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NONLINEAR DYNAMIC ANALYSIS OF PILE FOUNDATION: EFFECT OF SEPARATION AT SOIL-PILE INTERFACE

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SUMMARY

During strong ground motion there are two special effects on the pile foundation. Firstly soil surrounding the piles behaves nonlinearly. Secondly, large inertia forces are generated in the soil around the pile heads causing the separation between soil and pile. In this paper a rational approach is proposed to overcome the material nonlinearity of the soil as well as geometrical nonlinearity arising due to separation. Analysis is carried out in two steps.

Approach is based on Green's function formulation for the linear pile analysis while equivalent linearization is used to deal with material nonlinearity. Hyperbolic model of soil is used to define the nonlinear stress-strain relationship of the soil. To deal with the separation Winkler soil model with an interface element is used to properly model gap formation. Depending on the level of excitation different cases of separation arises which are investigated with skeleton curves. It has been found that due to separation response is increased while it decreases the dynamic stiffness of the soil-pile system.

INTRODUCTION

Response of the pile foundation depends very much on the behaviour of soil media in which piles are embedded. Much work i.e. Kaynia & Kausel (1982) has been carried out for the analysis of pile group. But in this analysis as well as by most of the other researchers the nonlinear behavior of soil-media is neglected. Also during strong ground motion or dynamic excitation from the pile cap (or foundation structure), such as caused by machine type excitation or wind induced vibration forces, large inertia forces are generated in the soil around the pile heads causing the phenomena of slippage and separation. Due to complexity of modelling involved, most of the existing theories dealing with the dynamic behaviour of soil-pile system assume perfect contact between pile and soil, which cannot hold for such large excitations.

When shear strains in soil media falls in the medium range i.e. approximately 10^{-5} to 10^{-3} then hyperbolic model of soil is proved to be quite promising to deal with nonlinearity. For such cases shear modulus and damping ratio, both of which depends on the level of strain, are the key parameters to model the soil medium. Equivalent linearization along with hyperbolic model is used to deal with material nonlinearity. A brief introduction of this methodology is described here, detail can be found in Maheshwari & Watanabe (1998). Once material nonlinearity of the soil media is overcome then Winkler soil model is used to deal with separation. Earlier using this model some work had been carried out by Nogami & Konagai (1986 & 1988). Though here model used is same as proposed by these authors but methodology as well as treatment of material nonlinearity is quite different.

Depending on the level of excitation, there may be a number of cases for separation. Broadly they can be classified into three groups, skeleton curves for all the three cases are derived and relevant formulation is presented. Linear and nonlinear response of a single pile is presented, methodology can be extended for pile group also.

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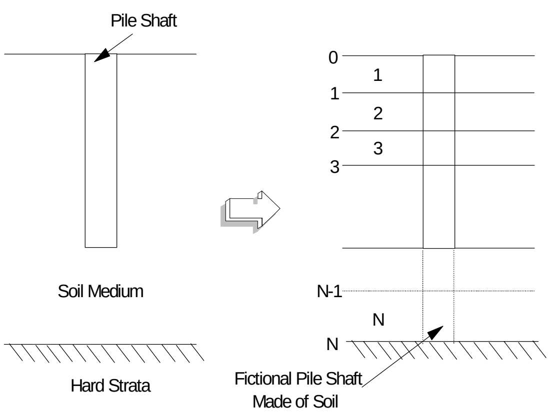
MODELLING

A hard stratum either at pile tip or at some finite depth below the tip is assumed. Thus, piles which are not directly resting on the bed rock can be analysed using the same methodology as end bearing piles by assuming a fictitious pile, made of soil, below pile tip. As shown in Fig. 1., soil-pile system is divided into a number of layers. Properties of soil media may vary from layer to layer but they are assumed to be constant in a particular layer. Load is assumed to act at the pile head, which may be either due to machine type excitation or inertia force generated due to seismic excitation.



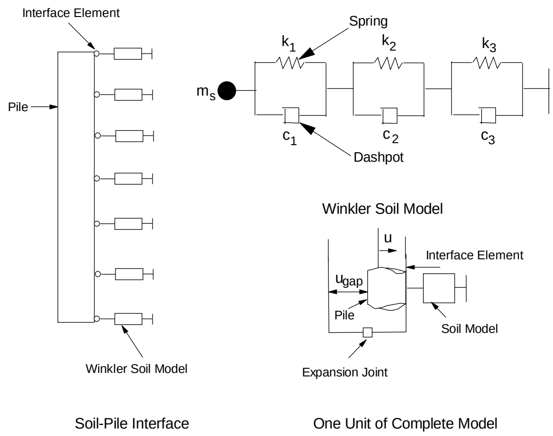


Fig. 1: Soil-Pile System Divided into a Number of Slices **Fig. 2: Model of Soil-Pile System for Separation**

Winkler's hypothesis is used to analyse each layer of the soil-pile system. According to this hypothesis soil-pile interaction force at one level is related to the displacement at that level only. Thus for each layer a separate Winkler model is used which is uncoupled from that used in other layers. As shown in Fig. 2, Each unit of Winkler soil model consists of three Voigt model connected in series where each Voigt model consists of a spring and dashpot connected in parallel.

To model the separation an interface element (Fig. 2) is used, this interface model works like a rigid frame with an expansion joint hence can change its size as well as position at different instants of time. The expansion joint increases the opening of the frame by the plastic deformation of the soil. Here though plastic deformation (yielding) of soil occurs but no permanent gap is considered in the soil.

FORMULATION

Following methodology is adopted to reach at a rational solution of this complex problem. First two steps i.e. 3.1 & 3.2 describe in brief the methodology to deal with material nonlinearity, while 3.3 & 3.4 presents a methodology to deal with separation.

Shear Strains in Soil Media:

For determination of shear strains in soil media a very rigorous three-dimensional approach, based on Green's function formulation and proposed by Kaynia & Kausel (1982) is used. First of all, displacements, in the near vicinity of pile, are computed in all the three directions at different points, in each layer of soil and then shear strains are determined. Thus maximum shear strain in each layer is found at a particular frequency. This process is repeated for all the frequency under consideration to find the absolute maximum of shear strain in each layer.

Hyperbolic Model and Equivalent Linearization:

As shear modulus and damping ratio, both of which depends on the level of shear strain, are the key parameters to model the soil medium, therefore hyperbolic model of soil is used to deal with nonlinear behaviour of soil. Following are the governing equations for this model.

$$\frac{G_s}{G_{\max}} = \frac{1}{1 + y/y_r} \tag{1a}$$

$$\frac{D}{D_{\max}} = \frac{y/y_r}{1+y/y_r} \tag{1b}$$

Where G_s and D represent the shear modulus and damping ratio respectively at a particular strain y while $G_{\max}$ and y_r represent maximum value of G_s & reference strain for the given soil media respectively. With the 2/3 of the absolute maximum shear strain determined earlier, and using Eqns. (1a) and (1b), new properties of soil medium are found. Thus iterations are carried out until properties of soil get converged.

Time Domain Winkler Soil Model:

Frequency independent parameters of Winkler soil model (Fig. 2), as proposed by Nogami and Konagai (1988) are

$$m_s = \xi_m(\nu_s)\rho_s \pi r_0^2 \tag{2a}$$

$$\begin{Bmatrix} k_1 \\ k_2 \\ k_3 \end{Bmatrix} = \xi_k(\nu_s) G_s \times \begin{Bmatrix} 3.518 \\ 3.581 \\ 5.529 \end{Bmatrix} \tag{2b}$$

$$\begin{Bmatrix} c_1 \\ c_2 \\ c_3 \end{Bmatrix} = \xi_k(\nu_s) \frac{G_s \times r_0}{v_s} \times \begin{Bmatrix} 113.097 \\ 25.133 \\ 9.362 \end{Bmatrix} \tag{2c}$$

Where $\xi_m(\nu_s)$ and $\xi_k(\nu_s)$ are functions of Poisson's ratio of soil and given in Nogami & Konagai (1988), r_0 is the radius of the pile, while v_s and ρ represent shear wave velocity and density of soil media respectively. Using this model complex soil stiffness of the medium for lateral vibration at a particular frequency ω is given by:

$$k_u = k_s - m_s\omega^2 \tag{3a}$$

Where $$k_s = \left[\sum_{n=1}^{3} \frac{1}{(k_n + i\omega c_n)}\right]^{-1} \tag{3b}$$

The loading time history is digitised at each time increment. Thus governing equation for the flexural response of the pile at $t = t_i$ as shown by Nogami & Konagai (1988), is

$$E_p I \frac{d^4 u_i}{dz^4} + m_p \ddot{u}_i = -p_i \tag{4}$$

Where u_i and $\ddot{u}_i$ are lateral displacement (i.e. displacement at the soil-pile interface) and acceleration of the pile respectively at time t_i; $E_p I$ is the bending stiffness of the pile shaft; m_p is mass per unit length of the pile; and p_i is the soil- pile interaction force at t_i. By expressing the acceleration $\ddot{u}_i$, in terms of the displacement u_i, known displacement, velocity, acceleration at time t_{i-1} and also expressing interaction force p_i in terms of displacement u_i, above equation is solved for response u_i of soil-pile system.

Possible Cases of Separation:

As level of excitation (depending on the magnitude and frequency contents) increases, the force at soil-pile interface increases. When this force exceeds certain threshold value(s), given by confining pressure and shear strength of the soil, separation occurs in a particular way. Though, there may be a number of cases for this phenomena, following major one are considered:

(a) No separation:

It is assumed that pile and soil will remain in perfect contact, if soil-pile interaction force

$$p_i \le p_c \qquad \text{Where} \qquad p_c = 2\pi r_0 \sigma_c \tag{5}$$

Where p_c is the threshold value for the interaction force, derived from the confining pressure σ_c in the soil springs and r_0 is the radius of the pile. For this case p_i can be expressed in terms of displacement, as shown by Nogami & Konagai (1988)

$$p_i = q_i + m_s \ddot{u}_i \tag{6a}$$

Where $q_i = ku_i + d_i$ (6b)

Where $k = \left[\sum_{n=1}^{3} I_n(\Delta t) \right]^{-1}$ (6c)

And $d_i = -k \sum_{n=1}^{3} u_{i-1,n} e^{-\kappa_n \Delta t} - kp_{i-1,n} \sum_{n=1}^{3} H_n(\Delta t)$ (6d)

Where $H_n(t) = \frac{A_n}{\kappa_n} \left[\frac{1}{\kappa_n \Delta t} e^{\kappa_n \Delta t} - (1 + \frac{1}{\kappa_n \Delta t}) \right] e^{-\kappa_n t}$ (6e)

and $I_n(t) = \frac{A_n}{\kappa_n} \left[(1 - \frac{1}{\kappa_n \Delta t}) e^{\kappa_n \Delta t} + \frac{1}{\kappa_n \Delta t} \right] e^{-\kappa_n t}$ (6f)

Where $A_n = 1/c_n$ and $\kappa_n = k_n / c_n$ (6g)

It shall be noted that k_u in Eq. (3a) represent the dynamic stiffness for Eq. (6a). However, while comparing these two equations one shall be recalled that former is in frequency domain while latter is in time domain. Converged properties of soil, obtained after equivalent linearization are used for determination of the constants k_n and c_n .

(b) Separation on one side of the pile only:

In this case, it is assumed that at a time soil will separate on one side of the pile only. In other words, at all time it will remain in contact, at least on one side of the pile. This would be possible only, if the gap formed on one side, until rebound occurs from another side, is less than the elastic displacement of soil. This will occur if

$$p_c \le p_i \le p_f \qquad \text{Where} \qquad p_f = 2\pi r_0 \sigma_f \tag{7}$$

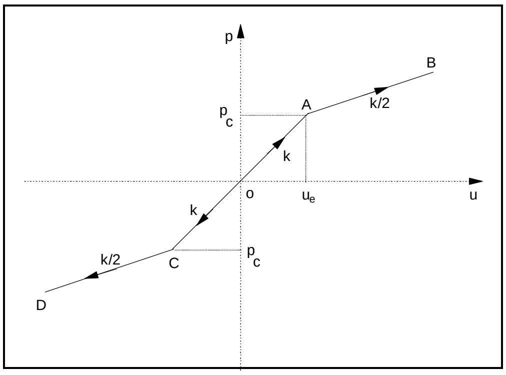
Where p_f is the ultimate threshold value for interaction force, derived from the compressive strength σ_f of soil. Since soil resistance of both side of the pile has been modelled by a single spring, when soil at one side of the pile is separated, the dynamic stiffness of this spring k_u, will be reduced to half for further loading. Dynamic stiffness (including the effect of inertia) of the soil spring in lateral direction is given by Eqs. (3a) & (3b). It can be seen from these equations that dynamic stiffness will be reduce to half, if each parameter of Winkler soil model i.e. all three springs and dashpot as well as lumped mass of soil is reduced to half. Thus when separation occurs on one side of the pile, Eqs. 6 are still valid provided stiffness of the spring is reduced to half by multiplying each parameter of Winkler soil model by 50%. The skeleton curve showing force-displacement relationship of soil spring for this case will be as shown in Fig. 3. Condition for separation and recontact, can be derived from this figure.

(c) Separation on one face while yielding on other one:

In this case, it is assumed that soil on one side of the pile is separated and before reversal of load, force in the soil spring on other side reaches its ultimate limit. Thus yielding of soil will occur on the other side. Though yielding occurs here but no permanent gap in soil is considered. Here displacement up to first separation will be called as elastic displacement (u_e) and the displacement during yielding as a plastic one (u_p), for subsequent reference. Before reversal of load, reaction force reaches the yielding value and the condition for this case are

$$p_i \geq p_f \quad \text{and} \qquad u_p \leq 2u_e \tag{8}$$

When yielding occurs, the stiffness of soil spring will reduce to zero and displacement will occur at a constant value of force equal to p_f. Skeleton curve for this case may be as shown in Fig. 4.



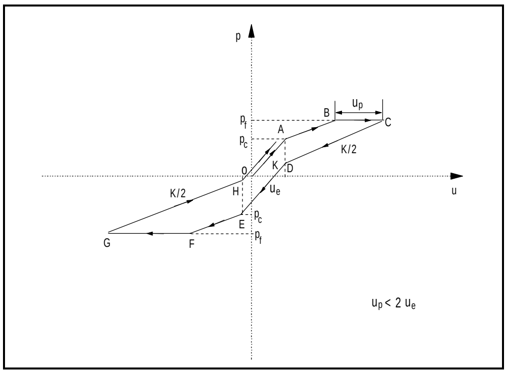


Fig. 3: Skeleton Curve for Separation on One Side

Fig. 4: Skeleton Curve for Separation on One Face, Yelding on Other Face

(d) Separation on both faces:

In this case, force in the spring that is not separated will, reach a zero value before pile meets the separated part (on another face). Since all the potential energy is also released hence soil get separated from other side too. Thus delinking of soil and pile occurs and pile will move freely to another side until it comes in contact to other side. The skeleton curve for this case may be as shown in Fig. 5 and condition for this case to be exist, are

$$p_i \geq p_f \qquad \text{and} \qquad u_p > 2u_e \tag{9}$$

During delinking right-hand side of equation of motion is zero and Eq. 4 is solved for free movement of pile.

EFFECTS OF NONLINEARITY

The effect of separation on the behaviour of single end bearing pile is examined for harmonic loading using time domain approach. The time history is plotted and then amplitude of interaction force and displacement at pile head is noted to infer various results. Following initial properties for soil and pile are used in computation

$$E_p / E_s = 800; \quad \rho_s / \rho_p = 0.7; \quad \sigma_c = 100kN/m^2; \quad \sigma_f = 200kN/m^2; \quad \nu_s = 0.3;$$

Where modulus as well as strength of soil, are those at the surface, and are assumed to be linearly increasing with depth with a value for the bottom layer, twice of that at the top.

Depth of Separation:

First of all to estimate about the depth of separation, the variation of maximum interaction force and lateral displacement with depth is plotted in Fig. 6, assuming no separation, where depth *z* is normalised w.r.t. length *L* of the pile. It can be seen that both force and displacement have higher values at around the top of the pile and decrease rapidly at greater depth. As shown in this figure soil strength is higher at greater depth while interaction force is lower there. This suggests that separation will occur only in some top layers.

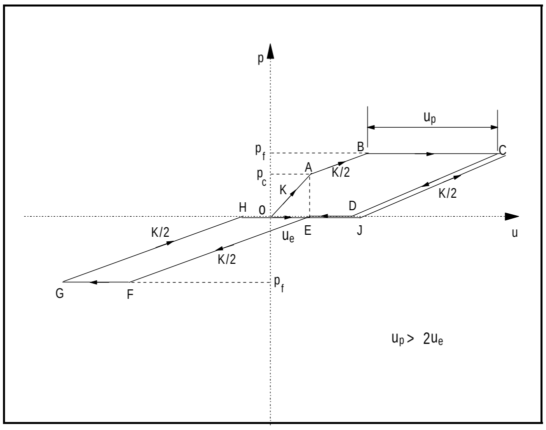


Fig. 5: Skeleton Curve for Separation on both Faces

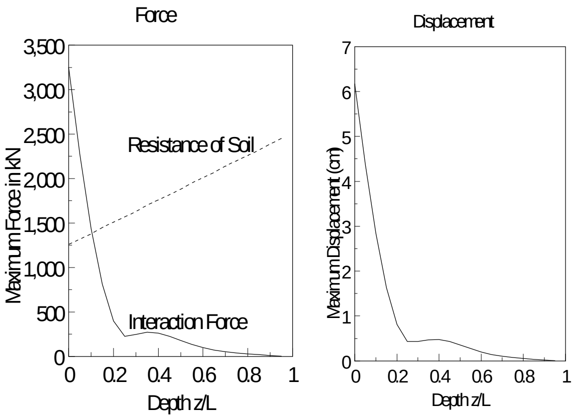


Fig. 6: Variation of Maximum Force and Displacement at Soil-Pile Interface with Depth.

Response for No Separation:

Fig. 7 shows the various time histories for a single pile assuming no separation, for top layer. As expected, this represents a steady-state condition.

Separation on One Face:

As it is assumed that separation occurs when force in soil reaches to threshold value p_c. In case of no damping in soil, there will be no time lag between load and displacement hence load vs. displacement can be traced correctly on the hysteresis curve. However, in case of exiting damping, the time lag disturbs recognising the trace of true load corresponding to displacement (response) of recontact on the hysteresis curve. Thus if the calculated load corresponding to the displacement at the point of recontact is adopted, this is not the true load on the hysteresis. Therefore, time lag must be removed to know where load and displacement are on the hysteresis curve. Due to this lag as shown in Fig. 8, force and displacement time history doesn't attain steady state condition.

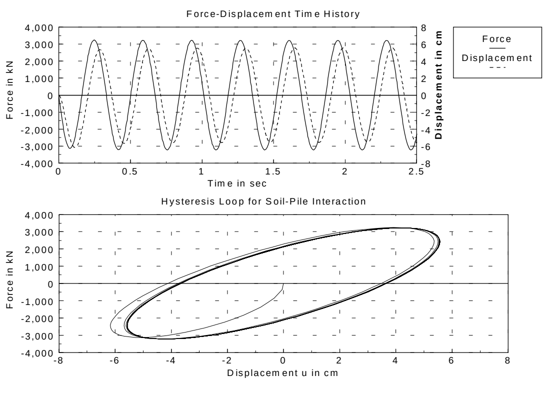


Fig. 7: Behaviour of Soil-Pile Interaction in Top Layer assuming No Separation

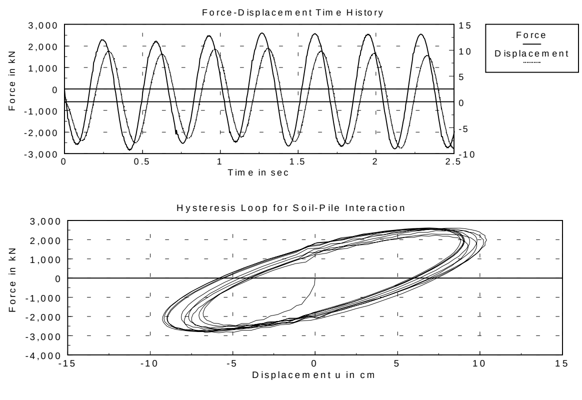
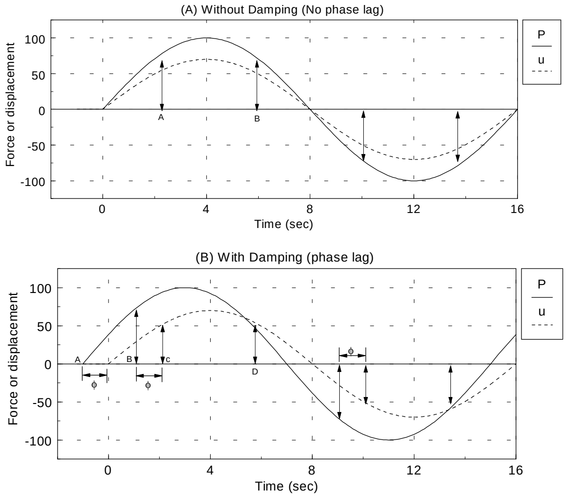


Fig. 8: Behaviour of Soil-Pile Interaction in Top Layer assuming Separation at One Face (without phase correction)

Fig. 9 shows the process to remove this time lag, so called concept for the phase correction. Essence behind this phase correction is that after separation (defined by the value of force), recontact should be at a time where after accounting for the time lag we obtain the same force as it was at the time of separation. Using this phase correction, Fig. 10 shows the force displacement relationship for top layer for this case. Effect of phase correction makes both force and displacement response in steady state.



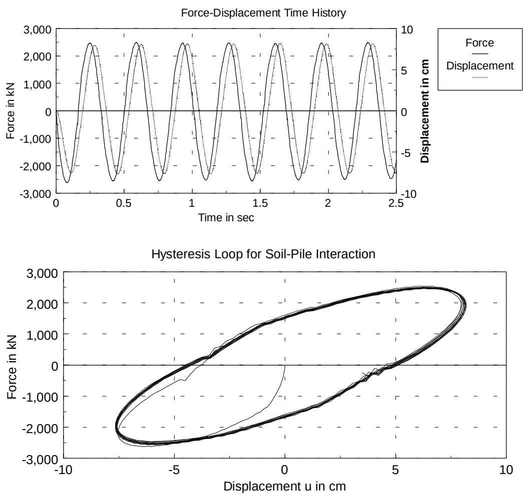
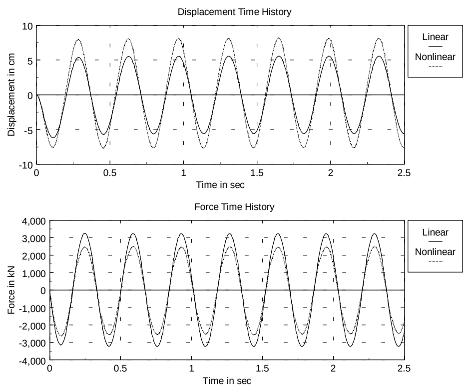


Fig. 9: Concept of the Phase Correction

Fig. 10: Behaviour of Soil-Pile Interaction in Top Layer for Separation on One Face (with phase correction)

The response for linear (no separation) and nonlinear (separation) case are compared in Fig. 11. As expected separation is increasing displacement and decreasing force, i.e. nonlinearity is reducing stiffness of soil. Dynamic stiffness of a single pile-soil system is computed at different frequency by this time domain approach for linear and nonlinear case. As it can be seen from Fig. 12 that due to nonlinearity both real and imaginary part of the stiffness is decreasing.



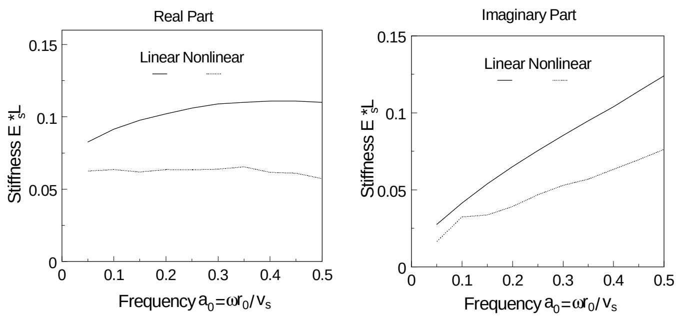


Fig. 11: Comparison of Linear and Nonlinear Response of a Single Pile

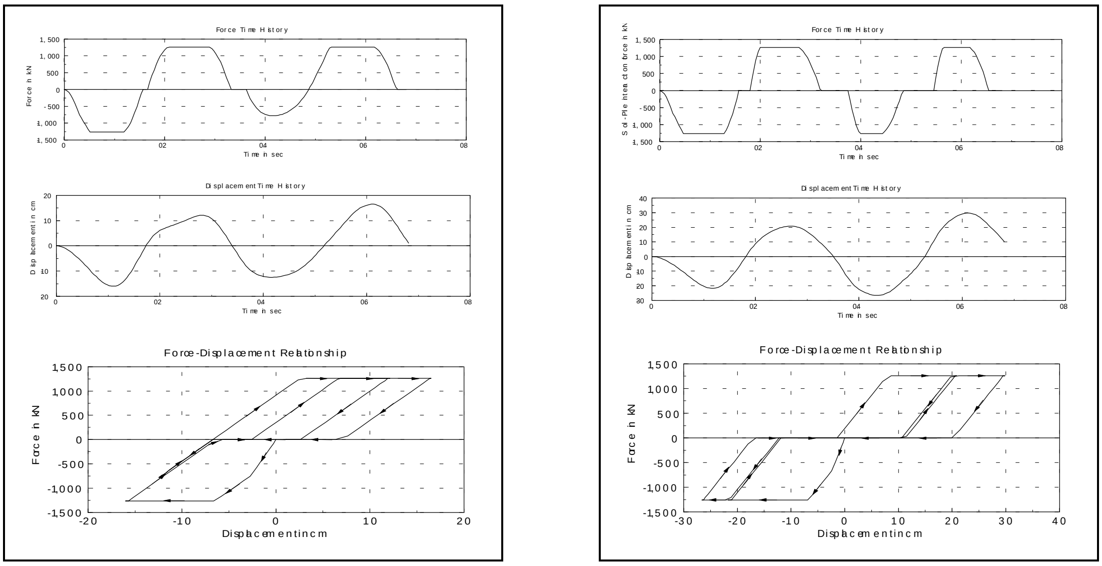
Fig. 12: Linear and Nonlinear Pile-Head Stiffness wih Frequency

Separation on Both Faces:

Further results are derived for separation on both faces i.e. when gap is also formed. Fig. 13 and 14 shows these results for two cycles of loading when there is no damping in the soil media for two different levels of nonlinearity which is defined by the factor *R* given by

$$R = P_{\max} / (p_c \times L) \tag{10}$$

Where $P_{\max}$ is the amplitude of force for harmonic excitation, while p_c is given by Eq. 5. It can be seen that as time elapses, amplitude of displacement in both the cases increases, while force remains limited up to threshold value for yielding.



(a) R = 0.30 **(b) R = 0.35**

Fig. 13: Behaviour of Soil-Pile Interaction in Top Layer assuming Separation on Both Faces

CONCLUSIONS

In this paper, a new approach is developed to carry out the analysis for separation using existing time domain Winkler soil model. Constitutive equation is formulated for different possible cases in the phenomena of separation and relevant formulation is developed. It was found that a phase correction is necessary while dealing with separation and method to estimate this is proposed.

Effect of separation on the response depends very much on the level of nonlinearity, since accordingly various states i.e. separation, yielding and delinking are determined. Due to separation, there is increase in displacement while force is decreased which shows that stiffness of soil is decreased. Separation decreases the dynamic stiffness of the soil-pile system. As the level of nonlinearity increases, separation becomes more intense heading towards yielding and delinking and thus increasing the gap.

Though results derived in this paper is for a single pile only but methodology developed can be extended for pile group also.

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