Applications of Seismic Disaster Simulation Technology on Risk Management

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ABSTRACT

This paper introduces the applications of Taiwan Earthquake Loss Estimation System (TELES), which is developed by the National Center for Research on Earthquake Engineering (NCREE). Seismic disaster simulation technology (SDST) integrates geographical information system to assess the distribution of ground shaking intensity, ground failure probability, building damages, casualties, post-quake fires, debris, lifeline interruptions, economic losses, etc. given any set of seismic source parameters. The SDST may integrate with Taiwan Rapid Earthquake Information Release System (TREIRS) developed by Central Weather Bureau (CWB) to obtain valuable information soon after large earthquakes and to assist in decision-making processes to dispatch rescue and medical resources more efficiently. The SDST may also integrate with probabilistic seismic source model to evaluate various kinds of risk estimates, such as average annual loss, probable maximum loss in one event, and exceeding probability curves of various kinds of losses, to help proposing feasible countermeasures and risk management strategies.

Keywords: seismic disaster simulation, earthquake loss estimation, risk assessment and management

APPLICATION FRAMEWORK

National Science Council of Taiwan started HAZ-Taiwan project in 1998 to promote seismic disaster simulation technology (SDST). In order to fully utilize the local inventory data, analysis models and associated parameters, the National Center for Research on Earthquake Engineering (NCREE) in Taiwan develops a new generation of earthquake loss estimation system in Taiwan, named "Taiwan Earthquake Loss Estimation System (TELES)". The general analysis framework and methodology of HAZUS (RMS, 1997) was adopted in developing TELES. However, there are many new features added to TELES, such as running multiple instances at the same time, providing a multiple document interface, displaying multiple map windows in the same project, allowing customizable data classification schemes, and so on. Capabilities of Early Seismic Loss Estimation (ESLE) and Probabilistic Seismic Risk Assessment (PSRA), which are important in emergency response and disaster risk management, are also included in the application framework of TELES and will be briefly demonstrated in this paper.

The application framework of TELES combines deterministic seismic disaster simulation technology and probabilistic seismic risk assessment in single software and is schematically shown in Fig. 1. The main items involved are summarized as follows:

– Collect various kinds of data including historical earthquake catalog, active fault maps and associated attributes, various inventory databases of structures and facilities, and so on.

– Develop seismic disaster simulation technologies to integrate the state-of-the-art analysis models and to calibrate the associated parameters. The simulation outcomes may include ground excitation intensity, soil liquefaction potential, damage-state probabilities of civil infrastructures, number of casualties and temporary shelter needs, direct/indirect economic losses, etc. when a scenario earthquake occurs.

– Develop seismic scenario builder to run a series of predefined scenario earthquakes in batch mode and to obtain seismic scenario database based on the simulation results. The set of the predefined scenario earthquakes should cover all possible events, which may influence the study region.

– Develop probabilistic seismic hazard analysis module, not only to obtain hazard curves or hazard maps in terms of ground motion parameters, but also to obtain the annual occurrence rate of each scenario earthquake in the seismic scenario database.

– Combine the seismic scenario database and the results of probabilistic seismic hazard analysis to obtain seismic event loss table, which can be used to calculate various kinds of risk estimates within different regions or of specific targets. The risk assessment can be applied in insurance industries or disaster mitigation plans (Dong, 2001).

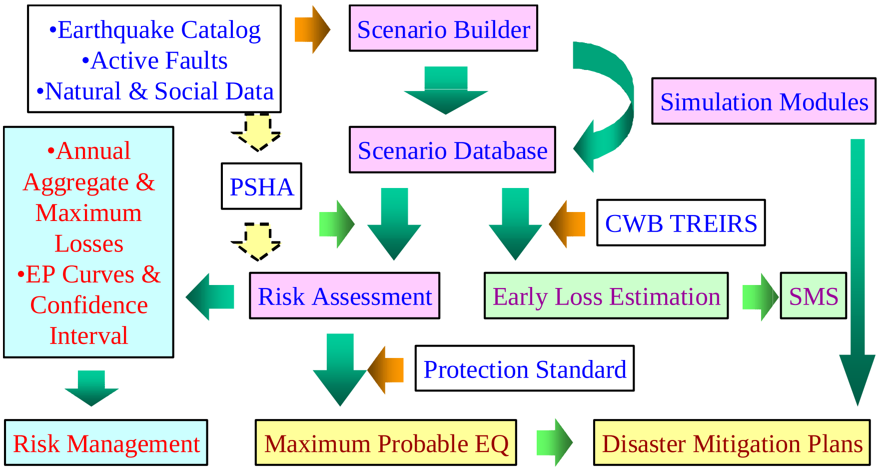

Fig. 1 Analysis framework and probable applications of TELE

DETERMINISTIC SEISMIC DISASTER SIMULATION TECHNOLOGY

The first step in seismic disaster simulation is to define source parameters of a scenario earthquake. The source parameters may include earthquake magnitude, epicenter location, focal depth, fault rupture length, width, dip angle, etc. Depending on the input source parameters, the energy release mechanism of an earthquake may be modeled as a point-source, a line-source or a plane-source. As shown in Fig. 2, based on the source parameters of a scenario earthquake, the distribution of ground motion intensity (in terms of peak values and response spectra) and ground failure extent (in terms of permanent ground displacement) can be estimated through empirical attenuation laws, site-modification factors and soil liquefaction models. All of the analysis models have been studied carefully and the associated parameter values have also been calibrated by using strong-motion records and engineering borehole data that were collected in Taiwan (Yeh et al, 2001; Yeh et al, 2002). Depending on the ground shaking intensity and ground failure extent, the damage-state probabilities of various kinds of civil infra-structures, such as buildings, bridges and buried pipelines, can also be estimated (Yeh et al, 2000; Loh et al, 2003; Yeh et al, 2004). All of the damage functions, such as capacity/fragility curves of model building types, casualty rates for each model building type under different damage states, etc, have been carefully studied and calibrated by using investigation data of the Chi-Chi Taiwan earthquake in 1999.

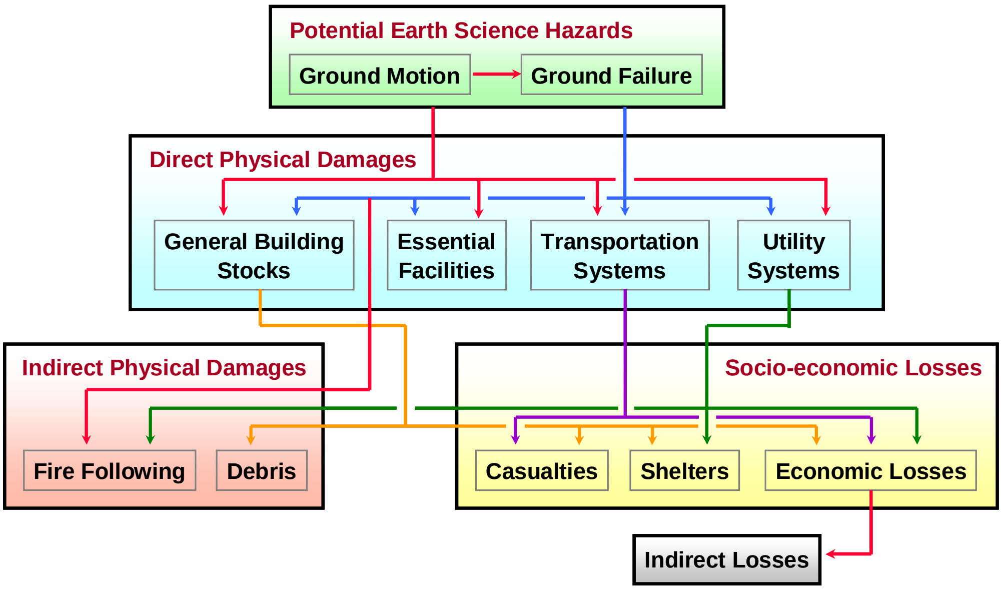

Fig. 2 Analysis modules and framework of Taiwan Earthquake Loss Estimation System

In order to extend the applicability of SDST in early seismic loss estimation and probabilistic seismic risk assessment, it is necessary to establish database which contains simulation results due to a complete set of scenario earthquakes, which may represent all of the possible events occurred in the future. To fulfill the objective, the software architecture of TELES was upgraded so that it can be run in batch mode when the study region is subjected to a series of scenario earthquakes. Some pieces of data in each scenario, such as the number of damage buildings, the number of human casualties and the quantity of economic losses, can be summarized in a separate table and referred to as a seismic scenario database (SSD). It is noted that the computation time to establish a SSD is much longer than that to run seismic hazard analysis and risk assessment. Therefore, it is desirable to reuse the SSD in the following steps of risk assessment.

Generally speaking, two types of seismic sources are included. The first type belongs to active faults that have known geometric properties such as the surface fault trace and the dip angle of fault plane. The fault geometry, characteristic earthquake magnitude, long-term average annual slip-rate, etc. of each active fault in Taiwan have been investigated by the Central Geological Survey Bureau (CGSB). There are 42 active faults in total which were published by CGSB; among them, only 13 class-1 active faults are shown in Fig. 3. The discrete scenario earthquakes are modeled as plane-sources so that effects of hanging-wall versus foot-wall sides will be observed in the simulation results.

The second type of seismic sources is referred to as area source that has unknown fault trace and rupture direction. In order to cover all the possible earthquake events, the rectangular region around Taiwan (see Fig. 3: longitude: from 119 to 123 degree and latitude: from 21 to 26 degree) is divided into 500 grids with 0.2 degree increments along longitudinal and latitudinal directions, as shown in Fig. 3. Six focal depths (10, 20, 30, 50, 70 and 90 km) are chosen to represent possible future earthquakes. In each grid and at each focal depth, earthquake magnitudes from 5.1 to 7.5 with 0.2 increments are simulated in the SSD. The length of fault rupture and the number of rupture directions to be simulated in the SSD are functions of earthquake magnitude. For example, four rupture directions are simulated when earthquake magnitude is greater than 7.

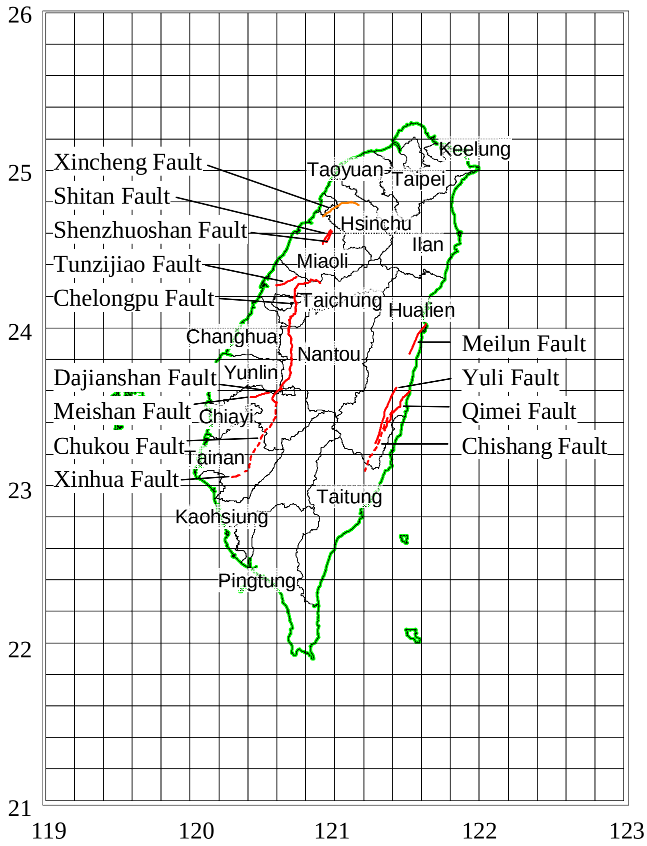

Fig. 3 Boundary map of counties and cities in Taiwan, 13 class-1 active faults classified by CGSB, and the grid system of seismic area sources around Taiwan

PROBABILISTIC SEISMIC SOURCE MODEL

In general, probabilistic seismic hazard analysis (PSHA) involves four steps. The first step is to identify and to characterize seismic sources in the neighborhood of the study region. The second step is to characterize the temporal distribution of earthquake recurrence for different magnitudes and to determine the probable ultimate magnitude in each seismic source. The third step is to select an appropriate ground-motion prediction model. The last step is the summation of individual effect due to different seismic sources. The uncertainties in earthquake location, fault rupture direction and ground-motion prediction model should be taken into consideration in hazard analysis.

The quality of historical earthquake catalog may significantly influence the results of PSHA. Therefore, the completeness of earthquake catalog during different time periods, the consistency of magnitude scale, and the measurement accuracy of epicenter and focal depth should be checked and calibrated carefully. The magnitude scale used in this study is Richter scale, which may saturate at about 7.5, to consist with the magnitude scale used in ground motion prediction model.

The ultimate magnitude (m_u) in each source zone can be estimated graphically based on the assumption of constant energy accumulation and release (Makropoulos et al, 1983). The estimated m_u may increase 2 to 5 percents to consider the uncertainty. The famous Gutenberg-Richter (G-R) magnitude recurrence relationship is often used in PSHA, especially when the earthquake occurrences are modeled as stationary Poisson processes. The parameters in G-R relationship include the annual occurrence rate (ν_0) of earthquakes with $m \geq m_0$ and the relative frequency of various magnitude (β). However, ν_0 and β may be obtained by different regression models, such as two-stage least square method (Loh et al, 2004; denoted by LST) or maximum likelihood estimation (Weichert, 1980; denoted by MLE). Depending on the regression methods, the parameters in G-R relationship have slightly different values, which can be seen as imperfection or uncertainty of the model. The parameters m_u, ν_0 and β may also be obtained by using different zoning schemes. It is essential to compare the analysis results from different zoning schemes.

The seismic source zones are further divided into smaller grids in calculation of hazard curves or risk estimates. The annual occurrence rate of earthquakes in each grid can be assumed to be uniform within each source zone or proportional to the number of historical earthquakes occurred within the grid. In view of the uncertainty in future earthquakes and the tendency of occurrence in particular regions, it is most likely that the true annual occurrence rate of earthquakes in each grid lies within the previous bounds. The annual occurrence rate of each scenario earthquake in the SSD may be calculated by reasonably distributing the occurrence rate in each grid to different focal depths and rupture directions.

Based on paleoseismicity, fault slip rate and geometry, characteristic earthquake magnitude and recurrence rate of each fault can be assumed. It is noted that, unlike area sources, the characteristic earthquake magnitude of an active fault, bounded by m_0 and m_u, is determined by fault length or historical earthquakes; and the associated recurrence rate ν_{Target} is determined from field investigation or monitoring of fault slip rates. To prevent double count of the seismic hazard, the recurrence rate ν_{Target} has been reduced by certain amount $\bar{\nu}$, which was half of the occurrence rate of earthquakes from area source within 20 km and with magnitude in the range between m_0 and m_u.

PROBABILISTIC SEISMIC RISK ASSESSMENT

The PSHA is often applied in estimating seismic hazard at different sites or for critical facilities (e.g., nuclear power plants, dams, etc.). The seismic hazard curves are often in terms of exceeding probability of ground motion parameters during a particular time period. Other risk quantities, such as damage-state probabilities of civil infra-structures, human casualties, economic losses, etc. are then derived indirectly from the hazard curves of ground motion parameters. However, there are many factors which may influence the analysis results of damage/casualty/loss quantities. In other words, these damage/casualty/loss quantities can not be expressed as one-to-one functions of ground motion parameters. Thus, the accuracy of risk estimates obtained indirectly from hazard curves and empirical regression formula is questionable. To overcome the shortage in the previous approach and increase the accuracy of the risk estimates, this study combines the PSHA with seismic scenario simulations to obtain various kinds of seismic risk estimates.

The expected consequences (L_k) of each scenario earthquake k in SSD can be obtained through seismic scenario simulation, while the annual occurrence rate (ν_k) for each scenario earthquake can also be determined from PSHA once the zoning scheme and the various kinds of fault attributes have been assumed as in section 5. The annual occurrence rate, expected consequence and associated uncertainty for each scenario earthquake are summarized in a table (see Table 1), which is named seismic event loss table and is very useful in risk assessment. In general, one seismic event loss table could be virtually established for each kind of damage/casualty/loss and for each target (either a study region or a critical facility).

In practice, given occurrence of a scenario earthquake, the standard deviation and the upper-bound of losses may be estimated by the degree of accuracy of analysis models, experiences and experts' opinions. The distribution of losses given an earthquake may be modeled as a beta distribution with mean value equal to the expected loss from scenario simulation (Dong, 2001). The beta distribution has four parameters. Two of them control the lower and the upper bounds, while the other two parameters (denoted by p and q) define the shape of probability distribution function. According to the experiences from early seismic loss estimation (Yeh, 2004), the upper bound of losses may be assumed to be 3 to 5 times of the mean value. The shape parameters of beta distribution can be assumed to be ($p=2$, $q=4$) or ($p=2$, $q=8$) with coefficients of variation about 0.53 and 0.6, respectively.

Table 1. Contents in the seismic event loss table

Scenario ID	Annual Occurrence Rate	Expected Loss	Standard Deviation of Loss	Total Exposure
1	v_1	L_1	σ_1	X_1
2	v_2	L_2	σ_2	X_2
…	…	…	…	…
k	v_k	L_k	σ_k	X_k
…	…	…	…	…
J	v_J	L_J	σ_J	X_J

Once the seismic event loss tables have been obtained, various kinds of risk estimates can be calculated. For example, let L_j denote the losses due to scenario earthquake *j* with annual occurrence rate v_j. The average annual loss and standard deviation of the loss (denoted by μ_L and σ_L, respectively) can be expressed as:

$$\mu_L = \sum_j L_j \cdot v_j \quad \text{and} \quad \sigma_L = \sqrt{\sum_j L_j^{\,2} \cdot v_j} \tag{1}$$

We can also identify the seismic sources which contribute the most risk to a particular region. Let L^J denotes the expected annual loss caused by seismic source *J*. If there are m disjoint scenario earthquakes in the seismic source *J*, the expected annual loss caused by the seismic source *J* can be calculated as follows:

$$L^J = \sum_{k=1}^{m} L_k \cdot v_k \tag{2}$$

Suppose that there are N disjoint scenario earthquakes which may cause losses in the study region. The N sets of losses can be sorted in descending order, that is,

$$L_1 \geq L_2 \geq \ldots \geq L_K \geq \ldots \geq L_N \tag{3}$$

The corresponding annual occurrence rate of each disjoint scenario earthquake is v_1, $v_2 \ldots$

$\nu_K \ldots \nu_N$, respectively. According to the definition, the annual occurrence rate with $L \geq L_1$ is ν_1; the annual occurrence rate with $L \geq L_2$ is $\nu_1 + \nu_2$. In general, the annual occurrence rate with $L \geq L_K$ is ν^K, which can be expressed as

$$\nu^K = \sum_{j=1}^{K} \nu_j \tag{4}$$

Assuming the earthquake occurrences are stationary Poisson processes, the annual occurrence probability of event $L \geq L_K$ can be expressed as

$$P(L \geq L_K) = 1 - \exp(-\nu^K) \tag{5}$$

If the uncertainty of losses given occurrence of scenario earthquakes is not considered, the exceeding probability curves of loss estimates can be calculated through Eq. 4 and 5.

DETERMINATION OF PROBABLE MAXIMUM EARTHQUAKES

The probable maximum earthquakes (PME) in this study refer to the probable strong earthquakes which may result in severe damages, casualties and losses; and the earthquakes are expected to occur with reasonable probability within a specified period of time. Determination of PME for counties/cities is an important subject in proposing effective disaster reduction plans and emergency response strategies. All the governmental sectors should apply state-of-the-art technologies to estimate the most severe and still probable consequences based on the selected PME.

Table 2 lists the average annual loss/casualty estimates due to earthquakes around Taiwan by using Eq. 1. As an example, the annual average casualty is about 90 persons for the whole Taiwan and it means that about 4,500 persons will be killed or severely injured due to earthquakes in every 50-year. The disaster scale is about the same as that caused by Chi-Chi Taiwan earthquake in 1999.

It is noted that depending on the simulation results (L_j) and the annual occurrence rates of scenario earthquakes (ν_j), the average annual loss/casualty estimates may have different values. Besides, the simulation results and the occurrence rates depend on the parameter values used in seismic disaster simulations and the assumptions applied on seismic source models. The uncertainty in analysis models should be considered in more sophisticated ways, such as those used in insurance markets; but they are out of scope of the present study. It is also noted that the sum of average annual loss/casualty in individual county/city is equal to the average annual loss/casualty of the whole Taiwan area. Since different results may be obtained by using different seismic source models, it is important to conduct sensitivity study to find reasonable confidence intervals.

Based on the SSD and the results of PSHA without secondary uncertainties, the loss/casualty of general building stocks in each county/city corresponding to 200-year and 50-year return periods are calculated by Eq. 5 and listed in Table 3. If the secondary uncertainties of loss/casualty estimates were considered, they are often modeled as beta probability distributions with proper bounds and shape parameters. According to the simulation results, the risk estimates may increase about 14% to 20%. The variances and the confidence intervals of EP curves for the loss/casualty estimates can be studied through Monte Carlo simulation (Dong, 2001). Various kinds of EP curves for risk estimates, such as those for occurrence and aggregate annual losses, of each county/city have been obtained.

It is important to know how to interpret the data in Tables 2 and 3. For example, from

Table 3, the casualty estimate is about 879 persons corresponding to 50-year return period for the whole Taiwan. Comparing with the information in Table 2, there are about 4,500 persons killed or severely injured in 50 years, but the largest disaster event causes about 879 persons killed or severely injured in every 50-year period.

As a second example, if the protection standard is decided to be 200-year return period, the rescue and medical resources in Taipei City should prepare to manage a disaster with more than 86 persons in danger at the same time. However, it is also noted in Table 3, corresponding to 200-year return period, that the sum of casualties in each county/city (3,071) is smaller than that of the whole Taiwan (3,569). It means that if every county/city independently prepares its rescue and medical resources, they are not sufficient for the whole Taiwan. Since the finance and economic conditions are quite different in each county/city, it is suggested that a wealthy county/city should allocate more budgets on the preparedness of rescue and medical resources. The insufficient portion of the rescue and medical resources should be prepared by the central government. Secondly, in order to achieve the goal, nearby counties or cities should sign agreement to cooperate and manage disaster together.

It is also noted that the sum of loss/casualty in each county/city becomes larger than that for the whole Taiwan when the return period becomes bigger. For example, corresponding to 200-year return period, the sum of individual losses is about 133 billions, which is larger than 85 billions for the whole Taiwan.

Table 2. List of average annual losses and casualties in each county and city of Taiwan

District	Loss (million NT)	Casualty (person)
Taipei City	170	2.8
Taiwan	**3,067**	**90.2**

Table 3. List of losses and casualties in different return periods

District	200 years		50 years	
	Loss (million NT dollars)	Casualty	Loss (million NT dollars)	Casualty
Taipei City	9,839	86	88	0
Taiwan	**85,337**	**3,569**	**31,525**	**879**
$\sum L_i$	**132,622**	**3,071**	**25,114**	**230**

Based on data in Tables 2 and 3, together with the other related information, it is possible to propose PME in a probabilistic sense. Traditionally, the PME for a specific county/city may be solely determined by PSHA. Only hazard curves of PGA may be taken into consideration. De-aggregation of hazard sources would be used to determine the location and magnitude of PME. In such cases, the quantity and distribution of vulnerable exposures are not properly considered and would lead to erroneous choice of PME. To emphasize the importance of consequence, it is suggested that once the protection standards have been determined, the PME for each county/city should be selected from the SSD with similar disaster scale, having the largest occurrence rate, and contributing the most of risk sources. Based on the simulation results of the PME, distribution of rescue and medical resources can be arranges to manage the possible disaster patterns.

CONCLUDING REMARKS

Integration of the seismic disaster simulation technology and the probabilistic seismic hazard analysis may have many potential applications. First, it can be used in early seismic loss estimation, because the distribution and scale of disasters may be calculated before earthquake occurrence and thus the response time is significantly reduced. Second, it may be used in seismic risk assessment and catastrophic risk management, especially in defining the probable maximum earthquakes for each county/city in probabilistic sense. The proposed probable maximum earthquakes are useful in proposing seismic disaster mitigation plans to estimate the possible disaster extent and loss distribution in each county/city and to prepare adequate amount of rescue and medical resources. The systematic approach to estimate seismic hazard and risk is also useful in proposing seismic insurance policy of residential buildings, retrofit prioritization of highway bridges and school buildings, etc.

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