Non-Linear Sway-Rocking Stiffness of Pile Foundation

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Abstract. Sub-structure approach is a well-accepted and simplified method for analysis of seismic soil structure interaction (SSSI) problems. Past studies suggested equivalent springs and dashpots to represent soil-foundation system in sub-structure analysis. The primary limitation of this analysis is that foundation behaviour is considered to be elastic and hence nonlinear behavior of foundation could not be accurately predicted. As a result, accurate prediction of seismic response of structure incorporating SSSI condition may be missed out due to this limitation. In this context, present study attempts to propose nonlinear dynamic stiffness of equivalent pile-soil springs which may be used to capture the sway-rocking mode of vibration of the whole system. Three dimensional (3D) finite element model (FEM) of single free head pile is primarily analysed considering coupled static horizontal and moment load at the top of pile which finally utilized to generate dynamic nonlinear stiffness of pile group foundation by multiplying frequency and dynamic group interaction factor with nonlinear stiffness obtained from static FEM analysis. Proposed dynamic nonlinear stiffness of single pile with respect to pile deformation is presented in a simplified non-dimensional form as a function of linear stiffness. Non-dimensional results presented in this present study may provide ready solution to carry out SSSI studies for pile supported structure considering nonlinear behavior of foundation.

Keywords: Nonlinear, Sub-structure approach, ABAQUS/CAE, Pile, Coupled sway-rocking, FEM

1 INTRODUCTION

Multistory structures are usually supported on pile foundation which is subjected to settlement reducer. A geotechnical assessment for design of such foundation system therefore needs to consider the acceptable settlement of the pile elements interaction under serviceability loading. Seismic soil-pile foundation-structure interaction (SSPSI) was addressed to be an important seismic design consideration for pile foundation supported structure. Failures of pile supported structures in previous earthquakes (1964 Niigata earthquake, 1964 Alaskan earthquake, 1985 Mexico City earthquake, 1995 Kobe earthquake and 1989 Loma Prieta earthquake) has pointed out the importance of dynamic soil structure interaction (DSSI) to be incorporated in seismic design. Traditionally, seismic design of structures was performed assuming fixity at the base of superstructure and ignoring DSSI effects. Beneficial attribute of DSSI as suggested in earlier code guidelines (ATC (03) 1978, NEHRP 1997) and modelling complexity may be the reason behind no consideration of such effect in seismic design. However, the present guideline suggests for incorporation of DSSI in obtaining design forces based on detrimental behaviour as revealed in post analysis study of different case studies (Gazetas and Mylonakis 1998, Yashinsky 1998). State of the art research presents different approaches of modelling technique of DSSI. Among various techniques, substructure based modelling approach (Wolf 1985) was considered to be relatively simplified approach compared to beams on nonlinear foundation (BNWF) approach or 3D finite element (FE) analysis or boundary element method (BEM) of analysis. The substructure based method of analysis is performed in two steps for simplification. First, dynamic impedances are calculated considering pile foundation is embedded in homogenous or layered elastic half space medium and foundation input motion (FIM) is also obtained which is known as kinematic interaction study. In second step, dynamic analysis of the whole structure is performed after attaching the foundation impedance springs (pile-soil flexibility) and dashpots (pile-soil damping) in all possible degrees of freedom at the base of superstructure. Past literature indicates that pile-soil impedance springs and dashpots were suggested as linear behaviour (Gazetas 1984) assuming soil and pile as elastic. The limitation of such linear pile foundation impedances, i.e., springs and dashpots attached in translational and rocking degrees of freedom of structure is that the nonlinear pile-soil interaction behaviour under moderate to strong earthquake motion which is more physically acceptable could not modelled with these springs and dashpots. This may lead to inaccurate seismic response of structure for moderate to strong motions which may be a significant bottleneck of substructure based analysis. A recent study (Gazetas et al. 2013) suggested for nonlinear impedance equations for springs and dashpots considering shallow foundation.

From this viewpoint, present study is an attempt to propose nonlinear pile-soil spring stiffness for coupled horizontal-rotational direction as a function of pile-soil displacement of pile respectively based on 3D finite element (FE) analysis. Soil and pile are modelled as nonlinear and linear material respectively. A single RC free head pile is considered to be embedded in homogenous clay. Static analysis is performed attributing coupled horizontal and moment load applied at the top of single pile. The deformation with respect to load/moment is recorded for further calculation of static stiffness for coupled horizontal-rotational direction as a function of deformation. So the nonlinear stiffness calculation is more importance solution for seismic analysis of structure supported on pile foundation.

2 System Modeling and Method of Analysis

Three-dimensional finite element analysis is carried out using ABAQUS/CAE 6.8 to model the soil- pile foundation system embedded in soil. The soil-pile foundation system modelled using 3D solid deformable interface. The experimental examination of nonlinear behavior of soil is very tough, expensive and time taking and hence the finite element modelling is used to analyse the nonlinear behavior of soil. The numerical analysis of a single pile of RCC floating pile embedded in homogeneous clay deposit is carried out using 3D finite element based software ABAQUS/CAE version 6.8.

2.1 Soil modeling

The soil is modelled as a nonlinear elastoplastic material. The elasto plastic behavior of soil is mainly defined by cohesion, internal friction angle, dilation angle, Modulus of Elasticity and Poisson's ratio. The soil is assumed as homogeneous clay and having internal friction angle zero. Soil was modelled using 4-noded linear tetrahedral elements. The Modulus of Elasticity of soil is assumed to be constant throughout the depth of soil. The dimension of soil part modelled in ABAQUS for the current study is of 10m×10m and with 18m depth.

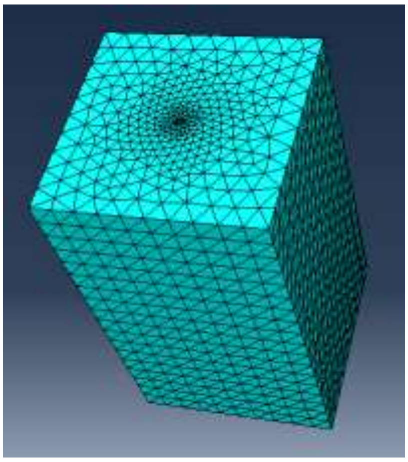

Fig.1. Soil model for single pile

2.2 Pile Modeling

The pile is modelled using 3D solid deformable element in ABAQUS CAE version 6.8. The is modelled as linear elastic RC material, defined by Poisson's ratio, Modulus of Elasticity and Density. The pile embedded in soil up to some depth with 1m free head at top of soil. The pile is mashed using 6-nodded hexagonal element in mesh module section of ABAQUS. The meshing of the system of soil-pile foundation system has been done in parts, as to make it feasible for analysis and to reducing the time taken in analysis. The soil part meshed as finer element in stress vicinity zone or nearby pile area and coarser element in far field.

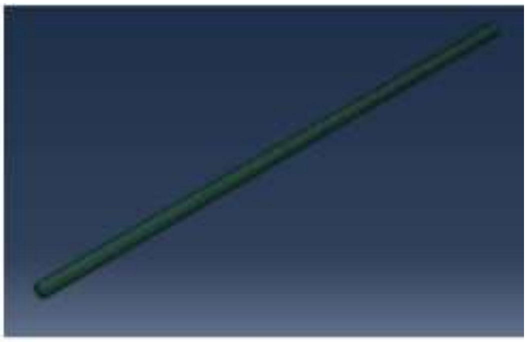

Fig.2. Single pile model

2.3 Pile-Soil Contact Behavior Modeling

The contact boundaries between soil and pile is defined by interface element. In many cases of soil-pile interaction, simple model may be adopted for interfaces as they usually involve compressive contact stresses. In this case, it may be convenient to model interface behaviour by refining the finite element mesh in the immediate vicinity of the interface and by defining the friction coefficient of 0.5 between soil and pile contact surfaces, for this ABAQUS provides interface provision facility in interaction module section. The surface to surface contact was used at soil-pile interface with frictional coefficient of 0.5. The interface elements can transfer only shear forces across their surfaces when a compressive normal pressure acts on them; otherwise a gap opens between them. When contact exists, the relationship between shear force and normal pressure is governed by a modified Coulomb's friction theory. Thus, these elements are completely defined by their geometry, a friction coefficient and an elastic stiffness used to provide convergence.

2.4 Boundary Conditions

The boundary at the bottom of the soil element is assumed to be fixed in the vertical and horizontal direction, while, the displacement of lateral boundaries is restricted in the normal direction. The top surface of the soil is remaining free to displace in all directions. For providing fixed boundary conditions ABAQUS provides boundary condition in load module section and for providing side boundary condition ABAQUS has z-asymmetric boundary condition which restrains the lateral movement of soil boundaries.

2.5 Application of Load

Load and moment are applied at the top of the pile in case of single pile, the load is applied in gradually increasing manner. For applying and spreading the load on whole pile top in single pile case, we created one reference point at the top of the pile, then coupled it with whole surface's mesh nodal points. For creating reference point and coupling it with surface, ABAQUS provides this facility in create constraint part in interaction module section.

2.6 Analytical Approach

Increase in displacement and rotation of top of the pile due to the presence of an identical adjacent pile can be expressed in terms of an interaction factor (α). In case of single pile in clay soil, the dynamic stiffnesses can be calculated by using dynamic stiffness co-efficient proposed by Gazetas (1984) in form of graphs for different Ep/Es ratio and variation in Young's Modulus of Elasticity of soil with depth, in present case we are taking E_p=E_s. Gazetas also proposed some simple closed form equations for calculation of static linear stiffnesses, by using these equations we can easily calculate the static linear stiffness of single pile. For the case of single pile, the linear stiffness in case of coupled loading is given as-

$$K_{HM}{}^{s} = 0.22 \times (\frac{E_p}{E_s})^{0.50} \times d^2 \times E_{sc} \tag{1}$$

Where, E_p = Young's modulus of solid pile, E_s = Young's modulus of soil at one diameter depth of pile, d = diameter of pile, E_{sc} = Young's modulus of soil at mid depth of the layer which will be equivalent to present study.

For calculation of dynamic stiffness (impedance), which is a complex function of frequency (ω=2πf) and damping-

$$\kappa = K(k + 2iD) \tag{2}$$

Where, κ = dynamic stiffness of single pile, K= Static stiffness of single pile, k= dynamic stiffness coefficient, D= effective damping ratio of the system.

We need some dynamic stiffness coefficients, proposed by Gazetas (1984) in form of graphs with respect to the different frequency ratios (f/f_1). Using these coefficients, can calculate the dynamic stiffness of pile by multiplying these coefficients with static nonlinear stiffness.The variation in dynamic stiffness with respect to the displacement are plotted. Also, the variation in ratio of dynamic nonlinear to static linear stiffness with respect to the displacement to are also plotted and analyzed. So, this analytical approach highlights the idealization of structure and method of analysis used for finding out the dynamic responses considering the effect of soil structure interaction.

2.7 System Parameter

Table 1 Dimension and parameters of pile

Parameters	**Value**
Diameter	0.4 m
Length	16 m
Modulus of Elasticity (E_p)	30×10^6 kPa
Cohesion (c)	0.33

Table 2 Parameters of soil

Parameters	**Value**
Modulus of Elasticity (E_s)	6×10^3 kPa
Internal Frictional Angle (φ)	0°
Poisson's Ratio (μ_s)	0.4
Cohesion (c)	25 kPa
Dilatancy Angle (Ψ)	1°

3 Result and Discussion

The load vs deflection curve is plotted for the case of coupled horizontal and moment loading. From these load vs deflection curves, the static nonlinear stiffnesses are calculated at different deflection values. Further, the static nonlinear stiffness vs deflection curves are plotted to show the nonlinearity in stiffnesses with increase in deflection and rotation. The dynamic nonlinear stiffnesses for single pile case has been calculated using the dynamic stiffness coefficient given by Gazetas (1984) in the form of dimensionless graphs for different frequency ratios (f/f_1). The variation of these dynamic nonlinear [k_{xy} (dynamic nonlinear)] stiffnesses with increase in displacement or rotation has been plotted and examined. Figure 3 (a) presents load deformation behavior of single pile embedded in homogenous clay for coupled load applied at pile head respectively. It is observed that the load deformation behavior is nonlinear with increase in deformation of pile under coupled loading. Further, Figure 3 (b) presents the stiffness of pile-soil system as a function of pile deformation for coupled load. It is observed that the stiffness variation with respect to deformation of pile is nonlinear. However, the nonlinear coupled swaying-rocking stiffness is observed 180000 kN/m at 0.028 mm of deflection of pile, which decreased to 20000 kN/m at 0.14 m deformation of pile. Figure 3 (c) presents the normalized static nonlinear coupled sway-rocking stiffness of single pile with respect to the deformation of pile in horizontal direction. It is observed that the ratio of nonlinear to static linear stiffness is increasing with increase in deformation in elastic zone but after getting a maximum value the plastic deformation starts and the ratio starts decreasing with increase in deformation. It observed that the maximum peak of normalized stiffness occurs at 12, which further decreased to 1.4 with increase in plastic deformation. Figure 3 (d) presents the variation of dynamic nonlinear stiffness at different frequency of motion with respect to the displacement. From the figure it is observed that in the case of coupled sway-rocking stiffness, significant effect of dynamic loading on stiffness is observed. It is also found that the maximum decrease and increase in nonlinear dynamic stiffness for lower and higher range frequencies are found in order of 88% and 30% respectively. Figure 3 (e) represents the normalized dynamic coupled sway-rocking stiffness at different frequency of motion in horizontal direction of deformation. The trend of variation is similar to dynamic stiffness variation.

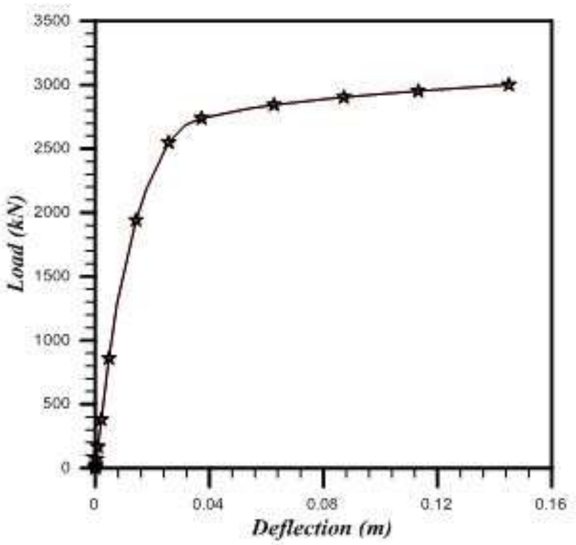

Fig.3(a). Pile deformation in horizontal direction with respect to applied coupled horizontal and moment on single floating pile embedded in clay.

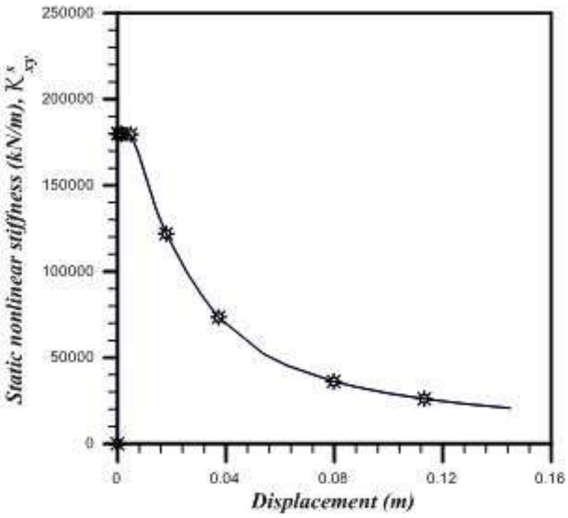

Fig.3(b). Nonlinear static coupled sway-rocking stiffness of single pile embedded in clay with respect to pile deformation in horizontal direction.

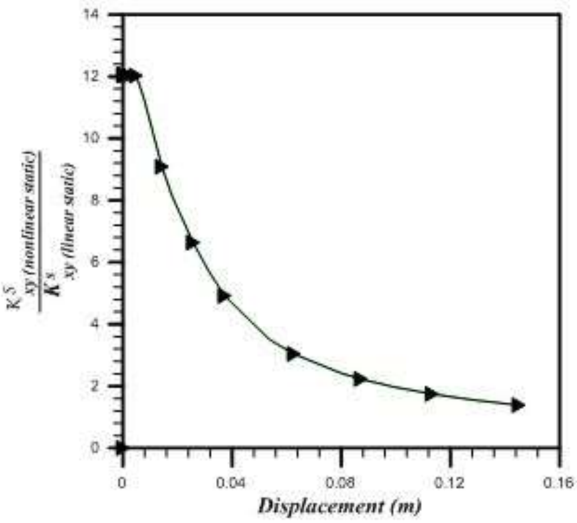

Fig.3(c). Ratio of nonlinear static coupled sway-rocking stiffness to static linear coupled sway-rocking stiffness with respect to pile deformation in horizontal direction.

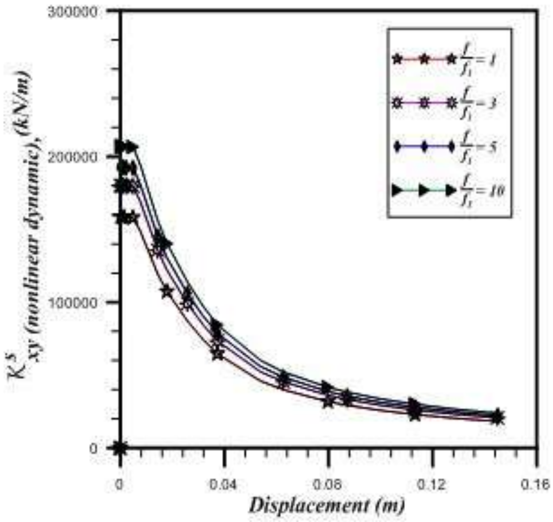

Fig.3(d). Nonlinear dynamic coupled sway-rocking stiffness of single pile with respect to pile deformation horizontal direction at different frequency of motion.

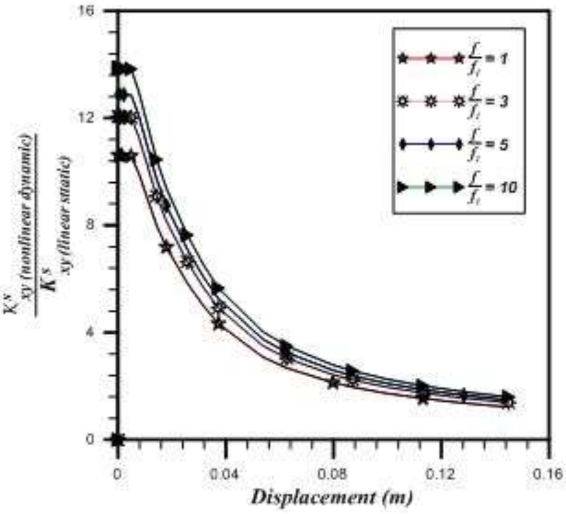

Fig.3(e). Normalized nonlinear dynamic stiffness of single pile with respect to pile deformation in the horizontal direction at different frequency of motion.

4 Conclusion

In summary, the present study is an attempts to propose nonlinear dynamic soil-pile stiffness in coupled sway-rocking mode of vibration of the foundation with respect to the horizontal deformation of single pile of interest used in sub-structure method of SSI modelling. 3D finite element based numerical analysis is performed on single pile embedded in homogenous soft clay to derive the nonlinear pile-soil stiffness as a function of pile deformation. Further, the effect of dynamic loading is incorporated by introducing frequency dependent dynamic stiffness coefficient proposed elsewhere (Gazetas 1984) with multiplication to static stiffness. Finally, nonlinear coupled swaying-rocking dynamic stiffness of single pile proposed considering piles are embedded in homogenous soft clay with different E_p/E_s ratio. The results presented herein would be useful for design purposes. However, the following conclusions are made based on the inferences made in the present study.

i. The non-linear dynamic sway-rocking stiffness is found to be significant increasing for initial range of deformation and further goes downwards asymptotic trend with increase in deformation.

ii. For instance, the significant change in stiffness for coupled sway-rocking is observed within a range of 0.008m to 0.08m respectively.

iii. On the other hand, it is also observed that frequency has minimum influence on dynamic nonlinear sway-rocking stiffness.

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