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Prediction of nonlinear characteristics of soil-pile system under vertical vibration

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Abstract. In the present study an attempt was made to predict the complex nonlinear parameters of the soil-pile system subjected to the vertical vibration of rotating machines. A three dimensional (3D) finite element (FE) model was developed to predict the nonlinear dynamic response of full-scale pile foundation in a layered soil medium using ABAQUS/CAE. The frequency amplitude responses for different eccentric moments obtained from the FE analysis were compared with the vertical vibration test results of the full-scale single pile. It was found that the predicted resonant frequency and amplitude of pile obtained from 3D FE analysis were within a reasonable range of the vertical vibration test results. The variation of the soil-pile separation lengths were determined using FE analysis for different eccentric moments. The Novak's continuum approach was also used to predict the nonlinear behaviour of soil-pile system. The continuum approach was found to be useful for the prediction of the nonlinear frequency-amplitude response of full-scale pile after introducing the proper boundary zone parameters and soil-pile separation lengths.

Keywords: boundary zone parameter; layered soils; nonlinear response; soil-pile separation; vertical vibration; 3D finite element analysis

1. Introduction

Geotechnical engineers usually face problems associated with the design of pile foundations under dynamic loads originating from any controlled phenomenon such as machinery and vibrating equipments. The pile foundations are used for machines and other vibrating equipment to reduce the vibration amplitude to an acceptable limit where block type foundations are not feasible. Also the pile foundation is the only option to support a machine where the construction of block or frame foundations are not possible for the geotechnical problems. Vibration of piled foundations from the operation of machine produces elastic waves within the soil mass. These waves are sometimes detrimental to the pile foundation and the surrounding structures. A key step to a successful design of the machine-pile foundation system is the careful engineering analysis of the pile foundation response to the dynamic loads from the anticipated operation of the machine.

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Different approaches have been developed to analyze the single and group pile under dynamic load both in uniform and layered soil medium. The continuum approach is most promising one among all the methods available in the literature such as equivalent cantilever method, mass spring dashpot model and Winkler foundation model for the prediction of the dynamic response of pile foundations. The elastic continuum method was based on closed form solution of Mindlin (1936) for the application of point loads to a semi-infinite mass. Then the continuum approach was modified by Novak (1974) based on the analytical solution of Baranov (1967) by introducing the dynamic soil-pile interaction. Further Novak and Aboul-Ella (1978a, 1978b) calculated the impedance functions (stiffness and damping) of a pile in layered soil medium. Novak and Sheta (1980) first proposed a concept of boundary zone around the pile to account the soil nonlinearity. Later Chau and Yang (2005) extended the continuum approach to 3D analysis to incorporate the nonlinear behaviour. This solution made it possible to predict the dynamic stiffness with soil nonlinearity, slenderness ratio of pile, tip condition, frequency and magnitude of vibration. Manna and Baidya (2010) established an empirical relationship using continuum approach to estimate the boundary-zone parameters and the extent of soil-pile separation.

The finite element method (FEM) is used by many researchers to study the dynamic response of pile by considering the nonlinearity of the soil medium and separation at the pile-soil interface. Kuhlemeyer (1979) presented finite element results of pile-soil systems and compared the results with lumped mass pile-soil model.

Then a revised FE model was proposed by Dobry *et al.* (1982) to study the dynamic response of a single pile in uniform soil. Lewis and Gonzalez (1985) investigated the nonlinear soil response of soil-pile system and soil-pile gapping using FE analysis. Later Bentley and El Naggar (2000) developed a 3D finite frequencies of excitations. The nonlinear response of the soil-pile system also studies by Ayothiraman and Boominathan (2006) considering Mohr-Coulomb soil model by a two dimensional FE software package, PLAXIS. The dynamic response of coupled soil-pile-structure systems was studied by Rovithis *et al.* (2009) using three dimensional finite element models. A three-dimensional viscoelastic BEM-FEM formulation for the dynamic analysis of pile supported linear structure was proposed by Padron *et al.* (2009). Manna and Baidya (2009) used a simple axisymmetric two dimensional finite-element model for the prediction of the dynamic response of full-scale single pile. It was observed that the finite-element model predicted the natural frequency and peak displacement amplitude of pile reasonably well. However, a very few studies are available to model the full-scale pile-soil system using rigorous 3D finite element model. Prediction of the boundary zone parameters and the soil-pile separation lengths are the key aspect of nonlinear response of full-scale pile which have not been studied in details.

Hence in the present study, the nonlinear response of the soil-pile system was investigated by a 3D finite element package. Parametric study was performed based on element model by considering the soil nonlinearity, discontinuity conditions at the soil-pile interface, energy dissipation, wave propagation, and actual in-situ stress conditions, to evaluate the kinematic soil-pile interaction. In order to study the significance of soil nonlinearity for pile foundation under dynamic loading, Maheshwari *et al.* (2005) developed a three dimensional finite element programme. It was found that the nonlinearity of soil had significant effects on the pile response for low and moderate the comparison between finite element analysis results and vertical vibration test results of full-scale single pile. The continuum approach of Novak was also used to predict the dynamic nonlinear response of the pile foundation using the boundary zone parameters and soil-pile separation lengths.

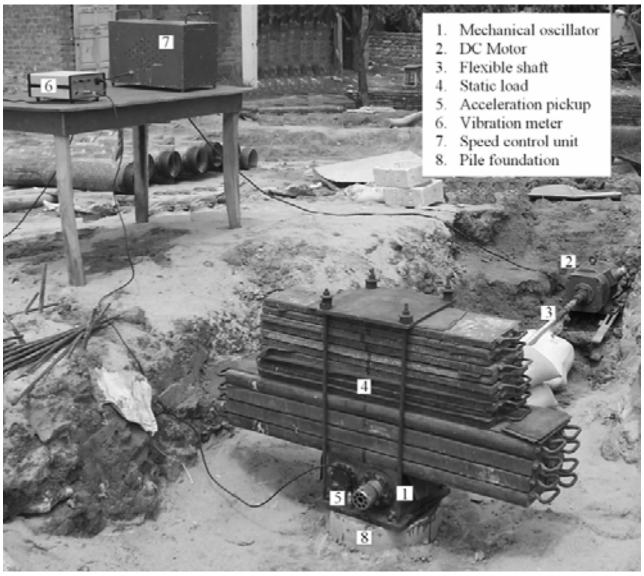

Fig. 1 Complete setup of vertical vibration test on full-scale pile

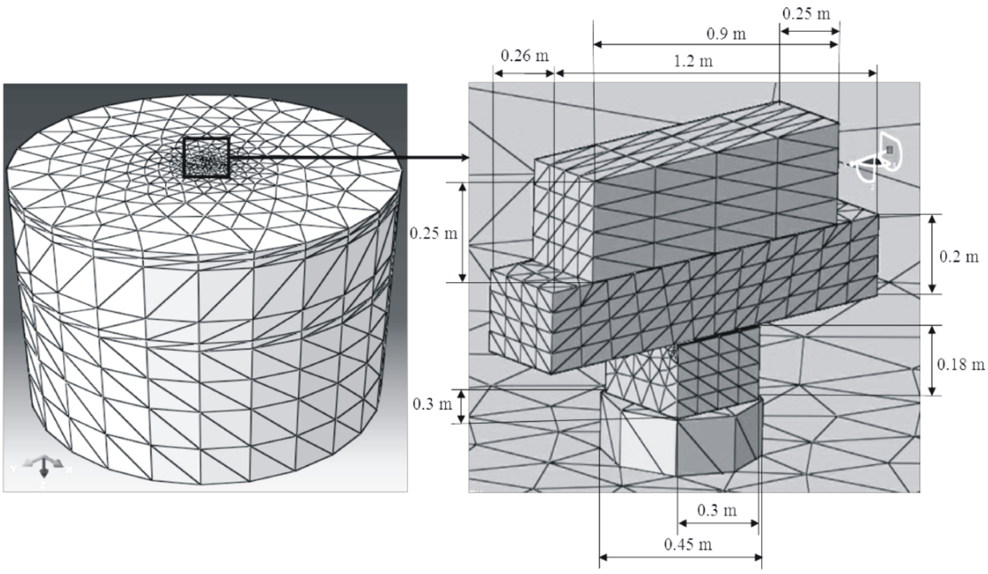

Fig. 2 3D Finite element model developed in ABAQUS

2. Experimental background

The vertical vibration tests on the full-scale single pile were conducted at I.I.T. Kharagpur Extension Centre, Block No. HC, Plot. 7, Sector - III, Salt Lake City, Kolkata, India (Manna and Baidya 2009). In the field three bore holes were made and soil samples were collected. The depth of exploration below ground level was 30.45 m. Disturbed representative soil samples and undisturbed soil samples were collected from the field. During boring ground water was encountered in all the three boreholes and it was found that the position of standing water table was at 1.25 m below the ground level. Standard penetration tests (SPT) were carried out in the field and the SPT - *N* value was determined at different depths of the soil strata. Based on different laboratory observations and field test results the site soil was divided into six different layers. The RCC piles were constructed at site using cast in situ technique. The diameter and length of the pile were 0.45 m and 22 m respectively. Forced vibration tests were conducted on the piles in vertical direction. The mechanical oscillator (Lazan type) was used to induce unidirectional vibrations on pile foundation. The mechanical oscillator was connected by means of a flexible shaft with a motor and its speed was controlled by a speed control unit. The vibration measuring equipment consisted of a piezoelectric acceleration pickup and the associated vibration meter. The complete dynamic test set up is shown in Fig. 1. The amplitudes were measured at different frequencies for each eccentric setting. Tests were conducted for four different exciting moments (0.278, 0.366, 0.45, and 0.529 Nm) under different static loads (8 kN and 10 kN).

3. Three dimensional finite element modelling

A 3D FE model was developed to study the nonlinear soil-pile interaction using the finite element software, ABAQUS/CAE 6.11 (2010). A harmonic vibration load was applied i.e., rotating mass type machine at the top of a 0.45 m diameter single pile having 22 m length. Both the pile and soil mass were meshed using tetrahedral solid elements (10 nodded) where elements were more closely spaced near the pile compared to the outer region shown in Fig. 2. Boundary conditions were applied to those regions of the model where the displacements and/or rotations were known. Bottom soil boundary nodes were considered as fixed against displacements and rotations at all directions. At the side soil boundary, nodes displacement and rotation were allowed only in vertical *Z* direction though no displacement or rotation was observed at the outer soil boundary nodes.

The soil-pile interaction was modelled using surface-to-surface contact algorithm, where relative movement between soil and pile was allowed for considering friction. The tangential contact between the pile and the surrounding soil was defined using Coulomb's Law. The friction coefficient is estimated by the tangent of the friction angle between pile and soil. The normal behaviour was considered to be hard (no penetration to each other) allowing separation after contact.

The whole system was modelled in six layers of soil as found in site investigation (Manna and Baidya 2009) and the sectional view of the model is shown in Fig. 3. The phreatic level was considered 1.25 m below the ground surface as observed in site investigation and the effective soil pressure was applied in the whole geometry according to this phreatic line. The properties of soil for all the layers, pile and steel plate are listed in Table 1. It is found from Table. 1 that soil layers are mainly clay dominated soil which is very relevant to this kind of nonlinear problem. Soil behaviour was considered as elasto-plastic. The displacement of soil had both a recoverable and non-recoverable component under load. Therefore, there was a need to include a failure criterion in the elastic models to define the stress states that would cause the plastic deformation. Mohr-Coulomb model was adopted for soil to simulate the elasto-plastic behaviour. For analysis the FE model material damping was considered. The Rayleigh damping coefficients (α) and (β) was used to define in each layer and the coefficients were determined from the relationship given below

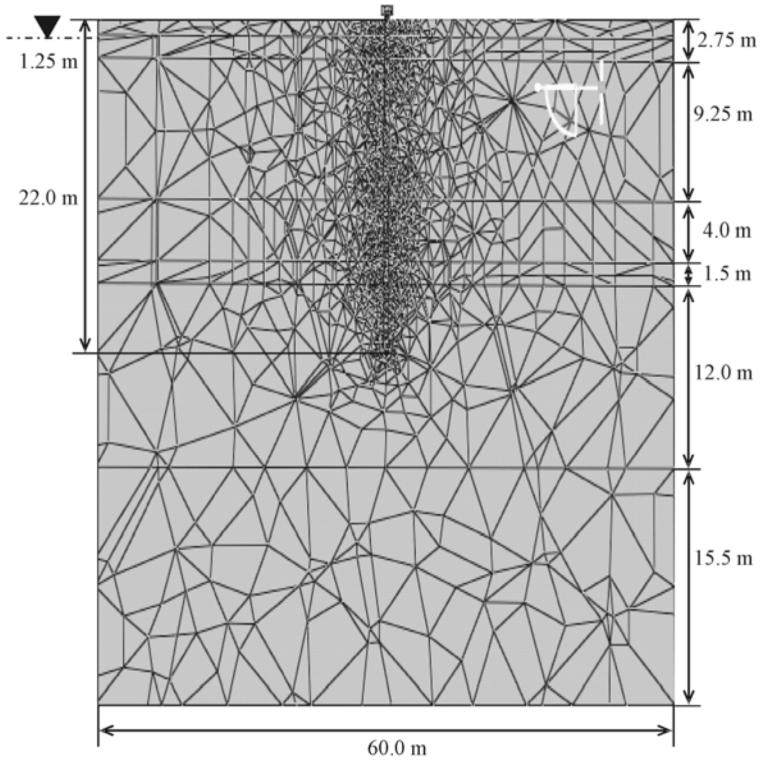

Fig. 3 Geometry of soil layers and pile in finite element model

Table 1 Material properties used in FE analysis

Material	Model	Dry unit wt. (kN/m^3)	Saturated unit wt. (kN/m^3)	Young's modulus (kPa)	Poisson's ratio	Cohesion (kPa)	Friction angle (^{o})	Type of soil
Soil layer-1	Mohr-Coulomb	12.7	17.8	10,000	0.25	0.3	22	Silty sand (SM)
Soil layer-2	Mohr-Coulomb	12.0	17.9	8,000	0.35	18	5	Inorganic clay with high plasticity (CH)
Soil layer-3	Mohr-Coulomb	13.0	18.9	25,000	0.35	63	7	Inorganic clay with low plasticity (CL)
Soil layer-4	Mohr-Coulomb	13.0	18.8	30,000	0.35	75	4	Inorganic silt and fine sand (ML)
Soil layer-5	Mohr-Coulomb	15.0	20.0	40,000	0.35	10	35	Silty sand (SM)
Soil layer-6	Mohr-Coulomb	13.0	18.8	30,000	0.35	75	4	Inorganic silt and very fine sand (ML)
Pile	Linear elastic	24.0	---	3×10^7	0.20	---	---	---
Steel plate	Linear elastic	78.5	----	20×10^7	0.25	---	---	---

$$\alpha + \beta\omega_i^2 = 2\omega_i D_i \qquad (1)$$

where D_i = damping ratio corresponding to frequency of vibration ω_i

It was assumed that 60 rad/sec and 500 rad/sec were the limit of predominant frequencies in dynamic testing i.e., all damping values for different layers were less than the damping values (D_1, D_2) considered here in this frequency range. The damping values were taken from guidelines given by Bowles (1996). Finally the (α) and (β) coefficients were calculated by using Eq. (1).

The model was analyzed in three calculation phases. First gravity analysis was performed only in soil mass in vertical Z direction. In the next step, the pile-soil interaction was introduced as well as static load was applied on the top of the pile. A steel plate was provided on the pile head to simulate the exact static load (8 kN and 10 kN) applied on pile. In the third phase the dynamic FE analysis was performed by applying sinusoidal vertical load on the pile using a dynamic multiplier function at wide range of frequencies (5 to 60 Hz). According to the values of eccentric moments (0.278 Nm, 0.366 Nm, 0.450 Nm and 0.529 Nm) and operating frequency of the motor, the dynamic load amplitudes were determined.

4. Results and discussion – 3D finite element analysis

4.1 Validation of finite-element model

To monitor the boundary effect, the model was analyzed with different boundary radii. The analysis results are shown in Fig. 4. Based on the results, the boundaries of soil mass around the pile were considered with a radius of 30 m and height of 45 m to avoid the direct influence of the boundary conditions. Static load analysis was carried out and the results obtained from FE analysis were compared with the static load test results. The comparison of static load test results with the

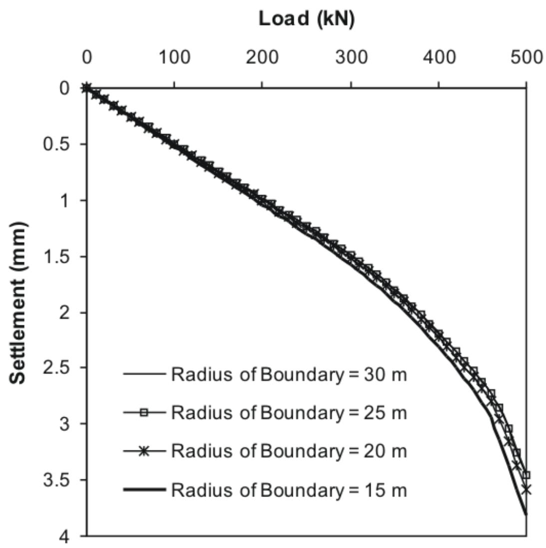

Fig. 4 Load verses settlement curve of FE model with different soil boundary

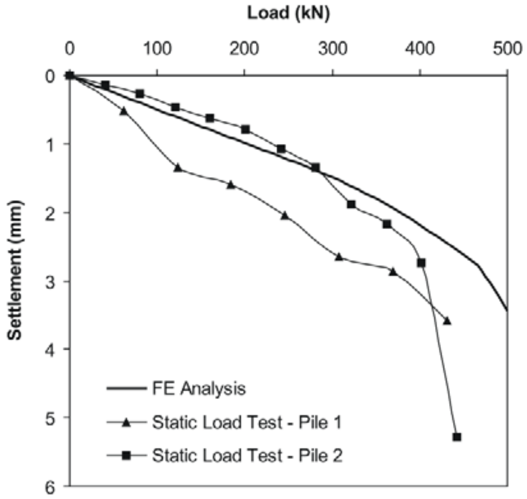

Fig. 5 Comparison of load verses settlement curve obtained from FE analysis and static load test

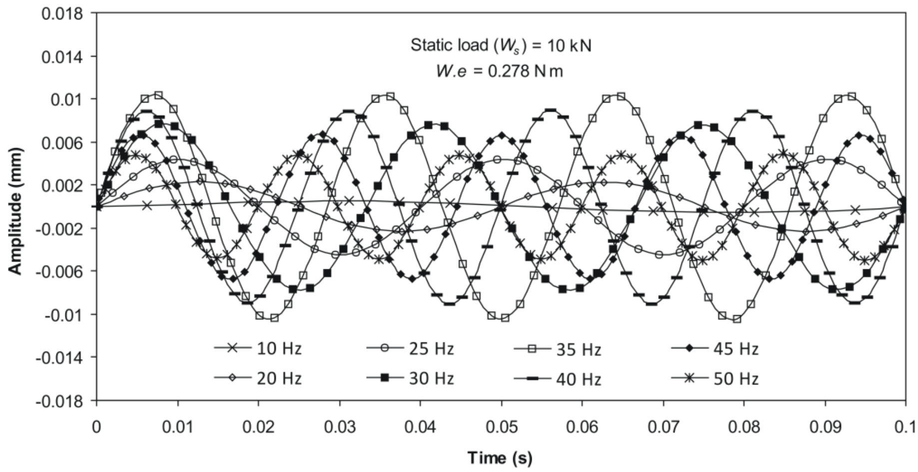

Fig. 6 Time-amplitude response of pile at different frequencies (FE analysis)

FE analysis is shown in Fig. 5. The predicted settlement obtained from FE analysis is approximately 1.45 mm and observed settlement is 1.45 mm and 2.3 mm for pile 1 and pile 2 respectively at calculated safe load (283 kN).

4.2 Comparison between finite-element analysis and dynamic test results

The time versus amplitude curves were obtained from FE analysis at different operating frequencies of machine for different static load and eccentric moments. A typical response curve is presented in Fig. 6 for static load of 10 kN. From the time versus amplitude curves, the frequency versus amplitude curves were obtained and compared with the field vibration test results. The typical comparison of frequency-amplitude response obtained from FE analysis and test results are shown in Fig. 7 for pile 1. It is found from Fig. 7 that the predicted resonant frequency and

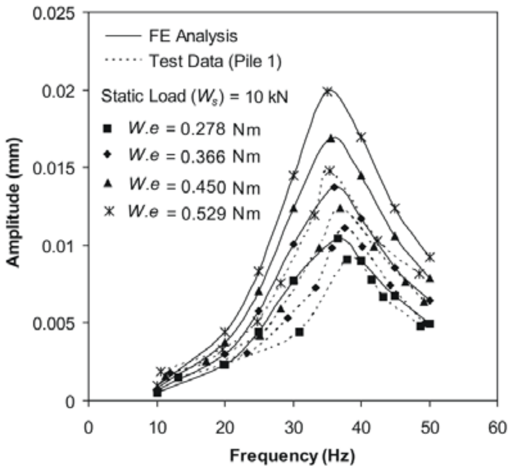

Fig. 7 Comparison of frequency-amplitude curve obtained from FE analysis and dynamic test results

amplitude are very close to the vertical vibration test results. The resonant frequencies are decreased with the increase of eccentric moments under same static load. This phenomenon indicates the nonlinear behaviour of soil-pile system obtained from FE analysis which is similar to the field test results. This nonlinear response of the soil-pile system is due to the material nonlinearity which is nothing but reduction in shear modulus during vibration. The negligible difference in resonant frequencies with the test results are due to the average soil properties and stratifications considered in the FE analysis. Though there is a significance difference in amplitude values but it is understandable that it can be optimize by implementing precise represented field damping values of soil. In spite of nonlinearity, the FE model can also able to describe vibration theories by showing the pattern of reducing resonant frequency and amplitude values with the increase of static load on pile for same eccentric moment which shown in Table 2.

4.3 Soil-pile separation from finite element analysis

The bonding between the soil and the pile is rarely perfect and the slippage or even soil-pile separation often occurs during vibration of pile. Furthermore, the soil region immediately adjacent to the pile can undergo a large degree of straining, which would cause the soil-pile system to be having in a nonlinear manner. Hence in the present study, the soil-pile separation length for different eccentric moment has been predicted from 3D finite element analysis. The relative movement between pile and soil surface was measured at the resonant frequency. A small variation of the soil-pile separation length was found along the periphery of the pile. So the average of measurement at 45°, 135°, 225° and 300° along the pile cross section plane were taken. The amount of separation between the soil and pile for different eccentric moments along the depth is showed in Fig. 8. It can be observed that the amount of separation is reduced drastically with the increase of the depth. The effect of the eccentric moment on soil-pile separation length is shown in Fig. 9. It is found that though the eccentric moment increases but separation length is not increase beyond the depth of water table which is very practical phenomena at the site. The accuracy of the predicted depth of separation from the FE analysis depends on the mesh size of the model.

Table 2 The comparison of results obtained from vertical vibration test, FE analysis and nonlinear continuum approach of Novak

Eccentric moments (Nm)	Static load (W_s) = 8 kN		Static load (W_s) = 10 kN	
	Resonance frequency (Hz)	Vertical amplitude (mm)	Resonance frequency (Hz)	Vertical amplitude (mm)
		Experimental results (Pile 1)		
0.278	39.01	0.0102	38.01	0.0091
0.366	38.23	0.0121	37.66	0.0111
0.450	37.64	0.0142	36.95	0.0124
0.529	36.14	0.0158	35.42	0.0148
		Experimental results (Pile 2)		
0.278	36.25	0.0100	34.70	0.0073
0.366	35.90	0.0108	33.28	0.0089
0.450	34.76	0.0118	32.75	0.0102
0.529	34.53	0.0134	32.10	0.0128
		3D finite element analysis		
0.278	37.5	0.010865	36.5	0.010435
0.366	37.0	0.014150	36.0	0.013750
0.450	36.5	0.017250	35.5	0.016905
0.529	36.0	0.020220	35.0	0.019875
		Continuum approach of Novak (Nonlinear)		
0.278	36.61	0.01130	35.81	0.01112
0.366	35.81	0.01475	35.01	0.01455
0.450	35.01	0.17760	34.22	0.01750
0.529	34.22	0.02025	33.42	0.01997

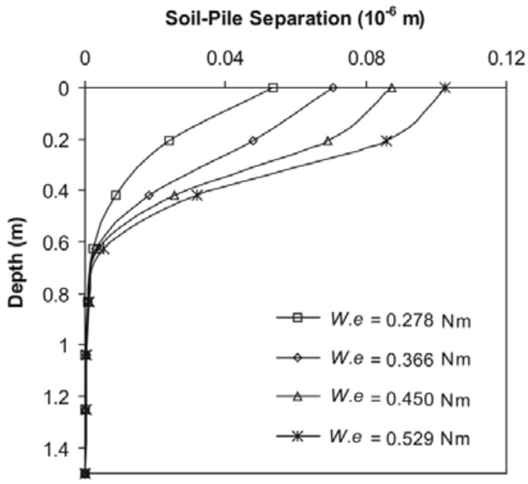

Fig. 8 Amount of separation at soil-pile interface (FE Analysis)

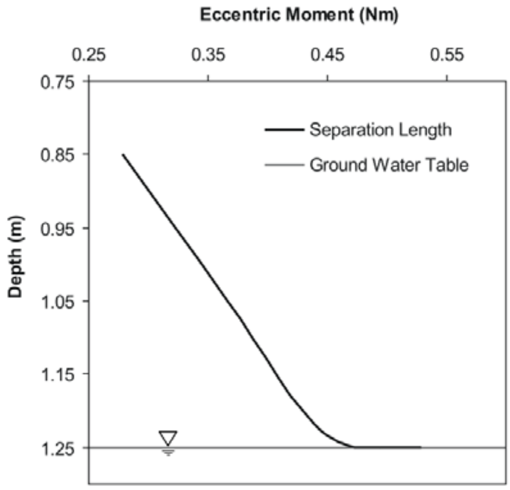

Fig. 9 Variation of soil-pile separation length with eccentric moments (FE Analysis)

5. Continuum approach of Novak

The dynamic behaviour of pile foundation was also analyzed by Novak's continuum method which was available as a computer code DYNA 5 (Novak *et al*. 1999). In this study, both linear and nonlinear analysis was performed. The linear analysis was described by Novak and Aboul-Ella (1978). In this method the equation of motion was derived by considering two nodded pile elements. The complex soil stiffness (k_w) proposed by Novak *et al*. (1978) for homogeneous medium was used to define the dynamic soil impedance for vertical vibration as given below

$$k_w = G_s\left[S_{w1}(a_o, D_s) + iS_{w2}(a_o, D_s)\right] \tag{2}$$

in which G_s is the shear modulus of homogeneous soil, a_o is dimensionless frequency, D_s is dimensionless damping constant, S_{w1} and S_{w2} are the real and imaginary parts of the dimensionless complex stiffness of homogeneous medium, respectively. After implementing proper boundary conditions and necessary derivations, finally the stiffness (k_{w1}) and damping (c_{w1}) constants of the single pile (Novak and Aboul-Ella 1978) were obtained as

$$k_w^1 = \frac{E_p A_p}{R} f_{w1} \tag{3}$$

$$c_w^1 = \frac{E_p A_p}{V_s} f_{w2} \tag{4}$$

where V_s is the shear wave velocity in the lowest layer of soil at the pile tip; E_p is the Young's modulus of the pile material, R is the radius of the pile, A_p is the cross sectional area of pile, and f_{w1} and f_{w2} are the dimensionless stiffness and damping parameters, respectively.

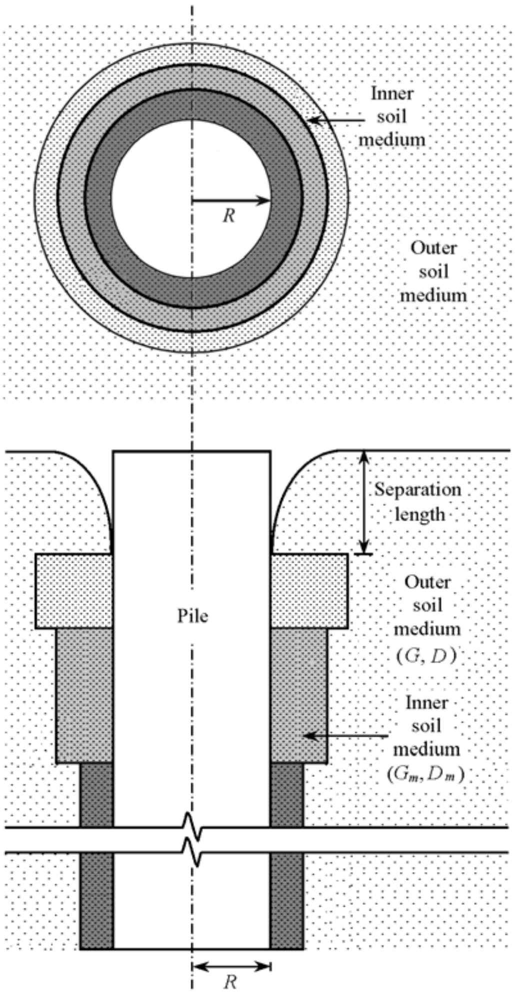

Fig. 10 Schematic diagram of boundary zone around the pile

The effect of nonlinearity and slippage was taken into account by considering a weak boundary zone around the pile (Fig. 10) with reduced soil modulus and higher soil damping as compared to the outer zone (Novak and Sheta 1980). Based on the energy dissipation of the composite medium through wave propagation, the complex dynamic stiffness (k_{wc}) was given by

$$k_{wc} = G_s \left(S_{w1c} + iS_{w2c} \right) \tag{5}$$

in which the dimensionless stiffness (S_{w1c}) and damping (S_{w2c}) parameters of composite medium are real and depend on dimensionless frequency a_o, t_m/R, G_m/G, D, and D_m. Here, tm is the thickness of the inner soil medium and D_m is the dimensionless damping constant of inner weak soil medium. Using the ratio $G_m/G = 0$ in the topmost layer, the separation between the pile and soil was considered.

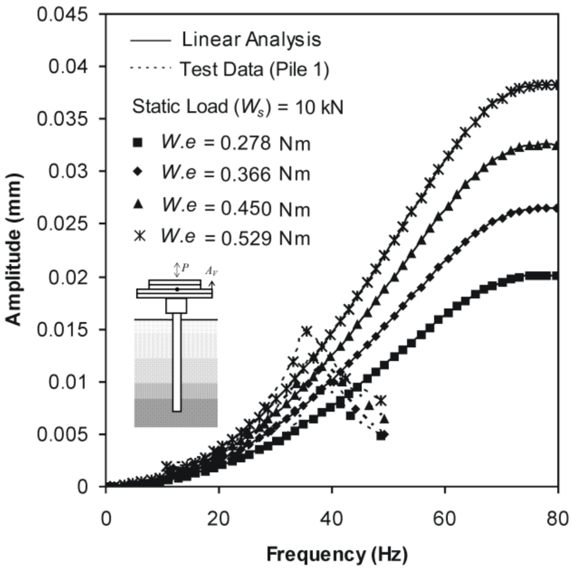

Fig. 11 Comparison of frequency-amplitude curve obtained from continuum approach of Novak (linear) and dynamic test results

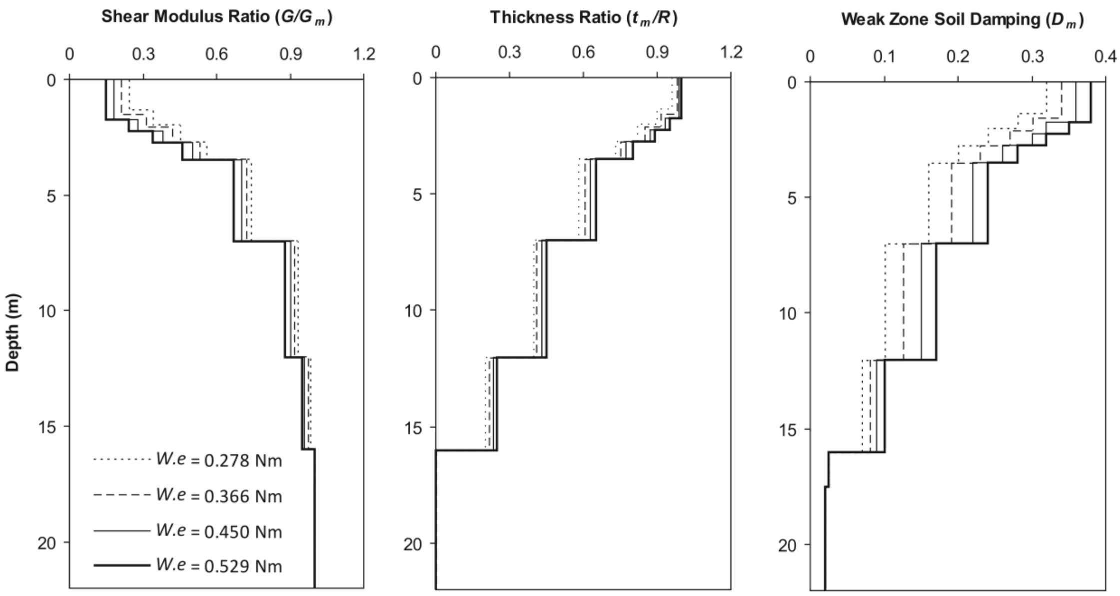

Fig. 12 Variations of boundary zone parameters with depth for different eccentric moments

6. Results and discussion – Continuum approach of Novak

Novak (1974)'s linear theory is very well accepted in many literatures for prediction of the dynamic pile response and this method is widely used in practice due to its simplicity and computational efficiency. The linear dynamic analysis was performed using the continuum

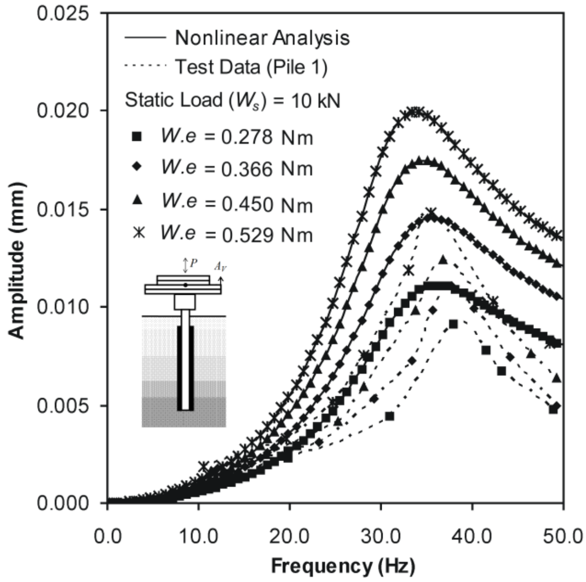

Fig. 13 Comparison of frequency-amplitude curve obtained from continuum approach of Novak (nonlinear) and dynamic test results

approach and the results were compared with the test results as shown in Fig. 11. A wide variations of results are found between the dynamic test results and the results obtained by Novak (1974)'s solution which are definitely due to the non inclusion of material nonlinearity.

To predict the actual material nonlinear properties, a nonlinear dynamic analysis was performed by Novak's continuum approach. A weak zone or yielding of soil was considered around the pile in this modified model to get the nonlinear response by this linear-elastic based mathematical model. Some nonlinear parameters like modulus reduction factor (G_m/G), weak zone soil damping (D_m), thickness ratio (t_m/R) and most importantly separation length were incorporated to predict the nonlinear frequency verses amplitude response. For different excitation intensities, the soil parameter in the weakened zone were adjusted so that the nonlinear theoretical response curves approach the dynamic test results. The variations of weak zone parameters with depth for different excitation levels are shown in Fig. 12. An approximate step-variation trend was assumed for the nonlinear parameters which follow approximately a parabolic variation with the depth. It can be noted that as the excitation intensity increases, the shear modulus ratio (G_m/G) reduces, whereas the thickness ratio (t_m/R) and weak zone soil damping (D_m) increases. The values of G_m/G are increased with depth but the t_m/R and D_m are decreased with depth for all excitation level.

Using those nonlinear parameters, the frequency verses amplitude curves were obtained using continuum approach. The comparison of the frequency-amplitude response obtained from the continuum approach and vertical vibration test are shown in Fig. 13. It can be seen from the comparison curves that the resonant frequency obtained from continuum approach are within the acceptable limit. However, there is a little variation of the resonant amplitudes and this discrepancy is due to the assumption of lower damping value considered in the continuum approach.

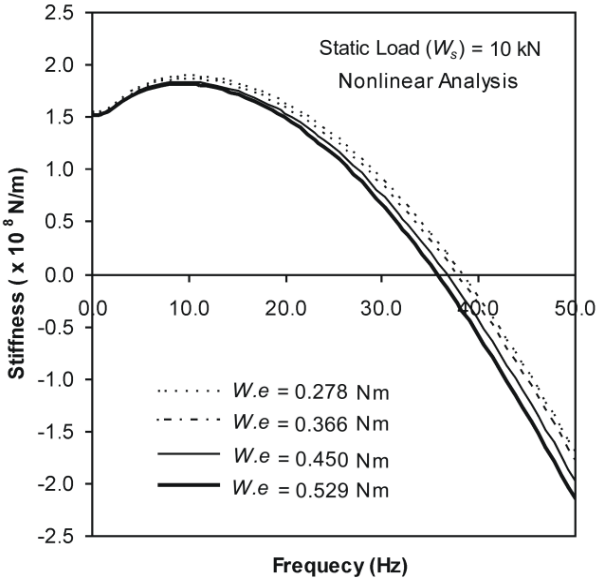

Fig. 14 Variation of stiffness with frequency

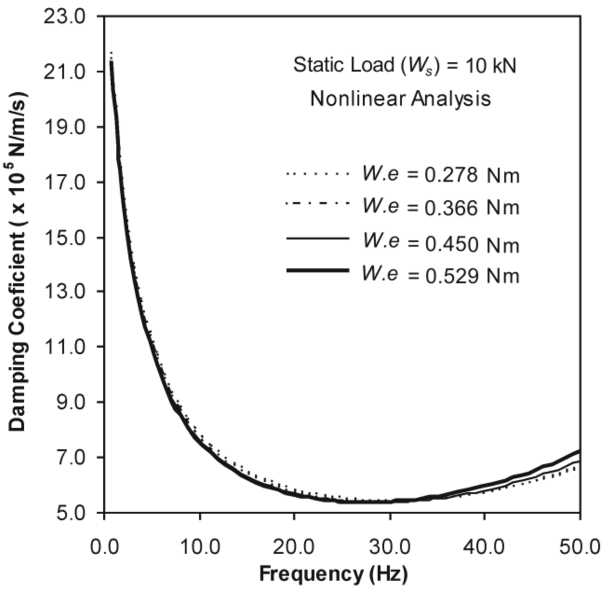

Fig. 15 Variation of damping co-efficient with frequency

The variation in stiffness and damping with frequency for different eccentric moment are presented in Figs. 14 and 15 respectively. It can be observed that the stiffness value is increased with the decrement of eccentric moments. The stiffness values are varied with frequency and the stiffness values are found close to zero at the resonance frequency. On the other hand, the damping coefficient value decrease rapidly at the low frequency range and the minimum value reached before the resonance frequency achieved.

7. Evaluation of nonlinear parameters

The typical features of nonlinear vibrations are the changes in resonant frequencies with different eccentric moment and the lack of proportionality between exciting forces and the resonant amplitudes. The inverse problem of nonlinear vibration was encountered here from the measured nonlinear response to identify the parameters of the pile-soil system. The nonlinear restoring force, the damping and the effective mass of the system were determined from the measured nonlinear response curves using the methodology proposed by Novak (1971). The inverse problem of steady state oscillation excited by a harmonic force whose amplitude increases with the square of the frequency as in the most general case and it is also assumed that the stiffness of soil-pile system is independent of frequency. The reduction of natural frequency is recognized using backbone curve which can be established on the measured response curve. The backbone curve describes the variation of the undamped natural frequencies $\Omega(A)$ with amplitude. A simple relation was proposed (Novak 1971) assuming that the restoring force is nonlinear and the damping force is linear with a character of viscous damping.

$$\Omega = \sqrt{\omega_1 \omega_2} \tag{6}$$

where, ω_1 and ω_2 = the frequencies corresponding to the points of interaction between the response curve and a line passing through the origin.

In the present study, the nonlinear frequency-amplitude response obtained from the field tests of pile 1 for static load of 10 kN was considered. The backbone curve $\Omega(A)$ was constructed to each response curve by intersecting the response curves by a trace of lines shown in Fig. 16. It can

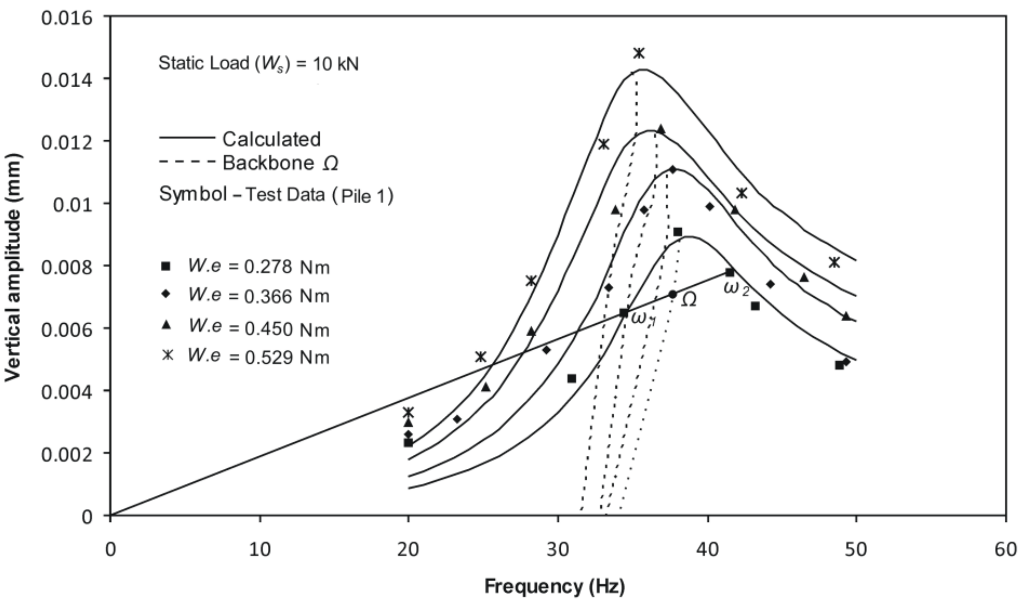

Fig. 16 Back calculated and observed frequency-amplitude curve

be observed that each response curve has its own backbone curve. From the nature of backbone curve it can be seen that the stiffness characteristic of the pile-soil system varies with the different level of excitation intensity.

The stiffness characteristic can be expressed assuming the restoring force $F(A)$ as nonlinear for every steady state amplitude A which linearizes to give the equivalent linear stiffness depending on amplitude A. The damping and effective mass were determined (Novak 1971) using the geometric properties of the nonlinear response curves. For the nonlinear response, the effective mass (m_{eff}) was found much greater than the mass of pile cap-loading system ($m_s = W_s/g$; W_s is the total static load on pile including the mass of pile cap, steel ingots and exciter). The apparent additional mass can be expressed in terms of the mass coefficient as

$$\xi = \frac{m_{eff} - m_s}{m_s} \tag{7}$$

The characteristics of the restoring force were also determined from the backbone curve Ω and the calculated values of effective mass to each response curve. The typical restoring force versus displacement characteristics is shown in Fig. 17. It can be observed that the stiffness of the system decreases with the increase of eccentric moments. The calculated values of effective mass, stiffness and damping for different eccentric moments are given in Table 3.

It can be seen that the damping values are increased with the increase in excitation moment. However, the effective mass and stiffness values are decreased with higher eccentric moments. It indicates that the effect of separation is more prominent at higher excitation intensities. The frequency-amplitudes curves were back calculated using the nonlinear theory with the calculated pile-soil system mass, damping, and the characteristic of restoring force and these response

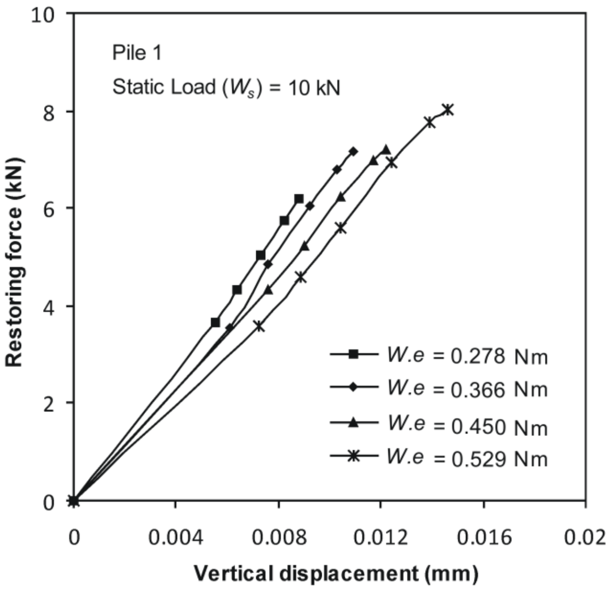

Fig. 17 Pile restoring characteristics with pile displacement

Table 3 Nonlinear parameter of soil-pile system under vertical vibration

Exciting moment (Nm)	Mass of pile cap-loading system (kg)	Effective mass		Damping	Stiffness (kN/mm)
		Effective mass (kg)	Mass coefficient (ξ)		
0.278	1000	12322.7	11.32	0.14	706.77
0.366	1000	12123.2	11.12	0.15	658.77
0.450	1000	12098.0	11.09	0.16	583.76
0.529	1000	11726.0	10.73	0.17	557.97

curves were compared with the field test results as shown in Fig. 16. It can be seen that the theoretical back calculated response curves agree with the test data obtained from vertical vibrations test on pile. So, it can be concluded that the nonlinear parameters obtained from the theoretical analysis (Novak 1971) are accurate and quite acceptable.

8. Conclusions

In this study, the vertical vibration test results of two full-scale single pile were used to predict the nonlinear characteristics of the soil-pile system using 3D finite element package and continuum approach of Novak. The nonlinear parameters of the soil-pile system were also extracted from the dynamic test results.

The complex soil-pile interaction as per actual field condition was simulated using 3D finite element analysis. The frequency-amplitude responses obtained from FE analyses are found very satisfactory comparing with the dynamic test results. A most critical parameter, soil-pile separation lengths for various eccentric moments were also determined from 3D FE analysis. The soil-pile separation length is increased gradually with the increase of eccentric moments but there is no effect of soil-pile separation below the ground water table. The nonlinear 3D finite element model is found to be very efficient for the prediction of dynamic response of full-scale pile in layered soil medium.

The linear continuum approach of Novak is found unsatisfactory for the prediction of the dynamic response of full-scale pile. It is not a safe and cost effective solution due to its overestimation of resonant frequency as well as amplitude value.

The nonlinear continuum approach was used by introducing the boundary zone parameters and the soil-pile separation varying with eccentric moments to predict the full-scale pile response under vertical vibration. The possible variations of boundary zone parameters like modulus reduction factor (G_m/G), damping factor (D_m) and thickness ratio (t_m/R) are fine-tuned for different eccentric moments. It is found that the frequency-amplitude response obtained from the nonlinear continuum approach was very close to the field response curve. The nonlinear response of pile foundation is found mainly due to the geometric nonlinearity (soil-pile separation) and material nonlinearity (modulus reduction). The stiffness and damping values are reduced significantly due to the soil-pile separation. On the other hand, the stiffness values are decreased and the damping values are increased due to the material nonlinearity. It is found that the phenomenon of modulus reduction is not significant after a certain depth of the pile.

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