Seismic-sequence damage to buildings in Japan and Iran
(Project No.2023LS-01)

Disaster Prevention Research Institute (DPRI), Kyoto University, Kyoto, Japan

Principal Investigator: Mahnoosh BIGLARI, Dr. Eng., Associate Professor, Department of Civil Engineering, School of Engineering, Razi University, Kermanshah, Iran
ORCID: 0000-0002-1245-7740

DPRI Contact Person: Yoshiki IKEDA, Dr. Eng., Professor, Disaster Prevention Research Institute, Kyoto University, Kyoto, Japan
ORCID: 0000-0002-8581-3806

Collaborative Professor: Hiroshi KAWASE, Dr. Eng., Professor, Disaster Prevention Research Institute, Kyoto University, Kyoto, Japan
ORCID: 0000-0001-8370-1707

Seismic-sequence damage to buildings in Japan and Iran

Summary

Purpose

Due to complex fault systems worldwide, successive ruptures in the seismic layer cause numerous aftershocks, leading to sequential earthquakes. Some earthquakes occur in a short interval and can have an amplitude equal to or greater than the first shock, resulting in twin earthquakes. The impact of sequential earthquakes on structures cannot be ignored. This study investigates the impact of sequential earthquakes on seismic fragility curves of 3-, 6-, and 9-story reinforced concrete buildings constructed before and after 1982 in Japan. The research proposes analytical fragility curves based on dynamic nonlinear multi-degree-of-freedom analyses under the influence of single and sequential shock of recorded motions of six destructive earthquakes in Japan.

Research Progress

The fragility curves are developed for both single shock and sequential shocks. A multi-degree-of-freedom nonlinear dynamic analysis was conducted using the Newmark-beta method with a degrading tri-linear hysteresis-type spring to determine the probability of damage ratio in fragility curves. The study analyzed each building's response to 420 single shock records and 420 sequential shock records collected from the K-NET and KiK-net databases for the six major earthquakes in Japan during the last century. The analysis is conducted for buildings built before and after 1982 in Japan. All the records were modified and merged to produce sequential records with 30-second intervals. The probability of heavy damage or collapse was plotted with the log-normal PGA distribution for the results of the defined damage ratio for both the single first shock and the sequential shocks.

Research Findings

The study found that the probability of damage to buildings was higher when sequential records were examined compared to examining a single record. Although damage to new buildings decreases, the likelihood of damage and the number of collapsed buildings increases as the height of buildings increases. The increase in the probability of damage resulting in sequential earthquakes follows a Gaussian function. The best agreement is established with the results of old 3-story buildings, and the weakest agreement is seen for old 9-story buildings due to the asymmetry of the results. Finally, the best regression model for estimating the probability of damage due to sequential earthquakes will be presented to help correct the fragility curves of a single shock.

Publications of Research Findings

The research article entitled "Fragility curves of sequential earthquakes for RC buildings in Japan" was accepted and will be published in *Bulletin of Earthquake Engineering,* accepted for publication

Introduction

Buildings in areas prone to earthquakes are susceptible to accumulative damage from sequential shocks, a phenomenon that remains largely unexplored in construction engineering. This study, therefore, represents a significant advancement in our understanding of these effects, providing crucial knowledge to tackle the challenges of accumulative damage.

Due to complex fault systems worldwide, successive ruptures in the seismic layer cause numerous aftershocks, leading to sequential earthquakes. Some earthquakes occur in a short interval and can have an amplitude equal to or greater than the first shock, resulting in twin earthquakes. The impact of sequential earthquakes on structures cannot be ignored.

Seismic fragility curves are useful tools for estimating the likelihood of different damage levels based on the strong ground motion parameters for specific types of structures. These curves are often presented for undamaged structures during the main seismic shock. However, it is unrealistic to assume that the buildings are only affected by the mainshock or that they are immediately renovated or retrofitted. Therefore, our research findings have direct and practical implications for the vulnerability assessment of buildings in earthquake-prone areas, underscoring the relevance and importance of our work.

The study examines how sequential earthquakes affect the seismic fragility curves of 3-, 6-, and 9-story reinforced concrete buildings in Japan, both those built before and after 1982. The research proposes analytical fragility curves based on dynamic nonlinear multi-degree-of-freedom analyses under the influence of single and sequential shocks from six destructive earthquakes in Japan.

Input Ground Motions

The selected earthquakes include the 2004 Mid Niigata Prefecture earthquake (Mj 6.8), the 2008 Iwate–Miyagi Nairiku earthquake (Mj 7.2), the 2011 Fukushima-Hamadori earthquake (Mj 7.0), the 2016 Kumamoto earthquake (Mj 6.5), the 2018 Hokkaido Eastern Iburi earthquake (Mj 6.7) and the 2021 Fukushima-ken Oki earthquake (Mj 7.3). The study uses a strong-motion database constructed from the K-NET and KiK-net strong-motion seismograph networks (NIED, 2019) to incorporate real seismic records with various peak ground accelerations (PGAs) and different frequency content. This eliminates the need to scale the records in the classical incremental dynamic analysis method. Eight hundred forty accelerograms in two horizontal directions were selected from various affected stations. For each selected station and earthquake event, a first shock and several sequential shocks were chosen.

Dynamic response analysis

The analysis utilized a nonlinear dynamic analysis code by material properties introduced by Nagato and Kawase (2001). The plan's impact and structural element details are incorporated into the structural parameters, utilizing the characteristics of a nonlinear spring with degrading trilinear hysteresis. The damage ratio is the weighted ratio of cases where the drift angle exceeds the damage criterion. Nagato and Kawase (2001) determined the parameters for these structures, considering the revision of the Japanese building standard code for buildings constructed before 1982 (referred to as "old") and after 1982 (referred to as "new"). If the drift angle of even one story exceeds 1/30 radians, the damage is classified as heavy damage or collapse.

Seismic fragility curves

Seismic fragility curves are proposed based on the assumption that the likelihood of heavy damage or collapse follows a log-normal distribution when a specific peak ground acceleration (PGA) is exceeded. The standard normal distribution function analyses the damage ratios obtained from nonlinear dynamic analysis conducted on various processed ground motion records with known corresponding PGA values. Therefore, the probability of damage under the condition of exceeding PGA, $P(D \mid PGA)$, can be expressed by Equation 1.

$$P(D|PGA) = \Phi\left[\frac{1}{\beta}\{\ln(PGA) - \mu\}\right] \tag{1}$$

where, Φ represents the standard normal cumulative distribution function, β is the weighted standard deviation of the natural logarithm of PGA of the damage state, and μ is the weighted median value of the natural logarithm of PGA of the damage state.

By determining the mean value and standard deviation for each type of structure, the probability of collapse can be determined by substituting a wide range of arbitrary PGA values. Biglari et al. (2024) presents the β and μ values for the seismic fragility curves of old and new Japanese RC buildings, ranging from 3 to 9 stories, as analyzed through nonlinear dynamic analysis for both the first shock and sequential shocks.

Figures 1(a), 1(b), and 1(c) illustrate the seismic fragility curves for 3-, 6-, and 9-story old buildings, respectively. The solid lines represent the proposed fragility curves of the first shocks, while the dashed lines indicate the proposed fragility curves for sequential shocks. The spots show the buildings' average damage ratio of 12 resistance modes. Similarly, Figures 2(a), 2(b), and 2(c) display the seismic fragility curves and their corresponding average damage ratio data for new buildings.

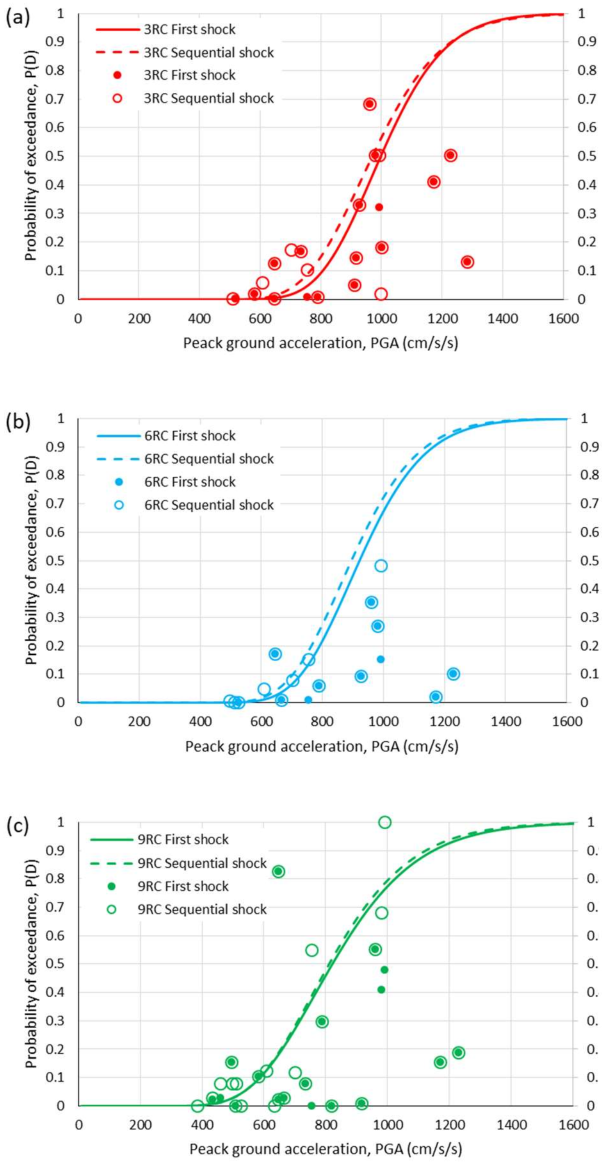

Figure 1. Fragility curves of old RC buildings for heavy damage or collapse for first shock and sequential shocks for (a) 3-story (b) 6-story (c) 9-story

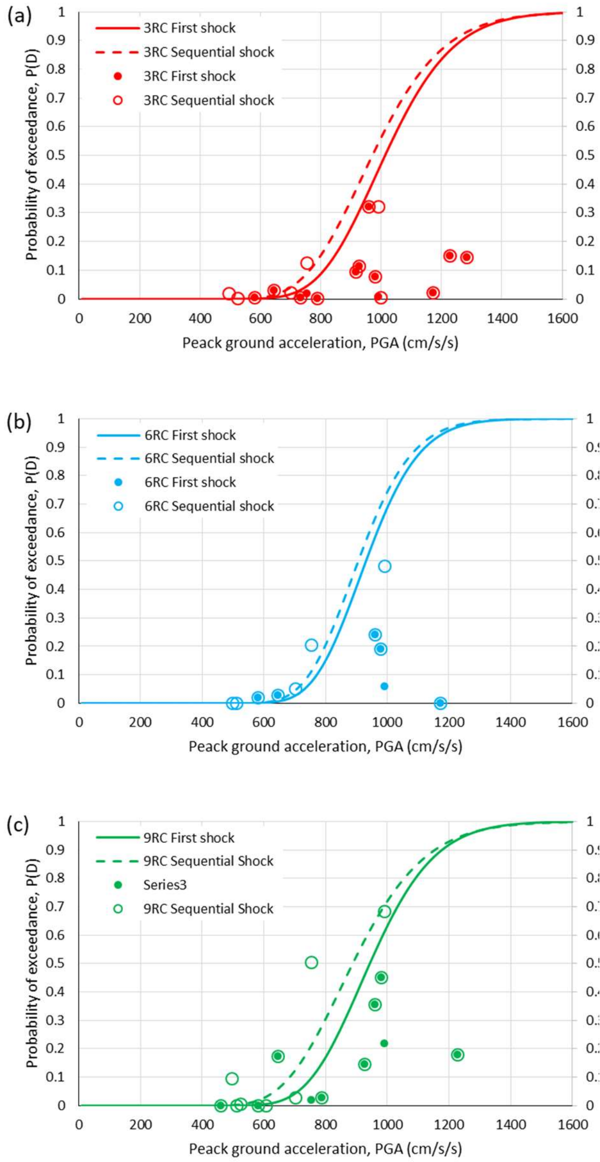

Figure 2. Fragility curves of new RC buildings for heavy damage or collapse for first shock and sequential shocks for (a) 3-story (b) 6-story (c) 9-story

Predictive sequential regression models

The results demonstrate that the seismic sequence raises the probability of damage ratio. This increase in the fragility curve follows a Gaussian function.

Based on the research, it has been established that the Gaussian function, represented by Equation 2, is the best-fitted function.

$$P\left(D_{sequential\ shock-first\ shock}\right) = a\exp\left(-\frac{1}{2}\left(\frac{PGA-b}{c}\right)^{2}\right) \qquad (2)$$

where, $P(D_{sequential\ shock\text{-}first\ shock})$ is the difference in probability ratio of damage caused by sequential and first shock records, PGA is the desired peak ground acceleration, and a, b, and c are the correlation parameters. Biglari et al. (2024) provide the parameters and coefficient of determination (R^2) for each model in the Gaussian regression model. If sequential fragility curves are unavailable, the introduced regression models can be used to estimate them on single shock fragility curves.

Conclusion

The study revealed that the likelihood of damage to buildings was higher when sequential records were examined compared to examining a single record. Although damage to new buildings decreases, the likelihood of damage and the number of collapsed buildings increases as the height of buildings increases. On average, sequential shocks result in a 15% higher damage ratio exceedance probability compared to a single event at the median value of PGA. The increase in the probability of damage resulting in sequential earthquakes follows a Gaussian function. The best agreement is established with the results of old 3-story buildings, and the weakest agreement is seen for old 9-story buildings due to the asymmetry of the results. Finally, the study presents the best regression model for estimating the probability of damage from sequential earthquakes to help adjust the fragility curves from a single earthquake.

References

Biglari M, Ikeda Y, Kawase H (2024) Fragility curves of sequential earthquakes for RC buildings in Japan, *Bulletin of Earthquake Engineering*, https://doi.org/10.1007/s10518-024-01949-2

Nagato K, Kawase H (2001) Damage evaluation models of reinforced concrete buildings based on the building damage statistics and simulated strong motions, *Journal of Structural and Construction Engineering* (*Transactions of AIJ*), Issue 544, pp.31–37 (in Japanese with English abstract). https://doi.org/10.3130/aijs.66.31_5

National Research Institute for Earth Science and Disaster Resilience, NIED K-NET, KiK-net, *National Research Institute for Earth Science and Disaster Resilience* 2019, https://doi.org/10.17598/NIED.0004