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Seismic Assessment of Uplift Allowed Soil–structure Systems with Deteriorating Behavior

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Abstract

Combined effects of soil-structure interaction, foundation uplift and structural material deterioration have not been explicitly addressed in the literature. In this paper, the effects of flexural degradation on the response of an equivalent single-degree-of-freedom soil-structure system representing the first mode response of a structure are investigated. The system is mounted on a rigid foundation including distributed Winkler springs to allow uplift. In addition to the common dimensionless parameters for modeling soil-structure system, three deterioration levels are defined for the flexural response, namely, low, moderate and high degradation and the response of the structure is presented for each case. Comparison of the results indicates that considering deterioration and uplift have significant effects on the response of soil-structure systems.

Keywords: Degradation, Soil-Structure interaction, Foundation uplift, Displacement ratio

1. Introduction

One of the basic parameters in seismic design of structures and evaluation of the performance is inelastic displacements. A case in point is that for structural collapse analyses or structural passive/active control, inelastic displacements are of particular importance. In recent decades, to simplify tedious computational efforts, modern codes have utilized a series of conditional displacement ratios to represent relations between elastic and inelastic displacements. In accordance with ASCE 7-13, these ratios fall into two distinct categories. In the first category, deteriorations in the strength and stiffness are not considered; however, in the second category these effects are taken into account [1,2].

One of the first studies on displacement ratios indicated how inelastic responses showed variations in resistance reduction factor for a single-degree-of-freedom (SDOF) system with elastic perfectly plastic (EPP) behavior [3]. The research demonstrated that the stiffer the structure, the more the ratio of inelastic to elastic displacements. Later in 2003, Miranda and Ruiz-Garcia investigated amount of inelastic displacements of a SDOF structure which lied on a soft surface and calculated displacement ratios. They also investigated that drops in stiffness of the SDOF system have direct effects on inelastic displacement increments [4]. Numerous studies [5,6] have been conducted in this field in which simplification of structural hysteretic behaviors have been considered. In this regard, an EPP model has been commonly used [3] and strength/stiffness deteriorations have been ignored which in turn structural displacements and dynamic stability have been assessed in an unrealistic way

There are many hysteretic models in technical literature that incorporate deterioration models. Clough and Johnston were among the first to introduce more complicated models. In their model, reload deterioration branch on the maximum displacement that occurs in the loading direction was considered [7]. After that, several other hysteretic models were introduced which also considered deterioration, but none of them considered all sources of deterioration. Later in 1993, Rahnama and Krawinkler presented a model [8] that captures stiffness/strength deteriorations based on constant energy concept; this model was extensively used in later years by other researchers [9]. The model was recently completed by Lignos and Krawinkler [10] and was named modified Ibara-Medina-Krawinkler (IMK). Effects of strength/stiffness deterioration on inelastic displacements were investigated by Song *et.al* [11]. Their efforts concluded that deterioration effects causes a drastic increase in displacement demands, although they neglected P-delta effects in their studies. Moreover, Rahnama and Krawinkler investigated effects of soft soil and hysteretic models including deterioration of strength and stiffness on amount of seismic demands in elastic and inelastic regions [8].

For more accurate investigations of displacement ratios soil-structure interaction should be considered since this phenomenon has a dramatic impact on response of structures in elastic and inelastic regions. The basic consequence of soil-structure interaction is an increase in natural period and effective damping ratio [12]. Many researchers investigated displacement demands in elastic range for soil-structure systems [13] and all the results showed significant effects of this phenomenon. Aviles and Perez-Rocha adopted resistance reduction factors for soil-structure systems using EPP behavior [6]. Several researchers investigated that soil-structure interaction for SDOF systems plays an important role in variation of ductility demands compared to the other counterparts considering rigid base [14, 16]. Recently, foundation uplift has been considered as a crucial factor in altering displacement demands especially when severe ground motions have been taken into account [15]. Ghannad and Jafarieh [5] concluded that foundation uplift results in displacement increments for both ranges of elastic and inelastic behavior; however, the selected hysteretic model just were deemed to be a simplified EPP behavior which in turn strength/stiffness degradation had been neglected [5]. The aim of this paper is to investigate simultaneous effects of soil-structure interaction and material nonlinearities focusing on strength/stiffness deterioration on displacement ratios of a SDOF system.

2. Methodology

The SDOF system is composed of a single mass attached on the top of a column with a nonlinear rotational spring at the bottom of the column, shown in Figure 1. The system has a rigid foundation mounted on Winkler Springs representing soil flexibility both in horizontal and vertical directions. The vertical springs are calculated in a such way that the rocking behavior coincides with the recommendations of FEMA 440 [16]. The vertical springs are defined to have zero strength in tension to be able to capture foundation uplift under severe ground motions.

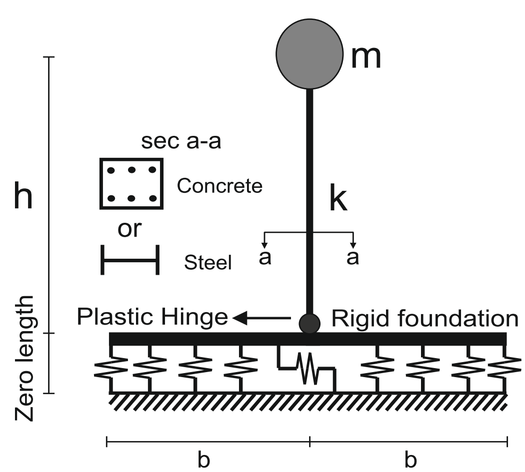


Figure 1: Model of soil-structure system

The system behavior can be better described using dimensionless parameters. The first ratio is the uplift index which is defined by Eq. (1). P_{iu} is the minimum lateral force that can cause uplift in the foundation and can be calculated by Eq. (2), and $(F_{el})_{Nouplift}$ is the maximum elastic force required in order to prevent foundation uplift. The ratio of resistance of the system (R_f) is defined by Eq. (3).

$$R_d = \frac{(F_{el})_{Nouplift}}{P_{iu}} \tag{1}$$

$$P_{iu} = \frac{m\ g\ b}{h} \tag{2}$$

$$R_f = \frac{F_y}{P_{iu}} \tag{3}$$

In Eq. (3), F_y is the yield force and m shows the mass of the superstructure. In order to describe the interaction between soil and structure, two other ratios which are common in technical literature are used. First, aspect ratio of the system (h/b) which means the ratio of the height to half the width of the foundation and the second ratio is the period of the system with flexible base (T_{ssi}) to that of the rigid base (T_{str}), shown by (T_{ssi}/T_{str}).

In order to study the effects of interaction and uplift, the following ratios according to Ghannad and Jafarieh's study [5] (Eq. (4)) are considered. In these equations, Δ shows the drift of the corresponding model calculated in different modes considering foundation uplift in the elastic and inelastic models.

$$C_{d1} = \frac{(\Delta_{el})_{Uplift}}{(\Delta_{el})_{NoUplift}}\ ,\ C_{d2} = \frac{(\Delta_{in})_{NoUplift}}{(\Delta_{el})_{NoUplift}}\ ,\ C_{d3} = \frac{(\Delta_{in})_{Uplift}}{(\Delta_{el})_{NoUplift}} \tag{4}$$

To simplify the modelling of Winkler's springs, the modelled foundation is a square with the dimension of $2b$ in accordance with the recommendations of FEMA440 [16]. The stiffness of the springs is defined by Eq. (5), (6).

$$K_x = 8/(2-\upsilon)G\ r_x\ ,\ r_x = \sqrt{A_f/\pi} \tag{5}$$

$$K_\theta = 8/3(1-\upsilon)G\ r_\theta^3\ ,\ r_\theta = \sqrt[4]{4I_f/\pi} \tag{6}$$

where, K_x and K_θ are the stiffness of the spring in x-direction and rotational direction, respectively. r_x and r_θ are the radius of the equivalent circular foundation for the translational displacement mode and the rotational displacement mode, respectively. υ is the Poisson's ratio of the soil which is assumed to be 0.4. Also, A_f is the area of the foundation and I_f is the moment of inertia of the foundation which are equal to $(2b)^2$ and $1/12\ (2b)^4$, respectively. Using equilibrium equations, the relation between rotational and vertical stiffness is derived using Eq. (7). As a result, by Eq. (6) the relation between horizontal and vertical stiffness can be computed by $K_x / K_{ver} = 3.75$.

$$K_{ver} = \frac{K_\theta}{110 b^2} = 7.5\ G\ b \tag{7}$$

The ratio of mass of the model to mass of the soil with the same volume in the system is presented by γ shown in Eq. (8) [16]. In this paper γ is assumed to be 0.15 as suggested by Velestos and Meek [12]. In Eq. (8), ρ is the density of the soil which is assumed to be 2000 kg / m^3. Noting that the assumptions just stated, the relationship between the mass of the model and geometry can be calculated via Eq. (9) which can be paraphrased with the aid of the aspect ratio in accordance to Eq. (10). All calculations are conducted for three heights of low, medium and high that respectively corresponds to 3, 9 and 18 meters. Ground motions used in this study include a set of 20 records of class C soil introduced in FEMA 440 [16].

$$\gamma = \frac{m}{\rho A_f\ h} \tag{8}$$

$$m = 30 b^2 h \tag{9}$$

$$m = 30 b^2 h = 150 b^3\ h/b \tag{10}$$

As mentioned, the effect of deterioration in strength and stiffness is also considered to more accurately measure the response of structures. For this purpose BILIN material in Opensees is used in this research [17]. The diagram of force-displacement of the model is shown in the Figure 2. Three parameters of θ_p and θ_{pc} and Λ show, respectively, the rotation after the point of yield to the capping point and rotation after capping and deterioration rate, are the main parameters which control deterioration, considering Lignos and Krawinkler studies [8]. Since these parameters have a rather high correlation, they are categorized in three general groups presented in Table 1.

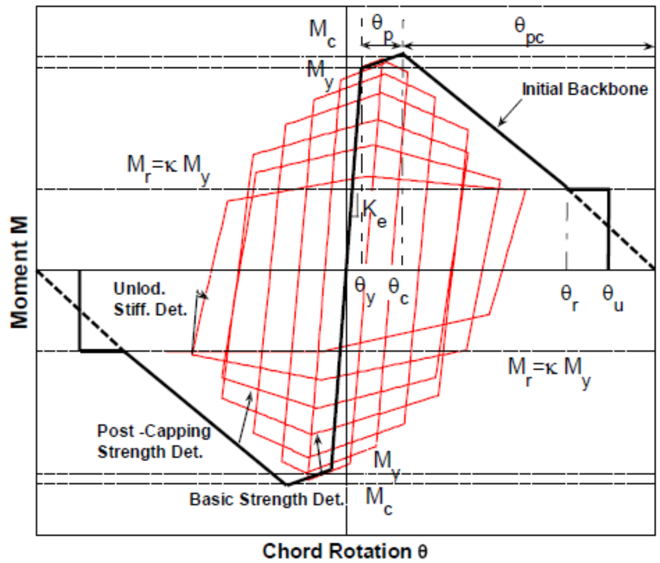


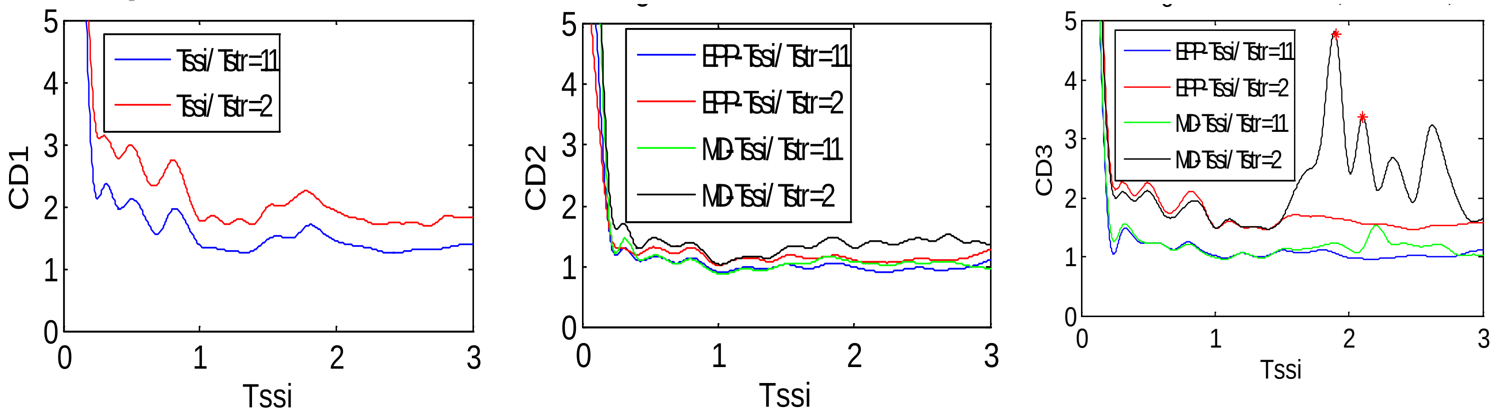
Figure 2: Modified IMK model

Table 1: Categorization of deterioration parameters

Degradation level	θ_p	θ_{pc}	Λ
High (HD)	0.01	0.1	0.4
Moderate (MD)	0.03	0.25	1
Low (LD)	0.06	0.4	2

4. Results

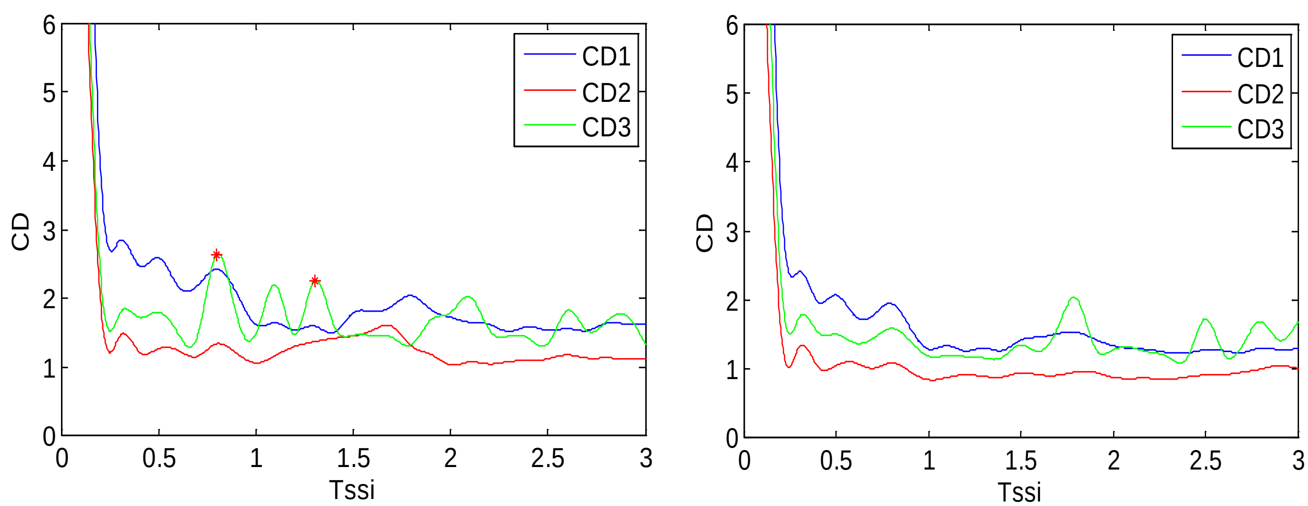
Figure 3 shows the effect of T_{ssi} $/T_{str}$ and deterioration of the model on C_{d1} , C_{d2} , C_{d3}. As can be observed in Fig. 3(a), the more the effect of soil-structure interaction, more flexible system, the more the deformation due to foundation uplift. Generally, according to Fig.3, as T_{ssi} $/T_{str}$ increases, the structure experiences higher deformations. The effect of deterioration can be seen in both Fig. 3(b) and (c) that show a drastic increase in displacement demands within longer periods. Moreover, when the effect of deterioration is taken into account, in some points, marked up with star signs, the structure experiences excessive deformations compared to that of the elastic model, meaning that the structure undergoes to the incipient collapse stage. Note that, this phenomenon cannot be observed when EPP model is used that is the case in most of the previous studies. It is interesting to note that the worst scenario for the displacement demands is obtained when the combination of soil-structure interaction, foundation uplift, and strength/stiffness deterioration is taken into account, as can be seen in Fig.3 (c).



(a) C_{d1} (b) C_{d2} (c) C_{d3}

Figure 3: Effect of moderate degradation and T_{ssi}/T_{str} on C_{d1}, C_{d2}, C_{d3} $(h/b=1, h=9, R_f=2.5, R_d=6)$

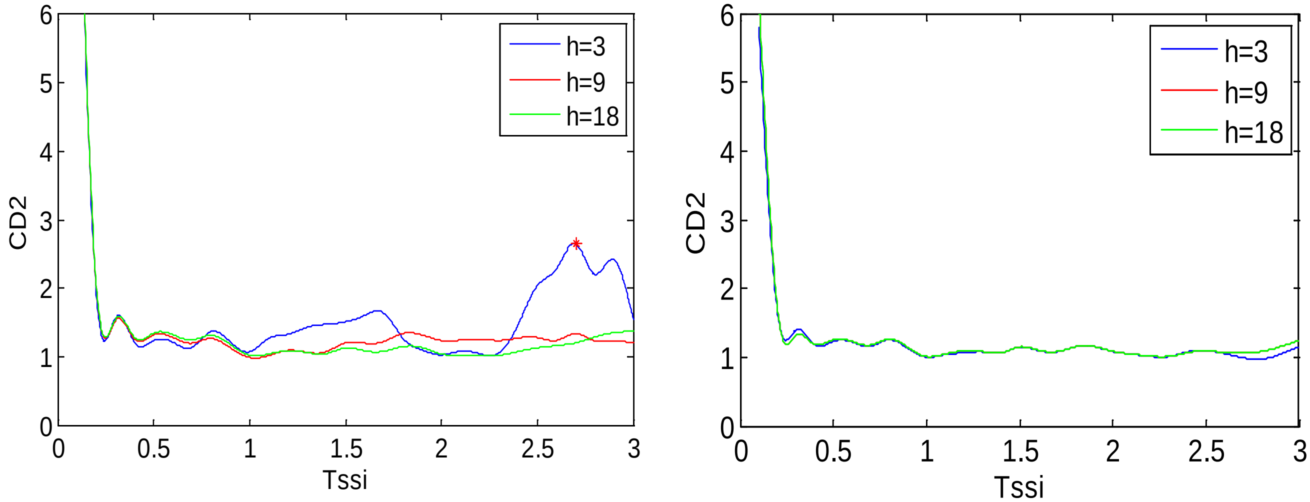
The effect of aspect ratio on C_{d1}, C_{d2}, C_{d3} is shown in Fig.4. As h/b increases, the effect of deterioration decreases, which means that a structure with a low aspect ratio experiences large deformations. According to Fig. 4(b) in higher aspect ratios, the deformation is smaller than a model with low aspect ratio. The effect of this parameter is more obvious in inelastic states rather than elastic ones.



(a) h/b=1 (b) h/b=5

Figure 4: Effect of aspect ratio on C_d with high degradation ($h=9, T_{ssi}/T_{str}=1.5, R_f=2.5, R_d=6$)

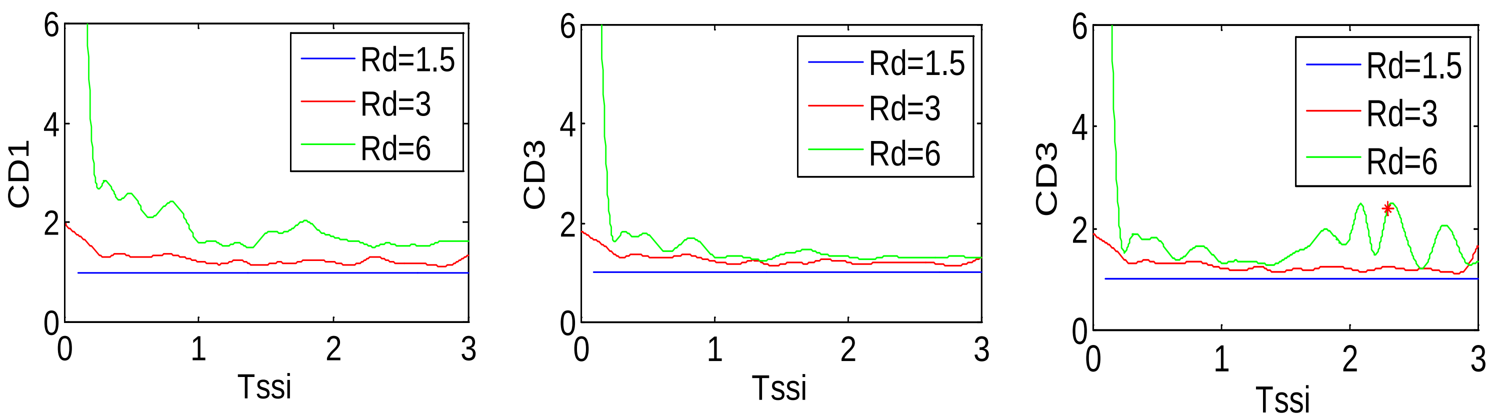
The effects of height on C_{d2} is presented in Figure 5. From Fig.5(a) and (b), the height is not of much importance in the EPP state of the model but considering the effect of deterioration in the model causes this parameter to become more important. It is shown that as the structure becomes shorter, the effect of deterioration and foundation uplift becomes more important specially in higher period.



(a) MD (b) EPP

Figure 5: Effect of degradation and height of model on C_{d2} $(h/b=1, T_{ssi}/T_{str}=1.5, R_f=2.5, R_d=6)$

Fig.6 shows variation of C_{d1} and C_{d3} with the index of uplift. As this index increases, the deformation of the structure, in both elastic and inelastic models, becomes higher. In fact, the less the resistance of the structure against uplift, the more the deformation. This shows the increasing effect of uplift on the deformations.



(a)C_{d1}, EPP (b)C_{d3}, EPP (c)C_{d3}, MD

Figure 6: Effect of moderate degradation and R_d on C_d $(h/b=1, T_{ssi}/T_{str}=1.5, h=9, R_f=2.5)$

5. Conclusion

The goal of this paper is to investigate the simultaneous effect of soil-structure interaction, foundation uplift and deterioration in resistance and stiffness of the model on the nonlinear response of the structures. For this purpose a SDOF model with rigid foundation including Winkler springs is used. Modified IMK model of opensees is implemented to account for the hysteretic behavior of the superstructure. The model is subjected to a set of 20 ground motions and the average response of the structure is presented. The principal conclusions are as follows:

- The deterioration in the resistance and stiffness of hysteretic model results in the increase of the structure response, especially in structures with higher periods. Moreover, in some cases the structure experiences the collapse state; this cannot be considered in models with EPP behavior.
- Generally, the interaction between soil and structure increases the structural response; this is more pronounced in the softer soils.
- In EPP model, the aspect ratio and height are two parameters that do not affect the structural response. However, in models with deterioration as aspect ratio and height increase, the displacement ratio decreases.
- Foundation uplift causes an increase in structural response. The less resistant the structure is to the foundation uplift, meaning higher uplift factor, the more intense this effect will be.

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