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Early Estimation of Seismic Hazard for Strong Earthquakes in Taiwan

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Abstract. A shakemap system providing rapid estimates of strong ground shaking could be useful for emergency response providers in a damaging earthquake. A hybrid procedure, which combines site-dependent ground motion prediction models and the limited observations of the Real-Time Digital stream output system (RTD system operated by Central Weather Bureau, CWB), was set up to provide a high-resolution shakemap in a near-real-time manner after damaging earthquakes in Taiwan. One of the main factors that affect the result of ground motion prediction analysis is the existence of site effects. The purpose of this paper is to investigate the local site effects and their influence in the ground shaking and then establish an early estimation procedure of potential hazard for damaging earthquakes. Based on the attenuation law, the site effects of each TSMIP station are discussed in terms of a bias function that is site and intensity-level dependent function. The standard deviation of the site-dependent ground motion prediction model can be significantly reduced. The nonlinear behavior of ground soil is automatically taken into account in the intensity-level dependent bias function. Both the PGA and the spectral acceleration are studied in this study. Based on the RTD data, event correctors are calculated and applied to precisely estimate the shakemap of damaging earthquakes for emergency response.

Key words: shakemap, damaging earthquake, earthquake emergency response, attenuation law, site effects

1. Introduction

The seismicity in Taiwan area is very high. In the last century many damaging earthquakes took place in Taiwan. Most damaging earthquakes occurred at the western part of Taiwan, the most populated areas. More than 7780 people were killed in these damaging earthquakes (Cheng *et al.*, 1999). Earthquake hazard mitigation is an important issue in Taiwan. Therefore, the government supported an extensive seismic instrumentation program, operated by the Central Weather Bureau (CWB) for the

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populated areas, with dense digital strong-motion networks. This instrumentation program consists of two networks around Taiwan: (1) The Taiwan Rapid Earthquake Information Release System (TREIRS, also known as the Real-Time Digital stream output system, RTD), and (2) The Taiwan Strong Motion Instrumentation Program (TSMIP). The locations of these two networks are shown in Figure 1. The RTD system using a real-time strong-motion accelerograph network of more than 80 stations is currently capable of routine broadcasting the earthquake location and magnitude about one minute after the occurrence (Wu *et al.*, 2002). The TSMIP system, consisting of more than 650 stations spaced approximately every 5 km in populated area, was widely deployed in Taiwan.

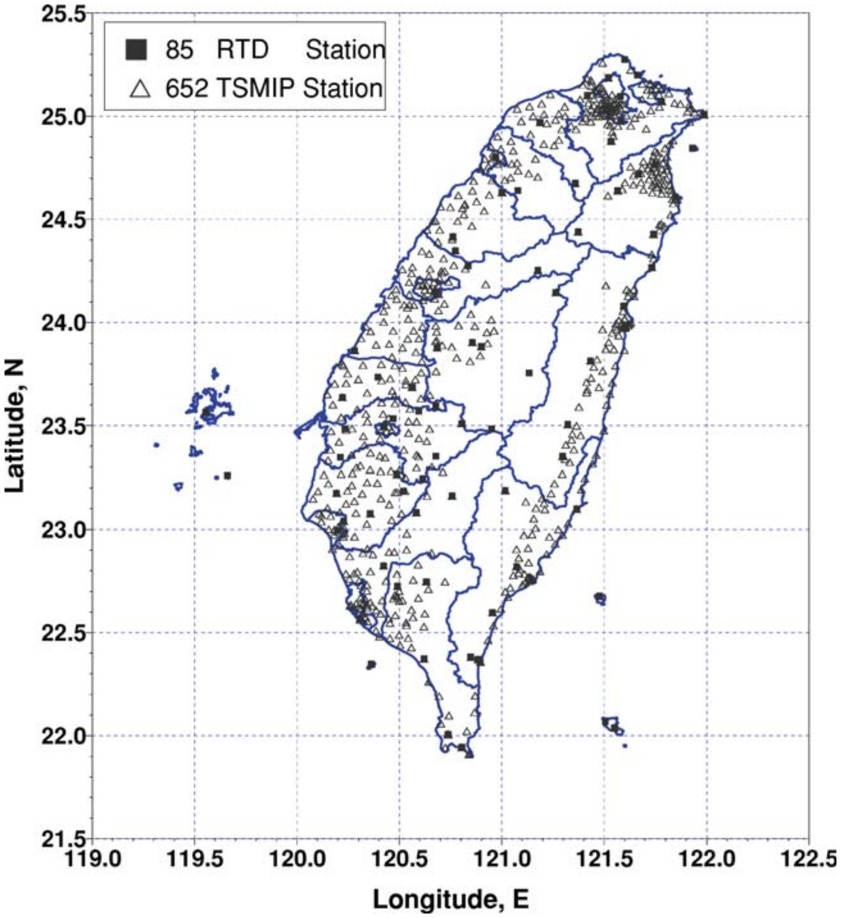


Figure 1. The station locations of Taiwan Strong-Motion Instrumentation Program network (TSMIP) and the Taiwan Rapid Earthquake Information Release System (also known as the Real-Time Digital Stream Output System, RTD).

With the support of the National Science Council, the National Center for Research on Earthquake Engineering (NCREE) started a seismic hazard mitigation program called "HAZ-Taiwan" in 1998. The application software "Taiwan Earthquake Loss Estimation System (TELES)" was also developed to estimate earthquake loss (Yeh *et al.*, 2003). One of the main features of TELES is to provide decision support soon after occurrence of strong earthquakes for emergency providers. For this purpose it needs rapid estimates of strong ground shaking after a damaging earthquake.

The seismic hazard analysis is usually required to develop rock outcrop or hard soil site ground motion for seismic design and earthquake loss estimation. One of the main factors that affect the seismic risk is the existence of site effects on the attenuation relations, which can be probabilistic descriptions of the level of ground motion as a function of the earthquake and site parameters. In order to make a good estimate of ground motion, many parameters are taken into consideration in the attenuation relations. Many researchers proposed several attenuation relations for different source regions and site classifications (Campbell, 1981; Abrahamson and Shedlock, 1997). In these attenuation relationships there is a degree of scatter about the median value calculated by the attenuation relations. An important issue is to find some measurable parameters or functions that can help to reduce the uncertainty (and/or bias) in the attenuation laws, which can be used in seismic hazard analysis and earthquake loss estimation.

The networks of RTD and TSMIP collect a large amount of high quality strong-motion data and provide useful information for seismology and earthquake engineering. The strong-motion data records yield a wide range of PGA due to different levels of excitation. These ground motion data offer a good opportunity to study attenuation models, and the site amplification effects for a given site in response to different levels of excitation. There are several site classification schemes used in engineering practices. However, the information for site classification may not be widely available for strong-motion station sites. An effective site-dependent attenuation model is needed for better estimate of ground motions.

2. Site Effects and Event Effects

One of the main factors that affect ground motion is the existence of the site effects. Based on many earthquake reconnaissance reports and research results, it is also found the site effects play a key role in the structural damage. The Southern California Earthquake Center completed a three-phase research project and pointed out some aspects about the ground-motion and the site effects in the phase-III report (Field *et al.*, 2000):

(1) in a single earthquake the ground shaking at one site can easily be 10 times stronger than that at a neighboring site;
(2) there are two important geologic factors, the softness of the rock or soil near the surface as well as the thickness of the sediments above hard bedrock, that can significantly affect the level of ground shaking.

A site- and intensity-level- dependent ground motion prediction model (attenuation form) is proposed in this paper. This model can be used to improve the results for seismic hazard analysis.

To demonstrate the above-mentioned effects, two CWB stations near the Taipei 101 building, TAP022 and TAP089, are considered to compare the site amplification as shown in Figure 2. The distance of these two stations is only about 300 m. It is easy to find that the PGA levels of station TAP022 are 3–4 times higher than those of the station TAP089. The horizontal axis indicates the predicted PGA value by the hard site attenuation model. The vertical axis indicates the observed data. For those data points fall onto the dashed line, it means that the hard site attenuation model can predict the PGA values very well. In other words, there is no significant site amplification. From the comparison of these two sites, it denotes that the TAP022 has more significant site amplification effects. Furthermore, for structural seismic design in engineering practice, the design PGA value or design spectrum is modified by an amplification factor for different site classification (BSSC, 1997). According to the Taiwan seismic design code, Taipei basin is classed as a special site S4 based on soil profiles and one particular design spectrum is applied in the whole basin. However, the plots in Figure 2 show a quite different site effects through the basin. An effective site-dependent attenuation model is needed for better estimate of ground motions for seismic design and loss estimation, especially for basin and plane areas.

Another conclusion made by the SCEC is that, for an individual earthquake, the intensity predicted by the attenuation model may not be adequate. Based on the earthquake data collected from TSMIP network, it is easy to find that the pattern of shaking varies from earthquake to earthquake, especially for some basins or soft soil plane areas (Jean and Loh, 2001). Figure 3 showed examples of the site amplification factors of the shake-map at Taipei basin due to two selected events. The site amplification factors were defined as the ratios of the PGA recorded at the study sites to that recorded at a reference station located on hard site at a comparable epicentral distance from the study site. The patterns were different from event to event. This discrepancy may be resulting from the site effects as well as the event and path effects. For an individual earthquake, some modifications of shakemap are necessary to take account the source and path effects.

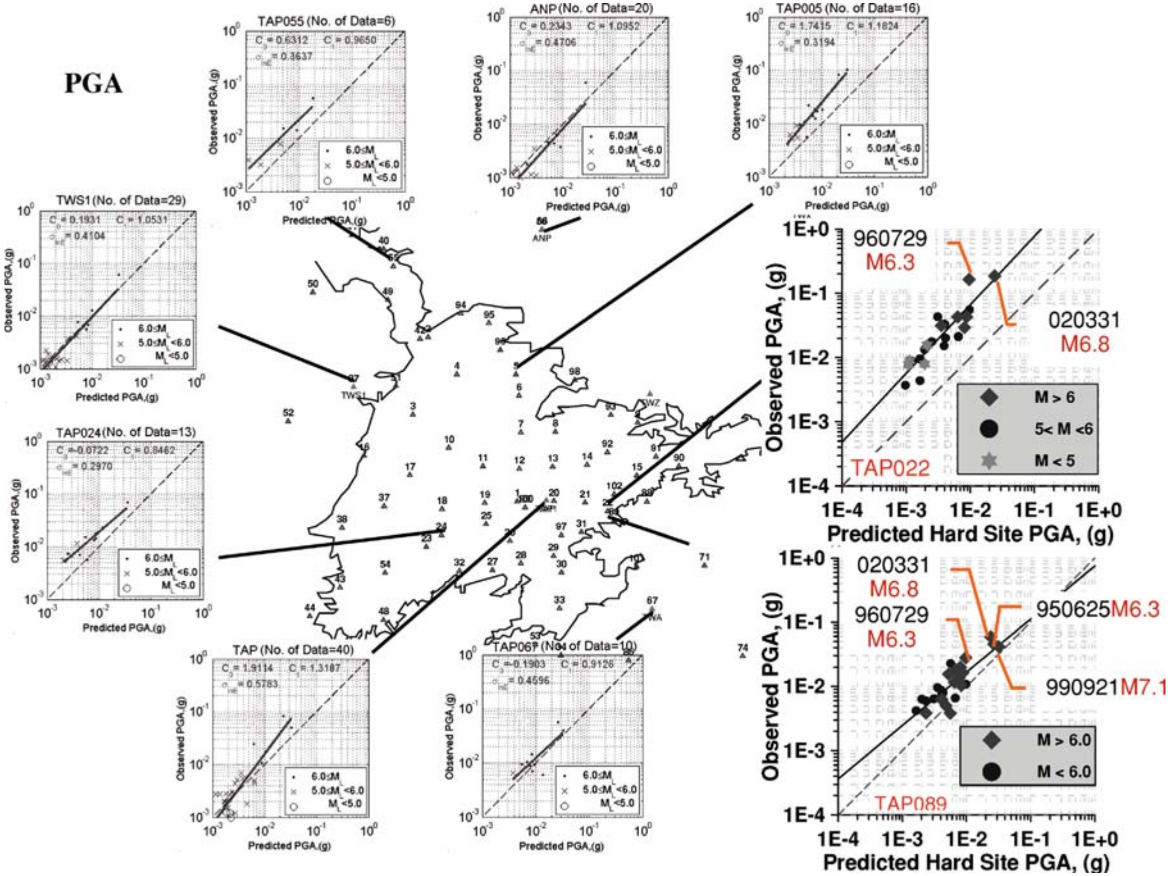


Figure 2. Comparison between the predicted and observed PGA to indicate the site amplification.

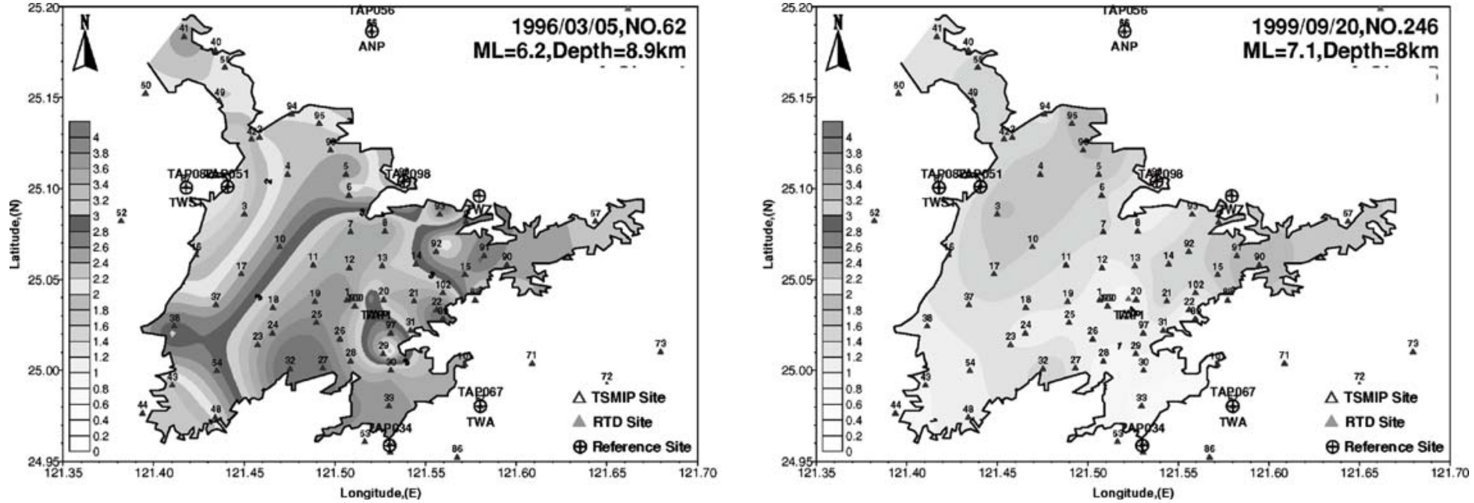


Figure 3. The samples of ground motion patterns of Taipei basin due to two earthquake events.

3. Proposed Empirical Procedure to Estimate Shakemap

It is believed that a theoretical 3-D model could be developed to precisely solve this problem of ground motion estimation. But, it takes time to develop such model and to determine its model parameters. Instead of such model, an empirical procedure is developed to correct the discrepancy of the ground shaking estimated from the attenuation form.

An empirical hybrid procedure was set up to provide a high-resolution shakemap in a near-real-time manner for earthquake emergency response. This procedure combines site-dependent ground motion prediction models and the limited observations of the Real-Time Digital stream output system (Jean *et al.*, 2003). The RTD system is capable of routine broadcasting of the earthquake location and magnitude about one minute after the earthquake occurred. The ground shaking information of the RTD site can also be automatically distributed in the same time. In this study, the RTD data are used as event correctors and the ground shake-map is modified for earthquake emergency response providers. The flowchart, as shown in Figure 4, shows the procedure to estimate the shakemap. Three steps are described below:

1. Reference Attenuation Form: the ground motion attenuation form for hard site is estimated in the first step. The site classifications of Taiwan free-field strong-motion stations reported by Lee (Lee *et al.*, 2001) were adopted in this study. The TSMIP stations of site class B, the shear

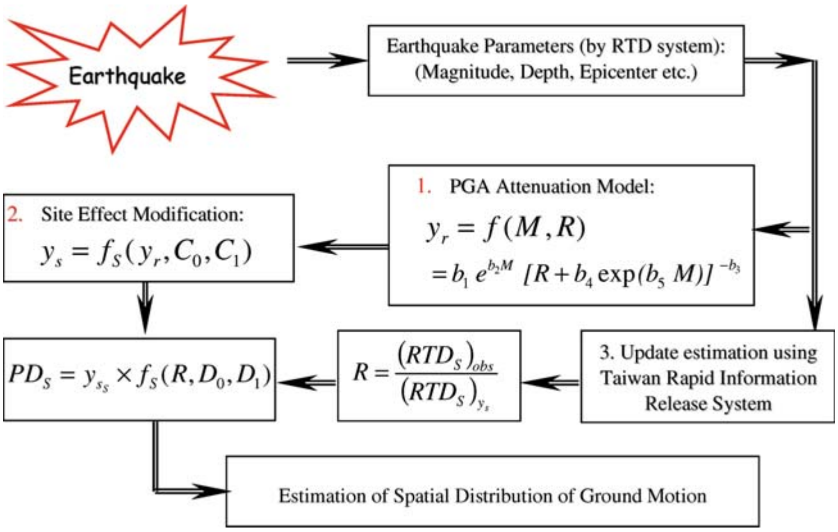


Figure 4. Procedure to estimate the shakemap of a damaging earthquake for emergency response.

wave velocity $\overline{V}_S$ is 760–1500 (m/s), were selected as the hard site stations. The hard-site attenuation forms were developed and then used as the reference model to study the site effect.

2. Site Corrector: the second step is to estimate the site- and intensity-dependent ground-motion prediction model for each TSMIP station and the reference RTD station. Based on residue analysis, the site effect modification function is generated to modify the attenuation obtained from Step 1.
3. Event Corrector: when an earthquake occurred, the earthquake parameters (magnitude and hypocenter) can be determined by the CWB RTD system within one minute. The ground-motion prediction models will, then, be applied to generate the shakemap that can take the site effects into consideration. In general, however, there still exists a bias in the shakemap for individual earthquake. This bias may be contributed from the event characteristics, and be corrected by the observations from the CWB RTD array data.

4. Earthquake Database

One of the purposes of this paper is to investigate the classification criterion of local site effects and its influence in the seismic risk estimation. Earthquake data collected from RTD and TSMIP system were used in the first two steps to develop the hard-site empirical attenuation form and to study the site amplification factors. The database collects 242 events of magnitude $M_L \geq 4.0$ from 1993 to 2002. Fifty-nine events of magnitude $M_L \geq 5.0$ are used to develop the hard-site attenuation form. It is noted that the distribution of the TSMIP stations is much denser in the populated areas, especially for some urban areas, than that in the mountain area (Figure 1). On the other hand, the RTD stations are almost uniformly distributed around the whole island. The earthquake data collected from the RTD network should be used in developing the attenuation forms to avoid inadequate weighting for some earthquake data of urban area. Considering the lack of near source earthquake data for the RTD network and the distribution of hypo-central distance, a hybrid database was collected from both the RTD and TSMIP networks for developing the hard-site attenuation forms. The database used in the first step was consisted by (1) all the RTD earthquake data, and (2) the TSMIP data those with hypocentral distance less than 25.0 km. On the step two, the whole database was used to estimate the site effects for each instrumental site. The 1999 Taiwan Earthquake main-shock and its aftershocks are also included in the database.

5. Attenuation Model for Hard Site

The attenuation relations are probabilistic descriptions of the level of ground motion as a function of the earthquake magnitude, distance and site parameters. Campbell's attenuation form (Campbell, 1981) can reasonably predict the characteristic of ground motion attenuation for TSMIP array data, and is applied in this study. Campbell's form is expressed as

$$Y_{\mathrm{r}}(g) = f(M, R) = b_1 e^{b_2 M}[R + b_4 \exp(b_5 M)]^{-b_3}, \tag{1}$$

where Y_{r} is peak ground acceleration (or the spectral acceleration), M is magnitude, and R is source-site distance, the coefficients b_1,b_2,b_3,b_4 and b_5 were obtained by regression analysis of earthquake data. The significant feature of the Campbell form is the term, $b_4 e^{b_5 M}$, which describes a magnitude dependence of the transition from near-field to far-field attenuation and it reflects a distance saturation that depends on the extent of fault rupture. The source-site distance R for the present study is taken as the hypocentral distance; however, for the earthquake data collected from the 1999 Taiwan earthquake the closest distances to the surface fault rupture are used. Figure 5 shows the comparison of the earthquake data with the attenuation form. The form satisfactorily fits the earthquake data. The standard deviation of the natural logarithm of the peak ground accelerations, $\sigma_{\ln\ Err} = 0.78$, representing the dispersion about their respective median value was calculated.

6. Modification of Site Effects

Based on the attenuation law, site effects are discussed in terms of a bias function that is site and intensity-level dependent function. The nonlinear behavior of ground soil is automatically taken into account in the intensity-level dependent bias function. More than 3000 seismic records from more than 242 earthquake events are used to study the site effects.

A systematic bias of the data scattering in the attenuation law is found from the earthquake data. It is believed that the systematic bias mainly comes from the site effects. It is necessary to reduce the data scattering in the attenuation law by removing the systematic bias. For this purpose, a residual is defined as the difference between the observed and predicted values of the natural logarithm of PGA (or other ground motion parameters). Comparison on the PGA and Sa-value between observed data and those calculated from the reference attenuation form (Equation (1)) is constructed. Some examples of this comparison are shown in Figure 2; these examples show that some sites have large amplification effects (such as

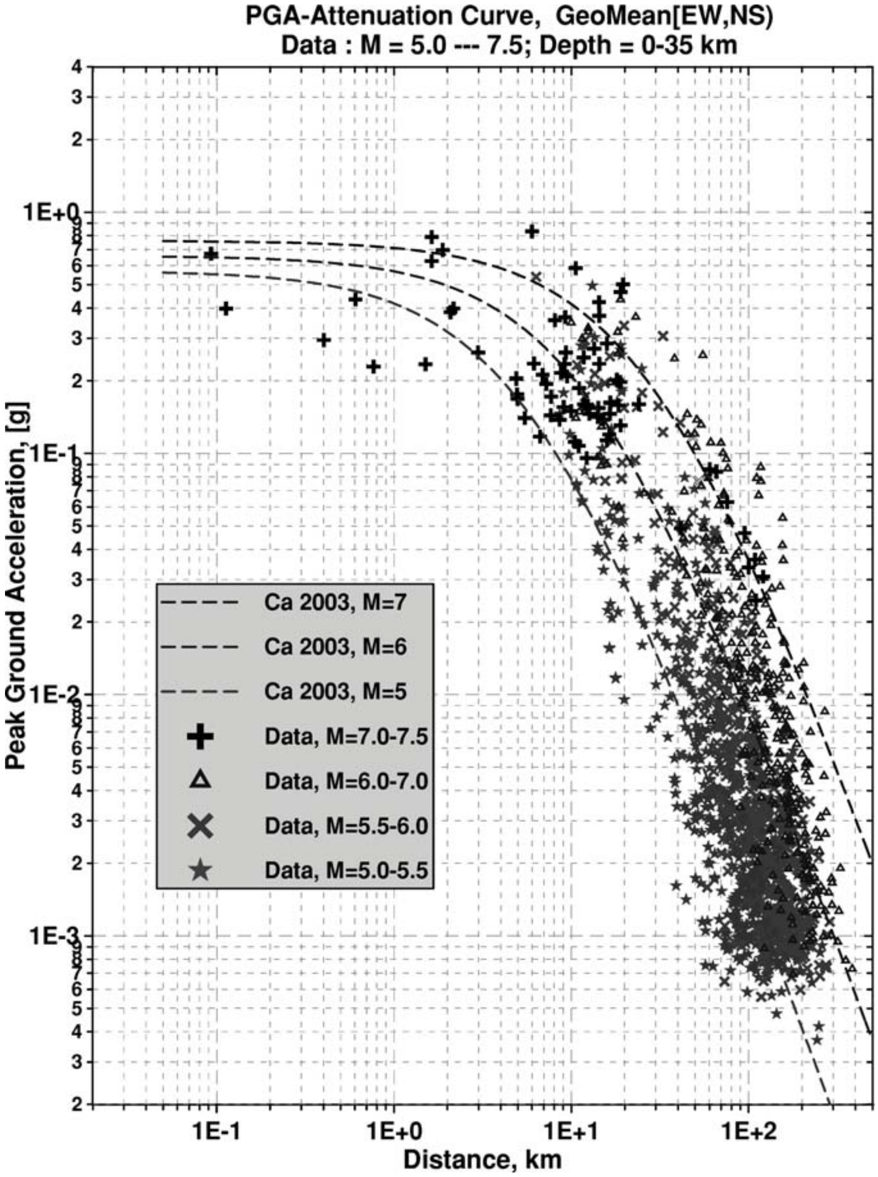


Figure 5. The PGA attenuation form (denoted as Ca2003) compared with earthquake data for hard site. (near source data of the 1999 Chi–Chi Taiwan Earthquake were also plotted for comparison, +)

stations TAP005, TAP022 and TAP055). For the case that the data points fall onto the dashed line means that the reference attenuation form can predict well for this site (no significant site effects).

Based on the intensity dependent residual model, a modified intensity prediction model is found for each site. A regression form is determined for each site

$$Y_{\mathrm{s}}(\text{estimated}) = f_{\mathrm{s}}(Y_{\mathrm{r}}, C_0, C_1) = \exp[C_0 + C_1 \cdot \ln Y_{\mathrm{r}}(M, R)], \tag{2}$$

where $Y_{\mathrm{r}}(M,R)$ is calculated from Equation (1), and then the site amplification factor can be calculated from the above equation. These models (Equation (2)) are used in seismic hazard analysis and earthquake loss estimation to account for site effects. The coefficients are also shown in Figure 2 for some stations. It is noted that for the case with coefficient $C_1 \cong 1.0$, the site effect is intensity (PGA-level) independent as applied in Wu's research work (Wu *et al.*, 2001), a constant modification factor, $\exp(C_0)$, can be used to represent the site effect. In general, the coefficient C_1 in not exactly equal to 1.0, therefore, the site effect is intensity (PGA-level) dependent. In this study, there are about 450 TSMIP stations collect enough earthquake data to perform these calculations for site modification functions.

7. Event Correctors

The RTD system is capable of calculating the earthquake location and its magnitude about 1 min after an earthquake occurs. The ground shaking information of the RTD site can also be automatically distributed at the same time. A predicted ground motion can then be generated form Equation (2) to take site amplifications into consideration for more than 450 TSMIP stations, which are enough to generate the first version of shakemap for Taiwan's populated areas.

Comparing the difference between the observed ground-motion and that predicted by Equation (2) for each RTD station, an event corrector (indicated in Figure 4) is used to modify the first version shakemap to complete the early estimation of shakemap for earthquake emergency response providers. The event corrector can be defined as following for each site i:

$$R_i = \left(\frac{Y_{\mathrm{OBS}}}{Y_{\mathrm{S}}}\right)_i. \tag{3}$$

The event correctors can be calculated for all collected earthquakes for each station (stations of both TSMIP and RTD networks). Based on the correlation analysis and the distance to the RTD stations, each TSMIP station is grouped with one RTD station. Comparison of event correctors, for example, for a TSMIP station TCU070 and those for a correlated RTD station (TCU) is shown in Figure 6. The event corrector of TCU070 station is different from that of TCU station. A linear correlation function

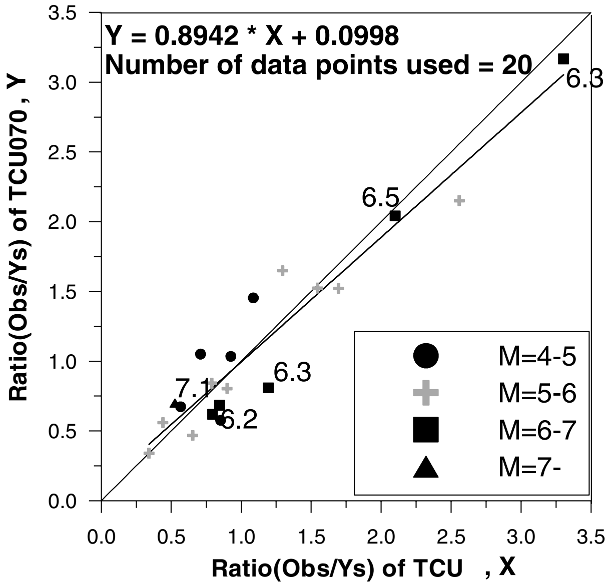
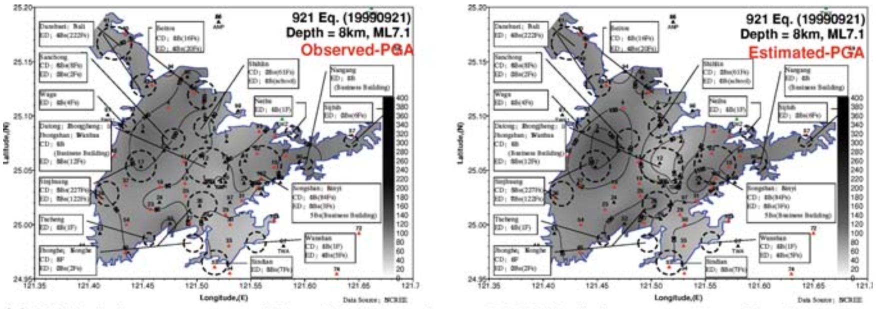


Figure 6. Comparison of event correctors for a TSMIP station (TCU070) and those for a correlated RTD station (TCU).

(indicated as $f_s(R,D_0,D_1)$ in Figure 4) between each TSMIP station and RTD station in the same group was assumed. Figure 6 shows an example of the correlation function for the TSMIP station TCU070 to the RTD station TCU ($D_0=0.0998$, $D_1=0.8942$). As the event corrector of RTD stations were found, then, the event corrector of each TSMIP station can be found by the correlation function for PGA, and Sa-values.

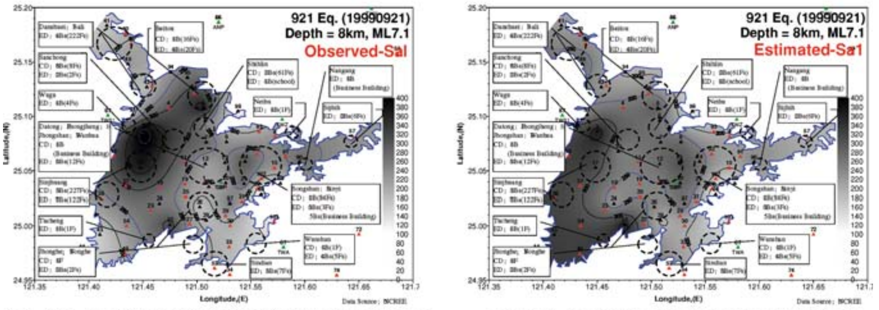
8. Case Study

Taipei City is the capital of Taiwan and it is located on a sediment-filled basin. The area experienced several damaging earthquakes, the most recent one of magnitude ML6.8 occurred on March 31, 2002. Even the earthquake located more than 80 km away; a large earthquake can still cause severe damage in the Taipei basin. In this study, the Taipei basin was taken for case study. The ML7.3 1999 Taiwan earthquake caused severe damage in central region of Taiwan. Many buildings totally collapsed and caused more then 120 people killed. The locations of damaged buildings are indicated in Figure 7 and compared with the early estimated shakemap. Not only the shakemap of PGA but also those of spectral acceleration of short period (Sas) and the long period (Sa1) are shown for comparison. These shake maps of spectral acceleration are used in the



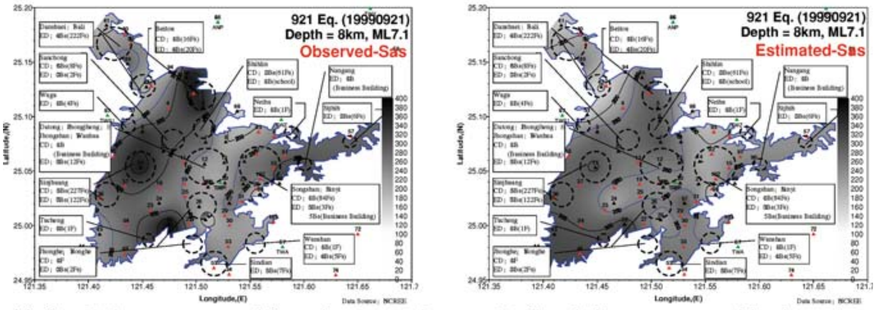
(a) PGA-shakemap generated from the observed data of the TSMIP stations.

(b) PGA-shakemap generated by the early estimation procedure.



(c) Sa1-shakemap generated from the observed data of the TSMIP stations.

(d) Sa1-shakemap generated by the early estimation procedure.



(e) Sas-shakemap generated from the observed data of the TSMIP stations.

(f) Sas-shakemap generated by the early estimation procedure.

Figure 7. Comparison of estimated shakemap and the distribution of damage statistics in the Taipei basin for the 1999 Chi–Chi Taiwan Earthquake. ED: extensive damaged buildings; CD: collapsed buildings.

earthquake loss estimation (Yeh *et al*., 2003). The early estimated shakemaps are also in good agreements with those generated from all the data collected from TSMIP stations, and can efficiently represent the distribution of the damaged structures for the 331 earthquake (March 31, 2002) (Jean *et al*., 2002). The shakemap estimated by this study and that generated directly from the observed data of the TSMIP stations, which could be collected more than one week latter and is too late for emergency response, are in good agreement in the ground motion intensity as well as the damage pattern.

9. Conclusions

The hybrid procedure, which combines site-dependent ground motion prediction models and the limited observations of the Real-Time Digital stream output system (RTD system operated by CWB), was set up to provide a high-resolution shakemap in a near-real-time manner. The site-dependent ground-motion prediction models are set up and ready for use. If a damaging earthquake occurs, the earthquake magnitude and its location can be determined and released within one minute by CWB. A predicted shakemap will be calculated by Equation (2). Comparing the difference between the observed ground-motion at the RTD stations and that predicted by Equation (2), an event corrector is, then, used to modify the predicted shakemap to complete the early estimation of shakemap. Testing with many observations of large earthquakes, it is concluded that this empirical procedure is able to provide very good estimation of shakemap in a near-real-time manner for earthquake emergency response providers. As more data from TSMIP stations are recovered after a damaging earthquake, the shakemap can then be revised.

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