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DEVELOPMENT OF A NATIONAL EARTHQUAKE RISK ASSESSMENT MODEL FOR TAIWAN

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SUMMARY

This paper summarizes the development of an earthquake risk assessment methodology for Taiwan. This earthquake loss model is the first model of its kind in Taiwan. The frame work of this model includes five basic components: ground shaking/failure, building damage, lifeline damage, economic losses, and social losses. Through this program the implementation of earthquake loss assessment and integrated GIS technology provide emergency planners and government officials with a variety of earthquake scenarios. It will also facilitate the rapid transfer of information between the academic/research community and the end user.

INTRODUCTION

HAZUS-97 is designed to produce seismic loss estimation for use by regional and local governments in planning for earthquake loss mitigation, emergency preparedness and response and recovery [HAZUS97, 1997]. The framework of the HAZUS methodology includes: potential earth science hazard, inventory collection, direct physical damage estimation (risk analysis), direct economic/social loss and indirect economic loss estimation. Based on the framework of HAZUS-97, the National Science Council of Taiwan is developing a similar methodology for earthquake loss estimation, called HAZ-Taiwan. The conceptual framework for HAZ-Taiwan program include four major sections [Loh and Yeh, 1998]:

(1) to develop methodologies for seismic hazard potential analysis (i.e., including ground motion and ground failure analyses), and to apply these results to evaluate seismic hazard for Taiwan,
(2) to estimate the direct physical damage of building stock, lifelines, critical facilities and bridges,
(3) to develop a disaster scenario display system in order to incorporate the risk assessment results (Taipei city and Chai-Nan areas are selected as two pilot study regions),
(4) to estimate the direct and indirect economic/social losses and to develop the hazard mitigation plans for the pilot study areas.

This paper will present the analysis modules for potential earth science hazard analysis, direction physical damage for building stock and bridges and the maps of damage estimates in pilot study region.

POTENTIAL EARTH SCIENCE HAZARD

Potential earth science hazards (PESH) include ground motion and ground failure (liquefaction, landslide and fault surface rupture). Methods for developing estimates of ground motion and ground failure are discussed in the following sections.

Ground Motion

Ground Motion intensity can be determined using either deterministic or probabilistic seismic hazard analysis. In deterministic analysis, seismic demands are calculated for user-specified scenario earthquakes. Given earthquake magnitude, location and depth (including fault type and rupture mechanism in some cases), attenuation relationships are used to calculate ground shaking intensity in rock sites, which is then amplified by

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factors based on local site conditions. There are three options in selection of a scenario earthquake, that is,
specify an event based on a database of seismically active faults,
specify an event based on a database of historical epicenters, or
specify an arbitrary event.

However, to be more realistic, the scenario earthquake should be selected based on probabilistic analysis. Scenario earthquakes are hypothetical earthquakes designed for engineering use by specifying their magnitudes and epicentral locations. Identify important source areas that have large values of the contribution factor for a prescribed value of probability value must be considered in the selection of scenario earthquake.

In probabilistic approach, the ground shaking intensity is characterized by contour maps of PGA, PGV and spectral values at some specific periods. These contour maps are constructed by performing seismic hazard analysis at many sites. The seismic hazard analysis calculates the exceedance probability of various shaking intensities at any given site. The total probability theorem is used to estimate the seismic hazard potential as

$$P[A > A_0] = \sum_{i=1}^{n} \int P[A > A_0 \mid E_{i,m}]\ f_M(m)\ dm \tag{1}$$

where n is the number of seismic zones, $P[A > A_0 \mid E_{i,m}]$ is the conditional probability of PGA being greater than A_0 given an earthquake of magnitude M occurring in seismic zone i, $f_M(m)$ is the probability density function of magnitude M. The contour map shows the ground shaking intensities for a given return period, i.e., with the same exceedance probability, at different sites. For example, the return periods of 100, 250, 500 and 1000 years are used in HAZ-Taiwan. Figure 1 lists the model parameters that are considered in seismic hazard analysis [Loh, 1997], where ground motion attenuation relationship plays an important role in this analysis. The attenuation relations recently proposed for peak ground acceleration, spectral acceleration at T = 0.3sec and T = 1.0sec are shown:

PGA attenuation: $y\ (\mathrm{g}) = 0.001 \times 272.5 \times 10^{0.303M} (R + 12)^{-1.518}$ (2)

S_a (T = 0.3sec): $y\ (\mathrm{g}) = 0.001 \times 292.8 \times 10^{0.385M} (R + 19.5)^{-1.598}$ (3)

S_a (T = 1.0sec): $y\ (\mathrm{g}) = 0.001 \times 2.90 \times 10^{0.66M} (R + 37)^{-1.60}$ (4)

To simply analysis procedure in building damage prediction, the spectral response based on a standard shape will be used in the estimation of earthquake demand spectra at a site. Different from the traditional representation of response spectral acceleration is plotted as a function of spectral displacement rather than as a function of period, as shown in Fig. 2. This is the format of response spectra used for evaluation of building vulnerability. The region of constant spectral acceleration is defined by spectral acceleration at a period of 0.3 second, $(S_A)_{T=0.3}$. The region of constant spectral velocity has spectral acceleration proportional to 1 / T and is anchored to the spectral acceleration at a period of 1.0 second, $(S_A)_{T=1.0}$. The intersection of the regions of constant spectral acceleration and constant spectral velocity defines the period T_{AV}, i.e., $T_{AV} = (S_A)_{T=1.0} / (S_A)_{T=0.3}$.

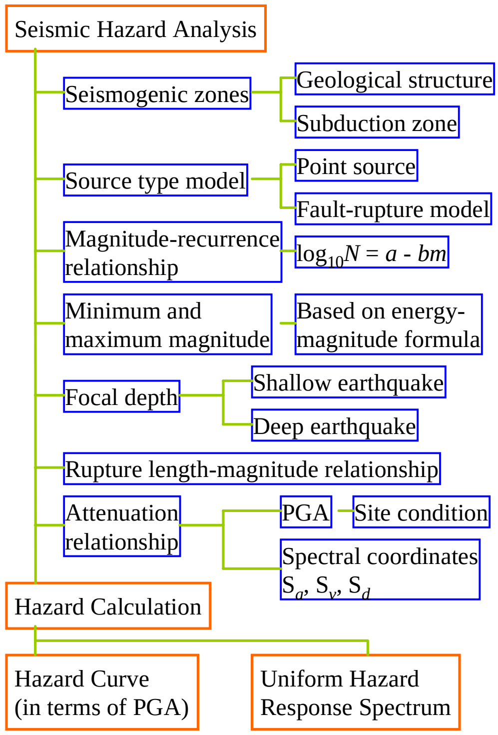

Figure 1: Required hazard parameters for seismic hazard analysis

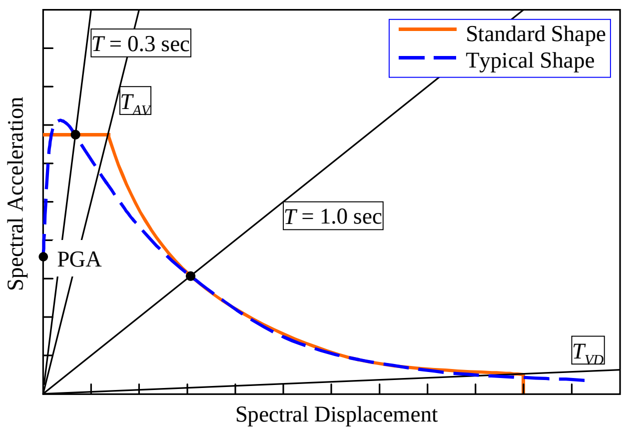

Figure 2: Standard response spectrum curve

Ground Failure

Three types of ground failure, i.e., liquefaction, landslide and surface fault rupture, are considered in HAZ-Taiwan. Each type of ground failure is quantified by the expected permanent ground deformation and the probability of occurrence.

Liquefaction is a soil behavior phenomenon in which a saturated soil looses a substantial amount of shear strength due to high excess pore-water pressure generated by and accumulated during strong earthquake ground shaking. For a given earthquake E, the probability of liquefaction at a site can be expressed as:

$$P_E[L] = P[L \mid E]\ P[E] \tag{5}$$

where $P_E[L]$ is the unconditional probability of liquefaction, $P[L \mid E]$ the conditional probability of liquefaction given occurrence of earthquake E, and $P[E]$ the probability that an earthquake occurs. From seismic hazard analysis, the annual probability of occurrence for different ground shaking intensity (i.e., PGA A_0) at a site can be calculated. Various methods have been proposed for predicting liquefaction potential, in this study the Seed's simplified method incorporated with Iwasaki's weighting scheme was used. The correlation between surface fault displacement and earthquake moment magnitude developed by Wells and Coppersmith [1994] is used to determine the permanent ground displacement induced by the surface fault rupture. It is based on the empirical data set for all types of faulting (strike slip, reverse and normal). For a given earthquake moment magnitude *M*, the median maximum displacement is given by $\log \hat{D} = -5.26 + 0.79\,M$.

DIRECT PHYSICAL DAMAGE — GENERAL BUILDING STOCK

Estimation of building damage and the associated probability in each damage state is one of the important issues in HAZ-Taiwan. Besides the earthquake demand spectra, two sets of functions, i.e., capacity and fragility curves are used to estimate the building damage resulting from the ground shaking. The capacity curves estimate peak building response for a given level of spectral demand. These curves are analogous to pushover curves of individual buildings. The fragility curves predict the probability of reaching or exceeding specific damage states for a given level of peak building response. The probability of being in a particular state of damage is calculated as the difference between fragility curves.

Building Classification

To facilitate estimation of structural/nonstructural damages and the associated economic losses, buildings are classified both in terms of their structural system, or model building type, and in terms of their use, or occupancy class, respectively. Classification of model building types are based on the material (wood, steel, reinforced concrete, masonry, etc.), lateral force resistance system (moment resisting frame, frame with bracing systems, frame with shear walls, etc.), and building height. To accommodate different seismic design level and code, each model building type is divided into four groups, that is, high-code, moderate code, low code and pre-code.

Building inventory data are collected for each basic geographic unit, that is Chunli in HAZ-Taiwan or census tract in HAZUS. The total floor area of each specific occupancy class is calculated. The distribution of model building types in each specific occupancy class is also determined by a mapping scheme.

Building Capacity Curves

A building capacity curve is a plot of a building's lateral load resistance as a function of characteristic lateral displacement. It is derived from a plot of static-equivalent base shear versus building displacement at the roof, which is known as a pushover curve of individual building. In order to facilitate direct comparison with earthquake spectral demand, the base shear is converted to spectral acceleration and the roof displacement is converted to spectral displacement using modal properties that represent pushover response. Building capacity curves are constructed for each model building type and seismic design level to represent different levels of lateral strength and displacement ductility.

Figure 3 shows the typical capacity curve of steel structures. From this capacity curve of typical structure, the yield strength, yield displacement, ultimate strength and ultimate displacement are obtained and implemented to the program of HAZ-Taiwan seismic loss estimation.

Building Demand Spectra

In general, peak ground acceleration (PGA), peak ground velocity (PGV) and spectral response characterize ground motion intensity in a given earthquake. To simplify analysis procedure in building damage predication, the spectral response based on a standard shape will be used in the estimation of earthquake demand spectra at a given site.

Generally, the inelastic demand spectrum is needed to define the building demand spectrum. The amount of spectrum reduction (inelastic response spectrum) typically increases for buildings that have reached yield and dissipated hysteretic energy during cyclic response.

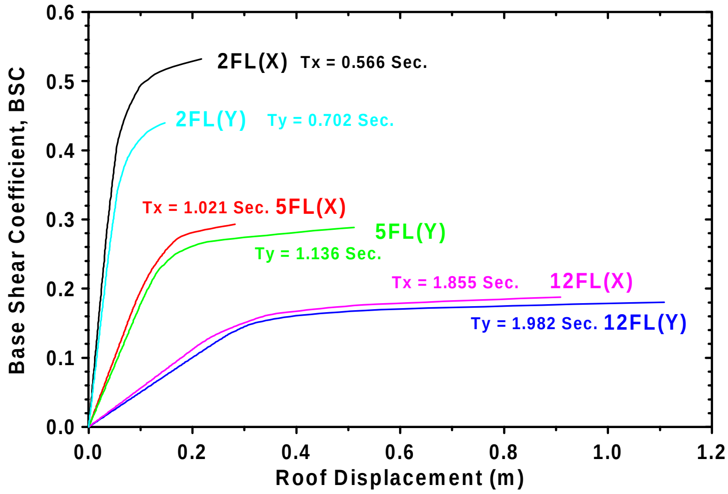

Figure 3: Capacity curves for 3 steel frame structures (2-story, 5-story and 12-story)

Effective damping, β_{eff}, is defined as the total energy dissipated by the building during peak earthquake response and is the sum of an elastic damping term, β_E, and a hysteretic damping term, β_H. The elastic damping term is assumed to be amplitude independent and is evaluated for materials at or just below their yield points. The hysteretic damping term is dependent on the amplitude of post-yield response and is expressed as

$$\beta_H = \kappa \left(\frac{A_H}{2\pi\, D\, A} \right) \tag{6}$$

where D and A represent the peak displacement and acceleration responses, respectively, A_H the area enclosed by the hysteresis loop, κ a degradation factor that defines the effective amount of hysteretic damping as a function of earthquake duration.

Building Fragility Curves

Building response is determined by the intersection of the demand spectrum and the building capacity curve. Figure 4 shows the intersections of three demand spectra representing weak, medium and strong ground shaking levels, and two building capacity curves representing a weaker and a stronger construction, respectively. As shown in the figure, the stronger and stiffener construction displaces less than the weaker and more flexible construction for the same level of spectral demand. Less damage is expected to the structural system and drift-sensitive nonstructural components.

To better estimate different types of losses, building damage functions separately predict damage to the structural system, drift-sensitive nonstructural components and acceleration-sensitive nonstructural components. Damage states are also defined separately for structural system and nonstructural components of a building. Although actual building damage varies as a continuous function of earthquake demand, four discrete damage states, i.e., slight, moderate, extensive and complete damage states are used to describe the building damage and to provide the user with an understanding of the building's physical condition. Structural and non-structural fragility curves are evaluated for spectral displacement and spectral acceleration defined by the interaction of the capacity and the demand curves of the building.

Fragility curves are log-normal functions that describes the probability of reaching or exceeding various damage states, given deterministic estimates of PESH parameters. Each fragility curve is defined by a median value of the demand parameter that corresponds to the threshold of that damage state, and by a logarithmic standard deviation associated with that damage state. Median values of structural component fragility are based on inter-story drift ratios that describe the threshold of damage states. In general, these estimates of drift ratio are different for each model building type and seismic design level. Structural and nonstructural fragility curves are evaluated for spectral displacement and spectral acceleration defined by the intersection of the capacity and the demand curves of the building. Cumulative probabilities are subtracted between adjacent fragility curves to obtain discrete probabilities of being in each of five damage states. Figure 5 shows the damage distribution of school building as well as the ground motion intensity distribution for a scenario earthquake occurred at northern part of Taipei basin.

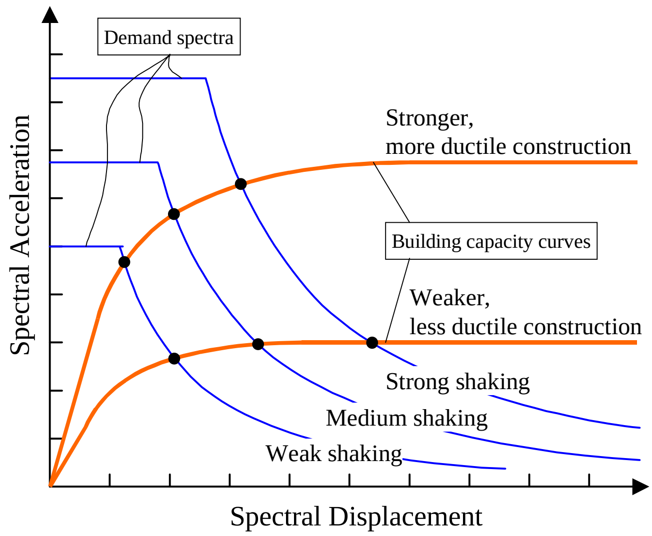

Figure 4: Intersection of demand spectra and building capacity curves

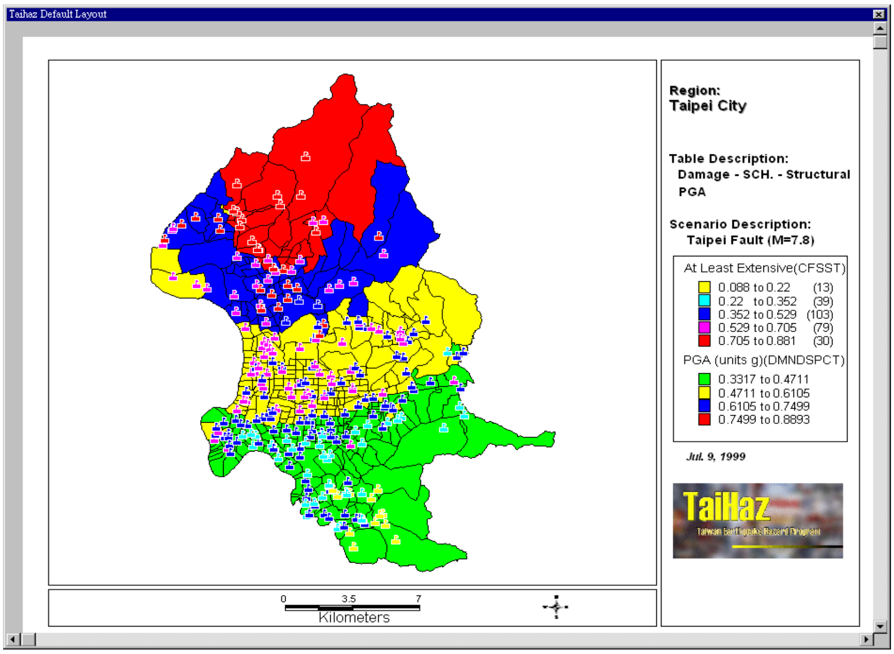

Figure 5: Distribution of ground motion intensity and damage of school building based on earthquake scenario (Taipei basin)

DIRECT PHYSICAL DAMAGE TO LIFELINES — BRIDGES

For the bridge classification the HAZ-Taiwan includes three bridge classifications: major bridge, continuous bridge and simple-supported bridge. Both of them are considered as seismically designed structures. Each classification is also based on the following structural characteristics:

- Number of spans: single *vs.* multiple span bridge

• Structural type: concrete, steel and others

• Pier type: single column bents, multiple column bents

• Abutment type and bearing type: monolithic *vs.* non-monolithic; neoprene rubber bearings and low steel bearing

• Span continuity: continuous, discontinuous and simply-supported

Similar to the analysis on building stock, the capacity curve of each bridge structure is generated. Different type of limit state, such as bending failure or shear failure in ultimate state of bridge pier is used to develop the capacity curve. Through Monte Carlo simulation the nonlinear dynamic response of the bridge structure is calculated and the probability distribution of response quantity is estimated for each ground motion intensity level. Figure 6 shows the probability of exceedance for a given PGA intensity level of ground motion excitation. Different bending moment capacity as limit-state condition will give different level of probability. It is one of the fragility curve for simply-supported bridge column. From which the damage level can be identified with different value of maximum base moment.

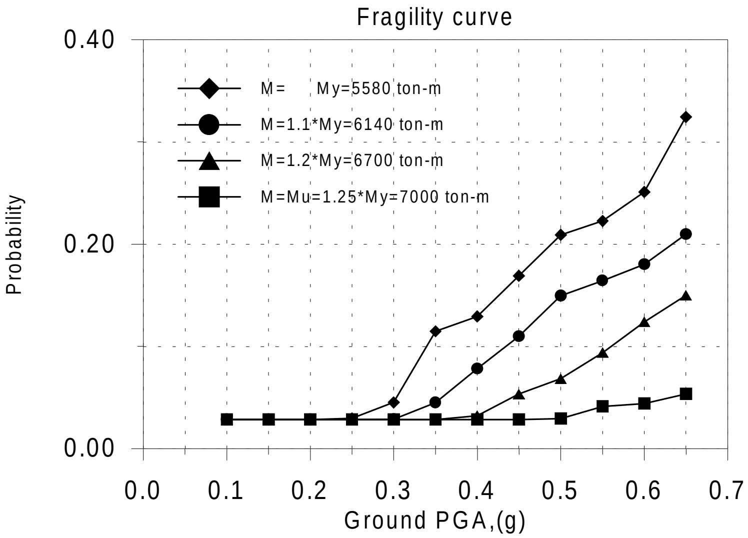

Figure 6: Plot of probability exceedance with respect to different PGA-levels for different limit-states

INVENTORY DATA NEEDED FOR HAZ-TAIWAN

The required inventory data can take two forms. The first is the inventory data such as the square footage of buildings of a specified type, the length of roadways or the population in the study region. They are used to estimate the amount of exposure or potential damage in the region. The second data type includes characteristics of the local economy, which are important in estimating losses, e.g., rental rates, construction costs, regional economic output, or regional unemployment rates. There is a large amount of inventory data, potential seismic hazard information, and analysis parameters in HAZ-Taiwan methodology. Collecting inventory data includes: general building stock, occupancy to model building type relationship, critical facilities, transportation lifelines and demographic information.

ESTIMATION OF EARTHQUAKE ECONOMIC LOSSES

To access the cost of damage, several approaches are applied including damage potential index, statistical qualitative analysis, and contingent valuation method. However, due to the shortage of accurate information of earthquake damage, the assessments tend to be rough. Based on the cost-damage analysis, the estimation of economic losses caused by earthquake hazard follows the steps:

(1) boundary definition;

(2) parameters of earthquake scenario;

(3) geographic attributes, including natural and man-made factors of hazard;

(4) probability function of damage for buildings, lifelines, facilities, and their loss of function;

(5) derive the direct and indirect economic losses; and

(6) strategic design for disaster prevention and mitigation.

Indirect economic losses are caused by the disruption of business for ward-links (rely on regional customers to purchase their output) and backward-links (rely on regional suppliers to provide their input) caused by earthquake damage. The major input of indirect economic module is the input-output transaction table. The data required to perform indirect economic loss estimation include the items of employment, income, major industrial sector, input, inventories of demand and supply, restoration function, etc.

CONCLUSIONS

The purpose of this paper is to introduce the development of a national earthquake risk assessment model for Taiwan, called HAZ-Taiwan. The framework of HAZ-Taiwan includes: potential earth science hazard analysis, physical damage assessment induced physical damage assessment, direct social/economic loss estimation and indirect economic loss estimation. The results can provide local and regional officials with the necessary tools to design the earthquake hazard mitigation plan and to prepare for emergency response and recovery from a disaster earthquake.

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