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Implementation of Displacement Coefficient method for seismic assessment of buildings built on soft soil sites

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ABSTRACT

This paper presents the results of an investigation aimed at extending the Coefficient Method for the seismic assessment of existing buildings built on very soft soil conditions. In the first part of this investigation, the lateral displacement response of four steel frames and six reinforced concrete frames under a set of 20 earthquake ground motions recorded on very soft soil sites of the old bed-lake of Mexico City is investigated. It is shown that the seismic response of the buildings strongly depends on the ratio of the first-mode period of vibration of the structure to the predominant period of the ground motion (T/T_g). In the second part of this study, a Displacement Coefficient method approach is employed for obtaining estimates of maximum inelastic roof displacement demands. Error statistics indicates that the Coefficient Method provides reasonably good estimates.

1. Introduction

Modern performance-based seismic assessment procedures for existing structures are based on the evaluation of: (a) the structure-specific lateral deformation capacity, and (b) the earthquake-induced displacement demand. Among them are the nonlinear static procedures discussed in FEMA-273/274 [1], FEMA 356 [2], and FEMA 440 [3] recommendations as well as the ASCE 41-06 [4] standard in the United States. They have become popular among American practicing engineers due to their simplicity and ability to provide useful insight regarding the expected performance of earthquake-resistant structures. In particular, the so-called Coefficient Method is employed for estimating the maximum roof (target) displacement demands for simplified performance-based assessment of existing buildings. Therefore, several studies have focused their attention on evaluating the ability of the Coefficient Method for predicting the maximum roof displacement demand of existing buildings (e.g. [5–8]), but considering only existing buildings subjected to far-field or near-fault earthquake ground motions recorded on firm soil site conditions. However, there is still a need of evaluating the ability of Coefficient-based methods for predicting the target inelastic displacement demand of existing buildings built on soft soil sites, such as the bed-lake zone of Mexico City or the San Francisco Bay Area, since significant structural damage has been reported in buildings placed in this type of soil when subjected to earthquake ground shaking (e.g. [9]).

The primary objective of the research reported in this paper is to evaluate the effectiveness of a Coefficient-based Method for estimating peak roof inelastic displacement demands of steel and reinforced concrete framed-buildings subjected to soft-soil earthquake ground motions. The evaluated method aims to provide initial screening of building performance during the first stage of seismic evaluation, but it does not aim to substitute a detailed seismic evaluation of the building under consideration (e.g. using dynamic nonlinear time–history analyses). In addition, it should be noted that the method is constrained to case-study buildings that are fixed at their base, which implies that soil–structure interaction effects are negligible, and the influence of the soft soil site conditions in the seismic response is taken into account through the frequency content of the earthquake ground motions.

2. Review of Displacement Coefficient method

2.1. Background

The pioneering interest of providing simplified procedures for estimating maximum lateral inelastic displacement demands (e.g. roof and maximum over all stories) for mid-rise reinforced concrete (RC) building structures dates back to mid-70s by Shibata and Sozen [10]. It should be noted that this interest was beyond providing estimates of nonlinear displacement response of simple structures, which can be modeled as single-degree-of-freedom (SDOF) systems, but primarily to provide a tool for practicing design engineers to meet framed-building lateral stiffness required to avoid undesirable level of damage related to threshold

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maximum inter-story drift demands [11]. For instance, the simplified method outlined by Shimazaki and Sozen [12] suggested that maximum inelastic roof drift demand can be obtained from the modification of spectral elastic displacement ordinates through two modification factors that represent: (1) the normalized inelastic displacement obtained from a constant lateral-strength SDOF oscillator with respect to its elastic counterpart; and (2) the mode participation coefficient. To the author's knowledge, this procedure could be named as the first "Displacement modification" method. Years later, Krawinkler and his co-workers [13–15] proposed a seismic design procedure for framed-building and wall structures based on achieving target ductility capacity for collapse safety, where a key step consists in including modification factors to obtain estimates of inelastic demands from elastic strength and displacement spectral ordinates. Similarly to Sozen's approach, modification factors proposed in Krawinkler's approach took into account the relationship between the elastic displacement response of a SDOF to a MDOF and the relationship of the inelastic to the elastic displacement demand of SDOF systems, but the effect of hysteretic behavior in the nonlinear displacement response of SDOF systems was considered as an additional modification factor [16]. It should be mentioned that other "Displacement modification" approaches have been proposed for the preliminary design of building structures, where an estimation of maximum roof and inter-story drift demands are of primary importance, such as those introduced by Qi and Moehle [17] and Miranda [18].

Based on the research developed by Krawinkler and his research group [13–16] and with the aim of providing a simplified tool for seismic assessment and rehabilitation of existing structures based on displacement-based procedures, the FEMA 273 [1] and FEMA-356 [2] guidelines introduced the Nonlinear Static Procedure (NSP) to obtain estimates of the seismic performance of buildings. The core concept was to apply monotonically increasing lateral forces to a mathematical model of the building under consideration until either a target displacement is exceeded or the building collapses. Based on extensive analytical studies, improvements to the estimation of the target displacement were proposed in FEMA 440 document [3] and later incorporated in the ASCE 41-06 [4] Standard Seismic Rehabilitation of Existing Buildings. In the ASCE 41-06 [4] Standard, the target roof displacement can be obtained as follows:

$$\delta_t = C_0 C_1 C_2 S_a \left(\frac{T_e^2}{4\pi^2}\right) g \tag{1}$$

where C_0 is a modification factor that relates spectral displacement and likely building roof displacement, C_1 is a modification factor to relate expected maximum inelastic displacements to displacements calculated from a linear elastic analysis, C_2 is a modification factor to represent the effect of hysteretic behavior on the maximum displacement response, S_a is the response spectrum acceleration at the effective fundamental vibration period and damping ratio of the building under consideration, and T_e is the effective fundamental period of the building. Particularly, the following expression for estimating coefficient C_1, is included in the ASCE 41-06 [4] Standard:

$$C_1 = \begin{cases} 1.0 & T_e > 1.0s \\ 1.0 + \frac{R-1}{aT_e^2} & 0.2s < T_e \leq 1.0s \\ 1.0 + \frac{R-1}{0.04a} & T_e \leq 0.2s \end{cases} \tag{2}$$

where a is a site-depended coefficient (e.g. equal to 130 for site class A and B, 90 for site class C, and 60 for site classes D, E, and F) and R is the strength ratio defined as the ratio of the elastic strength demand to calculated yield strength coefficient, which also represents the ground motion intensity with respect of the lateral strength of the buildings under consideration (i.e. a relative lateral strength measure). Likewise, the coefficient C_2 can be computed as follows:

$$C_2 = \begin{cases} 1.0 & T_e > 0.7s \\ 1 + \frac{1}{b}\left(\frac{R-1}{T_e}\right)^c & T_e \leq 0.7s \end{cases} \tag{3}$$

where b and c take values of 800 and 2. It should be noted that FEMA 440 recommendations [4] recognized the inherent uncertainty in the estimation of the target roof displacement. In particular, FEMA 440 [4] stated that "When interpreting results and assessing structural performance, engineers should consider the implications of such uncertainties. For example, the expression can be used with $a = 60$ for softer sites (class E and F) to estimate displacements, but it is less reliable due to the very high dispersion of results in studies of SDOF oscillators for soft sites.". Therefore, it is of particular interest to evaluate the accuracy of (1) in estimating maximum roof inelastic displacement demands of existing buildings when subjected to ground motions recorded in soft soil sites.

2.2. *Coefficient C_1 for soft soil sites*

A key factor in the estimation of the target displacement in Eq. (1) is the coefficient C_1, which is also known as the inelastic displacement ratio, C_R, in the literature [e.g. 19,20]. Previous studies developed by the main author had shown that the record-to-record variability in the estimation of inelastic displacement ratios for soft soil sites could be reduced if C_R ratios are computed from normalized period of vibration with respect to the predominant period of the ground motion, T/T_g [20]. However, it should be noted that the spectral shape of C_R computed from this approach significantly differs from that computed for firm soil sites as shown in Fig. 1. As a consequence, the functional form of Eq. (2) is not suitable for providing estimates of coefficient C_1. To remedy this issue, Ruiz-García and Miranda [20] suggested the following functional form to obtain estimates of C_R (i.e. coefficient C_1 in Eq. (1)) to be used in a Displacement Coefficient approach for performance-based assessment of existing buildings.

$$\begin{aligned} \overline{C}_R = & \theta_1 + (R-1)\left[\frac{1}{\theta_2 \cdot (T/T_g)^2}\right] \\ & + \theta_3 \cdot (T_g/T) \cdot \exp[-4.5 \cdot \{\ln(T/T_g - 0.05)\}^2] \\ & + \theta_4 \cdot (T_g/T) \cdot \exp[\theta_5 \cdot \{\ln(T/T_g + 0.67)\}^2] \end{aligned} \tag{4}$$

where T is the period of vibration, T_g is the predominant period of the ground motion and θ_1, θ_2, θ_3, θ_4,and θ_5 are parameters whose estimates depend on the type of soft soil site (e.g. old-bed lake zone of Mexico City or the bay-mud area of San Francisco) and they can be obtained through nonlinear regression analysis techniques. Parameter estimates that can be used for buildings built on soft soil sites of Mexico City can be found in Ruiz-García and Miranda [20].

3. Framed buildings and earthquake ground motions considered in this study

3.1. *Building frames and modeling assumptions*

Two families of regular framed-buildings were considered in this investigation. All buildings were assumed to be designed for office occupancy and located in the lake-bed zone of Mexico City. The first family includes four three-bay steel buildings having 4, 6, 8 and 10 stories. Fig. 2a shows the plan view of the steel buildings. All buildings were designed by an experienced structural engineering office to satisfy the 2004 Edition of the Mexico City Building Construction Code [21]. Moment-resisting frames were provided in both the longitudinal and transverse direction, while