Seismic Scenario Simulation and Its Applications on Risk Management in Taiwan

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Abstract: This paper introduces various kinds of applications of the scenario-based seismic risk assessment in Taiwan. Seismic scenario simulation (SSS) is a GIS-based technique to assess distribution of ground shaking intensity, soil liquefaction probability, building damages and associated casualties, interruption of lifeline systems, economic losses, etc. given source parameters of an earthquake. The SSS may integrate with rapid earthquake information release system to obtain valuable information and to assist in decision-making processes to dispatch rescue and medical resources efficiently. The SSS may also integrate with probabilistic seismic hazard analysis to evaluate various kinds of risk estimates, such as average annual loss and probable maximum loss in one event, in a probabilistic sense and to help proposing feasible countermeasures.

Key words: seismic scenario simulation, hazard analysis, risk assessment

INTRODUCTION

National Science Council of Taiwan started HAZ-Taiwan project in 1998 to promote seismic scenario simulation technology. Due to lack of experience and database at that time, the original version of data classification schemes, analysis models and associated parameters used in HAZ-Taiwan software are very similar to those of HAZUS 97, which was developed by Federal Emergency Management Administration (FEMA) of USA. Afterwards, in order to fully utilize the local inventory data and associated data classification schemes, to adopt the localized analysis models and associated parameters, and to make up for the shortcomings in the software of HAZ-Taiwan, National Center for Research on Earthquake Engineering (NCREE) develops a new generation of earthquake loss estimation system, named "Taiwan Earthquake Loss Estimation System (TELES)".

There are many new features of 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. These features are not seen either in the software of HAZUS or HAZ-Taiwan. Integrating inventory data, seismic hazard/damage/loss assessment models and GIS-based technologies, TELES is capable of estimating possible consequences of strong earthquakes around Taiwan. The earthquake loss estimation methodology and software intends to provide standardized scenario-based assessments for proposing seismic disaster reduction plans in normal times, and also helps to provide useful data for decision-making personnel soon after occurrence of strong earthquakes (Yeh, 2004).

Since there are large uncertainties in the earthquake occurrences and the associated consequences, seismic risk assessment is often carried out through a probabilistic approach. Since the extents of possible damages, casualties and losses are not simple one-to-one functions of ground motion parameters, the results of seismic hazard analysis in terms of hazard curves at a specific site or hazard maps of ground motion parameters can not fully represent the seismic risk of a study region, which may include very huge areas. In other words, we need a systematic approach to estimate risk instead of hazard of a wide region instead of a specific site.

This paper intends to briefly demonstrate the analysis modules and application framework of TELES. For example, TELES has developed Early Seismic Loss Estimation (ESLE) module, which is integrated with Taiwan Rapid Earthquake Information Release System (TREIRS) of Central Weather Bureau (CWB) in Taiwan. It takes only a few minutes after earthquakes to obtain valuable information about probable scale and distribution of disasters caused by the earthquake. Such kinds of information may help in the decision-making processes to dispatch the limited rescue and medical resources properly and efficiently. There are quite a few examples that have applied the seismic scenario simulation technology of TELES and integrate with probabilistic seismic hazard analysis to obtain various kinds of risk estimates in a probabilistic sense. The analysis results of quantitative seismic risk assessment have been applied in several fields in Taiwan as will be explained in the following sections.

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 and dip angle, etc. Depending on the information of 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 Figure 1, 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 assessment models. All of the localized seismic hazard analysis have been studied and updated accordingly. The associated parameter values have also been calibrated by using many observed strong-motion records and engineering borehole data that were collected in Taiwan (Yeh et al, 2001; Yeh et al, 2002).

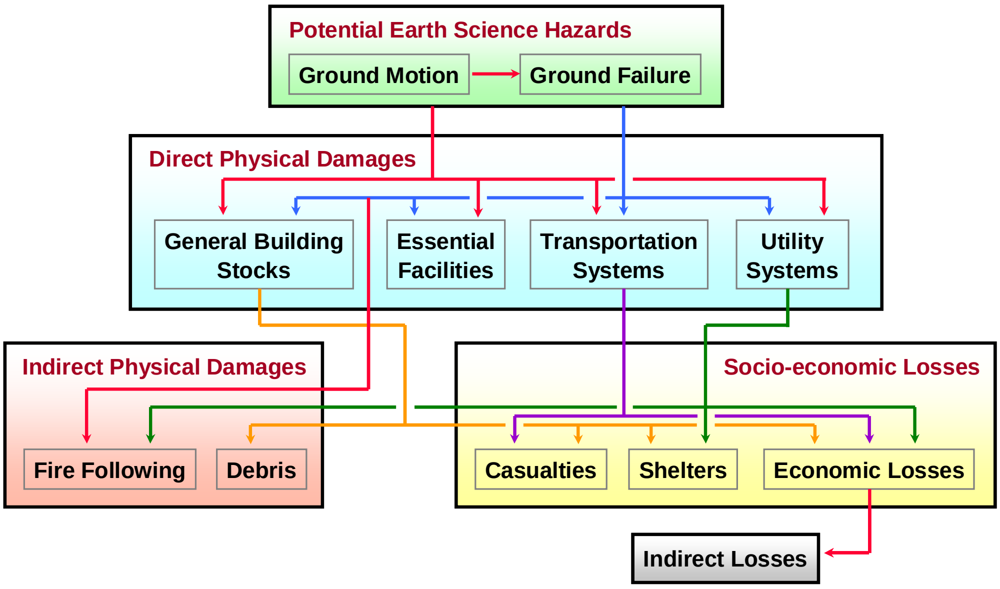


Figure 1. Analysis modules and framework of Taiwan Earthquake Loss Estimation System

Depending on the site-dependent 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).

For example, in order to obtain more rigorous estimates about damages and losses of general building stocks (GBS), the inventory database of GBS is derived from building tax data, which is maintained and updated yearly by Ministry of Finance. Various kinds of attributes such as structural type, building occupancy class, built year, floor area, number of stories, etc. may be found in the building tax data; therefore they can be incorporated in the analysis without too many subjective adjustments. Furthermore, phenomena of material hysteresis and structural system degradation have been taken into consideration in the damage assessment of buildings. The casualty estimates due to building damages have considered the population migration patterns during different time slots in a day and also applied different casualty rates for different model building types.

All the parameter values used in this study, such as attenuation laws, site modification factors, 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.

SEISMIC SCENARIO BUILDER AND DATABASE

In order to extend the applicability of SSS in early seismic loss estimation and probabilistic seismic risk assessment, it is often necessary to establish database which contains a complete set of simulation results due to many scenario earthquakes. The software architecture of TELES has been upgraded in its SSS capability so that it can be run in batch mode when the study region is subjected to a series of scenario earthquakes.

To be more useful in applications, the set of scenario earthquakes should represent all possible cases that may occur in the future around the study region. All of the simulation results should be systematically stored in subfolders of the project and could be retrieved easily, if inquired by the users. Depending on the application purpose, 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 in establishing the Taiwan seismic scenario database. The first type belongs to active faults that have known geographic properties such as the surface fault trace and the dip angle of fault plane. The fault geometry, characteristic and ultimate earthquake magnitude, average annual slip rate, etc. of each active fault in Taiwan have been investigated by the Central Geological Survey Bureau (CGSB), Taiwan. There are 42 active faults in total which were published by CGSB; among them, only 13 class-1 active faults are shown in Figure 2. 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 Figure 2: 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 Figure 2. Six focal depths, which are 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.

Since a fault-rupture model (Der Kiureghian and Ang, 1977) is normally preferred to a point-source model in assessing damage distribution and disaster scale, all the scenario earthquakes in Taiwan SSD are associated with fault ruptures. 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. There are 99,000 scenario earthquakes that belong to area sources in the SSD.

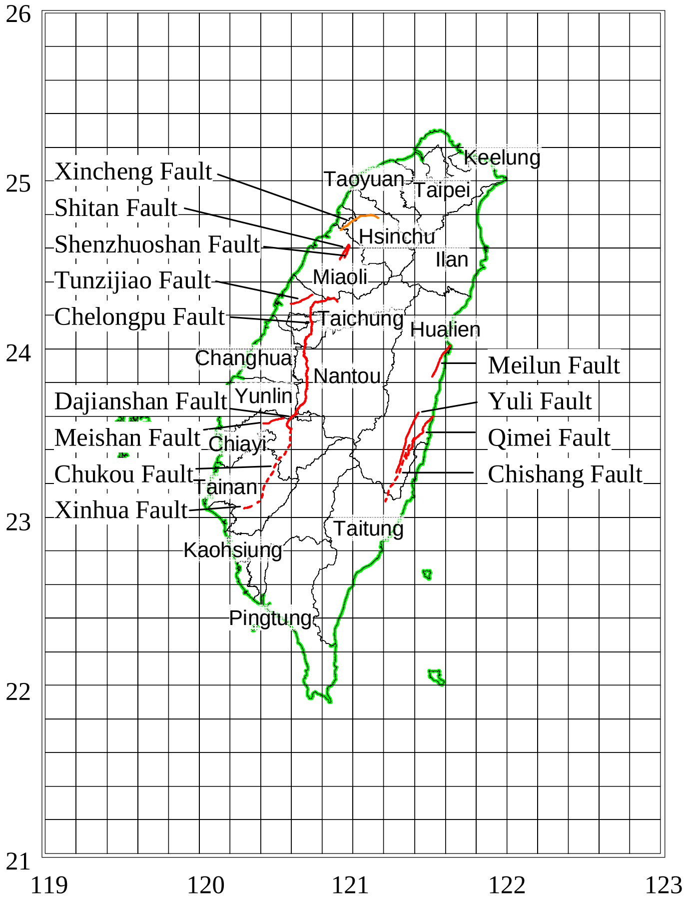


Figure 2. Boundary map of counties and cities in Taiwan, 13 class-1 active faults classified by CGSB, and the grid system of seismic area sources around Taiwan

APPLICATION ON EARLY SEISMIC LOSS ESTIMATION

Some of the essential facilities, such as communication and electric power systems, which are essential to collect and transmit disaster data, are vulnerable in strong earthquakes. Moreover, the response time may be further delayed because of highway damages after the strong earthquakes. Estimated distribution and amount of damages/casualties soon after strong earthquakes provide valuable information for decision-making to properly dispatch rescue forces and medical resources to the right places. Therefore, an Early Seismic Loss Estimation (ESLE) module in TELES was developed (Yeh et al, 2003).

The ESLE module is automatically triggered after receiving earthquake alert mails from the Central Weather Bureau (CWB) of Taiwan. The estimated damages and casualties are automatically output in the form of raster maps and ready-to-use tables to reduce man-works. In the first version of ESLE module, even though the analysis precision has been reduced and township instead of village has been chosen as the geographical unit, the required time to complete the hazard analysis and damage assessment still need 10 to 15 minutes depending on the earthquake magnitude, epicenter location and focal depth. Furthermore, since the seismic source information contained in the earthquake alerts from CWB is limited, a point-source model is applied in the first version of ESLE module. Using the point-source model is likely to underestimate the disaster scale.

The Taiwan SSD described in the previous section contains simulation results, such as ground motion intensity, soil liquefaction potential, amount of building damages, induced casualties/losses, etc. in each village, when scenario earthquakes with different magnitude, epicenter location and focal depth occur around Taiwan. If the SSD is integrated in the ESLE module, when any earthquake occurs, the only task that ESLE module remains to do is to search for the analysis results that coincide with the observed source parameters and the measured peak ground accelerations at the real-time stations. In this way, the SSD can be used to shorten the emergency response time and to increase the precision of analysis results at the same time.

Normally, the estimated results can be obtained within a few minutes after receiving the earthquake alert from CWB. TELES will automatically dispatch the summary information using simple message service through mobile phone and email through internet to emergency response personnel. The summary contains descriptive information such as the earthquake magnitude, the town name nearest to the epicenter, the amount of estimated casualties and the number of villages with PGA greater than 0.16g, which is considered to be the threshold of damaging intensity to the buildings in Taiwan.

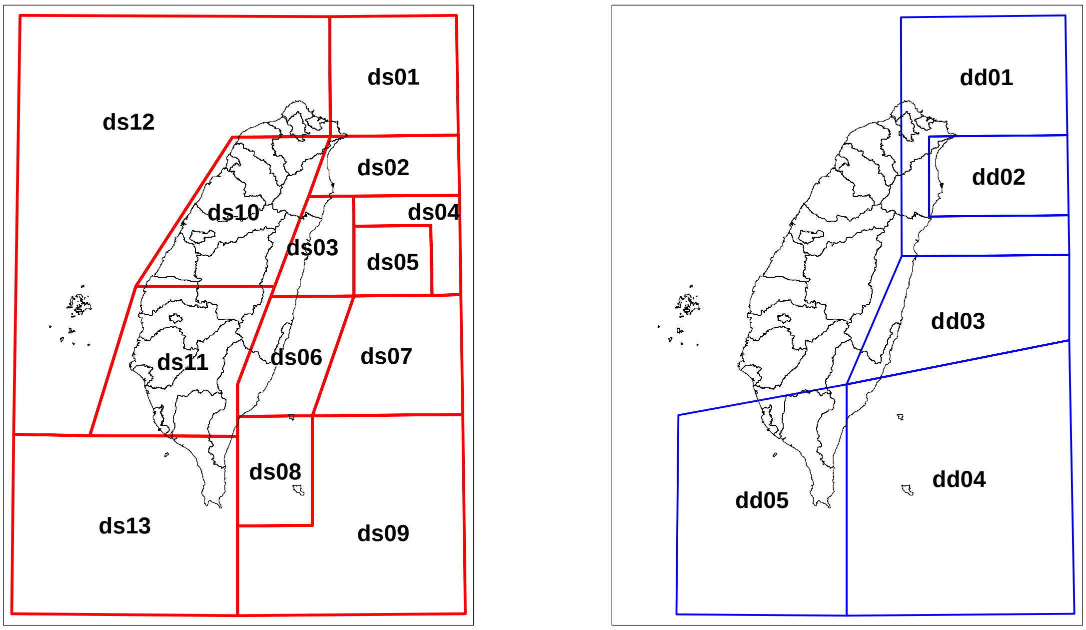
Other rescue and medical resources, such as the required number of rescue teams and equipments, the fire-fighting teams and water demands, the required number of medical doctors, nurses and ambulances, the induced amount of debris, and the other livelihood, may be calculated from the analysis results of building damages, casualties, shelter needs and post-quake fires. The various kinds of estimation results have been applied in the disaster reduction and prevention information system in Central Emergency Operation Center (CEOC) of Taiwan.

PROBABILISTIC SEISMIC HAZARD ANALYSIS

In general, probabilistic seismic hazard analysis (PSHA) involves four steps. The first step is to identify and characterize seismic sources in the neighborhood of the study region including probability distribution of location and direction of fault rupture. The second step is to characterize the temporal distribution of earthquake recurrence with respect to 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 to obtain the probability that the ground motion parameter will be exceeded during a particular time period.

The seismic source model in PSHA is simply a description of the spatial and temporary distribution of earthquakes with various magnitudes and focal depths. Referring to the fault-rupture model proposed by Der Kiureghian et al (1977), the known active faults, such as those identified by CGSB (shown in Figure 2), were classified as Type 1 sources. The rest of seismic sources with unknown fault location were classified as either Type 2 or Type 3 depending on whether the rupture direction is known or not. In practice, it is rather difficulty to distinguish between Type 2 and Type 3 sources. These sources are referred to as area sources in this study; and the probability distribution of fault rupture direction is not uniform for Type 2 sources.

The quality of historical earthquake catalog may significantly influence the results of PSHA. Therefore, the completeness of earthquake events during different time period, the definition consistency of magnitude scale, and the measurement accuracy of epicenter and focal depth should be checked and calibrated carefully in the historical earthquake catalog. The seismic source zoning schemes (shown in Figure 3) and the historical earthquake catalog used in this study were the same as those used in Loh et al (2004). 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.



(a) (b)

Figure 3. Example of seismic source zoning scheme for (a) shallow earthquakes and (b) deep earthquakes of area sources around Taiwan

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. Although results were not shown in this paper, the parameters m_u, ν_0 and β may be obtained using different zoning schemes. It is interesting and important 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. As an example, using the maximum likelihood estimation and assuming the average of two bounds to be the occurrence rate of earthquakes in each grid, Figure 4 shows the annual occurrence rate of earthquakes with $m \geq 5$ in each grid of seismic source zones. 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.

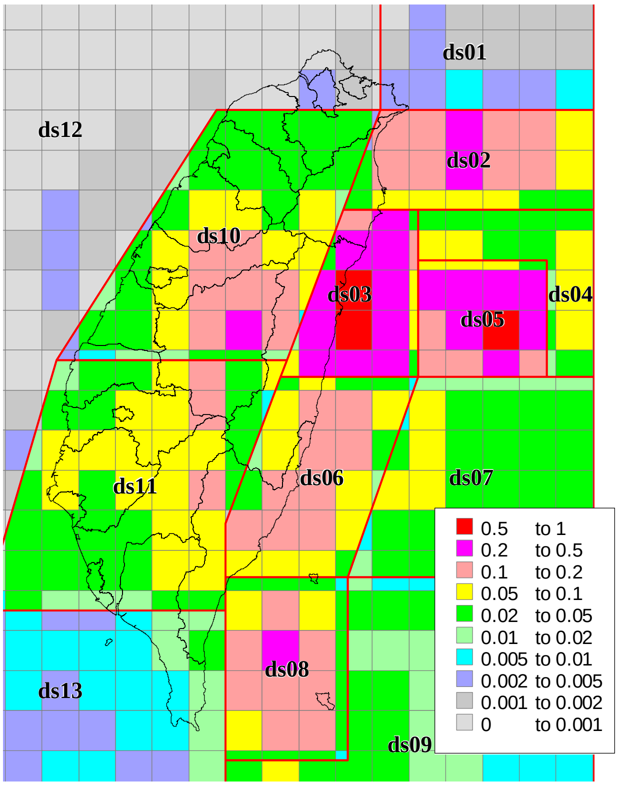


Figure 4. Map of annual occurrence rate of earthquakes with $m \geq 5$ in each grid around Taiwan. The coefficients in the Gutenberg-Richter relationship are calculated by maximum likelihood estimation

Paleoseismicity and fault slip data along major faults in southern California have been studied by Wesnousky (1994) and concluded that the characteristic earthquake model is more suitable than Gutenberg-Richter earthquake recurrence model in seismic hazard analysis and for engineering design purposes. Thus, it is one of the objectives to combine the two earthquake recurrence models in this study. The fault geometry, characteristic magnitude and recurrence rate of 13 class-1 faults are assumed and listed in Yeh (2008). 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.

Based on the attributes listed in Yeh (2008) for area sources and active faults, respectively, the probabilistic seismic hazard analysis can be carried out for different sites. As an example, Figure 5 compares the seismic hazard curves of PGA at six places in Taiwan. The intensity maps of PGA or response spectra corresponding to different hazard levels may also be obtained easily by using TELES.

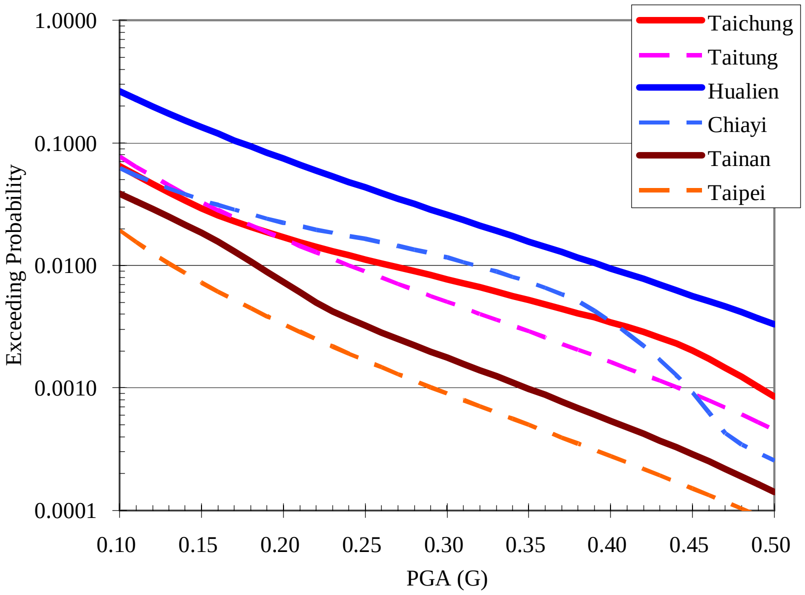


Figure 5. Hazard curves of peak ground acceleration at the selected sites of Taiwan

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 (v_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. The annual occurrence rate, expected consequence and associated uncertainty for each scenario earthquake are summarized in a table (schematically shown as 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).

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

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.

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,

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

The corresponding annual occurrence rate of each disjoint scenario earthquake is ν_1, $\nu_2 \ldots$ $\nu_K \ldots \nu_N$, respectively. According to the definition, the annual occurrence rate with $L \ge L_1$ is ν_1; the annual occurrence rate with $L \ge L_2$ is $\nu_1 + \nu_2$. In general, the annual occurrence rate with $L \ge L_K$ 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.

PRIORITIZATION FOR SEISMIC RETROFIT OF HIGHWAY BRIDGES

There are more than 20,000 highway bridges in Taiwan. Some (about 2,500) of them are located on the province highways, which are the main roads connecting counties and cities and hence belong to important bridges. Since many of the province highway bridges were constructed before modern seismic design codes were enforced, they should be examined, evaluated and retrofitted if necessary. In 2005, a project were issued by the Directorate General of Highways, MOTC, to investigate preliminarily the seismic capacity of the existing highway bridges, to estimate approximately the retrofit cost and to prioritize the retrofit sequence based on the results of seismic risk assessment.

Since there are many existing bridges, it is neither necessary nor practical to evaluate seismic capacity and vulnerability of each bridge in detail at the preliminary stage. To assess probable risk of highway bridges, all of the existing highway bridges were roughly classified into eight categories according to the number of spans, continuity of super-structures and type of piers. Each category of highway bridges was further classified into three sub-categories, i.e., traditional design, retrofitted and seismic design. The fragility curves of the prototype for each class and sub-class were calibrated using nonlinear push-over analysis of 148 existing bridges, which were in different bridge categories, at different locations and with various ages. Since different seismic design forces were used in different version of design codes and depended on seismic zoning schemes, the parameters of fragility curves for each individual bridge was modified based on its design year, site condition and seismic zone.

The losses considered in this project include direct losses due to structural damages and indirect losses due to interruption, restoration or reconstruction of bridges. Average daily traffic, detour length, probability of failure, restoration time, etc. had been taken into consideration in estimating the indirect losses.

Using the probabilistic seismic source model and the risk assessment methodology stated in this paper, it is possible to calculate the average annual loss of each bridge before and after seismic retrofit, denoted by L_c and L_r, respectively. In order to prioritize the retrofit sequence of bridges, two indicators have been proposed in this project. The indicators are defined for each bridge and are based primarily on the results of seismic risk assessment. The first one is called risk indicator (I_r) and is defined as follows:

$$0 \leq I_r = \frac{L_c \cdot N_c}{C_b} \leq 1 \tag{6}$$

where N_c denotes the expected service period (in years) of the bridge; C_b is the rebuild cost; and the value of I_r is bounded between 0 and 1. The second one is called beneficial indicator (I_e) and is defined as follows:

$$0 \leq I_e = \frac{L_c - L_r - (C_r / N_r)}{L_c} \leq 1 \tag{7}$$

where C_r is the estimated retrofit cost; and N_r is the expected service period (in years) of the bridge after retrofit.

The two indicators shown in Eq. 6 and 7 may be combined with other indicators such as importance indicator and used in prioritization of seismic retrofit of bridges.

APPLICATION FRAMEWORK OF TELES

This study combines the probabilistic seismic hazard analysis and the seismic disaster simulation technology in single software. The proposed analysis framework and possible applications of TELES are shown in Figure 6 and are summarized as the following steps:

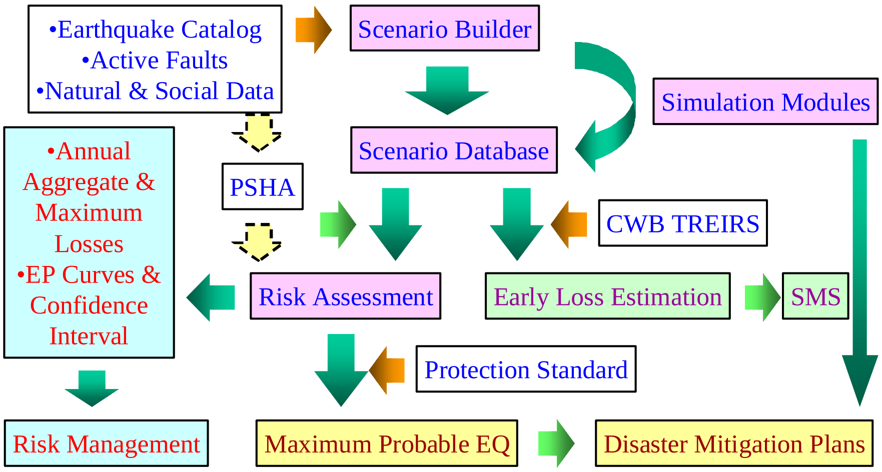


Figure 6. Analysis framework and probable applications of TELE

- 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 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).

CONCLUDING REMARKS

Taiwan Earthquake Loss Estimation System (TELES) is part of the research accomplishment of HAZ-Taiwan project. Integration of the seismic scenario database and the probabilistic seismic hazard analysis module 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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