Soil Dynamics and Earthquake Engineering 104 (2018) 75–87

Contents lists available at ScienceDirect

Soil Dynamics and Earthquake Engineering

journal homepage: www.elsevier.com/locate/soildyn

# Effect of soil-structure interaction on inelastic displacement ratios of degrading structures

Nemat Hassani[a,*], Majid Bararnia[a], Gholamreza Ghodrati Amiri[b]

[a] Department of Civil, Water & Environmental Engineering, Shahid Beheshti University, Tehran, Iran
[b] School of Civil Engineering, Iran University of Science & Technology, Tehran, Iran

ARTICLE INFO

*Keywords:*
Soil-structure interaction
Inelastic displacement ratio
Strength-stiffness degradation
Strength reduction factor

ABSTRACT

This study presents an evaluation of inelastic displacement ratios for degraded structures considering soil-structure interaction (SSI). In this regard, a wide variety of effective parameters of hysteresis models and soil-structure systems are considered. Four different hysteretic models a) bilinear, b) modified Clough, c) stiffness degrading, and d) strength-stiffness degrading, are assigned to represent force-displacement response of super-structure. The supporting soil is modeled using the concept of cone models. Inelastic displacement ratios were computed for 12,000 soil-structure models with periods between 0.1 and 5 s when subjected to 19 strong ground motions recorded on NEHRP site class D. In addition, a parametric investigation is performed to evaluate the parameters that could affect nonlinear response of structures with strength-stiffness degrading hysteretic model. It is observed that generally SSI increases the inelastic displacement ratios with exception of very short period structures. Also, it is demonstrated that the soil-structure systems with stiffness degrading hysteresis model in short period range could experience larger inelastic displacement compare to those in non-degraded soil-structure systems. In particular, the SSI substantially increases inelastic displacement ratios of strength-stiffness degrading structures.

## 1. Introduction

The main objective of performance-based seismic design (PBSD) is to control the maintenance and damage level of buildings when subjected to strong ground motions with different severities. For this purpose, the values of measurable structural response parameters, such as drift and ductility are limited to acceptable values which are selected based on intended performance level. As a part of PBSD, estimation of inelastic displacement plays a key role. Some recommendations for evaluation and rehabilitation of existing structures, i.e. FEMA 356 [1], introduced an analysis procedure to compute the target inelastic displacement using equivalent inelastic single-degree-of-freedom (SDOF) system.

In this method, the target inelastic displacement can be approximated by modifying the maximum elastic displacement demand. As a known modification approach, FEMA 356 [1] introduced inelastic displacement ratio for estimating the target displacement. Inelastic displacement ratio is defined as the ratio of the maximum displacement of an inelastic single degree of freedom (SDOF) system to the maximum elastic displacement of the SDOF system with the same period and damping ratio. The relationship between maximum inelastic displacement and maximum elastic displacement was investigated, for the first time, by Veletsos and Newmark [2]. They studied SDOF systems with elasto-plastic behavior and observed that in the low period region inelastic displacement is much greater than elastic one. However, in long period region there is no significant difference between the maximum deformation of inelastic and elastic systems which is known as equal displacement rule. A study on constant ductility inelastic displacement ratios ($C_\mu$) demonstrated that the earthquake magnitude and site to source distance have little influence on $C_\mu$ [3]. The study was conducted using 216 earthquake ground motions time history recorded on firm site condition and statistical analysis of results led to an expression for $C_\mu$.

Equations that are developed to estimate constant-ductility inelastic displacement ratios ($C_\mu$), can be used in design process of new structures. However, the use of these equations in seismic evaluation of existing structures, may lead to an underestimation of maximum inelastic displacement [4]. Thus, Ruiz-García and Miranda [4] developed an expression to approximate mean constant strength inelastic displacement ratios ($C_R$). They concluded that effects of site condition and earthquake magnitude are negligible for long period range ($T_n > 1.0$ s). Chopra and Chintanapakdee [5] investigated inelastic displacement

* Corresponding author.
*E-mail addresses:* n_hassani@sbu.ac.ir (N. Hassani), m_bararnia@sbu.ac.ir (M. Bararnia), Ghodrati@iust.ac.ir (G. Ghodrati Amiri).

http://dx.doi.org/10.1016/j.soildyn.2017.10.004
Received 3 September 2016; Received in revised form 13 June 2017; Accepted 1 October 2017
0267-7261/ 

ratios of SDOF systems with bilinear behavior and developed equations for $C_R$ and $C_\mu$. Ruiz-Garcia and Miranda [6] conducted a comprehensive statistical study on inelastic displacement ratios of structures located on soft soil site condition and proposed an equation for estimating inelastic displacement ratios. They evaluated the influences of earthquake magnitude, site to source distance, post yield stiffness, stiffness and strength degradation on constant strength inelastic displacement ratios. Ruiz-Garcia and Miranda [6] concluded that the stiffness and strength degradation have significant effects on inelastic displacement of structures built on soft soil. Also, the results showed that the combination of stiffness and strength degradation can increases inelastic displacement of structures with periods less than half of the predominant period of the ground motion.

In all the aforementioned studies the effects of soil-structure interaction (SSI) on nonlinear response of SDOF systems were ignored, even though it is known that SSI affects the linear and nonlinear response of structures. Based on the studies conducted in early 1970s, SSI effects on elastic systems could be divided into two parts. First, period of soil-structure system is greater than the fixed one and second, considering SSI increases the effective damping ratio of soil-structure system because of radiation and material damping of soil beneath the structure [7]. Thus, regulation codes suggest an equivalent fixed base system with modified fundamental period and damping ratio to include the SSI effects [8,9].

Avilés and Pérez-Rocha [10] evaluated the effects of soil-structure interaction on inelastic systems response and proposed an equivalent fixed base nonlinear system which is defined by effective ductility, period and damping ratio. The further study is conducted to investigate the influences of SSI on strength reduction factor and inelastic displacement ratios of elasto-plastic SDOF systems [11]. They used equivalent fixed-base nonlinear system in order to adjust the equation that had been proposed by Ordaz and Perez-Rocha [12], to consider the effects of SSI on strength reduction factor. Response data for 64 ground motions recorded on different site conditions demonstrated, that the SSI effects on $C_\mu$ for structures built on soft and very soft soil conditions should be considered, especially in short period region [13]. The results of this study are used to develop equations for estimation of $C_\mu$ regarding SSI effects and site conditions. Several other research efforts have focused on the evaluation of SSI effects on inelastic displacement ratios [14–16]. However, it should be noted that the results of these studies were restricted to the structural systems with bilinear hysteretic behavior.

In order to evaluate the influences of SSI on constant strength inelastic displacement ratios ($C_R$) of structures with stiffness degrading, Aydemir [17] conducted a study and concluded that the mean inelastic displacement ratios for degrading systems are greater than the corresponding ones of non-degrading systems up to period of nearly 1.0 s. In this study equivalent nonlinear fixed-base systems with modified Clough hysteresis model were used and the results led to an equation for estimating the inelastic displacement ratios of stiffness degrading soil-structure systems.

Based on new seismic provisions, it is assumed that the structures behave inelastically during sever earthquakes and will experience large inelastic deformation without losing strength, considerably [8,18]. However, it is observed that during strong ground motion, strength and stiffness degradation may occurred in structural components [19]. Deterioration in structural components can significantly increase lateral displacement and may lead to global collapse of structures. In several studies the collapse of structures are considered as the association of P-Delta effects and structural components deterioration [20]. Most of the previous studies that investigated the effects of strength-stiffness degradation on inelastic displacement demands were limited to fixed-base structures and the effects of soil-structure interaction were ignored. Aydemir [17] considered both foundation flexibility and stiffness degrading effects on inelastic displacement ratios. In practice most of structures exhibit stiffness degradation at unloading and reloading branches, whereas the unloading stiffness in modified Clough hysteresis model which is used by Aydemir [17], is kept equal to the initial elastic stiffness.

Recently there has been a renewed interest on the effects of SSI on inelastic response of structures and several studies demonstrated that soil beneath the structures could have significant effects on seismic demands of structures [21–25]. However, the effects of soil-structures interaction on seismic demands of degraded systems have not yet been well addressed and it is, thus, necessary to clarify the influences of SSI on these type of systems. In this study the effects of foundation flexibility on degraded super-structures are investigated. To model degraded super-structure, four different hysteresis behaviors were considered: a) Bilinear, b) modified Clough, c) stiffness degrading and d) stiffness-strength degrading. A parametric study is performed by using a simplified soil-structure interaction model with a wide range of effective parameters. Here, in this paper the results of a comprehensive statistical study on displacement demand and inelastic displacement ratios of degraded structural systems by considering soil-structure interaction are presented.

## 2. Soil-structure model

Seismic responses of structure to strong ground motions are affected by supporting soil behavior which is called soil-structure interaction (SSI). In general, these effects could be divided into two parts, which are known as; inertial – and kinematic effects [26]. In this investigation a simplified SDOF soil-structure model is applied to consider the inertial interaction phenomenon on super-structure seismic demands (Fig. 1). This model is capable enough to simulate the effects of SSI in MDOF systems. For this purpose, effective mass M* and effective height H* of equivalent SDOF system could be obtained from fundamental mode properties of MDOF system as follow [27]:

$$M^* = \frac{\left(\sum_{j=1}^{n} m_j \phi_{j1}\right)^2}{\sum_{j=1}^{n} m_j \phi_{j1}^2} \quad H^* = \frac{\sum_{j=1}^{n} h_j m_j \phi_{j1}}{\sum_{j=1}^{n} m_j \phi_{j1}} \tag{1}$$

where $m_j$ is the mass of the $j$th storey; $h_i$ is the height from the base level to level $j$; and $\phi_{j1}$ is the amplitude at $j$th storey of the first mode.

In practice, various approaches are used to model supporting soil in SSI problems, such as finite element and finite difference approaches. However, in this study lumped-parameter model (Cone model) is used, because of its simplicity and sufficient accuracy [28] (Fig. 2). In cone model, the soil beneath the structure is modeled as a homogenous half-space and the foundation is assumed to be rigid with circular shape

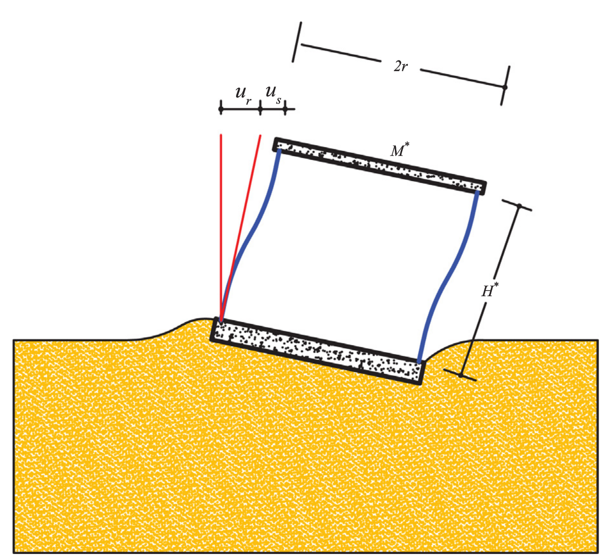


**Fig. 1.** SDOF soil-structure model used in this study.