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# Inelastic displacement ratios for soil-structure systems

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ABSTRACT

In this paper, effects of Soil-Structure Interaction (SSI) on Inelastic Displacement Ratios (IDRs) of superstructure are addressed. Four non-dimensional parameters are employed as the crucial parameters which affect the IDRs of soil-structure systems: (1) non-dimensional frequency as the structure-to-soil stiffness ratio; (2) aspect ratio of the superstructure; (3) relative lateral strength of the superstructure; and (4) strain hardening ratio. The soil beneath the superstructure is simulated based on the concept of Cone model. The superstructure is idealized as a nonlinear single-degree-of-freedom (SDOF) oscillator. An in depth sensitivity analysis is conducted to consider the effects of key parameters of soil-structure systems. The results are presented in the form of IDR spectra. The IDR spectra confirm that generally increasing non-dimensional frequency leads to amplification of IDRs. In soil-structure systems, the effect of aspect ratio is dissimilar before and after a threshold period of around 0.65 s. Within pre-threshold range, slenderizing superstructure decreases IDR spectra. The trend is reversed for post-threshold range. Increasing strain hardening ratio and relative lateral strength have the same influences on the IDRs of soil-structure system as those of fixed-base structure and give rise to smaller and larger IDRs, respectively. Also, a formula is proposed and respective coefficients are calibrated to obtain IDRs of soil-structure systems using model tree approach. This simple formula can predict the IDRs with acceptable accuracy.

## 1. Introduction

Seismic design provisions typically allow structures to undergo inelastic deformations under strong earthquake ground motions. However, in most practical design situations only linear elastic analyses are employed to estimate the maximum response of the structure and there is some allowance for the reduction of seismic forces. Even if availability and selection of adequate earthquake acceleration time histories for design purposes are not a problem, currently it is not still versatile to carry out nonlinear time history analyses for the most practical design purposes. Therefore, it is necessary to use simplified analysis techniques to estimate the maximum inelastic response of the structure during severe earthquake ground motions.

A particularly appealing approach is to estimate the maximum inelastic response, and especially the maximum lateral inelastic displacement demand, using the results obtained from a linear elastic analysis through Inelastic Displacement Ratios (IDRs). One of the primary relationships for IDRs were proposed by Veletsos and Newmark and Veletsos and Van [1,2]. They proposed $C_\mu = \mu/\sqrt{(2\mu - 1)}$ for acceleration-sensitive spectral regions and $C_\mu = 1$ for displacement- and velocity-sensitive regions. In recent decades, many studies (e.g., Nassar and Krawinkler [3]) were conducted to obtain the formulas for IDRs via a large number of ground motions. The effects of epicentral distance, earthquake magnitude, soil condition, and nonlinear hysteretic characteristics were investigated [4–6] during extensive series of statistical analyzes. These studies revealed that IDRs are not influenced considerably by local firm site conditions (A, B, C and D). However, they are affected significantly by soft soil conditions. In this condition, some approximate relations were published for $C_\mu$ and $C_R$ by Ruiz-Garcia and Miranda [7,8]. They stated that the IDRs of ground motions recorded on soft soil condition can be very different from each other, despite having the similar site class. In order to bring down the dispersion of IDRs, the vibration periods were normalized by the predominant period of ground motion, as first suggested by Miranda [9]. Ruiz-Garcia and Miranda proposed a probabilistic approach in order to estimate maximum inelastic displacement demands of SDOF systems [10]. Hatzigeorgiou and Beskos suggested a simple and effective method for the IDR estimation of a structure subjected to repeated or multiple earthquakes [11]. $C_1$ coefficients proposed by FEMA 356 and FEMA 440 documents are also IDRs that are utilized in Nonlinear Static Procedures (NSPs) to estimate the maximum inelastic displacements of structures [12,13]. In FEMA 440, significant modifications have been implemented on $C_1$ coefficient. $C_1$ coefficient is determined using Eq. (1) in which $R$ parameter denotes relative lateral strength that is calculated

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from Eq. (2); constant value of $\alpha$ is equal to 130, 90, and 60 for soil class of B, C and D, respectively. Also, this value is equal to 60 for soil classes of E and F.

$$C_1 = 1 + (R - 1)/\alpha T_e^2 \tag{1}$$

$$R = m^* S_a(T_e, \xi)/F_y \tag{2}$$

where $T_e$ is the effective fundamental period of the structure, $m^*$ is the effective fundamental modal mass of the structure and $F_y$ is the effective yielding force of the structure which is obtained from the pushover analysis. The above equation was extracted just for elastic perfectly plastic hysteretic models. Lin and Miranda evaluated equivalent linear methods proposed in FEMA 440 for estimating maximum displacement of structures [14]. In 2010, Erduran and Kunnath evaluated the coefficient method recommended in the FEMA 440 method under both far-fault and near-fault earthquake ground motions [15]. They concluded that it is practically difficult to reach high relative lateral strength equal to or greater than 6 for very stiff systems.

All aforementioned studies have been performed on fixed-base structures and the effects of soil beneath the superstructure have been disregarded. It is well known that Soil–Structure Interaction (SSI) can affect the structural responses through [16–18]. The soil–structure system has a longer natural period than the fixed-base structure. Also, it usually has a higher damping ratio, due to the radiation as well as material damping of the soil, which can drastically influence the response of the superstructure [19]. In 1970s, many researchers made attempts to estimate the SSI effects on elastic response of superstructures [16–18]. The nonlinear responses of soil-structure systems were also investigated to some extents in the same period [19,20]. However, it has received considerable attention in recent years [22–24]. Both the ductility and the strength demand of the superstructure may experience significant variations due to the SSI effect. It was shown that SSI effects also can change the damage index of buildings [25]. However, these investigations were not directly addressed for existing structures for which the relative lateral strength of the superstructure is known. Also, no clear regulation or formula was proposed in Nonlinear Static Procedures (NSPs) for IDRs of soil-structure systems.

The viewpoint of this paper is based on the estimation of IDRs considering SSI effects. For this purpose, by means of solving a linear elastic soil-structure system which is accurate enough for engineering purposes [26], inelastic demands will be determined directly using IDRs of nonlinear soil-structure systems. Therefore, main objective of this paper is to perform a deep sensitivity and parametric study and evaluate the effects of different parameters of soil–structure system on IDRs, qualitatively and graphically. Besides, a novel formula using model tree (MT) approach to directly estimate IDRs of soil-structure systems is developed according to various interacting parameters, such as the non-dimensional frequency, aspect ratio, strain hardening ratio and relative lateral strength. The simplicity and accuracy of proposed formula permit structural engineers to obtain the IDRs of soil–structure systems adequately.

## 2. Soil-structure model

As shown in Fig. 1, the assumed soil-structure system consists of a nonlinear SDOF oscillator and a foundation resting on a soil medium. In this investigation, the superstructure is idealized by bilinear hysteretic model with different strain hardening ratios. This parameter is denoted by $\alpha$ which takes values of 0, 0.05, 0.1 and 0.2. Consideration of softening behavior due to the dynamic instability produced in the superstructure [27] is beyond the scope of this paper. The range from 0 to 0.2 covers different values of strain hardening ratio for typical structures (from flexible structures to stiff ones). The SDOF oscillator is described by initial period ($T_{fix}$) and damping ratio ($\xi_o$). Parameters m and I are the effective mass and mass moment of inertia of the superstructure, respectively. Also, h is the effective height of the superstructure in the first mode. Viscous damping ratio is assumed to be 5%. The nonlinearity level in the superstructure is governed by relative lateral strength, $R$, varying from 1.5 to 6 (1.5, 2, 3, 4, 5, and 6). The selected values for $R$ comply with those of FEMA 440. Note that $R$ is defined as the relative lateral strength of fixed-base structure. The IDRs for soil-structure system are calculated assuming the same yielding strength of its fixed-base counterpart. Also, it is noteworthy that it is practically difficult to achieve high relative lateral strength equal to or greater than 6 for very stiff systems [15]. Elastic and inelastic displacements, used to calculate IDRs, are those of soil-structure system when the rigid body motions of foundation are removed. The relative displacement of the superstructure to the foundation is of interest for design purposes. It can be carried out as proposed by Aviles and Perez-Rocha [28]. This model is able to predict the response of a SDOF superstructure as well as MDOF superstructure having dynamic characteristics of its first mode in fixed-base condition. Ratio of foundation-to-structure mass ($m_f/m$) is assumed to be 0.25 that includes a wide variety of superstructures and this value is more applicable for conventional and practical buildings [23]. Structure-to-soil mass ratio ($m/\rho r^2 h$), where $\rho$ is the mass density of the soil, is considered 0.471 [26].

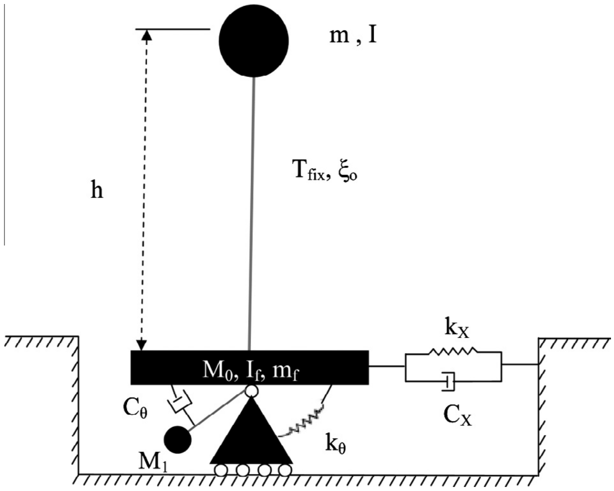

**Fig. 1.** Soil–structure model.

Various approaches are available to simulate soil and consider its effects on dynamic responses of the superstructure. Finite element methods are the most accurate approaches to investigate the SSI problem. However, structural engineers often adopt discrete models in order to monitor the SSI effects on the superstructure. It is confirmed that the discreet models (Cone models)

**Table 1**
Cone model for foundation on surface of homogenous half-space soil.

| Rocking motion | | Sway motion |
|---|---|---|
| *Lumped-mass parameter model* | | |
| $k_\theta = \frac{8\rho V_S^2 r^3}{3(1-\upsilon)}$ | | $k_X = \frac{8\rho V_S^2 r}{2-\upsilon}$ |
| $C_\theta = \frac{\pi}{4}\rho V_a r^4$ | | $C_X = \pi\rho V_S r^2$ |
| $M_1 = \frac{9\pi^2}{128}\rho r^5 (1-\upsilon)\left(\frac{V_a}{V_S}\right)^2$ | | |
| $M_0 = 0.3\pi\beta(\upsilon - 0.33)\rho r^5$ | | |
| If $\upsilon \leqslant 0.33$ | Then | $\beta = 0$ and $V_a = V_S$ |
| If $0.33 \leqslant \upsilon \leqslant 0.5$ | Then | $\beta = 1$ and $V_a = 2V_S$ |