cut-off frequency $f_{\max}$ which was first introduced by Hanks (1982) but which is still of uncertain origin. That $f_{\max}$ is the result of either the source or the site effect has yet to be resolved. In accordance with the specific barrier model, $f_{\max}$ is treated herein as a source parameter, being given *a priori* for the model. It is suggested that, for the ground motion estimate using the specific barrier model, $f_{\max}$ is better treated as a random variable with a reasonable range of values bounded by the local source characteristics involved. If an appropriate range of the source parameter is not conveniently available, a carefully chosen range of $f_{\max}$ values should be imported from other seismic regions similar to the area of interest.

The adopted method is limited to sites where suitable observational data are available for a wide range of magnitudes but where there is a lack of sufficient data in the near-source region for large earthquakes. Another limitation is that the radiated waves considered are restricted to direct shear waves in the near-source regime. The effect of topography is not

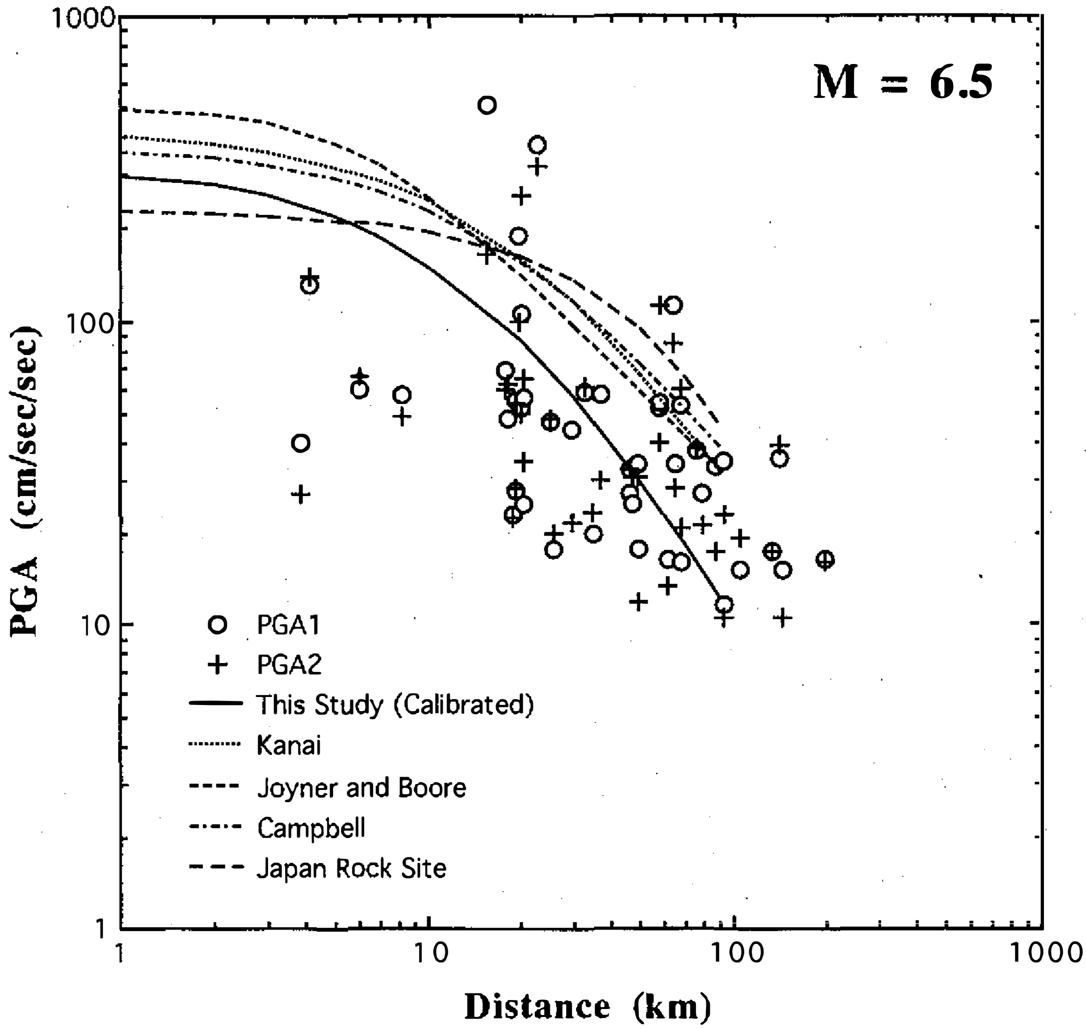



*Fig. 5.* Shown in the plot are the four attenuation curves of *M* 6.5 from Tsai *et al.* (1987), the simulated median curve (calibrated, see Figure 3) with the same magnitude using the specific barrier model and the observed ground motion data. Note that the attenuation curves from Tsai *et al.* (1987) are obtained from a different data set from that adopted in this study.

taken into account. Additionally, directivity is not deemed significant in the simulations.

If the relationship between stress drop and seismic moment is not known for the seismic sources affecting the sites of interest, or if the available data are not sufficient to determine the empirical relationship to the extent that the dependence of the stress drop on the seismic moment is clearly identified, the stress drop needed for the model may be presumed using a reasonable range sustained by local source parameters. The relationship between the fault

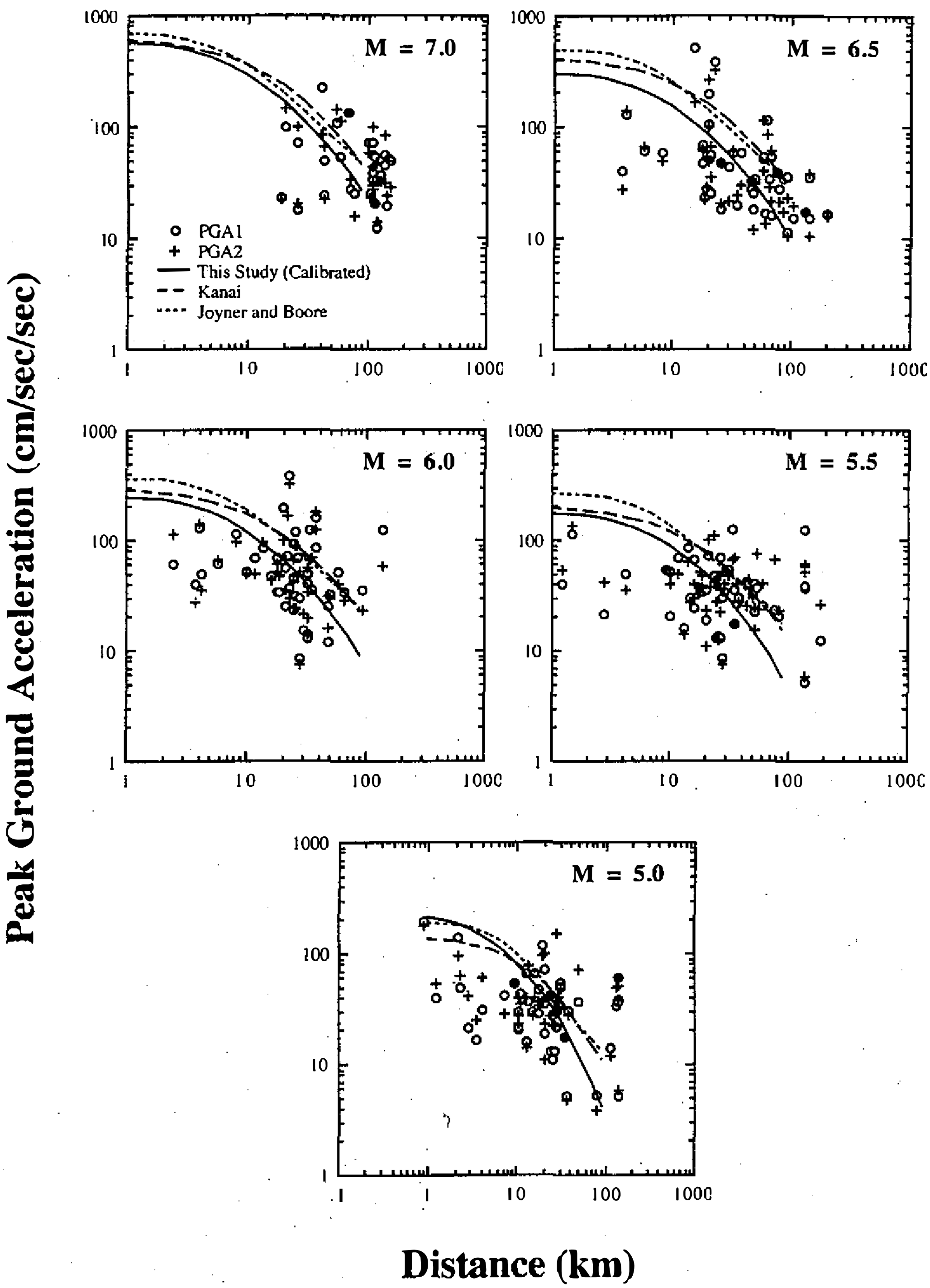



*Fig. 6.* More comparisons with multiple magnitudes for the Kanai and the Joyner and Boore forms.

rupture length and earthquake magnitude may be obtained by analyzing local empirical data. If it is difficult to do so, relationships obtained from worldwide data can be adopted; regardless, further parametric studies should be conducted for them.

Based on the simulated PGA curves using the specific barrier model, it seems that, among the four attenuation equations in Tsai *et al.* (1987), the Joyner and Boore's form may be the most adequate type of empirical equation for delineating the attenuation of peak ground accelerations in the near-source regime in Taiwan.

Although the proposed method of Tsai (1998) is implemented for only one dominant fault system and for rock sites only, it is very easy to expand the model and make it applicable to multiple fault systems with fault geometry varying in terms of length and width as well as to soil sites provided that strong-motion data are adequately available.

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