SEISMIC RESPONSE OF SOIL-PILE-STRUCTURE SYSTEMS WITH FOUNDATION UPLIFT

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ABSTRACT

The simultaneous effects of soil-pile-structure interaction, inelastic behavior of structure and foundation uplift on the seismic response of soil-pile-structure systems are studied in this paper. The considered model is composed of a single degree of freedom system including a column with a lumped mass on top that is placed on a rigid foundation mounted on a set of piles. Winkler springs are used for modeling piles with asymmetrical behavior under tensile and compressive loads. Moreover, a set of dampers parallel to the springs are used to account for soil-foundation compliance and material/radiation damping. The behavior of the structure is assessed for various tensile capacities of the piles. A new dimensionless parameter, Tension Index, is defined in this paper that controls the tensile capacity of the piles. In very extreme limits, for structures founded on very weak piles, the behavior of the structure is very similar to the structures with uplift allowed shallow foundations. In case of structures with very strong piles, no movement occurs in the piles, similar to the tied foundation structures. The results reveal that foundation uplift with low Tensile Index significantly increases the displacement ratios and decreases the drift ratios of soil-pile-structure systems in both elastic and inelastic regimes. More specifically, displacement ratios calculated in accordance with ASCE41-13 assuming fixed base condition, not accounting on pile-foundation uplift, might be underestimated once compared to the results of more realistic conditions.

Keywords: soil-pile-structure interaction, pile tensile capacity, foundation uplift, displacement ratios

1. INTRODUCTION

Performance-based earthquake engineering, as a novel design method, beckons a precision in analysis of structural systems. A customary assumption in the analysis of structures is fixed-based condition, which has been opposed by the experiences gained from recent earthquakes (Hokmabadi et al. 2014). Presumably, natural period elongation and increase in the effective damping are the primary effects of soil-structure-interaction (Novak 1974). Pioneer codes have offered methods to add these effects to analysis procedure (Applied Technology Council (ATC) 1978), which are the inspiration for more modern seismic codes (American Society of Civil Engineers (ASCE) 2010).

Shallow foundations have been the major concern of researchers in this field, and deep foundations are not much investigated. ASCE 41-13 offers simplified displacement ratios in the process of nonlinear static analysis in order to calculate the inelastic seismic response of structures having the elastic response (ASCE 2013). These equations are chiefly for structures in which foundation is tied to the soil, and the effect of deep foundations and foundation uplift is neglected. Several relationships for displacement ratios have been proposed by researchers. Veletsos and Newmark defined the so-called equal displacement rule, in which an equality of elastic and inelastic displacement responses is demonstrated (Veletsos and Newmark 1960). Ghannad and Jahankhah, posited that for structures without large

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inelastic deformations, considering SSI leads to less strength demands and as the inelastic deformation increases, it would result in lower strength reduction factors (Ghannad and Jahankhah 2007). This was later proved in a probabilistic framework in a study conducted by Mirzaei et al. (2015). Miranda analyzed more than 3000 elastic-perfectly plastic (EPP) models and derived equations which related inelastic and elastic responses (Miranda 1993a, 1993b, 1999). Behmanesh and Khoshnudian illustrated that addition of SSI effects to analysis process would result in more inelastic displacement than the elastic one in the entire period (Behmanesh and Khoshnudian 2008). Tabatabaieifar et. al. (2014) concentrated on mid-rise buildings and investigated the elastic and inelastic structural responses of these buildings including SSI. Foundation uplift is the missing point of all these above-mentioned studies, yet this phenomenon is proved to be very much probable in severe ground motions. Dolatshahi et.al. exemplified that foundation uplift causes more displacement ratios in both elastic and inelastic regimes, using an uplift-allowed single-degree-of-freedom (SDOF) model with EPP hysteresis and degradation behavior (Dolatshahi et al. 2017).

Numerical methods such as Finite Element (FE) (Luo et al. 2016; Cai et al. 2000) and Boundary Element (Guin and Banerjee 1998) methods, and the Winkler springs method (Boulanger et al. 1999) are three prevalent methods to consider SPSI. In a study on the response of an arched structure by FE method, Kildashti et al. claimed that a reduction in the overturning moment of the whole structure is forthcoming if SPSI is taken into action (Kildashti et al. 2016). Beam on nonlinear Winkler foundation (BNWF) model is the third commonly used method based on the study originally conducted by Winkler. Later, Matlock et al. considered nonlinear supports for a pile to model the soil effect and developed the p-y curves (Matlock et al. 1978). To take advantage of both FE and BNWF methods, Taherzadeh et al. offered simple formulas for horizontal and rocking stiffness (NISTGCR-12-917-21 2012) and damping coefficient of pile groups (Taherzadeh et al. 2009).

Various parameters such as structural nonlinearity, SSI, SPSI and foundation uplift, affect the seismic response of structures, and more specifically the inelastic displacement ratio (IDR) which is the focus of this study. The main purpose of this paper is to scrutinize the seismic response of structures with shallow or deep foundations by modeling SSI and SPSI effects. For this purpose, tensile index, as a new dimensionless parameter is introduced which determines the tensile load bearing capacity of the pile group. Very low values of tensile index represents a structure with uplift-allowed shallow foundation. On the other hand, a very high value of tensile index is equivalent to the structure with pile supported foundation with no pile slippage. Seismic behavior of SDOF models with pile foundations is investigated using BNWF method by variation of tensile index and other common dimensionless parameters over a probable range. In the following, first the model assumptions including the SPSI model and the computational algorithm are explained. Then, various displacement ratios are calculated for elastic or inelastic response of the structures. Finally, the results are compared with the seismic codes predictions and recommendations are made.

2. MODEL ASSUMPTIONS

2.1 Soil-pile-structure Interaction Model

The simplified SDOF model used for all analyses in this paper is shown in Figure 1. The structure consists of a column which is located on a rigid foundation with the width of $2b$. A plastic hinge with EPP behavior is embedded at the base of the column to account for the nonlinear response of the structure. The equivalent period and damping of the rigid-based structure is $T_{str}$ and $\xi_{str}$, respectively. The effective length of the piles, $l_0$, and the equivalent radius of the pile cap, $R_f$, are calculated using equations provided by Taherzadeh et al. (Taherzadeh et al. 2009). Following the studies of Taherzadeh et al., the pile group is converted to a simplified spring, $k_g$, and damper, $c_g$, at the top of the pile. Therefore, in order to model the flexible-based system, vertical Winkler springs are used for modeling of the rocking mode representing the effect of piles, Figure 1b. A number of dampers parallel to the springs are used to model the correct boundary conditions and to simulate Radiation damping (John
The stiffness of the vertical springs in Figure 1b is derived by transformation of the rocking stiffness, into the distributed uniaxial vertical springs. For simplicity, it is also assumed that the foundation is confined by soil, which causes no foundation sway motion.

Figure 1: Soil-pile-structure basic model (a) SPSI system (b) SPSI equivalent model

The piles have an asymmetrical behavior under tensile and compressive displacements. The nonlinear behavior of the piles follows an elasto-plastic behavior under tensile loads due to the friction between the pile skin and the soil. However, under compressive loads it is assumed that the stiffness of the piles is much higher than that of the tensile behavior because of the pile tip and pile cap contact to the soil; please see Figure 1b for more information. The summation of the tensile strength in all piles are shown by $F_t$. The magnitude of this parameter is controlled by variation of the proposed dimensionless ratio defined in Equation 1, tensile index ($R_t$).

$$R_t = \frac{F_t}{mg}$$  \hspace{1cm} (1)

2.2 Model Parameters

The most important dimensionless ratios in soil-structure interaction problems are periodic ratio ($T_{spsi}/T_{str}$) and aspect ratio ($h/b$) representing two obvious interaction effects. Aspect ratio, is the ratio of the height to the half width of the foundation and the periodic ratio is the ratio of the period of the system with the flexible-base ($T_{spsi}$) to the structure with a fixed-base ($T_{str}$), which is shown by $T_{spsi}/T_{str}$. Higher periodic ratios cause an increase in the period of the model and in most cases, increase in the effective damping of the structure. In this study, aspect ratio varies between one, two and five to represent typical slender, normal and squatty buildings, respectively. The periodic ratio is also selected between 1.1, 1.5 and 2.0 representing almost a fixed, flexible and very soft base model, respectively.

$p'_{iu}$ represents the minimum lateral load needed for pile slippage and foundation uplift. This parameter can be calculated by writing a moment equilibrium equation according to Figure 2 at the unset of uplift, shown in Equation 2. On the other hand, $p'_{over}$ represents the state of complete overturning of the structure that can be calculated using Equation 3. Similar formulations are already developed for structures with shallow foundations with no tensile capacity by Ghannad and Jafarieh (2014).

$$p'_{iu} = \frac{mgb}{3h}(1 + R_t)$$  \hspace{1cm} (2)

$$p'_{over} = \frac{mgb}{h}(1 + R_t)$$  \hspace{1cm} (3)
The resistance ratio $R_f = \frac{F_y}{p_{tu}'}$ is defined by dividing the yield force of the structure ($F_y$), to the minimum uplift force. One can categorize the nonlinear response of the structure based on $R_f$: if the ratio is below one, i.e. there is no uplift, and the structure enters the nonlinear behavior. When $R_f$ is between one and three, pile uplift and structure nonlinear behavior both exist. $R_f$ of more than three represents the structure that remains elastic since the yield force is larger than the overturning force of the model.

Dolatshahi et al. (2017) used parameter $R_d = \frac{(F_{el})_{Nouplift}/p_{tu}}{p_{iu}}$ to scale the ground motions. $p_{iu}$ in the denominator is equivalent to the minimum force to cause uplift for shallow foundations, i.e., set $R_t=0$ in Equation 2. Parameter $R_u = \frac{(F_{el})_{Nouplift}/p_{iu}'}{F_y}$ represents uplift index for both shallow and deep foundations. The relation between these similar parameters is described by Equation 4. Obviously, if $R_t$ reaches zero as a limit state, the foundation is equivalent to a foundation without any tensile strength and thus completely prone to uplift. Also, a very large $R_t$ is equivalent to a tied foundation with no uplift. Equation 5 shows how uplift index and resistance ratio affect strength reduction factor. In this paper parameters $R_f$, $R_d$, $R_u$ and $R_\mu$ are named as force dimensionless ratios.

\[
R_u = \frac{R_d}{(1 + R_t)} \tag{4}
\]

\[
R_\mu = \frac{(F_{el})_{Nouplift}}{F_y} = \frac{R_u}{R_f} \tag{5}
\]

Parameter $\gamma$, shown in Equation 6, is used in order to relate the mass of the superstructure ($m$) and the corresponding equivalent volume. In this equation $A_f$ represents the foundation area. In this equation, $\rho$ is the density of the soil and is assumed to be 1800 kg/m$^3$ and the mass ratio, according to Veletsos & Meek, is assumed to be 0.15 (Veletsos and Meek 1974).

\[
\gamma = \frac{m}{\rho A_f h} \tag{6}
\]

### 2.3 Computational Algorithm

In this study, the response of the structure is investigated by comparing the computed displacement at top of the column, in various conditions. Generally, this displacement is investigated by total displacement or drift ratio, both of which have great applications in structural design (ASCE 2013). Here, a series of displacement ratios, Equations 7, 8, 9 and 10 are utilized. The first two ratios, Equations 7 and 8, investigate the total displacement, and Equations 9 and 10 investigate the drift ratios. In these equations, $\Delta$ is the total displacement of the model and $\Delta^{dr}$ represents drift of the model which is
calculated in different conditions considering elastic or inelastic behavior for the model. The term “No uplift” used in the denominator is equivalent to a very large $R_t$.

\[
C_{pd1} = \frac{(\Delta_{el})_{uplift}}{(\Delta_{el})_{NoUplift}}
\]

\[
C_{pd2} = \frac{(\Delta_{in})_{uplift}}{(\Delta_{el})_{NoUplift}}
\]

\[
C_{pd1}^{dr} = \frac{(\Delta_{el})^{dr}_{uplift}}{(\Delta_{el})^{dr}_{NoUplift}}
\]

\[
C_{pd2}^{dr} = \frac{(\Delta_{in})^{dr}_{uplift}}{(\Delta_{el})^{dr}_{NoUplift}}
\]

The first displacement ratio, $C_{pd1}$, investigates the effect of tensile capacity of the piles on the response of a linear system. The second total displacement ratio, $C_{pd2}$, considers the simultaneous effects of pile tensile strength and inelasticity of the structure.

All results of this paper are obtained by averaging the results of 20 response history analyses of the records suggested by FEMA 440 which belong to soil class (C) (Federal Emergency Management Agency (FEMA) 2005).

3. RESULTS

3.1 Elastic

In this section, variation of total and drift ratio is investigated for various tensile index and dimensionless ratios assuming that the behavior of the structure is elastic. Figure 3 shows the effect of tensile index, $R_t$, on the response of the structure in the elastic regime, both total displacement (Figure 3-I) and drift ratio (Figure 3-II), for various periodic ratios. For both total displacement and drift ratio the curves corresponding to $R_t = 5$ are unity. This is due to the fact that $R_t = 5$ represents very strong piles that do not slip under seismic loads. From Figure 3, lower values of tensile index increase the total displacement ratio, since pile slippage participate in the total displacement of the structure. Also, lower values of tensile index decrease the drift ratio as pile slippage in this case acts as a fuse and does not let further forces be transferred to the structure.

By comparison of Figure 3a to Figure 3c, it can also conclude that increase of the periodic ratio also has the same influence on the total displacement and drift ratio as of the tensile index. This is well practiced in the soil-structure interaction literature since increase of the periodic ratio represents a more flexible base that leads to larger displacements of the structure (Dolatshahi et al. 2017).
Figure 3: $C_{pd1}$ and $C_{pd1}^{dr}$ for different soil-pile-structure systems and $R_z$ ($h/b = 2, R_d = 6$, (a) $T_{spsi}/T_{str}=1.1$, (b) $T_{spsi}/T_{str}=1.5$, (c) $T_{spsi}/T_{str}=2$, (I) $C_{pd1}$, (II) $C_{pd1}^{dr}$)

Figure 4 shows $C_{pd1}$ of the models with various periodic ratio, aspect ratio, $R_d$, and tensile index values. Generally, larger periodic ratio, aspect ratio, and $R_d$ lead to larger displacement ratios regardless of the tensile index value. Larger aspect ratios trigger higher rocking mode and consequently larger displacement ratios. As tensile index increases the total displacement ratio decreases for all cases.
Figure 4: Variation of $C_{pd1}$ for different soil structure systems and $R_t$ ($h/b = 2, R_d = 8, T_{spsl}/T_{str}=1.5$, (a) $R_d = 8, h/b = 2$, (b) $R_d = 8, T_{spsl}/T_{str}=1.5$, (c) $h/b = 2, T_{spsl}/T_{str}=1.5$, (I) $R_t=0.001$, (II) $R_t=0.1$, (III) $R_t=1$, (IV) $R_t=5$)

3.2 Inelastic

In this section, both the nonlinear behavior of plastic hinge and inelastic behavior of the piles are the source of nonlinearity in the models. In the following, the effect of tensile index and SPSI parameters are examined. Figure 5 demonstrates the effect of tensile index on both elastic and inelastic displacement ratios. According to Figure 5a, that shows the elastic ratio, $C_{pd1}$ is higher than unity for the cases with low tensile index. For the cases in Figure 5(a, III) and Figure 5(a, IV) with very large tensile index, $C_{pd1}$ is unity in all period ranges. This observation shows that the models with the tensile index of higher than unity have very strong piles that do not allow any pile slippage and uplift in the foundation. Figure 5a also compares the elastic, shown with the black line, and inelastic ratios, the red lines. It can be observed that in the cases with foundation uplift, low values of $R_t$, the inelastic ratio is always lower than the elastic ratio. By substituting Equation 5 into 4 it can be concluded that:

$$R_f = \frac{R_d}{(1 + R_t)R_\mu}$$

(11)

This equation shows that $R_f$ for the cases of Figure 5a is 2.0, 1.8, 1 and 0.3, respectively, from top to bottom. It also shows that the models with $R_f$ lower than unity do not have any uplift. Models with $R_f$ higher than unity experience a combination of foundation uplift and structural nonlinearity. The elastic and inelastic drift ratios are shown in Figure 5b. Clearly, for the elastic models the drift ratio is below unity for all cases. The inelastic drift ratios are always higher than the elastic ratios due to the nonlinear response of the structure.
As mentioned, periodic ratio and aspect ratio are among the most influential factors in SPSI. Figure 6 investigates the effect of these two parameters on the nonlinear displacement ratio, $C_{pd2}$. From Figure 6a to Figure 6c the effect of SPSI is pronounced by increasing the periodic and aspect ratio. In Figure 6a, $C_{pd2}$ for all values of pile tensile capacity is similar. The reason is attributed to the fact that in this case the nonlinear behavior is solely concentrated at the nonlinear behavior of the structure and no uplift has occurred in the pile and foundation of the structure. In the cases of Figure 6b and Figure 6c where SPSI is influential, decreasing the tensile index amplifies the nonlinear displacement ratio. In all three cases of Figure 6a, Figure 6b, and Figure 6c, $C_{pd2}$ is similar for $R_t=1$ and 5. For $R_t=1$ and 5 the calculated $R_f$ would be less than unity that implies the nonlinear behavior of the structure is dominant compared to the nonlinear behavior of the piles. Note that $R_t=0.001$ is equivalent to a model completely prone to upliftand $R_t=5$ is similar to a model with a foundation tied to the ground. Therefore, any other cases with various tensile index lie between these two limit states.

Figure 5: $C_{pd}$ and $C_{pd}^d$ for various $R_t$ ($h/b = 2$, $R_d = 6$, $R_d' = 3$, $T_{ssl}/T_{str} = 1.5$, (a) $C_{pd}$, (b) $C_{pd}^d$, (I) $R_t=0.001$, (II) $R_t=0.1$, (III) $R_t=1$, (IV) $R_t=5$)
Figure 6: $C_{pd2}$ for various $R_t$ and SPSI parameters ($R_d = 8, R_\mu = 3, \text{(a)} T_{spsi}/T_{str}=1.1, h/b = 1, \text{(b)} T_{spsi}/T_{str}=2, h/b = 1, \text{(c)} T_{spsi}/T_{str}=2, h/b = 5, \text{(I)} C_{pd2}$)

4. COMPARISON WITH CODE

The target displacement, $\delta_t$, in the nonlinear static procedure for a shallow foundation with no uplift can be calculated using Equation 12 and 13, following ASCE41-13 (ASCE 2013). In this code no prediction is provided specifically for displacement ratio of soil-pile-structure systems. $C_1$, in this equation, is the ratio of inelastic to elastic displacement, equivalent to the definition of $C_{pd2}$ in this paper. In calculation of $C_1$ in ASCE41-13 the effects of foundation uplift in displacement ratio are ignored.

\begin{equation}
\delta_t = C_0 C_1 C_2 S_a T_e^2 g \frac{4\pi^2}{T_{spsi}^2} g
\end{equation}

\begin{equation}
C_1 = 1 + \frac{R_\mu - 1}{aT_e^2}
\end{equation}

where, $C_0$ is the modification factor to relate spectral displacement of an equivalent SDOF and $C_2$ is modification factor to represent the effect of pinched hysteresis shape, cyclic stiffness degradation and strength deterioration on the maximum displacement response. Effective fundamental period ($T_{spsi}$) and response spectrum acceleration at the effective fundamental period and damping ratio of the structure is $T_e$ and $S_a$, respectively.

Here, in Figure 7 the code results are compared with that of the numerical models considering various $R_\mu$, tensile index, periodic ratio, and aspect ratio. The results clearly indicate that when foundation uplift is not significant, total displacement of the models are very close to the code prediction for shallow foundations. For the case of Figure 7(I), $R_\mu=4$, the behavior of the structure is dominated by nonlinear behavior of the structure and this is the reason why the code prediction is very close to the numerical results. Similarly, for the case with very low SPSI effects in Figure 7a no foundation uplift occurs and again the response of the structure is exclusively controlled by the nonlinear behavior of the structure. In this case again the code prediction is very close to the numerical results. As much as the SPSI effects are magnified from Figure 7a to Figure 7c and $R_\mu$ is decreased from Figure 7(I) to (III) the effect of foundation uplift is more pronounced and the results more deviate from the code prediction. More specifically, for the case of Figure 7(c, III) the numerical results very much deviate from the code prediction for low values of tensile index. In this case, in some period ranges, the nonlinear displacement ratio is more than twice of the code prediction.
Figure 7: Comparison with code \( R_d = 8 \), (a) \( T_{spi}/T_{str} = 1.1 \), \( h/b = 1 \), (b) \( T_{spi}/T_{str} = 2 \), \( h/b = 1 \), (c) \( T_{spi}/T_{str} = 2 \), \( h/b = 5 \), (I) \( R_\mu = 4 \), (II) \( R_\mu = 3 \), (III) \( R_\mu = 2 \)

5. SUMMARY AND CONCLUSION

A simplified model of the soil-pile-structure system is investigated in this paper under seismic loads. The model consists of a column and mass located on a rigid foundation. Winkler springs are used to simulate the flexibility of the soil-pile system. A dimensionless parameter, namely tensile index, is defined to vary the tensile strength of the piles. The model is subjected to 20 response history analyses and the average of the responses is calculated for various ranges of dimensionless ratios. Elastic and inelastic displacement and drift ratios are presented for various conditions of dimensionless parameters and finally the results are compared with the code prediction for the shallow foundation with no uplift, the only prediction available in ASCE 41-13. The main conclusions are as follows:

- Foundations with lower tensile index are more prone to uplift, and thus these models experience higher displacement ratios.
- Foundation uplift acts as a fuse controlling the input force into the structure.
- Foundation rocking and structural drift are two components of total displacement ratio. In elastic models, foundation rocking has a higher participation compared to the structural drift.
- ASCE41-13 predictions are very close to the numerical results for the cases with no foundation uplift. In models with foundation uplift, low tensile index and high aspect and
periodic ratio, the numerical results deviate from the code prediction up to 100%. More research should be conducted in future to provide predictive equations for soil-pile-structure uplift-allowed systems.

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