# REMOTE SENSING DATA BASED REAL-TIME EARTHQUAKE LOSS ASSESSMENT METHODOLOGY

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**ABSTRACT:**

Using satellite remote sensing data to derive building attributes and earthquake vulnerability characteristics makes the rapid assessment of dynamic earthquake losses in fast economic developing areas possible and practical. The key parameters in earthquake damage analyses such as building height and construction area can be extracted from remote sensing data using newly developed image processing techniques at relatively low cost. The building height is used to derive the vulnerability characteristic distributions for a loss estimate in conjunction with a composite earthquake vulnerability model or damage probability matrix (DPM) from a few typical structure types. Weighting factors in occupancy type, structure type, and year built band of buildings with a specific height category are used in loss calculations. The remote sensing information based earthquake loss assessment methodology and its specific implementation procedure are developed in this paper. It greatly enriches the general method of earthquake loss estimation in urban areas. The new methodology can also be used to rapidly report the damage distribution from a real earthquake event by incorporating the real-time ground motion distribution estimate for the event. The assessment of losses from scenario earthquakes in Zhangzhou, Fujian, China is used to demonstrate the application of the proposed methodology.

**KEYWORDS:** Remote sensing, Vulnerability, Characteristic distributions, Inventory

## 1. INTRODUCTION

The dynamic earthquake risk assessment including estimates of economic losses, casualties, and geological hazard distributions is the basis for a metropolitan government to develop earthquake emergency response plans and disaster mitigation strategies in its urban development. A rapid and accurate estimate of the geographic distribution of real-time earthquake damage to buildings and the impact to human life plays a critical role for a local government to effectively take an earthquake emergency action and facilitate the prompt and appropriate response to render necessary assistance and minimize further injury and damage in the disastrous area. Therefore, developing methodologies for a rapid, accurate, and reliable assessment of real-time earthquake loss distribution in urban areas is very important for the emergency response plan and disaster mitigation program.

An effective earthquake risk assessment system needs to include three basic components: an earthquake hazard analysis model to reflect the state-of-the-art scientific research in understanding local seismic hazard, a GIS database of buildings and engineering facilities to represent the existing urban construction development status and current population distribution, and the vulnerability models for various types of buildings, facilities, and casualties in the area. Among those, the building, facility, and population distributions are very time sensitive, especially in economic developing regions like most of the medium size cities in China and other developing areas around the world.

In traditional earthquake loss assessment methodologies, the building and facility inventory information including structure type, building height, year built, and construction area is developed through detailed on-site building inspections by specially trained engineering technicians and then the collected information is compiled into computer databases. Such procedure takes tremendous human efforts and a lot of time up to several months. In addition, the maintenance and update of building and facility information database after the computer system has been created may take even more effort in order to include the frequent changes in building inventory information of the area. In many cases, the building inventory information was created only based on a sample inspection of 5%-10% of the buildings in the area due to the lack of manpower and funding, or a tight schedule. With the rapid development in local economic activities and population growth, the inventory database and earthquake vulnerability categorization may no longer be valid to reflect the real development status of the area soon after the project is finished. The GIS database cannot represent the current building distribution. Therefore, an alternative of developing building inventory database without high cost and great demand for labor becomes a challenging task in earthquake loss assessments.

## 2. PROCEDURE OF EARTHQUAKE LOSS ASSESSMENT

An assessment of potential earthquake damage and losses is critical to urban disaster mitigation planning. It consists of the following tasks: regional seismic hazard analysis, building and infrastructure damage analysis, injury and casualty analysis, direct and indirect economic loss analysis, etc. The building inventory data and earthquake vulnerability characteristics are the keys to accurately estimate the earthquake damage and losses. In the analysis of earthquake damage to buildings and impact to human life, the building damage is usually classified into five damage states: no damage, slight damage, moderate damage, severe damage, and collapse. For a given level of ground motion intensity *I*, the damage to building structure and contents inside, and the number of injuries, death, and people in need of sheltering can be determined based on the probabilities of building damage in various damage states:

$$Loss(I)_{Property} = Area \times (Price\ of\ Reconstruction) \times \sum_{i=1}^{5} [CDF_i \times Prob_i(I)] \tag{1}$$

$$Loss(I)_{Life} = Area \times PopulationDensity \times (Proportion\ of\ People\ Inside) \times \sum_{i=3}^{5} [LCDF_i \times Prob_i(I)] \tag{2}$$

where $CDF_i$ is the building central damage factor, and $LCDF_i$ the average factor of injury, death, or people in need of sheltering at the *i*-th damage state, and $Prob_i(I)$ is the element of building damage probability matrix (DPM) for a specific type of building which is related to the construction material, structure type, height, year built, construction quality of the building. The damage to the property also depends on the reconstruction cost. The loss to human life is well correlated to the population density within the building of a specific occupancy type and the rate of people inside the building during an earthquake. In the traditional way of earthquake damage assessment, tremendous efforts have been put on manually collecting the building information such as construction area, structure type, number of stories, year built, and occupancy type and establishing the DPMs for many types of structures in the area. In most cases, the detailed building inspections are not practical for the economic and scheduling reasons because of the great demand for labor. Even though the building stock database has been established, the maintenance and upgrade of the existing database are still difficult due to the fast changes in urban development and economic activities of a developing region. The alternative of efficiently developing building inventory database and vulnerability models at relatively low cost is necessary for a rapid and effective assessment of earthquake losses in urban areas.

## 3. EXTRACTION OF DAMAGE ANALYSIS DATA FROM REMOTE SENSING IMAGES

The progress has been made in extracting critical information of buildings and facilities in large urban areas for the purpose of earthquake damage assessment by means of high-resolution satellite remote sensing images, such as the work by Miura and Midorikawa (2006), Jin and Davis (2005), Fraser et al. (2002), and Sohn and Dowman (2001). The high-resolution satellite images with a ground resolution of one meter or less as shown in Figure 1 have become more and more popular for civilian usage at reasonably low cost. Thus, it is feasible to make use of satellite images to get 3-D information for large quantity of individual buildings and facilities on the ground. With the new remote sensing information processing techniques, the edge and shadow of surface objects, roads, vegetation area, and water area can be identified. The height of an object on the ground can be calculated based on the length of its shadow from different viewing directions, the satellite angle, and the times during the day the images were taken. As shown in Figure 2, the building height $H$ can be calculated from the length of its shadow $L$ on the ground and the Sun elevation angle $\beta$ using a simple trigonometric relation: $H = L \times \tan(\beta)$. The shadow length $L$ is also related to the intersection angle $\alpha$ between the surface projections of the Sun illumination direction and satellite viewing direction. Usually, the base of a building in a satellite image is blocked by other surrounding structures such that the shadow length cannot be determined easily. In this case, the building height can be determined from the length of the line joining the points $A$ and $T$ on the image.

Using the average story height of typical buildings of the region, the number of stories of a building can be approximately derived. Finally, the total construction area of a building is calculated from its geometric shape and the number of stories. Once the building data is extracted from remote sensing images for the whole area, a comparison with the available existing GIS building inventory database of the region can provide information of new constructions in the same area.

Figure 1. Satellite Image of Buildings

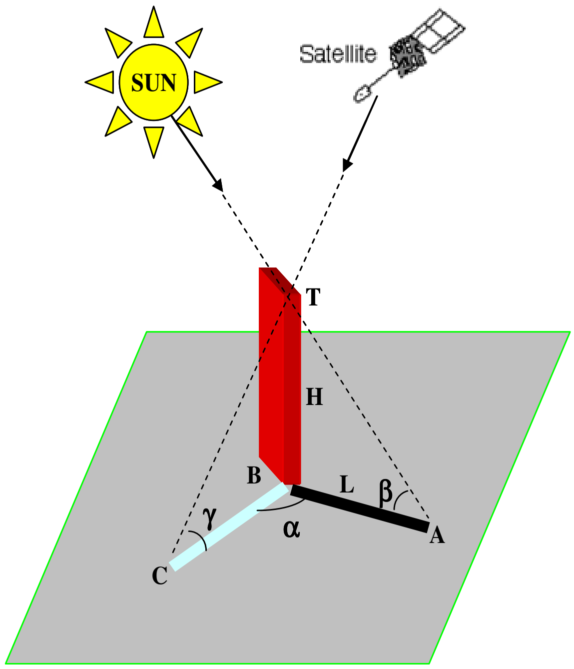


Figure 2. Geometry for Estimating Building Height

Although information on construction material and structure type may be still difficult to extract from remote sensing data, the geometric shape and height of a building can be directly or indirectly used to derive the primary building characteristics for earthquake damage analysis. The combination of building shape and height is used to determine not only the total area and the number of stories of a building, but also the distributions of typical structure type and year built band for buildings that fall in the same given **height** category and o**ccupancy** type in a sub-area based on the available existing building inventory database or construction statistics from local planning and construction departments. It is noted that the occupancy type of a building is an important parameter in earthquake loss analyses, especially for casualty and indirect economic loss assessments. The available existing building inventory database and the construction statistics for the local area should be considered for determining the occupancy type information.

## 4. VULNERABILITY CHARACTERISTIC DISTRIBUTIONS

It will be always difficult to get information on structure type, occupancy type, or year built of individual buildings directly from remote sensing data. To take the advantage of remote sensing information and image processing techniques for a better assessment of earthquake losses in large urban area, the available existing building inventory database and construction statistics from local design and construction departments have to be referred to determine a series of earthquake vulnerability characteristic distributions that reflect the compositions of typical loss analysis features of buildings in a given area. Those vulnerability characteristics normally include the distributions in terms of construction area by structure type, occupancy type, and year built band under various height categories such as low-rise (1-3 stories), mid-rise (4-7), high-rise (8-15), or super high-rise (15+). Tables 4.1 and 4.2 demonstrate the example distributions of occupancy type and structure type.

Table 4.1 Example Distribution of Occupancy Type by Height Category

| Height Category | Residential | Commercial / Office | Industrial | Public Facility | Sub-total |
|---|---|---|---|---|---|
| Low-Rise (1-3) | 40% | 25% | 25% | 10% | 100% |
| Mid-Rise (4-7) | 60% | 35% | 5% | 0 | 100% |
| High-Rise (8-15) | 50% | 50% | 0 | 0 | 100% |
| Super High (15+) | 20% | 80% | 0 | 0 | 100% |

Table 4.2 Example Distribution of Structure Type for A Specific Height Category

| Structure Type | Residential | Commercial/Office | Industrial | Public Facility |
|---|---|---|---|---|
| Masonry | 40% | 20% | 15% | 5% |
| Concrete | 50% | 60% | 55% | 80% |
| Steel | 5% | 15% | 30% | 15% |
| Others | 5% | 5% | 0 | 0 |
| Sub-total | 100% | 100% | 100% | 100% |

Once the earthquake vulnerability characteristic distributions of structure type, occupancy type, and year built band for a specific height category are created, the composite damage curve or DPM for such height category can be calculated by weighting the damage model from each individual representative structure type. The vulnerability characteristic distributions of those primary parameters may be determined in the following ways:

(a) For a region with an existing building inventory database available, those distributions can be derived from the existing database combined with the construction statistics from local planning, design, and construction departments for updating the contribution from new constructions.

(b) If an inventory database is not available, the construction statistics at various periods of time from local planning, design, and construction departments will be the major sources. If possible, a sample inspection of local buildings will be helpful to refine the statistic data.

(c) Collect expert opinions on those distributions from local architects, structural engineers, and planning personnel by making questionnaire. Sometimes, it is a more practical and reliable way to create those distributions.

Obviously, the uncertainty exists in determining building inventory information and earthquake vulnerability characteristic distributions from satellite remote sensing data. However, considering the great amount of uncertainties in earthquake prediction, seismic hazard analysis, and structural damage mechanism, the proposed methodology of updating building inventory database and vulnerability characteristic distributions is still in line with the accuracy of the traditional earthquake loss estimations. On the other hand, it is far more efficient and low in cost compared to traditional ways since it significantly reduces the human efforts on detailed building inspections and data collections. It will bring a significant impact to the traditional ways of generating building inventory database and vulnerability characteristics in earthquake loss estimations.

## 5. REMOTE SENSING DATA BASED EARTHQUAKE LOSS CALCULATION

In estimating earthquake losses based on satellite remote sensing data, the basic parameters are building location, height category, total construction area, and vulnerability characteristic distributions of occupancy type, structure type, and year built band for the given height category. The earthquake loss to a building of height category $H$ under a given ground motion intensity $I$ can be calculated based on the compositions of typical occupancy type, structure type, and built year band in the area where the building is located as follows:

$$Loss(H,I)=\sum_{Occ}\left(W_{Occ}(H)\times\sum_{Struct}\{W_{Struct}(H)\times\sum_{Year}[W_{Year}(H)\times Loss(Occ,Struct,Year,H,I)]\}\right) \tag{3}$$

where

| | | |
|---|---|---|
| $Occur$ | = | Occupancy type, |
| $Strict$ | = | Structure type, |
| $Year$ | = | Year built band, |
| $W(H)$ | = | Discrete value in vulnerability characteristic distributions of occupancy type, structure type, or year built band for height category $H$ (low-, mid-, high- or super high-rise). |

And the damage to building structure or contents inside, the numbers of casualties, injuries, and people in need of sheltering associated with the damage caused to the building of the specific occupancy type, structure type, year built, and height category for the given intensity ***Loss(Occur, Strict, Year, H, I)*** can be expressed in the following format by referring equations (1) and (2):

$$Loss(O,S,Y,H,I)_{Property}=Area\times Price(O,S,H)\times\sum_{i=1}^{5}[CDF_i\ (O,S,H)\times Prob_i(O,S,Y,H,I)] \tag{1a}$$

$$Loss(O,S,Y,H,I)_{Life}=Area\times Density(O)\times ProportionInside(O)\times\sum_{i=3}^{5}[LCDF_i\ (O,S,H)\times Prob_i(O,S,Y,H,I)] \tag{2a}$$

## 6. CASE STUDY: APPLICATION TO ZHANGZHOU CITY, FUJIAN, CHINA

In this section, the assessment of earthquake damage to buildings and contents and the impact to human life associated with the building damage in Zhangzhou City, Fujian, China is taken as an example to demonstrate the application of the proposed methodology.

### *6.1. Changes in Building Inventory Data*

During the Ninth and Tenth Five-Year Plan of China (1996-2000, 2001-2006), several projects related to the earthquake damage assessment and disaster mitigation strategies for the Zhangzhou area were carried out (IEM, 1999, Wei et al., 2005), which has benefited greatly to the establishment of the plans for urban construction developments, earthquake safety measures, and disaster mitigation programs for the local government. However, with the rapid economic development, the city of Zhangzhou has changed significantly not only in the original downtown area with the upgrade of old buildings and the addition of new buildings, but in the surrounding areas with large scale of expansion for residential and commercial facilities as well. A few economic development special zones were also developed in the outskirts of the old city area. The earthquake loss assessment and disaster mitigation strategies based on the building inventory data more than 10 years ago are obviously not consistent to the current city economic development scale. The building inventory database has to be updated and the vulnerability characteristics for new construction types also need to be considered in updating the earthquake loss results. However, it will take too much time and cost a lot to update the building inventory database with the traditional way of detailed building inspections. The sample inspection of 5%-10% buildings adopted previously may cause inaccuracy to the loss estimations. The proposed methodology provides an alternative for such task.

Based on the building data extracted from the satellite images of the Zhangzhou area taken in 2005, the building inventory database has been updated. Compared to the building data collected during the Ninth Five-Year Plan (IEM, 1999), the total construction area has increased from approximately 8 millions m$^2$ to 20 millions m$^2$. Figure 3 shows the changes of building distributions in part of Xinqiao District at the downtown area. It can be seen that some old low-rise buildings along the Jiulong River bank (near lower-left corner) have been upgraded while the mid- and high-rise buildings are still there. In addition, new buildings have filled in some open areas in the downtown area.

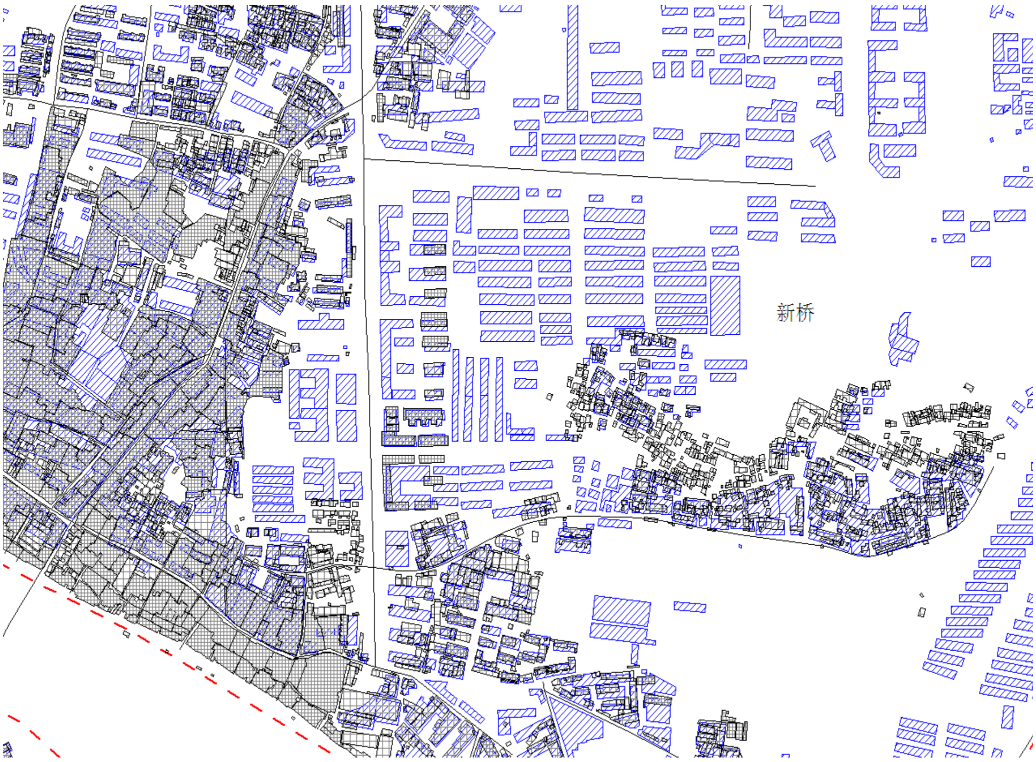


Figure 3. Comparison of Distributions of Old and New Buildings in Part of Xinqiao District, Zhangzhou (The darker area indicates the new or upgraded buildings.)

### *6.2. Statistics of Building Vulnerability Characteristics*

Based on the original building inventory data collected during the Ninth Five-Year Plan and the statistics from local planning and construction departments, the vulnerability characteristic distributions in terms of the proportion of construction area by height category, occupancy type, structure type, and year built band are determined as listed in Tables 6.1 to 6.3. Note that the data in Table 6.1 does not show a significant variation of structure type distribution with occupancy type in Zhangzhou.

Table 6.1 Distributions of Construction Area with Height and Structure Type in Zhangzhou

| Height Category | All Buildings | Reinforced Masonry | Reinforced Concrete | Sub-total |
|---|---|---|---|---|
| Low-Rise (1-3) | 42.5% | 89.2% | 10.8% | 100.0% |
| Mid-Rise (4-7) | 38.7% | 55.5% | 44.5% | 100.0% |
| High-Rise (8-15) | 17.3% | 0 | 100.0% | 100.0% |
| Super High (15+) | 1.5% | 0 | 100.0% | 100.0% |
| | 100.0% | | | |

Table 6.2 Distributions of Construction Area with Occupancy Type in Zhangzhou

| Height Category | Residential | Commercial/Office | Industrial | Public Facility | Sub-total |
|---|---|---|---|---|---|
| Low-Rise (1-3) | 68.1% | 13.5% | 15.3% | 3.1% | 100.0% |
| Mid-Rise (4-7) | 58.2% | 24.7% | 10.1% | 7.0% | 100.0% |
| High-Rise (8-15) | 26.1% | 58.9% | 10.9% | 4.1% | 100.0% |
| Super High (15+) | 2.0% | 88.5% | 0 | 9.5% | 100.0% |

Table 6.3 Distributions of Construction Area with Year Built in Zhangzhou

| Height Category | Pre-1965 | 1965 - 79 | 1980-90 | Post-1990 | Sub-total |
|---|---|---|---|---|---|
| Low-Rise (1-3) | 66.3% | 10.4% | 19.0% | 4.3% | 100.0% |
| Mid-Rise (4-7) | 3.9% | 9.2% | 52.3% | 34.6% | 100.0% |
| High-Rise (8-15) | 0.2% | 1.9% | 15.4% | 82.5% | 100.0% |
| Super High (15+) | 0 | 0 | 0 | 100.0% | 100.0% |

### *6.3. Assessment of Earthquake Losses*

The DPMs for various structure types developed during the Tenth Five-Year Plan (Wei et al., 2005) for the Zhangzhou area together with the building vulnerability characteristic distributions mentioned above are used in calculating the earthquake losses with the proposed methodology. Tables 6.4 and 6.5 summarize the direct economic losses from the damage to buildings and contents and the impact to human life associated with the building damage under several scenarios. The loss results are also generated at district level and block level. The new loss distributions from this study reflect the changes in building distributions captured by using the satellite remote sensing data.

Table 6.4 Property Losses at Various Levels of Intensity

| Intensity | Construction Area ($m^2$) | Direct Economic Loss (Million RMB) | | |
|---|---|---|---|---|
| | | Structure | Contents | Sub-total |
| VI | 19,924,761 | 170 | 45 | 215 |
| VII | | 1,015 | 445 | 1,459 |
| VIII | | 8,163 | 4,084 | 12,247 |
| IX | | 16,019 | 8,107 | 24,126 |
| X | | 23,021 | 12,298 | 35,319 |

Table 6.5 Impact to Human Life at Various Levels of Intensity

| Intensity | Earthquake during Night | | | Earthquake during Day | | |
|---|---|---|---|---|---|---|
| | Casualties | Injuries | In Need of Shelter | Casualties | Injuries | In Need of Shelter |
| VI | 0 | 2 | 0 | 0 | 2 | 0 |
| VII | 13 | 72 | 40,039 | 12 | 67 | 40,040 |
| VIII | 1,850 | 4,408 | 203,767 | 974 | 4,098 | 204,642 |
| IX | 5,974 | 13,065 | 297,665 | 3,084 | 12,593 | 300,555 |
| X | 11,152 | 23,549 | 330,358 | 5,813 | 23,442 | 335,697 |

Compared to previous studies for the Zhangzhou area (IEM, 1999; Wei et al., 2005), the total construction area in the updated building inventory database increases 2.5 times and the damage to buildings and contents increases by 5 to 8 times under severe earthquakes impact. The new earthquake loss assessment shows the necessity of updating the earthquake safety measures and disaster mitigation plans in consistence with the new scale of the city development in Zhangzhou.

## 7. CONCLUSIONS

The upgrade of building inventory database using remote sensing information and the calculation of earthquake losses associated with remote sensing data in Zhangzhou demonstrates the feasibility of using remote sensing information to rapidly assess earthquake losses in urban areas at relatively low cost. The proposed methodology outlines the detailed procedure of the loss calculation associated with remote sensing data by introducing regional earthquake vulnerability characteristic distributions or a composite vulnerability model. It constructs the base for the application of remote sensing information in urban earthquake loss assessment. It makes the dynamic earthquake loss assessment possible even in fast developing areas.

The wide application of the proposed rapid earthquake loss assessment methodology in China will significantly increase the efficiency and reduce the cost at the same time for local governments to perform the urban earthquake loss assessment and disaster mitigation planning.

The proposed method can also be used to rapidly report the loss distributions for a real earthquake by incorporating the real-time ground motion distribution estimate through digital earthquake observation networks (Jin et al., 2006) into the latest building inventory database updated from remote sensing information.

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