SCALING OF GROUND MOTION RECORDS FOR NONLINEAR TIME HISTORY ANALYSIS OF STRUCTURES

Elahe KHANSOLTANI
Graduated Student, University of Mohaghegh Ardabili, Ardabil, Iran
khansoltani@gmail.com

Kazem SHAKERI
Associate Professor, University of Mohaghegh Ardabili, Ardabil, Iran
Shakeri@uma.ac.ir

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ABSTRACT

Nonlinear time history analysis is a rigorous method for seismic response analysis of structures. The results of this method strongly depend on the selected ground motion records and the scaling procedure implemented. In order to achieve reliable analysis results, ground motion records should be properly scaled in order to accurately estimate the median engineering demand parameters (EDPs) and reduce the record-to-record variability effect on the considered EDPs.

In this paper a new method for scaling of ground motion records is proposed, in which the nonlinear behavior of structures is considered in the selection process. In the proposed method, named SSSP (Scaling based on Story Shear-based Pushover), the MDOF (Multiple Degree of Freedom) system is transformed to an equivalent inelastic SDOF (Single Degree of Freedom) system and the scaling is done in a way that the peak displacement of the equivalent inelastic SDOF system subjected to the scaled record is equal to inelastic spectral displacement (target displacement).

The characteristic parameters of the equivalent inelastic SDOF system are determined through pushover analysis, in which the load pattern is derived from the modal story shear profile of the structure. Therefore, the effects of the higher modes and interaction between them are considered in the equivalent inelastic SDOF system. The target displacement is determined by averaging the values of peak displacement of the inelastic SDOF system subjected to a large number of unscaled ground motion records.

The proposed method was evaluated through a typical 8-Story structure and compared with the current scaling method in the Iranian 2800 seismic code. 21 near-fault records are selected for this investigation and the analytical model of the structural systems considers nonlinear behavior of the structure. The results establish the accuracy and efficiency of the proposed procedure and demonstrate its superiority over the 2800 code scaling procedure.

INTRODUCTION

Earthquake is a natural phenomenon with an unknown nature which leads to several uncertainties in seismic design and response of structures. Since the seismic design of structures according to existing codes is based on the reduced seismic forces, it is expected that structures experience nonlinear deformation during severe ground motions. Thus, in a new approach, design codes and standards are changing perspective from force-based design to performance-based design procedure. Therefore, performing nonlinear analysis for designing and evaluating purposes of structures has become inevitable.

Nonlinear time history analysis is a rigorous method for seismic analysis of structures. The results of this method strongly depend on the selected ground motion records and the scaling procedure implemented. In order to achieve reliable results, ground motion records should be properly scaled in order to accurately estimate the median engineering demand parameters (EDPs) and reduce the record-to-record variability effect on the considered EDPs.

During the past years, several studies have been conducted on ground motion scaling methods that some of them are mentioned below.

According to ASCE 7-05, scaling of ground motion records is separately considered for two and three dimensional analyses. For two dimensional analyses, ground motions should be scaled so that the average value of the 5%-damped response spectra for the set of motions is not less than the design response spectrum for the site in 0.2T to 1.5T period range, where T is the vibration period of the structure in the fundamental mode for the direction in which the response is being analyzed.

For three dimensional analyses, ground motions should consist of pairs of appropriate horizontal ground motion components. For each pair of the horizontal ground motion components, a square root of the sum of the squares (SRSS) spectrum should be obtained by taking the SRSS of the 5%-damped response spectra for the scaled components (where an identical scale factor is applied to both components of a pair). Each pair of motions should be scaled so that for vibration periods between 0.2T and 1.5T, the average of the SRSS spectra of all the horizontal component pairs does not fall below 1.3 times the corresponding ordinate of the design response spectrum by more than 10% (ASCE, 2005). ASCE 7-10 scaling procedure is similar to ASCE 7-05. The difference is that in scaling ground motion records in three dimensional analysis according to ASCE 7-10, each pair of motions should be scaled such that the average of the SRSS spectra from all horizontal component pairs does not fall below the corresponding ordinate of the response spectrum used in the design in the period range from 0.2T to 1.5T (ASCE, 2010).

Kalkan and Chopra (2010a), proposed a method for scaling of ground motion records for two dimensional analyses according to ASCE scaling procedure. In this method first, an initial scale factor is calculated for each record by minimizing residuals between the record's scaled spectrum and target spectrum between 0.2T and 1.5T through the method of least square in which square of sum of residuals is expressed as:

$$\lambda = \sum_{i=1}^{n} \left[\bar{A}_i - \left(SF.A_i \right) \right]^2 \tag{1}$$

where $\bar{A}_i$ and A_i are the target spectral acceleration and unscaled record's spectral acceleration at i^{th} spectral period, respectively; n is the number of selected periods between 0.2T and 1.5T; SF is the scaling factor which minimizes λ based on $d\lambda/dSF \cong 0$ and it is computed from the below equation:

$$SF = \left(\sum_{i=1}^{n} \left(\bar{A}_i.\bar{A}_i \right) \right) / \left(\sum_{i=1}^{n} \left(\bar{A}_i.A_i \right) \right) \tag{2}$$

Note that although the initial scale factor (obtained from equation 2) makes the record's scaled spectrum close to the target spectrum between 0.2T and 1.5T, the average spectrum of the primary scaled records may fall below the target spectrum in this period range. If so, it is necessary to amplify all scaled records with a constant scaling factor (in addition to the initial factor of each record presented in equation 2) such that the average value of the response spectra does not fall below the design spectrum for periods ranging from 0.2T to 1.5T.

Scaling ground motion records according to Iranian 2800 seismic code is similar to ASCE 7-05 scaling procedure in three dimensional analyses, with the exception that according to 2800 code, each record should be scaled to its maximum value and the scale factor should be determined such that for each period between 0.2T and 1.5T, the average of the SRSS spectra of all horizontal component pairs does not fall below1.4 times the corresponding design spectra. The resulting scale factor should be applied to the records scaled to their maximum value and be used in dynamic analysis (Iranian code of practice for seismic resistant design of buildings, standard no 2800).

Kalkan and Chopra (2010b, 2012) proposed MPS method for scaling of ground motions. In the MPS method, the ground motion records are scaled so that the maximum displacement of the equivalent SDOF system matches the target inelastic spectral displacement. The properties of the equivalent inelastic SDOF system are determined corresponding to the first mode of pushover analysis.

To pursue the work of Chopra and Kalkan and by inspiration from the MPS method a new method for scaling of ground motion records, named SSSP (Scaling based on Story Shear-based Pushover), is proposed in the present study.

SSSP PROCEDURE PROPOSED

In the proposed method, considering the nonlinear behavior of structures and the effects of higher modes, the scaling is done in a way that the peak displacement of the equivalent inelastic SDOF system subjected to the scaled record is equal to inelastic spectral displacement (target displacement). The characteristic parameters of the equivalent inelastic SDOF system are determined through pushover analysis in which the load pattern is derived from the modal story shear profile of the structure. Therefore, the effects of higher modes and the interaction between them are also considered in the equivalent inelastic SDOF system (Shakeri et al., 2010). In order to determine the load pattern in the SSSP-based scaling procedure, in addition to structural properties, the characteristics of the selected ground motions are also considered as the applied load pattern is calculated based on the story shear profile of the structure obtained from the spectral analysis results.

The values of inelastic spectral displacement could be determined by averaging the values of the peak displacement of inelastic SDOF system subjected to a large number of unscaled ground motion records compatible with the selected seismologic zone.

Since in determination of the load pattern in the proposed method the effects of higher modes are considered, the load pattern is not compatible with any distinct mode shape. Therefore the assumed equivalent fundamental mode shape is derived from the existing load profile pattern and is used for converting the MDOF system to an equivalent inelastic SDOF system.

Since in the MPS scaling procedure, calculation of the scale factor is based on the inelastic SDOF system whose properties are determined by the aid of first mode pushover analysis, the effects of higher modes are not included in computing of the scale factor. While in the proposed method the effects of higher modes and interaction between them are considered.

The proposed procedure is summarized in sequential steps presented here. In steps 1-12, load pattern, assumed equivalent fundamental mode shape and capacity curve are defined. Scale factor of each ground motion record is computed in steps 13-17.

1. Creating the structural model considering nonlinear material characteristics.
2. Defining the target pseudo-acceleration spectrum.
3. Performing eigenvalue analysis in order to compute mode shapes and modal periods.
4. Calculating the modal story forces at each story level for selected number of modes using following equation:

$$F_{ij} = \Gamma_j \phi_{ij} Sa_j m_i \tag{3}$$

where i is the story number, j is the mode number, m_i is the translational mass of the story i, ϕ_{ij} is the component i of the eigenvector j (mode shape) and Sa_j is the spectral acceleration corresponding to the mode j.

5. Calculating the modal story shears for the considered modes.

$$SS_{ij} = \sum_{k=i}^{n} F_{kj} \tag{4}$$

where SS_{ij} is the story shears in floor i associated with mode j.

6. Combining the obtained story shear profiles by the aid of quadratic combination rule (e.g. CQC or SRSS rule) using following equation:

$$SS_i = \sqrt{\sum_{j=1}^{m} SS_{ij}^2} \tag{5}$$

where SS_i is the modal story shear in level i associated with all the considered modes.

7. Determining the load pattern profile based on the combined-story-shear profiles.

$$\begin{aligned} F_n &= SS_n \\ F_i &= SS_i - SS_{i+1} \qquad i = 1,2,\dots,(n-1) \end{aligned} \tag{6}$$

8. Normalizing the load pattern with respect to the total value in step 7.

$$\overline{F_i} = \frac{F_i}{\sum F_i} \tag{7}$$

9. Applying the normalized load pattern to the structure and developing pushover curve.
10. Computing the assumed equivalent fundamental mode shape and obtaining the force coordinates of the equivalent SDOF system using following equations:

$$\begin{aligned} \{\phi\} &= [m]^{-1} \times \{\overline{F_i}\} \\ F^* &= S_a = \frac{V_b}{M^*} \end{aligned} \tag{8}$$

where $\{\phi\}$ is the assumed fundamental mode shape, $[m]$ is mass matrix, V_b is the base shear, and $\{\overline{F_i}\}$ is the vector of the total forces in the structure.

11. Computing the equivalent displacement of the SDOF system according to energy method and following equations:

$$\begin{aligned} \Delta D^{(k)} &= \frac{\sum_{i=1}^{n}\left(\left(F_i^{(k-1)} + \tfrac{1}{2} df_i^{k}\right) \times \Delta d_i^{(k)}\right)}{\sum_{i=1}^{n}\left(F_i^{(k-1)} + \tfrac{1}{2} df_i^{k}\right)} \\ D^{(k)} &= D^{(k-1)} + \Delta D^{(k)} \end{aligned} \tag{9}$$

where $F_i^{(k-1)}$ is the existing force in the story i at the end of step k -1, $dF_i^{(k)}$ is the incremental applied force in the story i at step k. $\Delta d_i^{(k)}$ is the incremental displacement in the story i due to the incremental applied load at step k, $\Delta D^{(k)}$ is the incremental displacement of the equivalent SDOF system at step k, $D^{(K)}$ is the displacement coordinate of the equivalent SDOF system at step k.

12. Developing the Force-Displacement curve of the equivalent inelastic SDOF system with unit mass (spectral acceleration versus spectral displacement, S_a-S_d) based on the computed values in steps 10 and 11 and idealizing the curve as a bilinear curve.

Complementary details of these steps are presented in Shakeri et al., (2010).

13. Repeating Steps 4 to 12 for each of the selected records.
14. Determining the characteristics of the equivalent inelastic SDOF system: Since for determination of the load pattern profile, the corresponding spectral acceleration of each record is used, so the load patterns are different for each record. In other words, the number of equivalent inelastic SDOF systems is equal to the number of the records and each equivalent inelastic SDOF system has its unique parameters (initial stiffness, secondary stiffness and yield strength). By averaging the characteristic parameters of inelastic SDOF systems, a unique inelastic SDOF system is considered.
15. Computing the peak displacement of the equivalent inelastic SDOF system by performing nonlinear time history analysis utilizing unscaled ground motion records, $D = \max|D(t)|$.
16. Computing the target displacement of the equivalent inelastic SDOF system ($\overline{D}$) by averaging the peak displacement of the equivalent inelastic SDOF system due to each unscaled ground motion records

17. Determining the scaling factor for each ground motion to ensure that the peak displacement of the equivalent inelastic SDOF system due to the scaled record is close enough to a target displacement determined in Step 16.

In order to calculate the scale factor for each ground motion record by considering the initial scale factor equal to 1, the new scale factor is changed with the amount of ±0.01 until the objective of step 17 is acquired.

EVALUATION OF THE PROPSED METHOD

The accuracy and efficiency of SSSP method was evaluated in comparison to 2800 code scaling procedure based on a typical 8-story steel moment resistant frame building designed based on Iranian seismic design codes. The nonlinear 2D model of the structure was generated in OpenSees software, using Displacement-Based Beam-Column Elements. Since drift values are one of the most important factors controlling the damage in structures, this engineering demand parameter was selected for evaluation of the proposed method.

GROUND MOTION RECORDS

21 near-fault records which Kalkan and Chopra have been used in their study (2010b) are considered (listed in Table 1). These records belong to site classes of C and D according to NEHRP classification, which are similar to soil types of 2 and 3 according to Iranian 2800 code. The records are available in the Pacific Earthquake Engineering Research (PEER) ground motion database.

Most of the standards (e.g. Iranian 2800 code) define the final structural response as being the average of structural responses under 7 records or as the maximum value of the structural responses under 3 records. Thus, 21 selected ground motion records are divided into 3 sets each containing 7 records.

Efficiency and accuracy of the proposed method is evaluated for each set of ground-motions. The result of nonlinear time history analysis due to ground motion set 1 is presented in this paper. In Figure 1, the pseudo-acceleration response spectrum for each ground motion record and the median of them, which is considered as design spectrum, are displayed.

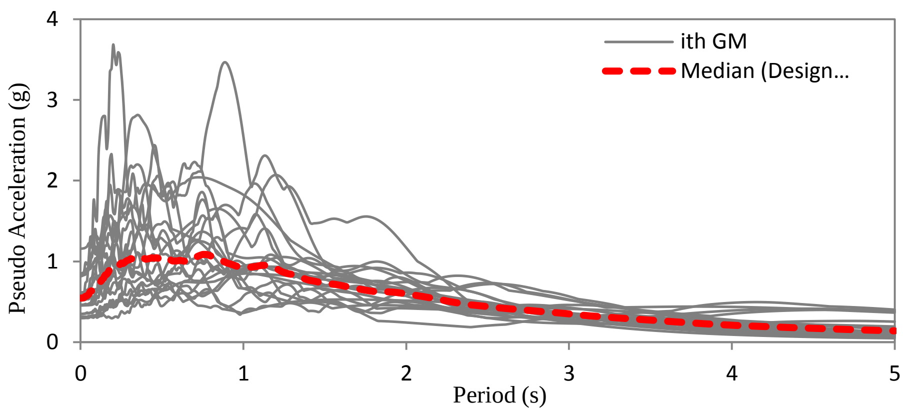


Figure 1. Individual response spectra for 21 ground motions and the corresponding median response spectrum (design spectrum) for 5% damping ratio

Table 1. Selected Earthquake Ground Motions

No.	Earthquake	Year	Station	M	R_{cl} (km)	PGA (g)	Ground motion set number
1	Tabas, Iran	1978	Tabas	7.4	2.1	0.85	1
2	Imperial Valley	1979	EC Meloland Overpass FF	6.5	0.1	0.3	1
3	Imperial Valley	1979	El Centro Array #7	6.5	0.6	0.46	3
4	Superstition Hills	1987	Parachute Test Site	6.5	1.0	0.46	2
5	Loma Prieta	1989	LGPC	6.9	3.9	0.56	3
6	Erzincan, Turkey	1992	Erzincan	6.7	4.4	0.51	1
7	Northridge	1994	Jensen Filter Plant	6.7	5.4	0.59	2
8	Northridge	1994	Newhall - W Pico Canyon Rd	6.7	5.5	0.46	3
9	Northridge	1994	Rinaldi Receiving Sta	6.7	6.5	0.84	3
10	Northridge	1994	Sylmar - Converter Sta	6.7	5.4	0.61	1
11	Northridge	1994	Sylmar - Converter Sta East	6.7	5.2	0.83	2
12	Northridge	1994	Sylmar - Olive View Med FF	6.7	5.3	0.84	3
13	Kobe, Japan	1995	Port Island	6.9	3.3	0.26	1
14	Kobe, Japan	1995	Takatori	6.9	1.5	0.62	2
15	Kocaeli, Turkey	1999	Yarimca	7.4	4.8	0.35	2
16	Chi-Chi, Taiwan	1999	TCU052	7.6	0.7	0.35	1
17	Chi-Chi, Taiwan	1999	TCU065	7.6	0.6	0.81	2
18	Chi-Chi, Taiwan	1999	TCU068	7.6	0.3	0.57	3
19	Chi-Chi, Taiwan	1999	TCU084	7.6	11.2	1.16	1
20	Chi-Chi, Taiwan	1999	TCU102	7.6	1.5	0.3	2
21	Duzce, Turkey	1999	Duzce	7.2	6.6	0.54	3

SCALE FACTORS DETERMINED BY SSSP METHOD

The most important goal of SSSP method is to consider the nonlinear behavior of structure in scaling of ground motion records. Thus, the selected records should be strong enough and drive the structure into the inelastic domain. In order to check this, the roof displacement values determined by nonlinear time history analysis due to 21 unscaled ground motions and the median of them are displayed on the first mode pushover curve.

As shown in Figure 2-a, the building is driven into inelastic range due to each ground motion record. In Figure 2-b, the pick displacement of equivalent SDOF system due to unscaled records (step 15 of proposed method) and the median of them (target displacement, step 16) are displayed.

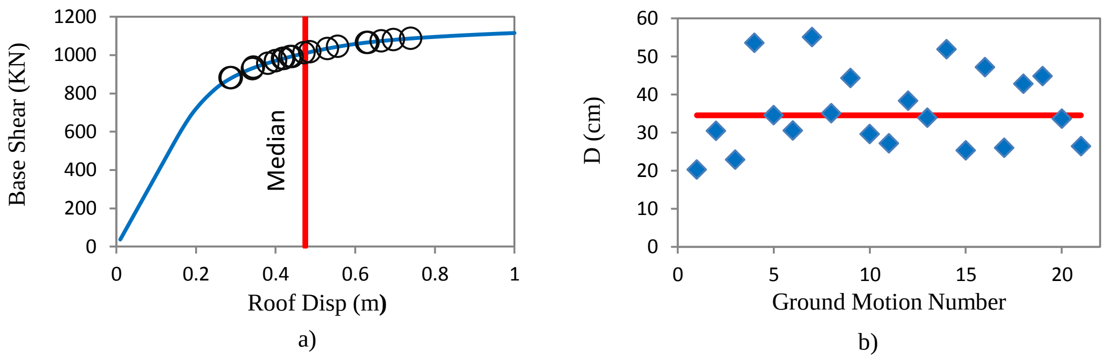


Figure 2. (a) Roof displacements determined by nonlinear time history analysis due to 21 ground motions identified on (D), first mode pushover curve, (b) Peack displacement of equavelent inelastic SDOF system for 21 ground motions Horizontal line shows the median value ($\overline{D}$)

Based on the proposed method, the scale factor for each record in the defined ground motion sets is calculated in a way that the peak displacement of the equivalent inelastic SDOF system subjected to the scaled record is equal to target displacement, which is determined under 21 unscaled ground motions. Scale factors determined by SSSP method are shown in table 2.

SCALE FACTORS DETERMINED BY IRANIAN 2800 SEISMIC CODE

Iranian 2800 seismic code states that “The motions should be scaled such that the average value of their SRSS spectra does not fall below 1.4 times the Standard Design-Spectra for periods of 0.2T second to 1.5T seconds, where T is the fundamental period of vibration”. According to this method, a similar scale factor is obtained for all records in a set.

2800 code scaling procedure is based on pairs of horizontal ground motion acceleration components which is suitable for 3D analysis. In this research a 2D model is used, so by inspiring from the ASCE scaling procedure, one component of each ground motion is used and the ground motions are scaled such that the average value of the 5%-damped response spectra is not less than the design response spectrum for periods ranging from 0.2T to 1.5T.

In this paper scaling of ground motion records based on 2800 code is done in 2 ways:

1. 2800-a: Calculating the smallest possible scale factor in a way that the average spectrum does not fall below the design spectrum for periods of 0.2T to 1.5T. The calculated scale factor is the same for the records of each set and is applied to records that are scaled to their own maximum value.
2. 2800-b: In this method, by utilizing an initial scale factor for each record, the difference between the record’s scaled spectrum and target spectrum is minimized in the period range of 0.2T and 1.5T through the method of the least squares. Then the secondary scale factor is computed so that the average spectrum of the scaled records by initial factors does not fall below the design spectrum for periods of 0.2T to 1.5T. The final scale factor of each record is applied to record that is scaled to its own maximum value.

Scale factors determined by 2800-a and 2800-b methods are shown in table 2.

Table 2. Scale factors determined by SSSP, 2800-a and 2800-b methods

Record number / Scaling method	1	2	6	10	13	16	19
SSSP	1.43	1.15	1.11	1.13	1.03	0.7	0.6
2800-a	0.61	0.61	0.61	0.61	0.61	0.61	0.61
2800-b	0.92	0.57	0.71	0.59	0.43	0.45	0.6

EVALUATION OF ACCURACY AND EFFICIENCY OF SSSP, 2800-a AND 2800-b SCALING METHODS

In order to investigate the accuracy of the studied methods, the median values (the geometric mean) of EDPs, determined by nonlinear time history analysis of the building due to 21 unscaled ground motions is considered as the benchmark result. The median values of EDPs determined by nonlinear time history analysis due to scaled records are compared to benchmark result.

To evaluate the efficiency of the different scaling methods, the dispersion of EDPs due to the scaled records is determined. The scaling procedure is considered efficient if the dispersion of EDPs due to the scaled records are small.

The median value, $\bar{x}$, and dispersion of EDPs due to the n scaled records (σ) are calculated from the following equations:

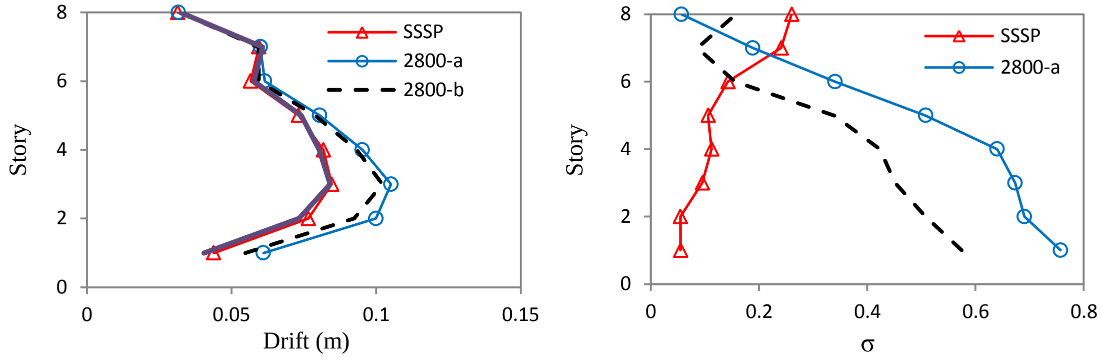
$$\bar{x} = \exp\left[\frac{\sum_{i=1}^{n} \ln x_i}{n}\right], \quad \sigma = \left[\frac{\sum_{i-1}^{n} \left(\ln x_i - \ln \bar{x}\right)^{1/2}}{n-1}\right] \tag{10}$$

where x_i is the structural response due to the record i.

Figure 3-a shows the median values of EDPs determined by the nonlinear time history analysis of the structure subjected to the scaled records of set 1 against the benchmark results. As presented in this Figure, the SSSP method estimates median values of EDPs due to scaled records much closer to the benchmark

values in comparison to the 2800 code scaling procedure. Besides, the result of 2800-a and 2800-b scaling methods are close to each other.

The dispersion of EDPs due to the scaled ground motions (set 1) is presented in Figure 3-b. As shown in this figure, the dispersion of EDPs due to the proposed scaling method is much smaller compared to the 2800 code scaling procedure.



a) Median of EDPs b) Dispersion of EDPs

Figure 3. Median and dispersion of EDPs for ground motion set 1 scaled according to SSSP and 2800 code procedures

CONCLUSIONS

A new method for scaling of ground motion records regarding nonlinear behavior of the structure was developed in this study. In the proposed method, named SSSP (Scaling based on Story Shear-based Pushover), scaling is done in a way that the peak displacement of the equivalent inelastic SDOF system subjected to the scaled record is equal to inelastic spectral displacement (target displacement). The characteristic parameters of the equivalent inelastic SDOF system are determined through pushover analysis in which the load pattern is derived from the modal story shear profile of the structure. Therefore, the effects of the higher modes and interaction between them are considered in the equivalent inelastic SDOF system. The proposed method was evaluated through a typical 8-Story structure and compared with the current scaling method of the Iranian 2800 seismic code.

In this paper, scaling of ground motion records based on 2800 code scaling procedure was evaluated in two different ways denoted as 2800-a and 2800-b. In the 2800-a scaling method the smallest possible factor was calculated so that the average value of the 5%-damped response spectra for each set of the scaled records is not less than the design response spectrum in the period range of 0.2T to 1.5T. In the 2800-b scaling method, by minimizing the difference between the scaled spectrum of each record and target spectrum, an initial scale factor was calculated. Then, the second scale factor is calculated as discussed in 2800-a method. The main conclusions are as follows:

1. SSSP method estimates median values of EDPs much closer to the benchmark values than 2800 code scaling procedure. The dispersion of EDPs due to ground motion scaled by the SSSP method is much smaller compared to 2800 code scaling procedure. This demonstrates the accuracy and efficiency of the proposed SSSP procedure and illustrates its superiority over the 2800 code scaling procedure.
2. Although both of 2800-a and 2800-b methods provide median values of EDPs that are almost equal, the dispersion of EDPs due to the ground motions scaled by the 2800-b method is much smaller compared to the 2800-a method. This indicates the appropriateness of the 2800-b method in terms of obtaining responses with relatively lower variability.

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