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Damage-based strength reduction factor for nonlinear structures subjected to sequence-type ground motions

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ABSTRACT

This paper investigates the strength reduction factor of single-degree-of-freedom (SDOF) system subjected to the mainshock–aftershock sequence-type ground motions. Both displacement ductility and cumulative damage are considered in the reduction factor. Records of mainshock-aftershock earthquakes were collected and classified according to site properties. The aftershock ground motions in sequence are scaled to five relative intensity levels. Based on the nonlinear time-history analysis of inelastic SDOF systems, the effects of natural period, ductility factor, damage index and aftershock have been studied statistically. The results indicate that the aftershock ground motion has significant influences on strength reduction factors, and the damage-based strength reduction factor is about 0.6–0.9 times of the ductility-based strength reduction factor. Finally, an empirical expression for strength reduction factor was established by regression analysis.

1. Introduction

According to statistics, about 88% of strong earthquakes are accompanied by aftershocks. An aftershock is defined as a smaller earthquake following the mainshock, which is the largest earthquake in the sequence. Structural damage caused by the mainshock is further aggravated under aftershocks and can even lead to structural collapse. The 2010 New Zealand [1] and the 2015 Nepal earthquakes [2] experienced both mainshock and aftershock ground motions, and are good examples of why sequence-type ground motions are important issues at the structural design stage. In recent years, researchers have explored the effect of aftershock from different aspects. Some studies explored the effects of sequence-type ground motions on inelastic spectra such as strength reduction factor spectra [3,4], damage spectra [5], ductility factor spectra [6,7], etc. Others focused on the changes of structural response, e.g. steel frame buildings [8] and RC frames [9], under sequence-type ground motions. All the results clearly show larger peak displacement or increased structural damage due to sequence-type ground motions than that of one major earthquake. The effect of aftershock should not be overlooked at the structural design stage.

Current seismic design principles include analysis of a structure's elastic-plastic behavior under moderate/rare earthquakes. Since the design strength of most structures is generally much lower than the minimum strength required to maintain the elastic stage under strong earthquakes, a reduction factor is often used to reduce the elastic strength demand and thereby obtain the elastic-plastic strength demand of a structure. Theoretical analysis and experimental studies of strength reduction factors have demonstrated that the structure ductility has a significant effect on the strength reduction factor. The displacement ductility factor helps to assess the extent of structural damage [10–12]. Therefore, a ductility-based strength reduction factor R_μ can be defined as:

$$R_\mu = \frac{F_e}{F_{y,\mu}} = \frac{F_y(\mu = 1)}{F_y(\mu = \mu_i)} \tag{1}$$

where $F_y(\mu{=}1)$ is the yield strength required to maintain the structure in elastic stage; $F_y(\mu{=}\mu_i)$ is the yield strength required to maintain the ductility demand of the structure equal to a given target ductility value as μ_i.

Moreover, the cumulative damage of nonlinear hysteresis cycles also plays a significant role in determining the damage level of a structure. Some studies suggest that cumulative damage can be accounted for by modifying the ductility capacity, such as the equivalent ductility method [13] or introducing a weighted ductility factor [14]. These methods indirectly take into account the influence of cumulative damage. Some other studies consider the cumulative damage directly by employing a damage model in the determination of the seismic demand for a given damage level or performance level.

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Table 1
Number of recorded sequence-type ground motions used in this paper.

Earthquake name	Mainshock		Aftershock		Number	
	Time	M_W	Time	M_W	Site B	Site C
Managua, Nicaragua	1972/12/23 06:29	6.2	1972/12/23 07:19	5.2	0	2
Imperial Valley	1979/10/15 23:16	6.5	1979/10/15 23:19	5.0	0	26
Mammoth Lakes	1980/05/25 16:34	6.1	1980/05/25 16:49	5.7	2	4
Coalinga	1983/05/02 23:42	6.4	1983/05/09 02:49	5.1	0	2
Whittier Narrows	1987/10/01 14:42	6.0	1987/10/04 10:59	5.3	6	14
Superstition Hills	1987/11/24 05:14	6.2	1987/11/24 13:16	6.5	0	2
Northridge	1994/01/17 12:31	6.7	1994/01/17 12:32	6.1	14	13
Umbria Marche	1997/09/26 09:44	6.0	1997/10/03 08:55	5.3	8	4
Chichi	1999/09/20	7.6	1999/09/20 17:57	5.9	49	36
Wenchuan	2008/05/12 14:28	7.9	2008/05/12 19:11	6.1	12	7
L'Aquila	2009/04/06 01:33	6.3	2009/04/07 17:47	5.6	9	0
New Zealand	2010/09/03 16:35	7.0	2011/02/21 23:51	6.2	9	33
East Japan Earthquake	2011/03/11 13:46	9.0	2011/03/11 15:15	7.7	34	29
Kumamoto	2016/04/14 21:26	6.2	2016/04/16 01:25	7.0	11	16
				Total	154	188

Table 2
Damage index ranges for different performance levels.

Performance level	Degree of damage	Damage index range
Operational	Negligible	$0 < D < 0.1$
Immediate occupancy	Minor	$0.1 < D < 0.2$
Damage control	Moderate	$0.2 < D < 0.5$
Life safety	Severe	$0.5 < D < 0.8$
Collapse prevention	Near collapse	$0.8 < D < 1.0$
Loss of building	Collapse	$1.0 < D$

The strength reduction factor obtained in this way is therefore referred to as a damage-based strength reduction factor R_D [15], which can be written as:

$$R_D = \frac{F_e}{F_{y,D}} = \frac{F_y(\mu = 1,\, D = 0)}{F_y(\mu = \mu_i,\, D = D_j)} \tag{2}$$

where $F_{y,D}$ is the inelastic strength demand to limit the inelastic response of the structure to a specified damage level D_j for a given ductility capacity μ_i. In this study, the performance levels of a structure are defined using a damage index to take the cumulative damage of the structure into consideration.

As mentioned above that the aftershock will aggravate structural damage, current damage-based strength reduction factor, however, does not reflect the influence of aftershock ground motions. In this regard, the current study explores this issue through extensive numerical calculations on a nonlinear SDOF system subjected to sequence-type ground motions. Section 2 collects real mainshock and aftershock ground motion records that are essential to investigate R_D. The collected records are then divided into different categories according to the site condition. Section 3 defines the performance level and computational parameters to be used in the calculation of R_D. In Section 4, extensive elastic-plastic time history analysis of a nonlinear SDOF system with various parameters are then carried out to determine the R_D for two cases, i.e., mainshock only and mainshock plus one aftershock. The influence of ductility factor, damage index and some other parameters on R_D are explored in Section 5 through parametric studies. Finally, an empirical formula for damage-based strength reduction factor is proposed in Section 6.

2. Records and classification of sequence-type ground motions

A sequence-type ground motion record usually consists of one mainshock event and one or multiple aftershock events, which are called as one earthquake (mainshock only), a sequence of two earthquakes (mainshock plus one aftershock), a sequence of three earthquakes (mainshock plus two aftershocks), and so on. Scenario of mainshock plus one aftershock was commonly considered in previous studies [5,7,8]. Their results demonstrated that two-sequence earthquakes can provide valuable information about the influence of aftershock. Therefore, sequence-type ground motion in this study is specified as one mainshock plus one aftershock.

To build up a ground motion of two earthquake events, one can connect two artificial ground motions [5] or connect a real earthquake record with its duplicate [16]. This usage of artificial ground motions, however, might lead to significant overestimation of maximum lateral drift demands [17]. The degree of overestimation is case-based due to the random nature of artificial ground motion simulation. The repeated earthquake methodology, on the other hand, actually assumes that the mainshock and aftershock have same power spectrum density which may not be tenable for real situation. To avoid the above problems, this study uses real earthquake records available in Pacific Earthquake Engineering Research Center (PEER) [18] and Strong-motion seismograph networks (K-NET, KiK-net) [19] to construct sequence-type ground motion by the following steps and criteria: (1) collect records from seismostations located on free-field or low-rise buildings to avoid possible soil-structure interaction effects; (2) among all the records from same station and same earthquake event, the one happening earlier and having a peak ground acceleration (PGA) larger than $0.10g$ is taken as the mainshock, the one having the second largest PGA and larger than $0.05g$ is taken as the aftershock; (3) the earthquake magnitude of mainshock and aftershock is larger than 6.0 and 5.0, respectively; (4) connect the selected mainshock and aftershock with a time gap of 100 s in between, which is long enough to cease structural vibrations caused by mainshock; (5) classify the connected sequence-type ground motion according to site classification method of United States Geological Survey.

In total, we constructed 342 sequence-type ground motion records for site classes B and C as listed in Table 1. The number of qualified records for site classes A and D are too small to conduct any meaningful statistical analysis. For further analysis, the PGA of mainshock of all the selected sequence-type ground motion records were scaled to an identical value of $0.2g$.

The relative peak ground acceleration of aftershock ground motion γ is defined as:

$$\gamma = \frac{PGA_{as}}{PGA_{ms}} \tag{3}$$

where $\mathrm{PGA_{as}}$ is the PGA of aftershock ground motion, $\mathrm{PGA_{ms}}$ is the PGA of mainshock ground motion. The parameter γ was introduced to represent the relative intensity level of aftershock with respect to the mainshock. The intensity of aftershock is usually smaller than that of mainshock. However, the aftershock ground motions with greater intensity with respect to that of mainshock ground motions do exist