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Study on the Cumulative Damage Effect Induced by Aftershocks for RC Structures

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Abstract: The main purpose of this work is to develop an estimation procedure for resilience-based seismic design level for RC bridge piers considering aftershock-induced seismic hazards. This work builds a simulation method of the seismic hazards induced by aftershocks and takes an example of the Chi-Chi Earthquake in Taiwan. The number of aftershocks is assumed to follow the modified Gutenberg-Richter law with lower and upper bounds when analyzing the cumulative density function of the magnitude of the aftershock within a specified post-mainshock period for the earthquake. Additionally, this work considers the spatial uncertainty in the hypocenters of aftershocks to assess the aftershock-induced seismic hazards. Fragility curves and residual factors of damaged RC piers are used in the transition probability matrix of Markov Chain model for considering the cumulative damage induced by aftershocks By incorporating uncertainty into aftershock events, as well as into structural capacity and residual factors corresponding to a specified damage state, the exceedance probabilities for different damage states can be estimated using Markov Chain and Monte Carlo Simulation.

Keywords: **Markov Chain, Cumulative damage, Residual factor, Aftershock, Seismic hazard, Reinforced concrete, Pier**

1. General

The mainshock of an earthquake is generally followed by a number of aftershocks (usually smaller in magnitude) occurring in a limited area (i.e., the aftershock zone) around the epicenter of the mainshock. This sequence of aftershock events can last for months. Although these events are smaller in magnitude than the mainshock, they can still be destructive. The residual seismic capacity of a structure following a large earthquake is calculated according to the mainshock-induced damage levels. Additionally, post-mainshock deterioration of a structure owing to a sequence of aftershocks may be an obstacle to re-occupancy. That is, a well-constructed civil structure, which meets the seismic design code, may still be damaged by sequent ground motions because design objectives allow for acceptable damage under the mainshock of an earthquake. Therefore, the major concerns in the post-earthquake period are the serviceability and safety of damaged structures. Selecting the appropriate maintenance actions for damaged structures in the post-earthquake period is an important topic. Since a structure with serious post-earthquake damage requires the seismic retrofit, recovering its function quickly is not easy. For improving the resilience of a post-earthquake damaged structure, the seismic design level of a structure can be upgraded to protect it from serious damage or collapse under the sequent ground motions, including the mainshock and aftershocks of an earthquake. Therefore, for a structure, in addition to the minimum requirement of a specified seismic design code, its seismic design level should be upgraded appropriately according to the post-earthquake resilience.

This work proposes an estimation procedure for a resilience-based seismic design level for RC piers considering aftershock-induced seismic hazards. This work initially constructs an approach for analyzing the seismic hazards induced by aftershocks for the Chi-Chi Earthquake in Taiwan. The number of aftershocks is assumed to follow the modified Gutenberg-Richter law with lower and upper bounds when analyzing the cumulative density function (CDF) of the magnitude of the aftershock within a specified post-mainshock period for the earthquake. Additionally, this work addresses the spatial uncertainty in the hypocenters of aftershocks to assess the aftershock-induced seismic hazards within specified weeks following the mainshock. The transition probability matrix of the Markov Chain model for estimating the occurrence probability of a specified damage state utilizes fragility curves and residual factors of damaged RC piers to calculate the cumulative damage induced by aftershocks in the proposed estimation procedure for the resilience-based seismic design level. By incorporating uncertainty into aftershock events, as well as into structural capacity and residual factors, the exceedance probabilities for various damage states can be estimated using Markov Chain model and Monte Carlo Simulation (MCS). Finally, for the Chi-Chi Earthquake, the proposed procedure for determining the seismic design level is then applied to a case study of typical RC piers in Taiwan to demonstrate its applicability.

2. Cumulative damage assessment for RC piers considering aftershock-induced seismic hazards

An integral simulation procedure based on the Markov Chain model is utilized to acquire the post-earthquake reliability of resilience, which is related to an acceptable limit state for an RC structure in seismically active zones. The post-earthquake reliability of resilience demonstrates the influence of cumulative damage associated with aftershocks. That is, the simulated reliability function data can improve resource allocation and asset management.

The Markov Chain model is a stochastic process, a mathematical model for a system or an element with random outcomes. These outcomes are regarded as a function of an independent variable such as a temporal or spatial factor. For a discrete parameter Markov Chain model, the transitional probability from state i at time t_m to state j at time t_n is derived by Eq. (1). The Markov Chain model is homogeneous when $p_{i,j}(m,n)$ depends only on the difference between t_n and t_m. Equation (2) derives the k-step transition probability function. Additionally, a transition probability matrix can be created by summing the transition probabilities for a system with m states, as in Eq. (3).

$$p_{i,j}(m,n) = P\left(X_n = j \middle| X_m = i\right); n > m \quad (1)$$

$$p_{i,j}(k) = P\left(X_k = j \middle| X_0 = i\right) = P\left(X_{k+s} = j \middle| X_s = j\right); s \geq 0 \quad (2)$$

$$P_T = \begin{pmatrix} p_{1,1} & \cdots & p_{1,m} \\ \vdots & \ddots & \vdots \\ p_{m,1} & \cdots & p_{m,n} \end{pmatrix} \quad (3)$$

The probabilities of the initial states of a system can be listed in a row matrix, as in Eq. (4). The n- stages state probabilities can be expressed in matrix notation by Eq. (5).

$$P(0) = \left[p_1(0), p_2(0), \ldots, p_m(0)\right] \quad (4)$$

$$P(n) = p(0)\, p_T^n \quad (5)$$

where $p_i(0)$ is the probability that a system is initially in state i. In the special case for which the initial state of a system is known, such as at state i, then $p_i(0)$ = 1.0 and all other elements in the row matrix, $P(0)$, are zero.

In the homogeneous Markov Chain model, the transition probabilities depend only on current states, not on time. However, this is an assumption and it is questionable for a structure, because the seismic hazard of aftershocks varies over time. Therefore, to forecast post-earthquake seismic reliability for a structure while considering the seismic hazard of aftershocks, this work utilizes the non-homogeneous Markov Chain model. That is, the transition probability matrix, P_T, varies over time, and can be a specific period after the mainshock of an earthquake.

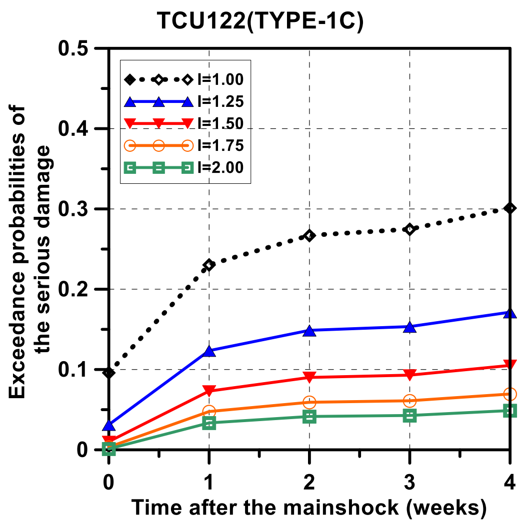
To construct a transition probability matrix for an RC pier, the pier is assumed to have already been damaged by a ground motion of an earthquake to a specific damage state. This workestimates the exceedance probability for a specified damage state j from a specified damage state i within the k^{th} week after the mainshock, p_{ij}^k, using MCS (Eq. (6)) by incorporating uncertainty into aftershock events, structural capacity and residual factors corresponding to a specified damage state. In Eq. (6), Z_{ci} denotes the seismic capacity of an RC pier in damage state i. The transition probability matrix, P_T, can be constructed by following the same evaluation procedure. Additionally, the occurrence probability of each damage state when repair work is not performed after the mainshock and aftershocks can be estimated using the Markov Chain model.

$$p_{ij}^k = \int \left\{\left[\int_0^\infty P_j^{frag}(a, Z_{ci}) \times f_k^{hazard}(a)da\right] \times f_{ci}^{damage}(Z_{ci})\right\} dZ_{ci} \quad (6)$$

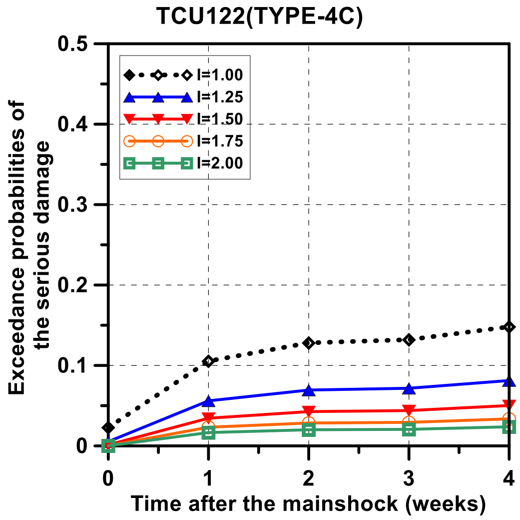
Generally, when the damage state of an RC pier reaches damage level IV, the seismic capacity decreases significantly and should be repaired or retrofitted as soon as possible. That is, the damaged structure should not continue to be used without any repair or retrofit. Additionally, according to the definition of the damage state, crushing of concrete with exposed reinforcing bars and spalling of cover concrete may appear in an RC pier with damage level IV (serious damage). Since an RC pier with damage level IV requires the seismic retrofit, its transportation function is not easy to recover in a limited period. Therefore, based on the resilience of a post-earthquake damaged structure, this work focuses on the non-exceedance probability of damage level IV, which is defined as the resilience reliability. That is, an appropriate seismic design level can be utilized to improve the reliability of resilience under sequent motions including the mainshock and aftershocks of an earthquake.

3. Case study

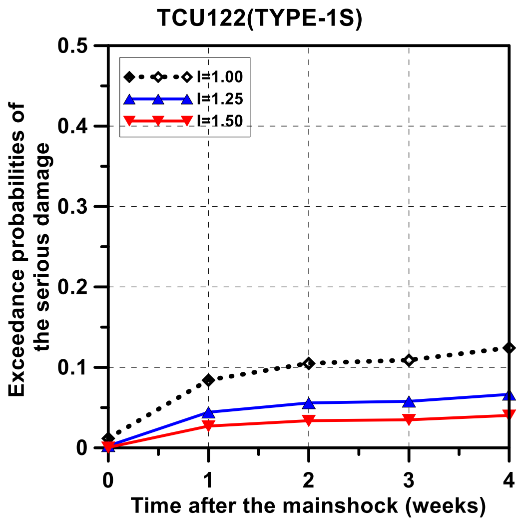
The previous research (NCREE, 2009) recommends utilizing fragility curves of various bridge systems in Taiwan for seismic risk analysis. Additionally, bridges in Taiwan are designed by determining the longitudinal and lateral reinforcements according to the AASHTO (American Association of State Highway and Transportation Officials, ASSHTO) Standard Specifications for Highway Bridges and MOI (2005). To investigate the effect of aftershocks on the seismic design of bridge systems, this the case study assumes six seismic design levels, given by I=1.0, 1.25, 1.5, 1.75, 2.0, 2.5 (I is an important factor that can be used to upgrade the seismic design level), for the selected bridges. For a specified RC pier with TYPE-1C, if the acceptable value of the reliability is set at 0.1, then the appropriate important factors for the location of TCU122 can be calculated as 1.75. However, if an important factor for an RC pier exceeds 1.5, then its corresponding seismic design is not easy to accomplish. Therefore, various structural systems, namely TYPE-1S, TYPE-4C and TYPE-4S, were investigated to determine the appropriate important factors. Simulation results demonstrate that if the structural system is changed to TYPE-4C, then the appropriate important factors for the location of TCU122 can be reduced to 1.25. Additionally, the appropriate important factor for an RC pier with TYPE-4S in location TCU122 can be set as 1.0.



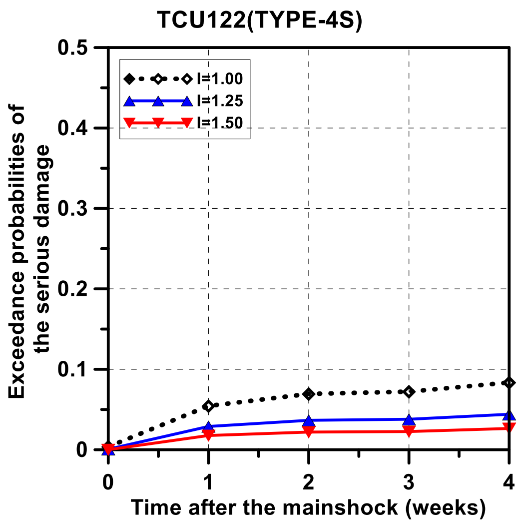
(a) TYPE-1C



(b) TYPE-4C



(c) TYPE-1S



(d) TYPE-4S

Figure 1 Probability of exceeding the serious damage state for each selected RC piers in TCU122.

4. Conclusion

In the post-earthquake, since a structure with serious damage requires the seismic retrofit, recovering its function quickly is not easy in a limited period. Accordingly, the corresponding social cost could be larger than the expected value. Therefore, based on the seismic resilience of a key facility structure, it is necessary that the seismic design level of a structure can be upgraded to protect it from serious damage or collapse under the sequent ground motions, including the mainshock and aftershocks of an earthquake. Therefore, for a structure, in addition to the minimum requirement of a specified seismic design code, its seismic design level should be upgraded appropriately according to the seismic resilience. This work proposes an estimation procedure for a resilience-based seismic design level for RC piers considering aftershock-induced seismic hazards. Taking an example of the Chi-Chi Earthquake in this work, according to the analytical results, an important factor and structural system can be utilized to improve the post-earthquake resilience reliability.

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