

A Review on the Selection of Real and Artificial Seismic Sequences for Analysis

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Abstract

A huge mainshock activates several aftershocks, divulging the public to serious risk and impeding building repair, rehabilitation, and restoration works. The performance of a structure during multiple earthquakes depends on structural properties and the characteristics of ground motion. Hence, the selection of seismic sequence plays a vital role in the analysis. Presumption of spatial and temporal characteristics of aftershocks is needed for the identification of these repeated motions. This paper further looks into statistical variability connected with aftershock sequences. A critical review of different real and artificial seismic sequences taken for the analysis is carried out. A few studies reveal that a strong motion database for procuring actual mainshock aftershock sequences could underrate the aftershock effects as the database is inadequate and imperfect. It is also observed that artificial sequences can take the place of real sequences especially when an ample data set of real mainshock aftershock sequences are not accessible.

Keywords: Earthquake, Real sequence, Artificial sequence, Scaling Laws.

1. Introduction

The behaviour of a structure in the course of an earthquake relies on the structural properties (mass, geometric configuration, natural frequencies, damping, and ductility) and the characteristics of an earthquake (magnitude, duration, peak ground acceleration, peak ground velocity, peak ground displacement, frequency content, amplitude, epicentral distance and fault properties). Notable field cases revealing the incidence of shock sequences represented by an earthquake with moderate magnitude succeeded by aftershocks with equivalent or even larger magnitude may happen in numerous disaster susceptible regions worldwide. These give rise to momentous menace to public life, disturb rescue and restoration activities, and also add damage to buildings. This accumulation of damage relies on the type of hysteretic structural behaviour and the features of the seismic shocks. The history of seismic sequences is marked with an earthquake striking Umbria–Marche, Italy in 1997. Based on the tectonical viewpoint, consecutive aftershocks appear as a result of increased regional stress contributed by the mainshock [4]. Hence, the occurrence of seismic sequences denotes an actual situation that necessitates special care in earthquake design. Recognition of these seismic sequences is typically a difficult problem as it involves assumptions on the spatial and temporal clustering of aftershocks. Another problem is regarding the connection between the mainshock magnitude, which started the aftershock sequence, and the aftershock magnitude. The sequence of foreshocks, mainshock, and aftershocks take place over a comparatively short period. In this paper, a review on the selection of real

and artificial seismic sequences for analysis is carried out. This is vital as ambiguities allied with input seismic motions tend to have more momentous effects on the susceptibility of structures than structural capacity-related parameters.

2. Real Time Forecasting Tools

Parametric studies of seismic sequences are associated with three empirical scaling laws: (a) Gutenberg-Richter frequency magnitude scaling law, (b) Bath's law (c) Omori's law [4][31].

2.1 Gutenberg-Richter Frequency Magnitude Scaling Law

This describes the number of incidence of earthquakes as a function of magnitude. Aftershocks also satisfy this law just like all earthquakes do.

Gutenberg–Richter law (GR law) expresses the relationship between the magnitude and the total number of earthquakes in a region in a given time period.

$$\log_{10}N = a - bM \quad (1)$$

Where N is the cumulative number of earthquakes in a specified region and time window with magnitudes greater than M. The constant b (b value or scaling parameter) relates the number of large events to small events and varies from region to region but is generally in the range of $0.8 < b < 1.2$. The constant a quantify the regional level of seismicity.

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Constants a and b are determined for a specific region and time.

2.2 Bath's Law

It avers that the standard variance in magnitude connecting mainshock and its largest aftershock is 1.2, irrespective of the size of a major shock.

2.3 Omori's Law

It states that the frequency of aftershocks decreases roughly with the reciprocal of time after the mainshock.

$$\frac{dN(\geq M)}{dt} = \frac{k}{(c+t)^p} \quad (2)$$

Where k , c , and p are Omori's constants, $\frac{dN}{dt}$ is the occurrence rate of aftershocks with a size bigger than or equivalent to M and t is the time period after the mainshock.

2.4 Generalized Omori's Law

It combines Gutenberg–Richter's law, Bath's law, and Omori's law. It also takes into account the association of aftershock productivity on mainshock magnitude.

3. Selection of Seismic Sequence

The organized and reliable procedure of the nationwide recording networks lessens the possibility of having missing events in seismic sequences. Additionally, the accessibility of high-quality numerical data enables the development of seismic sequences that are valid to a wide range of vibration periods. Valuable sources of information in generating real mainshock aftershock sequences can be obtained from K-NET, KiK-net, European Strong Motion Database (ESD), Pacific Earthquake Engineering Research (PEER) Center, Mexican strong motion database, NIED, COSMOS, and ITACA. Modern seismic-based codes stipulate that at least seven earthquake ground motions should be considered to obtain an average nonlinear response of RC structures [21]. The motion records are selected by several rules [1] to [30].

- Records are corrected before they are officially available.
- Accelerograms are computed on rock or stiff soil.
- The magnitudes of the Richter scale of all records are not lower than M5.0.
- The far-field records are preferred.
- Records can reveal noteworthy disparities in spectral characteristics and durations.
- PGA levels of all mainshocks are not less than 0.10g.

4. Real Seismic Sequence

Mahin [29] conducted the first pioneering analytical study on the nonlinear response of an elastic perfectly plastic SDOF oscillator to seismic events from 1972 Managua earthquake followed by two aftershocks. He observed a slight increase in displacement ductility and energy dissipation demands.

Aschheim and Black [24] carried a nonlinear response analysis of SDOF subjected to 18 real seismic sequences. Base input represents time period, diverse frequency characteristics, and the existence or truancy of near-field frontward directionality outcomes. They also focused on the estimation of the maximum deformation demand on existing structures.

Sarno and Elnashai [20] [21] analyzed the effects of 4 regular and irregular RC frames under 15 real sequences from the K-Net database embracing different magnitude and source to site distance from 2011 Tohoku seismic event. It was observed that no direct correlations exist between the predominant and mean period of the mainshocks and the counterpart values of aftershocks. They also observed an increase in inelastic displacements and ductility demand for multiple earthquakes.

Raghunandan et al. [26] enumerate the aftershock susceptibility of 4 ductile RC framed buildings subjected to 30 real seismic sequences from California to classify damaged buildings.

Rinaldin et al. [14] studied the impact of seismic sequences on the inelastic response of SDOF systems subjected to 10 recorded real seismic sequences which were selected based on PGA while the magnitude was ignored as it does not distinctly influence the ductility level. The seismic sequences are collected from NIED, COSMOS, and ITACA databases which are categorised into three different groups. In the first category, the elastic spectrum of the sequence accords with that of a single motion. In the second category, it assembles the sequences having a preponderance of a single event for a limited period range. For third, it embraces all the sequences where there is no leading record in the sequence spectrum, and all the single motions contribute to the envelope. They also observed an increase in ductility demand from 22% to 46% for Elastic Perfectly Plastic systems.

Wen et al. [30] studied the vulnerability of a 5 story RC structure subjected to 99 recorded mainshock aftershock sequences on firm soil which are selected from the Chi-Chi earthquake. It has been observed that energy-based damage measure is more effective than peak deformation based as it reflects the additional damage induced by an aftershock. Depending on the polarity of aftershock relative to the mainshock, there can be an increase or decrease in the residual roof displacement. This study is valid for low to mid-rise structures and seismic sequences having analogous characteristics with the Chi-Chi earthquake.

Abdelnaby [4] applied 240 real sequences taken from the 2011 Tohoku earthquake on 3 different RC frames to assess fragility. The use of real mainshock aftershocks sequences overwhelms the presumptions made in former research concerning single event scaling, the relationship between mainshock and aftershocks, and similar seismological situations and soil conditions. It was observed that aftershocks have a high damage potential towards structures than mainshocks.

Kalantari and Roohbakhsh [1] developed fragility curves of code-conforming RC moment resisting frames under aftershock considering 20 real seismic sequences each including two seismic events.

Sarno and Pugliese [22] assessed the seismic vulnerability of existing four story RC structures subjected to a set of 20 natural seismic sequences selected from the PEER database.

They concluded that repeated earthquakes have a serious effect on the seismic susceptibility of the building under study.

5. Artificial Seismic Sequence

When sufficient number of repeated ground motions are not available for deducing inferences regarding the consequences of aftershocks, false repeated ground motions that characterize the attributes of actual shocks have to be developed. Back-to-Back or repeated approach and randomized approach are the two strategies that are normally adopted in the dearth of actual shocks. The first strategy involves reiterating the actual mainshock, at an augmented or similar amplitude, like an artificial aftershock, thus presuming the attributes of earthquake like frequency characteristics and time period of the mainshock and aftershocks are similar. The second strategy comprises of gathering a set of actual ground motions and creating false repeated ground motions by choosing actual ground motions and generating the enduring aftershocks by reiterating the major tremor recurrently, at lower or similar amplitude, besides no alteration in spectral content [3][26].

5.1 Back-to-Back Approach

Hatzigeorgiou and Beskos [11] studied elastic-plastic SDOFs subjected to several artificially created mainshock aftershock sequences which are characterized by the repetition of earthquake motions after a short or long interval. They inferred that multiple earthquakes result in higher inelastic displacement demands, in comparison with single events.

Hatzigeorgiou and Liolios [12] conducted an extensive study on the inelastic response of four RC planar frames under five real seismic sequences downloaded from the Pacific Earthquake Engineering Research (PEER) Center. Repeated earthquakes have been noted at the same place, in a similar direction, nearly at equivalent fault distance, and in a short period. Each sequential seismic motion record is obtained by back-to-back arrangements of a single event. They found out that multiple earthquakes caused increased displacement which further gives rise to higher values of inter-story drift ratio and damage.

Zhai et al. [6] examined dynamic responses of a reinforced concrete containment building exposed to 10 real seismic sequences selected from the Pacific Earthquake Engineering Research (PEER) Center database and are modelled by back-to-back identical accelerograms. With contrast to single motion, repeated ground motions give rise to larger displacement.

Hatzivassiliou and Hatzigeorgiou [25] studied the inelastic behaviour of 3D RC structures which are regular and irregular exposed to 5 real strong repeated earthquakes. Each sequential ground motion from the PEER database is constructed as a distinctive seismic record (serial array). All these seismic motions are multiplied by appropriate factors, which can be considered rational and adequate as per the basic principles of engineering seismology. It was observed that repeated earthquakes lead to increased displacements and accumulated damage.

5.2 Random Approach

Moustafa and Takewaki [2] noticed a noteworthy rise in the damage of structures persuaded by randomly generated

repeated seismic motions. They observed that frequency content and amplitude for the individual sequences during repeated earthquakes for the same record could show a notable difference. Hence, it is not precise to consider that the acceleration sequences have similar frequency characteristics. The ground acceleration is epitomised as the product of a stationary Gaussian random process and an envelope function of repeated character.

Hatzigeorgiou [15-17] investigated ductility demands for nonlinear SDOF systems exposed to repeated near and far fault earthquakes. Studies were conducted on artificial sequences owing to the unavailability of as-recorded motions. These false ground motions were created by a rational and arbitrary amalgamation of as-recorded events downloaded from PEER under 4 cases of seismic sequence which depends on soil conditions such as hard rock, soft rock, stiff soil, and soft soil. He found out that separate ductility demands are required for near & far faults.

Faisal et al. [3] studied the influence of far-field recurrent earthquakes on maximum story ductility demands of inelastic concrete frames. Twenty ground motions chosen from European Strong Motion Database (ESD) are represented in a form of a combination of the bi-directional ground motion with single, double, and triple events. Artificial sequences were created by a rational combination of real single events. The average comparative increase in maximum story ductility demand was 1.4 and 1.3 times when dual and triple events of multiple earthquakes were induced.

Ruiz-García et al. [18] examined if aftershocks can upsurge highest and residual drift requirements in 2D structures with a different number of stories. Only two as-recorded seismic sequences are obtainable from the Mexican Strong Motion Database. Owing to the unavailability of as-recorded mainshock aftershock sequences collected in soft soil sites, two sets with about 56 false repeated ground motions were produced via randomized strategy with actual mainshock records gathered in soft soil sites. They inferred that the association of the mangled duration of the structure to the predominant duration of the aftershock has a momentous influence on the behaviour of the structure.

Guo et al. [1] studied 4 story and 12 story RC frames subjected to artificially treated 10 mainshock aftershock sequences. They found out that the interval between the vibration periods before and after yielding momentously influences structural responses and damage indexes. Smaller post-yielding stiffness designates more sensitivity of damage indexes to the vibrations over a long period. It was also observed that if a structure meets severe damage under the mainshock, the incremental seismic damage resulting from aftershocks is still controllable if structural vibration periods can deviate far from the predominant periods of seismic shocks. The cause for the alteration of vibration periods and the analogous resonance in aftershocks is due to the damage induced by the mainshock.

6. Combined Real and Seismic Sequence

Amadio et al. [5] studied the influence of multiple earthquakes on nonlinear SDOF systems using one natural and two artificial far-fault ground motions. Each of the three ground motions is normalized to PGA of one and applied one, two, or three times. The analysis outcomes proved that such system's response is mainly influenced by natural

structural periods of vibration, type of ground motion, and level of displacement ductility.

Luco et al. [23] developed a “calibrated” static approach for calculating residual capacity for recurrent events based on nonlinear dynamic analysis of case study buildings by employing a back-to-back approach for generating artificial seismic sequences.

Goda [19] found out a similar result for the highest ductility demand for both actual and artificial sequences, hence false repeated ground motions could take the place of actual motions especially when an ample data set of real mainshock aftershock sequences are not accessible. K-NET and KiK-net databases are used for choosing real Japanese records and time-history details of artificial seismic sequences are chosen based on generalized Omori’s law.

Goda and Taylor [13] determined peak ductility demands on inelastic SDOF systems by nonlinear dynamic analysis, exerting a set of actual and artificial Japanese seismic motions. The actual records were obtained from the Pacific Earthquake Engineering Research Center, but they were unfinished because of absent records. The artificial sequences were created as per generalized Omori’s law. Peak ductility demand obtained through actual sequences is comparatively smaller and that based on the artificial sequence is higher. Due to the lack of actual data set, the impacts of aftershock drew from the as-recorded sequences found to be underrated.

Ruiz-Garcia [27] studied the response of existing buildings subjected to 92 real mainshock-aftershock sequences in Northridge and New Zealand earthquakes. He observed that responses of structures based on actual and artificial sequences are not alike predominantly when a back-to-back approach for the artificial sequence is employed. They discovered that response on post mainshock depends on the predominant period of aftershock. Thus, it is essential to inspect the behaviour of buildings subjected to real and non-natural repeated ground motions and explore the exaggeration in drift requirements of non-natural repeated ground motions created from the back-to-back and randomized approach.

Zhai et al. [7-10] studied the strength reduction factor of SDOFs with constant ductility performance subjected to the seismic sequences using recorded motions selected from PEER and artificial motions are generated by arbitrarily combining two different real ground motions. It was observed that in the short period section aftershock sequences have more impact on strength drop factors than in the long period region.

7. Summary and Conclusion

The incidence of aftershock diminishes as time passes from the primary incidence of the major shock. Threat due to subsequent shocks at a location relies on the size and position of the mainshock. A review on the selection of as-recorded and artificial seismic sequences for analysis has been carried out. This is vital as ambiguities allied with input seismic motions tend to have more momentous effects on the susceptibility of structures than structural capacity-related parameters. It is identified that the interdependence occurs between mainshock and aftershock seismic motions, and the real sequences imitate this interdependence perfectly. But, there is no sufficient valuable information to quantitatively

and clearly define this interdependence. Following conclusions can be drawn from the review.

- Large samples of ground motions are used to disclose potential trends and aberrations in the result.
- Real seismic sequences are firmly reliant on the type of spot.
- Consecutive real sequences show diverse features, creating the study more complicated to evaluate and requiring a probabilistic strategy to figure it out. The frequency attributes and time period of the as-recorded major shocks and aftershocks vary momentarily. Thus, recurrence of augmented major shocks for creating realistic seismic sequences, without examining characteristics of seismic motion data, could instigate bigotry in the nonlinear structural reactions. Hence, it is vital to carry out the selection of seismic sequences in a cautious manner.
- Selections of seismic sequences from prevailing worldwide earthquake records may be ambiguous as they can be biased in terms of the ground motions properties.
- The use of real mainshock aftershocks sequences overwhelms the presumptions made in former research concerning single event scaling, the relationship between mainshock and aftershocks, and similar seismological situations and soil conditions, especially when there is no missing data.
- The use of Japanese strong motion data has momentous advantages over the PEER database, as a larger data set of the seismic sequences can be evolved and the created sequences are less likely to have missing events because of the organized recording of the networks.
- Studies show that artificial sequences could lead to diverse responses than those from the actual sequence.
- The frequency content and amplitude for the individual sequences during the repeated earthquakes for the same record could show a notable difference. Thus, it may not be exact to consider that the acceleration sequences have similar frequency content. Hence, modelling mainshock aftershock seismic sequences by back-to-back could be impractical.
- Recent studies have demonstrated that the first approach i.e. back-to-back strategy is senseless and guides to a completely diverse behaviour in contrast to actual motions. Thus, a randomized approach is preferred.
- Back-to-Back approach or randomized approach for generating artificial seismic sequences, contribute to a total misunderstanding of the behaviour of structures when compared with actual ground motions. This condition arises when the associations of the characteristics of earth movement between the major shock and the subsequent aftershocks are not accurately depicted in the false repeated ground motions.

Disclosures

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References

- Kalantari A, Roohbakhsh H. Expected Seismic Fragility of Code-Conforming RC Moment Resisting Frames Under Twin Seismic Events. *Journal of Building Engineering*, 2019.
- Moustafa A, Takewaki I. Response of nonlinear single-degree-of-freedom structures to random acceleration sequences. *Engineering Structures*, 2009; 33: 1251-1258.
- Faisal A, Majid TA, Hatzigeorgiou GD. Investigation of story ductility demands of inelastic concrete frames subjected to repeated earthquakes. *Soil Dynamics and Earthquake Engineering*, 2013; 44: 42-53.
- Abdelnaby A E. Fragility curves for RC frames subjected to Tohoku mainshock-aftershocks sequences. *Journal of Earthquake Engineering*, 2018; 22: 902-920.
- Amadio C., Fragiaco M. and Rajgelj S. The effects of repeated earthquake ground motions on the non-linear response of SDOF systems. *Earthquake Engineering and Structural Dynamics*, 2003; 32: 291-308.
- Zhai CH, Zheng Z, Li S, Xie LL. Seismic analyses of a RCC building under mainshock-aftershock seismic sequences. *Soil Dynamics and Earthquake Engineering*, 2015; 74: 46-55.
- Zhai CH, Wen WP, Li S, Xie LL. The ductility-based strength reduction factor for the mainshock-aftershock sequence-type ground motions. *Bulletin of Earthquake Engineering*, 2015; 13: 2893-2914.
- Zhai CH, Wen WP, Chen ZQ, Li S, Xie LL. Damage spectra for the mainshock-aftershock sequence-type ground motions. *Soil Dynamics and Earthquake Engineering*, 2013; 45: 1-12.
- Zhai CH, Wen WP, Ji D, Li S. The influences of aftershocks on the constant damage inelastic displacement ratio. *Soil Dynamics and Earthquake Engineering*, 2015; 79: 186-189.
- Zhai CH, Wen WP, Chen ZQ, Li S, Chang Z, Xie LL. The damage investigation of inelastic SDOF structure under the mainshock-aftershock sequence-type ground motions. *Soil Dynamics and Earthquake Engineering*, 2014; 59: 30-41.
- Hatzigeorgiou GD, Beskos DE. Inelastic displacement ratios for SDOF structures subjected to repeated earthquakes. *Engineering Structures*, 2009; 31: 2744-2755.
- Hatzigeorgiou GD, Liolios AA. Inelastic behaviour of reinforced concrete structures under repeated earthquakes. *Proceedings of the 8th International Conference on Structural Dynamics, EURO DYN 2011*.
- Goda K, Taylor CA. Effects of aftershocks on peak ductility demand due to strong ground motion records from shallow crustal earthquakes. *Earthquake Engineering & Structural Dynamics*, 2012; 41: 2311-2330.
- Rinaldin G, Amadio C, Fragiaco M. Effects of seismic sequences on structures with hysteretic or damped dissipative behaviour. *Soil Dynamics and Earthquake Engineering*, 2017; 97: 205-215.
- Hatzigeorgiou GD. Ductility demand spectra for multiple near- and far-fault earthquakes. *Soil Dynamics and Earthquake Engineering*, 2010; 30: 170-83.
- Hatzigeorgiou GD. Behavior factors for nonlinear structures subjected to multiple near-fault earthquakes. *Computers and Structures*, 2010; 88: 309-21.
- Hatzigeorgiou GD. Ductility demands control under repeated earthquakes using appropriate force reduction factors. *Journal of Earthquake and Tsunami*, 2010; 4: 231-250.
- Ruiz-García J, Marín M V, Terán-Gilmore A. Effect of seismic sequences in reinforced concrete frame buildings located in soft-soil sites. *Soil Dynamics and Earthquake Engineering*, 2014; 63: 56-68.
- Goda K. Nonlinear response potential of mainshock-aftershock sequences from Japanese earthquakes. *Bulletin of the Seismological Society of America*, 2012; 102: 2139-2156.
- Di Sarno L, Elnashai AS. Assessment of Structures Subjected to Multiple Earthquakes. *Proceedings of the 15 th World Conference on Earthquake Engineering Lisbon, Portugal*, 2012.
- Di Sarno L. Effects of Multiple Earthquakes on Inelastic Structural Response. *Engineering Structures*, 2013; 56: 673-681.
- Di Sarno L., Pugliese F. Seismic fragility of existing RC buildings with corroded bars under earthquake sequences. *Soil Dynamics and Earthquake Engineering*, 2020; 134: 106-169.
- Luco N, Bazzurro P, Cornell CA. Dynamic versus static computation of the residual capacity of a mainshock-damaged building to withstand an aftershock. *Proceedings of the 13th world conference on earthquake engineering. Vancouver, Canada:2004 Paper No. 2405*.
- Aschheim M and Edgar B. Effects of prior earthquake damage on response of simple stiffness-degrading structures. *Earthquake Spectra*, 1999; 15: 1-24.
- Hatzivassiliou M, Hatzigeorgiou GD. Seismic sequence effects on three dimensional reinforced concrete buildings. *Soil Dynamics and Earthquake Engineering*, 2015; 72: 77-88.
- Raghunandan M, Liel AB, Luco N. Aftershock collapse vulnerability assessment of reinforced concrete frame structures. *Earthquake Engineering & Structural Dynamics*, 2014; 44: 419-439.
- Ruiz-García J. Issues on the response of existing buildings under mainshock-aftershock seismic sequences", 15th World conference on earthquake engineering, Lisboa 2012.
- Shcherbakov R, Turcotte DL, Rundle JB. Aftershock statistics. *Pure and Applied Geophysics*, 2005; 162: 1051-76.
- Mahin SA. Effects of duration and aftershocks on inelastic design earthquakes. *Proceedings of the 7th world conference on earthquake engineering*, 1985; 5: 677-680.
- Wen WP, Zhai CH, Ji D, Li S, Xie LL. Framework for the vulnerability assessment of structure under mainshock-aftershock sequence. *Soil Dynamics and Earthquake Engineering*, 2017; 101: 41-52.
- Guo X, He Z, Xu J. Identification of incremental seismic damage development in RC structures excited with sequence-type ground motions. *Structures*, 2020; 24: 464-476.