pertaining to strength reduction factors were included in the final analysis. All analyses led to the development of a new empirical formula which helps to measure and define the damage-based strength reduction factor.

2. SEQUENCE-TYPE EARTHQUAKE GROUND MOTIONS AND SITE CATEGORIES CLASSIFICATION

Seismic input is a prerequisite to assessing the seismic response of a structure. Due to the inherent stochastic characteristics of ground motions, large quantities of natural earthquake responses are essential. Records of two sequential earthquake ground motions were used based on Eq. (1) successive ground motion records from the same station and Eq. (2) recording mainshocks with peak ground accelerations (PGAs) of 0.1g or more.

Because of the small number of strong motion monitoring stations in China, data observations are limited. Currently, researchers must also include ground motion data from the United States, Japan and other countries. However, the principles of site classification in the seismic codes of China and the United States are very different. To make better use of these differences, (Guo 2011) et al. compared and analyzed site classification indicators in the seismic design codes of China and the United States. Each site is divided according to the equivalent shear wave velocity V_{30} and the Chinese seismic design code, whereupon the regression formula is given as Eq. (3):

$$\ln(V_{20}) = 0.4109 + 0.908\ln(V_{30}) \tag{3}$$

Site categories are obtained by site conversion in China, as shown in Table 1. Using the 256 ground motions from the Pacific Earthquake Engineering Research Center (PEER), in accordance with the above principles, sequence-type ground motion were built and Chinese site categories were divided according to conversion relations, as shown in Table 2. Due to the small number of actual mainshock–aftershock sequence-type ground motions for Classes I and IV sites, this research included ground motion records for Class II and Class III sites. Meanwhile, the amplitude of the aftershock was modulated so that the aftershock peak acceleration values were the same as the mainshock peak acceleration values, that is, PGAas / PGAms = 1.

Table 1 Site Conversions

V_{30}	Site category	V_{20}
V_{30}>500m/s	Class I	V_{20}>596m/s
500m/s > V_{30}>250 m/s	Class II	596m/s > V_{20}>278 m/s
250m/s > V_{30}>150 m/s	Class III	278m/s > V_{20}>158 m/s
150m/s > V_{30}	Class IV	158m/s > V_{20}

Table 2 Number of recorded sequence-type ground motions used in this research

Name of the earthquake	Time	Magnitude of mainshock	Site category	
			Class II	Class III
Hollister	1961/04/09 07:23	5.6		1
Managua, Nicaragua	1972/12/23 06:29	6.2	2	
Imperial Valley	1979/10/15 23:16	6.5		26
Livermore	1980/01/24 19:00	5.8		1
Mammoth Lakes	1980/05/25 16:34	6.1	6	
Mammoth Lakes(1)	1983/01/07 01:38	5.3	2	
Coalinga	1983/07/22 02:39	6.4		2
Chalfant Valley	1986/07/20 14:29	5.8		3
Whittier Narrows	1987/10/01 14:42	6.0	16	4
Superstition Hills	1987/11/24 05:14	6.22		2
Northridge	1994/01/17 12:31	6.7	22	5
Chichi	1999/9/20	7.6	93	69
		Total	143	113

3. PERFORMANCE LEVEL DEFINITIONS AND LIMITS

Structure damage takes on various forms under an earthquake, and the extent of the structural damage may not be fully reflected only by maximum deformation. This is why reasonable indicators must be used to assess the extent of structural damage. At present, the international research community agrees that the maximum deformation of a structure and its hysteretic energy are the main factors of structural damage. This agreement, however, has been presented in a variety of two-parameter damage models. This paper uses the Park-Ang (Park 1985) model to assess the damage index, which can be written as Eq. (4):

$$D=\frac{\mu_m}{\mu_u}+\beta\frac{E_h}{F_y\mu_u x_y} \tag{4}$$

where D is the damage index; μ_m is the ductility factor when the structure reaches the maximum elastic-plastic deformation under ground motions; μ_μ is the ductility factor when the structure fails under monotonic loading; F_y is the yield strength; E_h is the cumulative hysteretic energy dissipation under ground motions; β is the energy factor, and it is 0.15 for frame structures.

Based on Park-Ang damage model, through the damage investigation of the actual structure, the structural damage under earthquake ground motion is divided into five performance levels as defined by (Ou 1999) et al. Each performance level corresponds to a damage index range as shown in Table 3.

4. ANALYSIS METHOD AND STRUCTURAL PARAMETERS

The equation of motion of a nonlinear single-degree-of-freedom system under earthquake ground motion is:

$$m\ddot{x}+c\dot{x}+f_s=-m\ddot{x}_g \tag{5}$$

where c is the damping coefficient; f_s is the restoring force of the structure; x is the relative displacement, and x_g is the ground displacement.

According to the definition of the strength reduction factor in Eq. (2) and Eq. (5), when the elastic vibration cycle, damping ratio and restoring force model of the single-degree-of-freedom system are known, it is able to iterate by numerical analysis the yield strength $F_y(\mu=\mu_i, D=D_j)$ for each input ground motion, and the specific period and target displacement, until the calculated displacement ductility factor μ_i and damage index D_j are within the allowable accuracy range, thus obtaining the yield strength $F_y(\mu=\mu_i, D=D_j)$ to calculate the strength reduction factor R_D. A series of strength reduction factors R_D within single-degree-of-freedom system in different ductility factors μ_i and damage indexes D_j can be obtained by calculating different periods and ground motions, which constitute the strength reduction factor spectra. The calculation steps are shown in Fig. 1, where a specific numerical analysis uses the Newmark-β method, and the relative error is controlled under 1%.

In this paper, a single-degree-of-freedom system is the research object, and the hysteretic model is the ideal elastic-plastic model, because of its simple constitutive relationship. Meanwhile, some characteristics of the structural system can be reflected by the structural response under earthquake ground motions. The vibration period of SDOF systems is from 0.1s to 6s with an interval of 0.1s, thus, a total of 60 different periodic points are calculated, with damping ratio of 5%, considering ductility factors of 2, 3, 4, 5, 6 and damage indexes as 0.2, 0.4, 0.6, 0.9, and 1.0, respectively.

Table 3 Damage index ranges for different performance levels

Performance level	Mainly intact	Slightly damaged	Moderate damaged	Serious damaged	Collapsed
Damage index	0<*D*<0.2	0.2<*D*<0.4	0.4<*D*<0.6	0.6<*D*<0.9	0.9<*D*

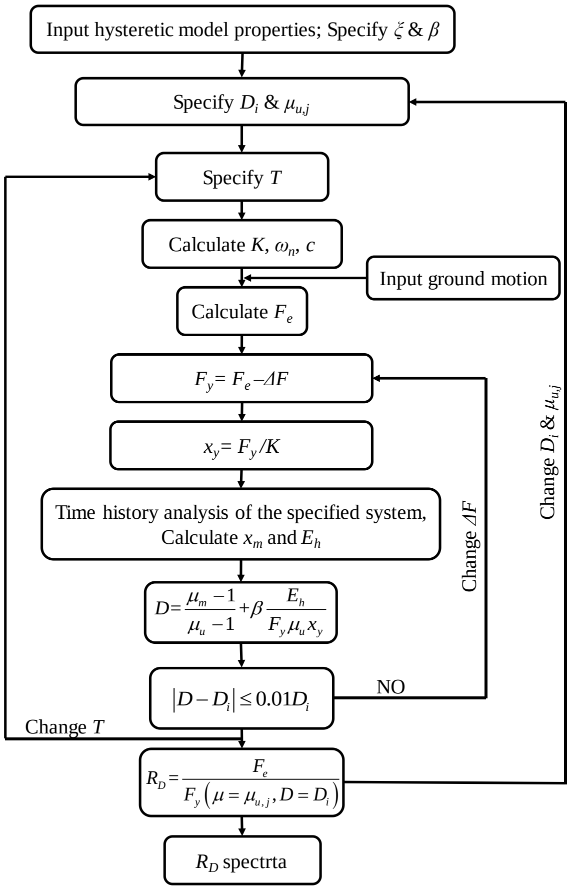

Fig. 1 Flowchart for computation of the strength reduction factor

5. THE AVERAGE STRENGTH REDUCTION FACTOR SPECTRA

Based on 512 selected ground motions (from single earthquakes and sequence-type earthquakes), a total of 768,000 working conditions with 60 vibration periods, five ductility factors and five damage indexes are calculated, to obtain strength reduction factors. The statistical analyses of those factors were used to obtain the corresponding average R_D spectra and the coefficient of variation. Due to space limitations, only part of the results can be presented in this paper. The average strength