INFLUENCE OF SOIL NONLINEARITY AND LIQUEFACTION ON DYNAMIC RESPONSE OF PILE GROUPS

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ABSTRACT

Nonlinearity of soil media plays an important role in soil-pile interaction problems. Moreover, during strong excitations, the soil may liquefy and this drastically affects the response of pile groups. In this study, a simple elasto-plastic constitutive model (the Drucker-Prager soil model) has been used to investigate the effect of soil nonlinearity in a three-dimensional soil-pile system. The model for the soil-pile system is idealized using 3-D finite elements. Kelvin elements are used at the boundary, simulating radiation conditions at infinity. The model and process of computation is verified using established results in literature.

To investigate the effect of liquefaction, effective stress approach has been adopted. The soil medium has been considered undrained so that the pore pressure may develop. The study has been performed for single pile as well as for pile groups. First, the effect of nonlinearity on the dynamic stiffness of the soil-pile system has been examined. Next the study has been extended for probable liquefaction in the soil medium.

KEYWORDS: Pile Groups, Nonlinearity of Soil, Dynamic Loading, Finite Elements, Liquefaction

1. INTRODUCTION

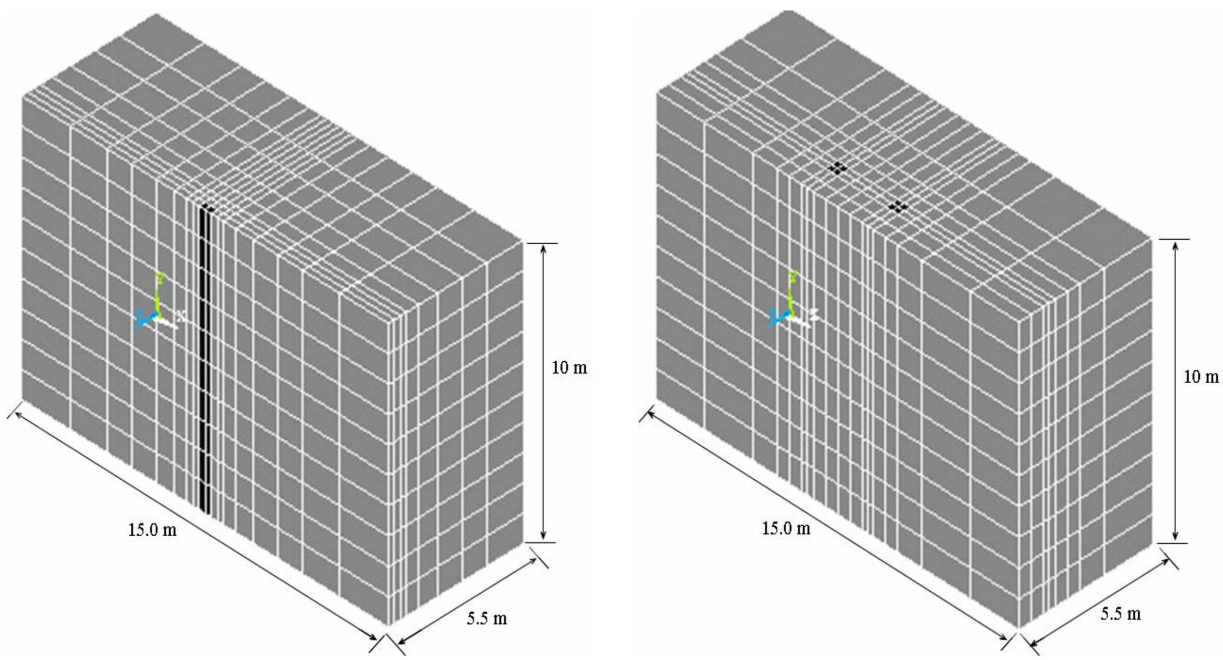
Recent earthquakes causing catastrophic damages to the existing structures have raised concern about the proper seismic design of the pile supported structures. Most of the studies reported in literature on soil-pile interaction problem have been performed either for linear or equivalent nonlinear case. Since the behaviour of the soil during strong excitations is highly nonlinear, the nonlinearity of soil plays an important role on the dynamic response of the soil-pile system. Also during recent past earthquakes e.g. Niigata (1964), San Fernando (1971), Kobe (1995), it was observed that many pile foundations collapsed due to liquefaction of the surrounding soil medium. However, very few studies are reported to investigate the effect of soil liquefaction on the pile foundation.

Novak (1974) has used subgrade reaction approach to deal with pile foundation including pile groups. Kaynia and Kausel (1982) have analysed piles and pile groups in a layered half space using Green's function formulation. Wu and Finn (1997) have done a time domain nonlinear quasi three-dimensional analysis for pile groups. An advanced soil-plasticity model (HiSS model) for clay was incorporated in the three-dimensional formulation by Maheshwari *et al*. (2004), however the liquefaction has not been considered. Liyanapathirana and Poulos (2005) modeled piles in liquefying soil with dynamically loaded beam on Winkler foundation. The model being based on Winkler's hypothesis, it may not be truly represent the three dimensional behaviour of the soil-pile system. Using the numerical model proposed by Seed *et al.* (1976), Maheshwari *et al.* (2008) presented the effect of liquefaction on response of pile foundation for vertical vibration.

In the present study, a full three dimensional nonlinear dynamic analysis is performed to investigate the effects of nonlinearity on the dynamic response of the soil-pile system. Study has also been conducted to evaluate the effect of probable liquefaction on the dynamic response for the pile groups. The objective of this paper is to underline the effect of soil nonlinearity and the probable liquefaction on the dynamic stiffness of the soil-pile system. The study is being extended for nonlinear seismic response of pile foundations.

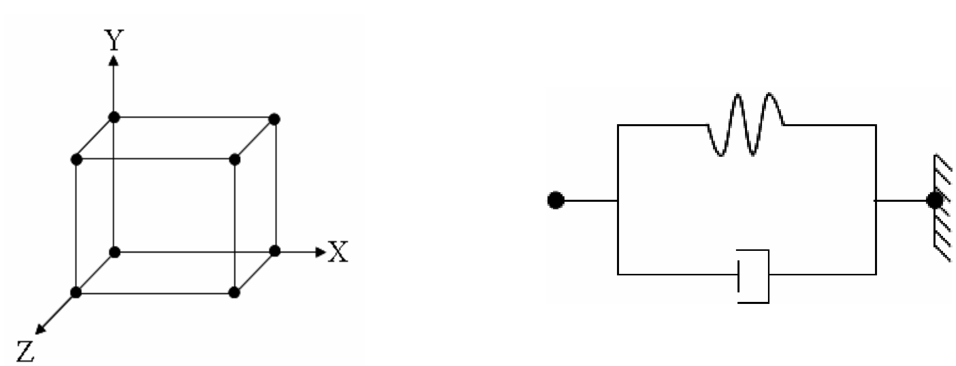
2. FINITE ELEMENT MODELING

The soil-pile system is modeled using finite elements. End bearing piles have been used for this study. A full three dimensional finite element model is considered. However, taking the advantage of symmetry only one-half of the actual models was built; this dramatically improves the efficiency of computation. Finite element half model of a single pile and 2 × 2 pile groups were developed. All piles are square in cross section (with dimension d), and socketed in the bedrock. For pile groups, three pile spacing (centre to centre) ratios s/d = 2, 5 and 10 were considered. Figure 1 shows the three dimensional finite element mesh for a single pile and a 2 × 2 pile group with spacing ratio s/d = 5. Since no commercial package is available to perform this nonlinear analysis considering liquefaction, a program has been developed in MATLAB (version 7.1) for performing nonlinear analyses. Soil-pile systems have been modeled and analyzed in the developed 3-D program.



(a) Single pile (b) 2 x 2 pile group with s/d = 5

Figure 1: Three-dimensional finite element meshes for the soil-pile system



(a) Eight-noded block element for soil and pile (b) Two-noded Kelvin element

Figure 2: Elements used for modeling

The soil and piles are modeled using eight-noded hexahedral elements (Figure 2a). Each node has three translational degrees of freedom in all three i.e. X, Y, and Z coordinate directions. Since with eight-noded solid elements, piles under bending deformations may show the shear locking phenomenon, for the pile elements the extra shape functions (ESF) are used (Cook *et al*. 1989). For all the models elements are kept very small near the pile(s) and gradually increase in size moving away from the pile(s). The size of the elements near the pile is kept less than one sixth of the wave length that corresponds to the highest frequency of 20 Hz. To simulate an infinite soil medium, Kelvin elements (spring and dashpot as shown in Figure 2b) are attached in all three directions (i.e. X, Y and Z) along the mesh boundaries to model the far field conditions. For transient excitation, the stiffness and damping constants of the Kelvin element can be evaluated based on the predominant frequency of loading. The constants of the springs and dashpots of the Kelvin elements were calculated using the solution developed by Novak and Mitwally (1988). Spring and dashpot constants are adjusted to match more rigorous solutions by choosing a suitable cutoff frequency.

3. VERIFICATION

The model and developed algorithm (in MATLAB) is verified with the results presented in the literature. This is performed first for static loading and then for dynamic loading for elastic case. The verification is presented in the following sections.

3.1. For Static Loading

For this case, a single end bearing pile is loaded horizontally at the pile head and the displacement is computed at the same location. Extra shape functions (ESF) are considered for the pile elements to account for the shear locking phenomenon. For this analysis the same material and geometrical properties are used as reported in Bentley and El Naggar (2000). Figure 3 compares static lateral pile head deflection values with those presented by Poulos and Davis (1980), Trochanis *et al.* (1991), Bentley and El Naggar (2000) and Maheshwari *et al.* (2004). It can be observed that the results obtained from the present study are in good agreement with those presented by Trochanis *et al.* (1991) because the square piles are used in both these studies. The deflection shown by the present study is greater than those shown by Maheshwari et al. (2004) because the ESF was not considered in that study.

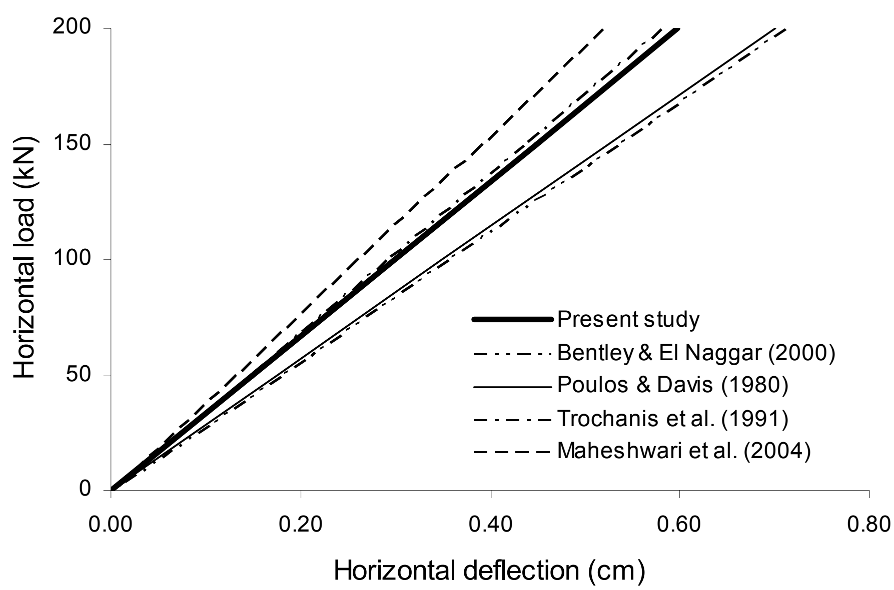


Figure 3: Verification for static loading on single pile

3.2. For Dynamic Loading

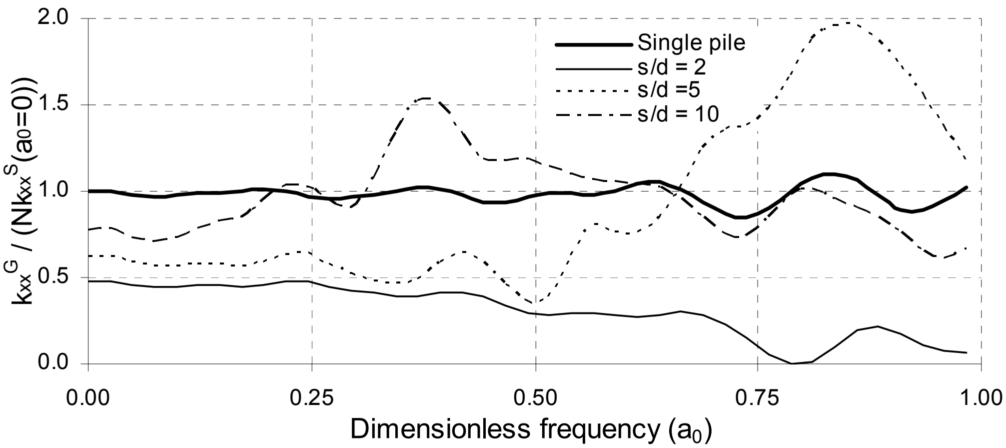
Impedance function or dynamic stiffness (K_c) for horizontal vibration has been calculated for the soil-pile system. In the frequency domain, the impedance function at a particular frequency ω is given by:

$$K_c = (K_{st} - \omega^2 M) + i\omega C \tag{3.1}$$

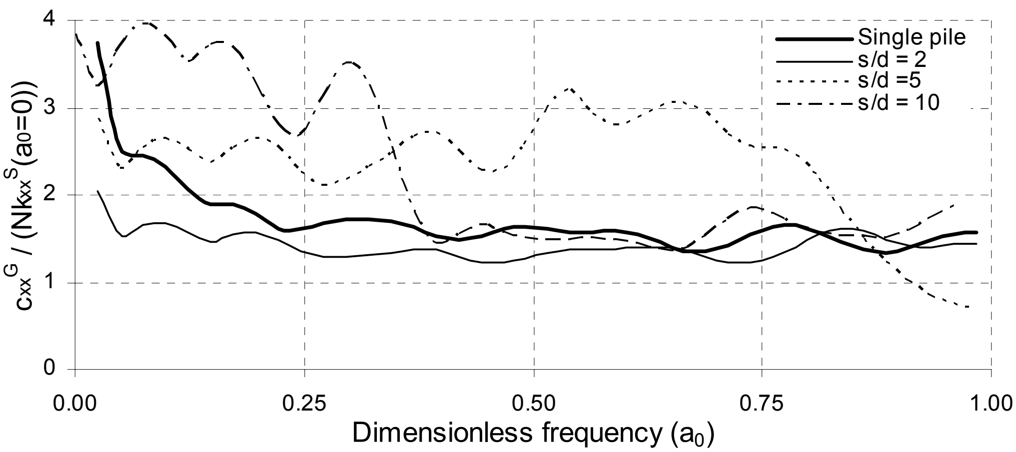
Where K_{st} is the static stiffness of the system, M mass of the system and C is the damping of the system.
Eq. (1) can be written as

$$K_c = k + i\, a_0 c \tag{3.2}$$

The real part, $k = K_{st} - \omega^2 M$ represents the stiffness (including the effect of inertia) and the imaginary part $k' = a_0 c$ represents damping of the system. Here, dimensionless frequency is $a_0 = \omega d/V_s$, where V_s is the shear wave velocity of the soil medium. For verification purpose these real and imaginary parts are determined by applying a harmonic load of different frequency at the centre of pile cap (or at the pile head for single pile) and computing the displacements at the same point. For the pile group all the pile heads are rigidly connected to the pile cap. The dimensionless parameters used in computation are: $E_p / E_s = 1000$; $\nu_p / \nu_s = 0.625$; $\rho_s / \rho_p = 0.70$. Here E stands for elastic modulus, ρ stands for mass density and ν for Poisson's ratio with $\nu_s = 0.4$. The subscript p is for pile property and s is used for soil property. Material damping considered for soil is hysteretic in nature and assumed to be 5%. No damping is considered in pile elements.



(a) Real part of dynamic stiffness



(b) Imaginary part of dynamic stiffness

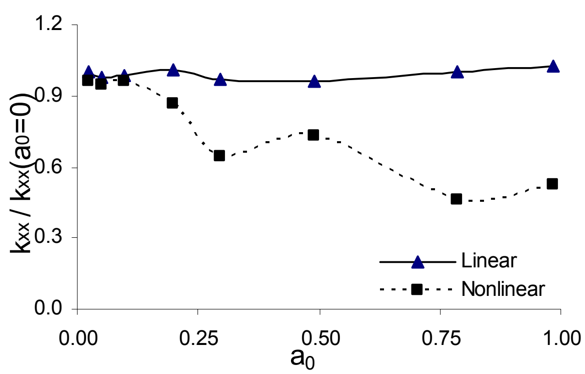
Figure 4: Verification for elastic dynamic stiffness

The real part, k and imaginary parts, c of dynamic stiffness for horizontal vibration are normalized with respect to horizontal static stiffness of a single pile multiply by the number of piles (i.e. N = 4). The normalized real part and imaginary parts are plotted against dimensionless frequency in Figure 4a and Figure 4b respectively.

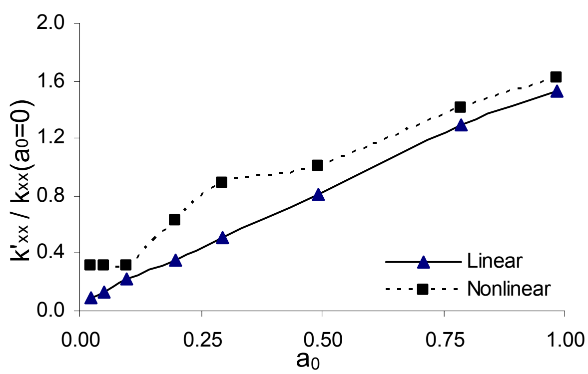
The plots in Figures 4a and 4b show the close resemblance of the results with Kaynia and Kausel (1982) as well as with Maheshwari *et al.* (2004). The slight deviations of the results with Kaynia and Kausel (1982) are due to the different solution methodology. Kaynia and Kausel (1982) used rigorous analysis formulation based on Green's functions and the results presented in the present study are with finite element analysis and Kelvin elements as radiation boundary. The plots also show that the behaviour of a pile group for very close spacing (e.g. s/d = 2) and up to a certain frequency is very similar to that of a rigid footing; i.e., stiffnesses decreases with frequency and becomes negative, indicating a behaviour dominated by inertia effects. The interaction effects among the piles start to dominate the overall behaviour of the group as frequency exceeds certain limit. The transition between the two modes of behaviour occurs at smaller frequencies as the distance between the piles increases (e.g. for s/d = 5 and s/d = 10, this threshold frequencies are a_0 = 0.84 and a_0 =0.37 respectively).

4. EFFECT OF NONLINEARITY ON DYNAMIC STIFFNESS

The effect of material nonlinearity of the soil is investigated. To evaluate the effect of soil plasticity on pile response, the soil was modeled as an elastoplastic material using the Drucker-Prager failure criteria (Chen and Baladi, 1985). It is assumed that there is no strain hardening and therefore no progressive yielding is considered. Since nonlinearity cannot be dealt in frequency domain, the nonlinear analyses are performed in the time domain. As the results of nonlinear analysis are very much dependent on the amplitude of the input excitation, it is necessary to specify it. In the present study a harmonic lateral load of amplitude P_0 = 100 kN is applied at the pile cap and resultant displacement time history at the same point is computed. From this steady state response, the peak amplitude of the response and its time lag with respect to the applied force amplitude are noted at the pile cap. With these observations, real part k and imaginary part k′ (Eqn. 3.2) of the dynamic stiffness of the soil-pile system can be determined. The real and imaginary parts of dynamic stiffness for horizontal vibration are normalized with respect to horizontal linear static stiffness of a single pile (k_{xx}) multiply by the number of piles. The results for single pile are shown in the Figure 5. Figures 6, 7 and 8 show the results for 2 × 2 pile group with s/d = 2, 5 and 10, respectively. It may be noted that no initial confining pressure was used in all these results. Material Properties used are: E_p = 20 GPa; E_s = 20 MPa; ν_p = 0.25; ν_s = 0.40, ρ_s / ρ_p = 0.70 with ρ_s = 1750 kg/m^3, cohesion C = 20 kPa; angle of internal friction $\phi = 30^0$. Material damping of soil is taken as 5%.



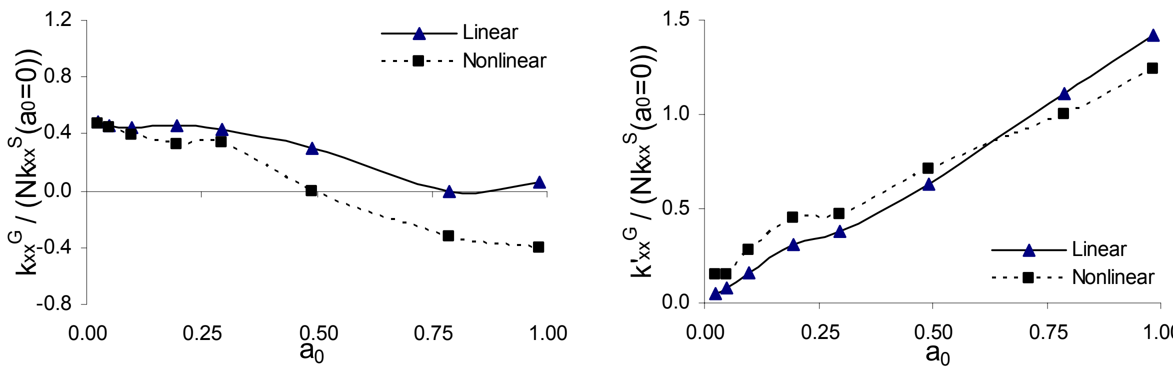
(a) Real part of dynamic stiffness



(b) Imaginary part of dynamic stiffness

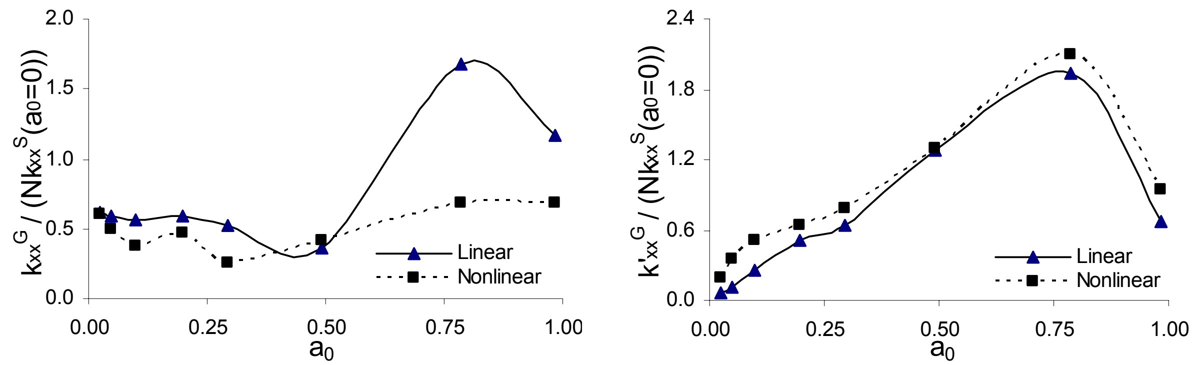
Figure 5: Comparison of linear and nonlinear dynamic stiffness of single pile

From Figures 5-8, it can be observed that due to nonlinearity the stiffness reduces significantly but the damping increases slightly. Also it can be observed that due to nonlinear effects the peak value (in the real part), which was due to the group effect is significantly reduced. Thus nonlinearity reduces the group effect considerably e.g. the peak value for s/d = 5 is decreased from 1.67 to 0.68 due to nonlinearity. The similar results were earlier observed by Maheshwari *et al.* (2004) though using HiSS soil model. Further, the effect of nonlinearity on the real part of the dynamic stiffness is increasing with frequency. Thus it appears that the effect of nonlinear soil model used (Drucker-Prager) is greater at higher frequencies for dynamic stiffness of the system.



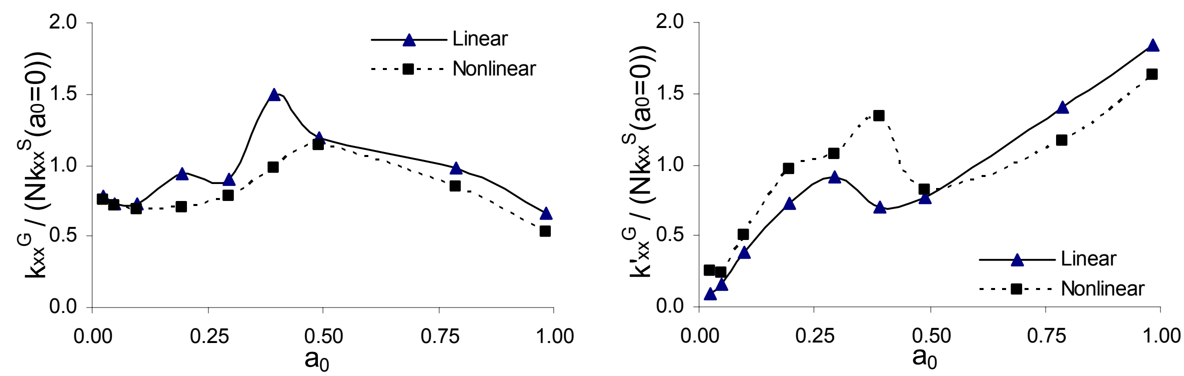
(a) Real part of dynamic stiffness (b) Imaginary part of dynamic stiffness

Figure 6: Comparison of linear and nonlinear dynamic stiffness of 2×2 pile group (s/d = 2)



(a) Real part of dynamic stiffness (b) Imaginary part of dynamic stiffness

Figure 7: Comparison of linear and nonlinear dynamic stiffness of 2 × 2 pile group (s/d = 5)

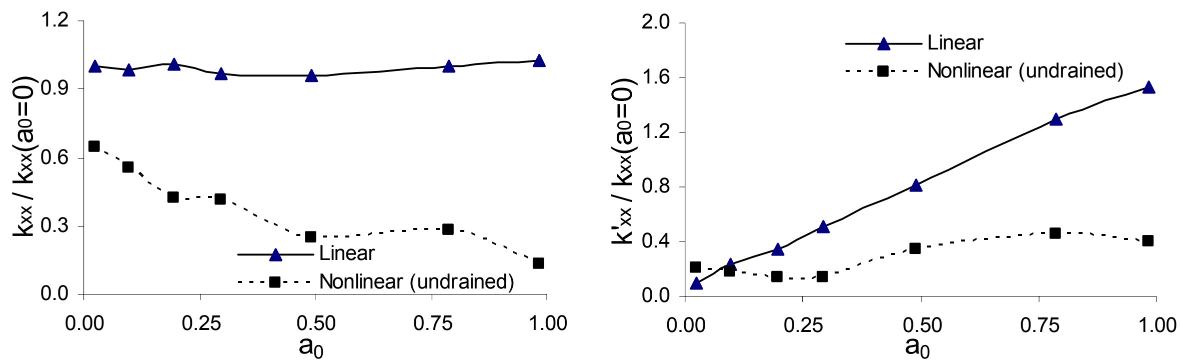


(a) Real part of dynamic stiffness (b) Imaginary part of dynamic stiffness

Figure 8: Comparison of linear and nonlinear dynamic stiffness of 2 × 2 pile group (s/d = 10)

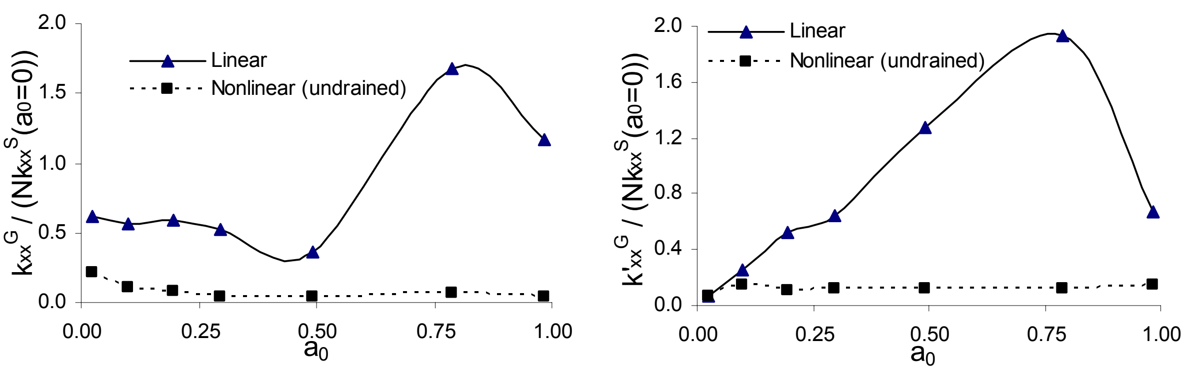
5. EFFECT OF NONLINEARITY WITH LIQUEFACTION

The program has been extended to incorporate the effective stress analysis for undrained condition by imposing total increment of volumetric strain as zero (Baladi and Rohani, 1979). In this way, the effect of liquefaction has been approximately taken into account. In this case, an initial effective confining pressure was considered in the analysis and assumed to increase with the depth. The lateral earth pressure coefficient at rest is assumed as 0.7. Dynamic stiffness values are computed and compared with the linear stiffness values. The material properties used are the same as discussed in section 4.



(a) Real part of dynamic stiffness (b) Imaginary part of dynamic stiffness

Figure 9: Comparison of linear and nonlinear (undrained) dynamic stiffness of single pile



(a) Real part of dynamic stiffness (b) Imaginary part of dynamic stiffness

Figure 10 Comparison of linear and nonlinear (undrained) dynamic stiffness of 2 × 2 pile group (s/d = 5)

Figure 9 and Figure 10 show the plots of dynamic stiffness considering undrained saturated sand as soil medium to simulate excess pore pressure for liquefaction for single pile and a 2 × 2 pile group with s/d = 5, respectively. It can be observed that due to liquefaction both the stiffness and damping parts reduces significantly. Also the results indicate that due to incorporation of liquefaction the group effect reduces drastically. For example, for s/d = 5, the real part of the dynamic stiffness is reduced from 1.67 to 0.07. Thus during liquefaction, at certain frequencies, the stiffness of the system may reduce to a negligible value, this suggest that it is very important to consider the liquefaction in the analysis. Also results are indicating that the effect of liquefaction is greater at higher frequencies for both a single pile and a pile group.

6. CONCLUSIONS

A three-dimensional nonlinear finite element dynamic analysis has been presented to investigate the effect of material nonlinearity and liquefaction on the dynamic stiffness of the soil-pile system. It was observed that both the effects significantly reduces the real part of the dynamic stiffness and diminishes the group interference among piles. Due to material nonlinearity, the damping of the system increases slightly however due to liquefaction it decreases significantly. Also it has been observed that the effect of liquefaction increases with increase in frequency of excitation. Due to liquefaction, the group stiffness may reduce to a negligible value at certain frequencies. However more parametric studies are required particularly to deal with liquefaction. Further the study is continuing to investigate the effect of liquefaction on the seismic response of pile groups. The results presented have very practical significance as dynamic stiffness is an important parameter for analysis and design of pile groups.

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