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Ground motion scaling for seismic response analysis by considering inelastic response and contribution of the higher modes

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ABSTRACT

This paper proposes a new scaling procedure to consider the inelastic response of structure along with the effect of higher modes in scaling the selected ground motions for seismic response analysis. This is done by obtaining the corresponding inelastic Single-Degree-of-Freedom (SDOF) system of the structure through performing a single-run modal pushover analysis with a load pattern consistent with the combined-modal-story-shear profile obtained from response spectrum analysis. Therefore, the effect of the higher modes and interaction between them in the nonlinear phase are reflected in the inelastic SDOF. The scaling process is performed such that the peak displacement of the inelastic SDOF system under the scaled record matches the inelastic spectral displacement (target displacement). The proposed procedure is evaluated through three regular and one irregular tall building. The results demonstrate the superiority of the proposed procedure in estimating the engineering demand parameters of structures with/without important higher modes effects.

1. Introduction

In the recent years, performance-based design methods have been widely developed by numerous researchers for design of structures. In the performance levels corresponding to large inelastic deformations, performing nonlinear analysis of the system is inevitable. Although the nonlinear static analysis is widely used as a practical tool for estimating the response of structures [1,2] and also many efforts have been done to improve the shortcomings of it [3–16], nonlinear time history (NTH) analysis is the most rigorous method to predict the seismic response of structures (considering the dynamic nature of the seismic loads). However, the results of NTH analysis depend strongly on the selected ground motions and the employed scaling procedure.

The performance-based design methodology requires defining the probability of exceedance of a specified limit state for the considered engineering demand parameters (EDPs). Therefore, in the ground-motion intensity scaling methods, preferred by structural engineers, the scale factors of the selected records must be defined in such a way that the mean of the structural response resulting from the NTH analysis under the small number of the scaled record is close to the mean value of EDPs resulted from the NTH analysis of a large number of ground motions which are compatible with the site-specific seismic hazard conditions. So that the estimation of EDPs from a small number of records, as it is done in most practical cases, is accurate. In addition, utilizing a scaling method that results in EDP distributions with small dispersions (i.e., efficiency in the scaling method) is an important aspect [17,18]. In this regard, many researchers have conducted studies on the ground motion scaling methods during the last years, as elaborated on here.

The primary scaling methods such as scaling to match target peak ground acceleration (PGA) or effective peak ground acceleration, or even methods of scaling to match Arias intensity, effective peak velocity (EPV) and maximum incremental velocity (MIV) [19] are established based only on the characteristics of the ground motions and not the dynamic behavior of the structure. Therefore, they do not lead to an accurate estimation of the structural responses, with a large scatter in the inelastic response and small efficiency for soft soil and near-fault sites [19]. Furthermore, several researchers have reported that the scaling to match PGA, as the most conventional approach, results in biased estimates with large dispersions [20–24].

In order to consider structural characteristics in the ground motion records scaling, Shome et al. [25] proposed a scaling method based on the spectral acceleration at the first vibration period of structure (Sa (T_1)) and scaled each record to match the target Sa (T_1). This scaling method is appropriate for structures whose responses are dominated by the first mode. However, its implementation for the structures with important higher mode effects may lead to less accurate estimation of the structural responses and increase the record-to-record variability

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[26,27]. Catalan et al. [28] found that using $1.1T_1$ as the reference period for scaling is more appropriate for structures that experience non-linear behavior.

By scaling records based on the spectral acceleration at first and second periods [29,30], although the accuracy of the resulted structural responses improved in comparison to the preceding method, the scatter of the responses became greater, especially for near-fault records [31].

Scaling method based on spectral acceleration ordinates over a range of periods [32,33] leads to scatter reduction of responses in comparison to scaling method based on the spectral acceleration at the fundamental period of structure. Kurama and Farrow [19] evaluate the effectiveness of the mentioned methods in comparison to the MIV procedure and have found that the effectiveness of the mentioned spectral acceleration-based scaling methods differ for different local site condition and also through the structural period ranges in comparison to the MIV method. Therefore, these methods are not necessarily appropriate for all site soil characteristics and period ranges.

According to ASCE 7–10 standard [34], 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 a set of scaled motions is not less than the design response spectrum for the period ranging from 0.2 T to 1.5 T, where T is the fundamental vibration period of the structure in the direction in which the response is being analyzed. For three dimensional analyses, each pair of ground motions should be scaled such that the average of the square-root-of-the-sum-of-the-squares (SRSS) spectra from all horizontal component pairs does not fall below the corresponding ordinate of the response spectrum used for design in the period range of $0.2T_1$ to $1.5T_1$.

Baker and Cornell [31,35] have developed a two-parameter scaling method consisting of Sa (T_1) and Epsilon (ε). Epsilon is the indicator of the spectral shape which is defined as the difference between the spectral acceleration of a record and the mean value of the spectral acceleration from a ground motion prediction equation at a given period. Although utilizing epsilon accounts for spectral shape in ordinary ground motions and leads to a decrease in the scatter of the responses, it is not effective in considering velocity pulse effects. Therefore, using ε is not appropriate for scaling of the pulse-like near fault ground motion records [36].

None of the preceding procedures explicitly consider the inelastic behavior of the structure and may not be suitable for conditions where the inelastic demand is significantly larger than the elastic response (e.g., near collapse state) [37–39]. Several attempts have been made to consider nonlinear behavior of structures in the scaling of ground motions and it was shown that scaling records based on the inelastic spectral displacement or combination of inelastic spectral displacement at the first mode and the elastic spectral displacement at the second mode is more appropriate for near-fault records and leads to more accurate estimation of the structural responses reducing the record-to-record variability [40–42]. According to FEMA 440 [43], ground motion records should be scaled so that the peak displacement of the roof matches the target displacement determined by nonlinear static analysis using the capacity spectrum method [44] or displacement coefficient [1].

To consider the structural strength effects in scaling of ground motions, recently the modal pushover-based scaling (MPS) procedure based on the inelastic first-mode pushover analysis has been proposed by Kalkan and Chopra [18,45,46] in which, through the first-mode pushover curve, the scaling process is performed so that the peak displacement of the corresponding first-mode inelastic SDOF (single-degree-of-freedom) system under the scaled record matches the inelastic spectral displacement (i.e., target displacement). Reyes and his coworkers have extended the MPS procedure for two components of ground motion records and also for asymmetric-plan buildings [47–49]. The previously proposed MPS procedures are appropriate for structures dominated by the first-mode. However, for structures where the higher modes have an important effects on the structural response, the MPS procedure has been extended by considering only the elastic deformation of second-mode SDOF systems in selecting a subset of scaled ground motions while the scaling procedure is still based on only the first-mode inelastic SDOF system [18,45,46]. There is a need for an effective method that can take higher modes contributions as well as the nonlinear characteristics of the structure into account to achieve a proper scaling of ground motions for seismic response analysis of structures with important higher mode effects, such as tall and height-wise irregular buildings. In an attempt to address this issue in this paper, a new pushover-based scaling procedure referred to as SSSP (Scaling based on Story Shear-based Pushover) is proposed, in which the inelastic behavior of the structure along with the contribution of higher modes in nonlinear phase and the frequency content of the selected records are considered.

In the following sections, the SSSP procedure is first developed and then evaluated based on series of analyses. Comparisons are made between the results of the SSSP, MPS and the scaling method in the ASCE 7–10 standard [34], and pertinent implications are discussed.

2. Development of the SSSP procedure

In order to consider the nonlinear structural behavior of multi-story buildings in scaling of ground motion records and also reduce the computational burden (in the proposed SSSP procedure), the multi-story structure is transformed to an equivalent inelastic SDOF (Single Degree of Freedom) system through a single-run modal pushover analysis by considering an assumed equivalent mode shape. The scaling process is performed so that the peak displacement of the equivalent inelastic SDOF system under the scaled record matches the inelastic spectral displacement (target displacement).

In order to consider the contribution of the higher modes in the nonlinear phase, the pushover analysis is performed by applying a combined modal load pattern rather than the load pattern consistent with the first mode shape. One of the first attempts to use combined modal load pattern in pushover analysis has been done by Lawson et al. [50]. They proposed a single-run modal procedure which defines the load pattern by combining the corresponding inertia forces of each considered modes using the SRSS combination method, but it leads to inaccurate responses of the structures (e.g. inter-story drift). The main reason for these poor results lies in violating the principle of modal response spectrum analysis which expresses that the total response of one parameter (e.g. inter-story drift) cannot be estimated based on the other parameter's total response (e.g. modal inertia forces). Therefore, the combined modal inertia forces profile cannot be used as the load pattern in nonlinear static analysis since utilizing it may lead to inaccurate story shears and subsequently inaccurate drifts. Since the inter-story drift profile of the structure, as a crucial EDP in seismic assessment and design of structures, is affected by the amount of the story shear, the load pattern in the modal single-run pushover analysis must be compatible with the combined modal story shear profiles rather than the combined modal inertia forces [9]. This concept is the main idea of the proposed pushover-based scaling method.

In the proposed SSSP method, the load pattern is derived from the combined modal story shear profile resulting from response spectrum analysis of the structure using the considered ground motion spectrum [Fig. 1(a) – (d)]. Therefore, unlike the MPS procedure, the effect of the higher modes and the interaction between them in nonlinear phase are incorporating in the proposed method, in addition to the frequency content of the selected ground motion, via utilizing the pseudo-acceleration of the given ground motion record in defining the load pattern. Consequently, these effects are reflected in the equivalent inelastic SDOF system. Although the proposed procedure is a multi-mode procedure and the effects of the higher modes are considered, the simplicity of the pushover procedure is maintained and the method requires only a single-run pushover analysis.