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Isointensity-isoexposure concept for seismic vulnerability analysis — A case study of the 1999 Chi-Chi, Taiwan earthquake

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ABSTRACT

Fragility curves can be developed using analytical or empirical methods. When the actual building damage records and the associated ground motion data are available, empirical methods are often adopted. Traditionally, *district-based* records of building damage are analyzed for developing such fragility curves. In this paper, a new procedure based on the concept of "*isointensity-isoexposure*" is developed. The new procedure is demonstrated through a case study of the building damage records collected from the 1999 Chi-Chi, Taiwan earthquake. The results show that the fragility curves developed with the proposed procedure are more in-line with observations than with the traditional district-based procedure. The developed fragility model may be used for earthquake loss estimation and future emergency planning in the study area. The limitations of the proposed approach include: (1) the developed fragility curves are area-specific and may not be readily applicable to other regions, and (2) ground motion intensity data may not be available at every location in an area of interest.

1. Introduction

Fragility curves provide estimates of the probabilities of a population of structures that reach or exceed various limit states at given levels of ground shaking. The building fragility curve is generally presented in a graph of damage probability at a specified damage level versus ground motion parameters such as peak ground acceleration (Onose, 1982; Hwang and Huo, 1997; Mosalam et al., 1997; Singhal and Kiremidjian, 1997; Lupoi et al., 2004; Choi et al., 2007; Rota et al., 2008), peak ground velocity (Miyakoshi et al., 1998; Yamazaki and Murao, 2000; Akkar et al., 2005), spectral acceleration (Hwang and Huo, 1997; Singhal and Kiremidjian, 1997; Park et al., 2009), spectral displacement (Rossetto and Elnashai, 2003; Colombi et al., 2008), and parameter-less scale of intensity (Spence et al., 1992; Orsini, 1999). The fragility curve is essential for the task of seismic risk analysis and earthquake loss estimation (Bommer et al., 2002). The fragility curve is often established with analytical or empirical methods. The former relies on structural analysis of prototype or model buildings subjected to scenario earthquakes. Many investigators have contributed to the development of this analytical approach (e.g., Mosalam et al., 1997; Singhal and Kiremidjian, 1997; Cornell et al., 2002; Lang, 2002; Masi, 2003; Barbat et al., 2008; Borzi et al., 2008; Erberik, 2008; Park et al., 2009). The main advantage of this approach is the ease of conducting parametric/sensitivity analyses. Because of the complexity of the interaction of many factors that affect the damage potential of buildings in a seismic event, such as building type and material, construction quality, geographical conditions, geological and soils conditions, and maintenance conditions, and so on, the analytical approach often has its limitations. The empirical approach, on the other hand, relies on building damage records obtained from post-event field investigations (Yamaguchi and Yamazaki, 2000; Yamazaki and Murao, 2000; Lee et al., 2003; Rota et al., 2008; Spence et al., 2008; Jaiswal et al., 2011). The empirical fragility curve, which reflects the *overall* earthquake-resisting capability of buildings in a locality, can be a useful tool for planning and design for a future event, and provide a basis for calibration of the analytical/theoretical models. Of course, the fragility curves developed with an empirical approach are area-specific and may not be readily applicable to other regions. The applicability of the empirical approach is also limited by the availability of ground motion intensity data in an area of interest.

The fragility curves may also be developed using the judgment-based rating methods (e.g., Casciati et al., 1994; Grant et al., 2007; Cole et al., 2008; Gent Franch et al., 2008). This approach involves the use of the opinions of experts with experience in earthquake engineering who are asked to make estimates of the likely damage distribution within building populations when subjected to earthquakes of different intensities. In recent years, hybrid approach has

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also been proposed, which attempts to compensate for the scarcity of observational data, subjectivity of judgmental data, and modeling deficiencies of analytical methods by combining data from different sources (e.g., Penelis et al., 2003; Kappos et al., 2006; Kappos and Panagopoulos, 2010).

In this paper, the focus is on the empirical approach taking advantage of the damage data from the 1999 Chi-Chi, Taiwan Earthquake. In an empirical approach, building damage records are traditionally compiled and analyzed on a district-by-district basis (Miyakoshi et al., 1998; Tsai et al., 2001; Spence et al., 2003; Wu et al., 2003). However, the vulnerability data established from the district-based records is often scattered and the fragility curve developed based on such data may not be representative. In this paper, the concept of "*isointensity-isoexposure*" is developed for processing building damage records and developing fragility curves. A new procedure based on this concept is then established and illustrated through a case study of the 1999 Chi-Chi, Taiwan Earthquake. A comparison of this new approach with the district-based approach is then made.

The concept of "*isointensity-isoexposure*" might be applicable to other areas or regions, although the developed fragility curve (i.e., empirical equation for damage rate) is "area-specific," which reflects the combined characteristics of seismicity, building type and material, construction quality, aging and maintenance conditions, geographical conditions, geological and soils conditions in the study area. The developed fragility model may be used for earthquake loss estimation and emergency planning in the study area.

It should be noted that a single parameter such as *PGA* cannot represent completely an entire function of time. *PGA* is an inadequate parameter for characterizing ground motion (Swell, 1989) and correlates weakly with both observed and theoretically computed structural damages (Kafali and Grigoriu, 2007). More advanced ground motion intensity measures have been reported and should be considered whenever feasible (Baker, 2007; Tothong and Luco, 2007). Nevertheless, *PGA* is a convenient design ground motion parameter, and the focus of this paper is to establish and validate the concept of "*isointensity-isoexposure*" and *PGA* is used as an example to demonstrate this concept and its advantages over the district-based fragility curves. Based on the results presented in this paper, *PGA* can be an effective parameter when it is used within the framework of the proposed *isointensity-isoexposure* approach.

2. Data collection

The Chi-Chi Earthquake ($M_L = 7.3$ or $M_w = 7.6$) struck the island of Taiwan on September 21, 1999 at 1:47 am local time (Shin and Teng, 2001). This earthquake caused a death toll of 2492 (Hsiao et al., 2001a; Tien et al., 2002; Pai et al., 2007). There were 51,778 totally collapsed buildings and 53,852 partially collapsed buildings in this event. After the event, experts and scholars are mobilized by the Ministry of Interior to investigate the casualties and damages to buildings, bridges and other infrastructures. The data used in this paper are buildings damage records (Hsiao et al., 2001b) in the Chi-Chi Earthquake, and the recorded earthquake ground motion parameters.

2.1. Ground motion parameters in the Chi-Chi event

Prior to the Chi-Chi event, the Taiwan Strong Motion Instrumentation Program was fully implemented by the Central Weather Bureau (CWB), Taiwan. There were 650 free-field seismograph stations, covered almost all population centers and known faults and free-fields with various geological conditions (Central Weather Bureau, Taiwan, 1999; Shin and Teng, 2001; Wen et al., 2001; Wu et al., 2003). The strong motion data used in this study is obtained from 384 seismic stations that recorded the main event in the Chi-Chi Earthquake (Pai, 2006). The locations of these seismic stations and the Chelungpu Fault, which was the source of this event, are shown in Fig. 1.

2.2. Building damage categories

In the post Chi-Chi Earthquake investigation, the building damage was grouped into two categories, totally collapsed (TC) and partially collapsed (PC), based on the criteria set by the Ministry of Interior, Taiwan. Buildings that were totally collapsed or buried by landslide, and those with excessive titling and severe cracking beyond repair are included in the TC category. Buildings that suffered damage that must be repaired to make them habitable are included in the PC category (Hsiao et al., 2001b).

For convenience of the subsequent fragility curve analysis, the number of "*damaged*" buildings (N_D) is defined as:

$$N_D = N_{TC} + N_{PC} \tag{1}$$

where N_{TC} and N_{PC} are number of totally collapsed buildings and number of partially collapsed buildings, respectively.

Next, the damage rate (D) is defined as:

$$D(\%) = \frac{N_D}{N} \times 100 = \frac{N_{TC} + N_{PC}}{N} \times 100 \tag{2}$$

where N is the total number of buildings in the study area.

2.3. Database of building damage in the Chi-Chi event

The database of building damage in the Chi-Chi event was published by the Architecture and Building Research Institute (ABRI), Ministry of the Interior, Taiwan (Hsiao et al., 2001b). This database includes address (location), building type and footprint area, building age and usage and building damage description (TC or PC). Table 1 shows a summary of district-based building damage statistics in Nantou and Taichung counties, Taiwan, which were the most severely damaged region in the Chi-Chi earthquake. Fig. 2 shows the locations of these districts in Central Taiwan. It should be noted that the *PGA* value listed for a given district is not exactly uniform across the entire district. Furthermore, the geological and soil conditions of the deposits can also affect the damage rate, and so do the building type and quality of construction (e.g., some districts have almost exclusively reinforced concrete and steel structure buildings that are more earthquake resistant).

3. District-based vulnerability analysis

Traditionally, the vulnerability data was derived from building damage records by district. The district-based vulnerability data is easier to compile since the disaster response and emergency management is usually carried out through districts. The population in a given district is often up-to-date and district-based damage records after an earthquake are readily available through emergency response and management agencies. It is generally convenient to develop the fragility curves using the district-based building damage data.

As an example, Table 1 shows the building "population" of each district (in terms of "township" in the study area) along with the number of partially collapsed (PC) buildings and the number of totally collapsed (TC) buildings and the overall damage rate (D). The data are compiled based on those acquired by the government emergency response and management agencies shortly after the 1999 Chi-Chi Earthquake. Although the district-based vulnerability data are easy to compile, large scatter often exists in these data because of the variation in the building population from district to district and the variation in the ground shaking level within a given district. This observation is elaborated later in this paper.