Three Dimensional Finite Element Nonlinear Dynamic Analysis of Full-Scale Piles under Vertical Excitations

Analyse dynamique non linéaire en 3D par éléments finis des pieux à grande échelle soumis à des vibrations verticales

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ABSTRACT: The present investigation emphasised on a comparative study between vertical vibration tests of full-scale single piles (length of 22 m and diameter of 0.45 m) with the three-dimensional (3-D) finite element (FE) analysis using Abaqus/CAE. A 3-D finite element model was developed to predict the nonlinear dynamic response of pile foundations in layered soil medium based on field data. First, the FE analysis was carried out for static load for the validation of the finite element model and the results were compared with the test results. Then, the vertical vibration analyses were conducted on the finite element model to determine the frequency-amplitude response of the pile and the FE results were compared with the vertical vibration test results of full-scale pile. It was found that the resonant frequency and amplitude obtained from the 3-D FE analysis were very close to the field test results of the full-scale single pile. Based on the FE analysis the variation of the soil-pile separation length with the depth was presented in this paper for different eccentric moments. It was found that the 3-D finite element model was found to be very efficient for the prediction of the nonlinear frequency-amplitude response considering complex nonlinear phenomena of soil-pile system in layered soil medium.

RÉSUMÉ : La présente étude a mis l'accent sur une étude comparative entre les essais de vibrations verticales à grande échelle des pieux simples (longueur de 22 m et un diamètre de 0,45 m) à l'aide d'une analyse par élément finis (EF) à trois dimensions (3D) en utilisant Abaqus / CAE. Un modèle des éléments finis 3D a été développé pour prédire la réponse dynamique non linéaire des pieux dans les sols multicouches en utilisant les données in-situ. Tout d'abord, l'analyse par éléments finis a été réalisée pour la charge statique à fin de valider le modèle et les résultats ont été comparés avec les mesures in-situ. Ensuite, les analyses de vibrations verticales ont été modélisées par éléments finis pour déterminer la réponse en fréquence d'amplitude du pieu et les résultats EF ont été comparés avec les résultats d'essais aux vibrations verticales des pieux à pleine échelle. Il a été constaté que la fréquence de résonance et l'amplitude obtenues à partir de l'analyse ont été très proches des résultats des essais in-situ du pieu à pleine échelle. La variation de la longueur de la séparation sol-pieu avec la profondeur a été calculée dans ce papier pour différents moments excentriques. Il a été constaté que le modèle 3D est très efficace pour la prédiction de la réponse de fréquence non linéaire-amplitude, compte tenu des phénomènes complexes non linéaires du système sol-pieu dans un milieu multicouches.

KEYWORDS: Layered soils; Nonlinear response; Soil-pile separation; Vertical vibration; 3-D finite element analysis.

1 INTRODUCTION

Vibration of pile foundation from the operation of machine produces elastic waves within the soil mass. The determination of pile stiffness and damping parameters is an important step in the analysis of pile-supported structures subject to dynamic loading due to machinery and vibrating equipments etc. 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. In recent years, a considerable amount of theoretical research has been accumulated in the area of dynamic behavior of piles, especially under linear elastic assumptions. On the other hand, the available literature on nonlinear soil-pile system subject to dynamic loading is limited.

The finite element method (FEM) was appropriate to study the response analysis of the pile by considering the nonlinearity of the soil medium and separation at the pile-soil interface. Kuhlemeyer (1979) introduced the finite element results of soil-pile system by a simple lumped mass model. Then Dobry et al. (1982) made a parametric study (stiffness and damping coefficients) of the dynamic response of single pile. Lewis and Gonzalez (1985) was investigated the nonlinear soil response of soil-pile system and soil-pile gapping using FE analysis. Bentley and El Naggar (2000) developed a 3-D finite element model that considers 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. Maheshwari et al. (2004, 2005) studied the significance of nonlinearity of soil-pile system by a three dimensional finite element programme. Ayothiraman and Boominathan (2006) was performed two-dimensional analysis using Mohr-Coulomb soil model to determine the soil-pile response by FE software package, PLAXIS. 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.

It can be concluded based on literature review that a very few studies are available to model of the full-scale pile-soil system using rigorous 3-D finite element model. Prediction of the boundary zone parameters and the soil-pile separation lengths are another key aspect of nonlinear response of pile foundation which has not been studied in details.Hence in the present study, the nonlinear response of the soil-pile system was investigated by a 3-D finite element package. Parametric study was performed based on the comparison between finite element analysis results and vertical vibration test results of full-scale single pile.

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 Figure. 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).

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

3 THREE DIMENSIONAL FINITE ELEMENT MODELLING

A 3-D 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 Figure. 2(a). 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.

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 with a friction coefficient estimated by the tangent of the friction angle between the two materials. The normal behaviour was considered to be hard (no penetration to each other) allowing separation after contact.

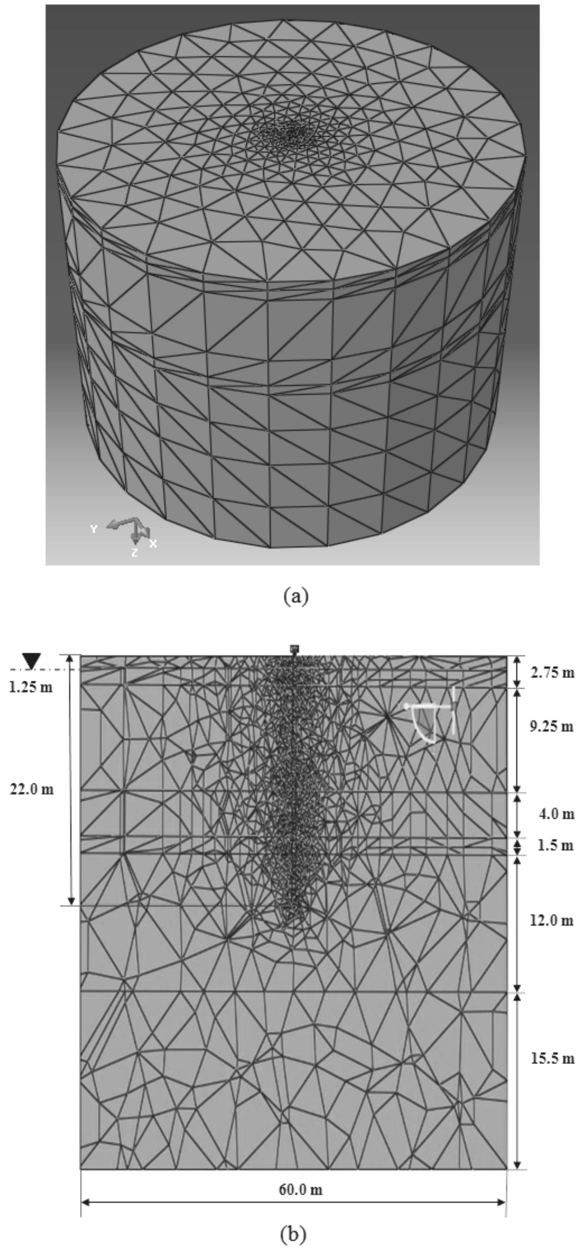

Figure 2. Three Dimensional Finite Element Model of Soil-Pile System: (a) 3-D view and (b) Sectional view.

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 Figure. 2(b). The phreatic level was considered 1.25 m below the ground surface and the effective soil pressure was applied in the whole geometry according to this phreatic line. 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:

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

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 analysed 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

4.1 Validation of finite-element model

To monitor the boundary effect, the model was analysed with different radius of boundaries. 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 FE analysis is shown in Figure. 3. 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).

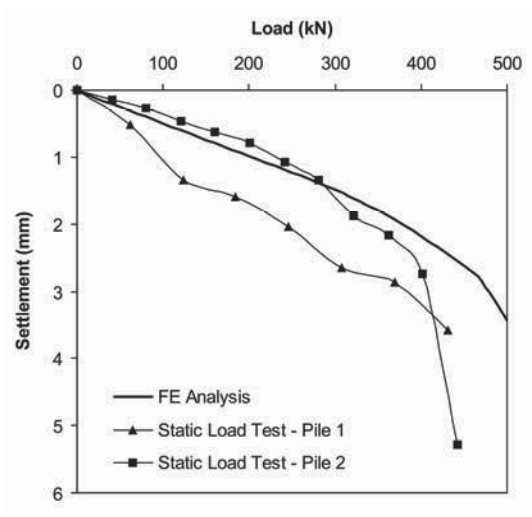

Figure 3. Comparison of load verses settlement curve obtained from FE analysis and static load test.

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 Figure. 4 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.

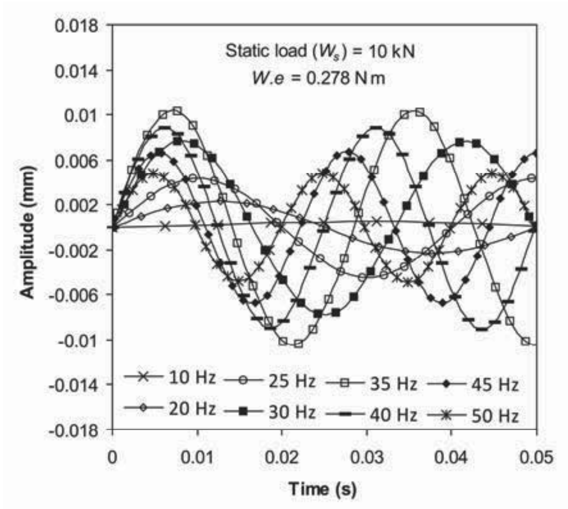

Figure 4. Time-amplitude response of pile at different frequencies (FE analysis).

The typical comparison of frequency-amplitude response obtained from FE analysis and test results are shown in Figure. 5 and Figure 6 for pile 1 and pile 2 respectively.

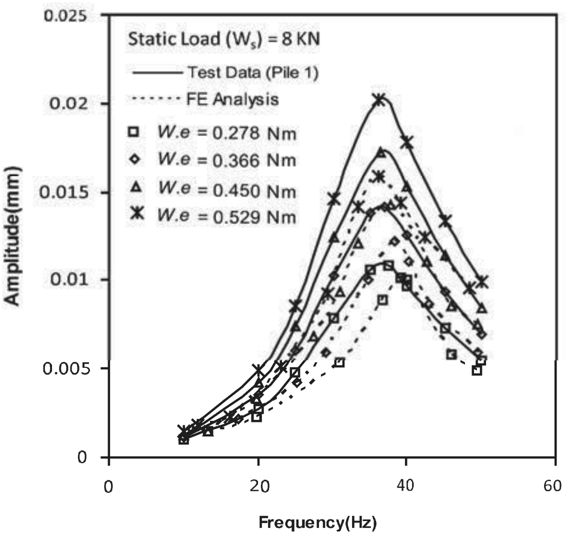

Figure 5. Comparison of frequency-amplitude curve obtained from FE analysis and dynamic test results (Pile 1).

It is found from these figures that the predicted resonant frequency and 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.

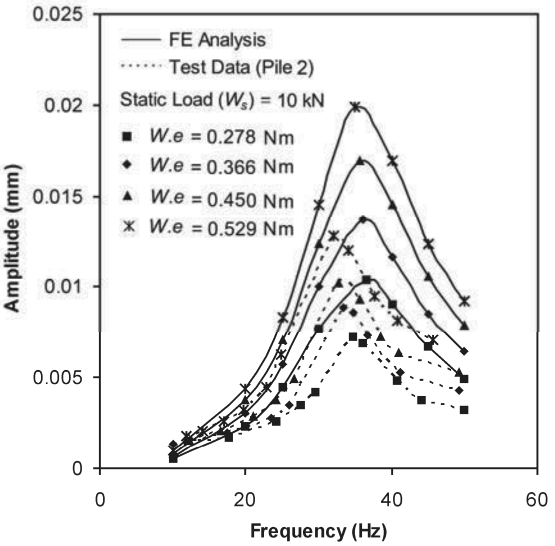

Figure 6. Comparison of frequency-amplitude curve obtained from FE analysis and dynamic test results (Pile 2).

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 3-D 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 Figure. 7. It can be observed that the amount of separation is reduced drastically with the increase of the depth. 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.

5 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 3-D finite element package. The complex soil-pile interaction as per actual field condition was simulated using 3-D finite element analysis. It is found from the FE analysis that the resonant frequencies are decreased with the increase of eccentric moments under same static load and resonant amplitudes are not proportional to the eccentric moments. This phenomenon indicates the nonlinear behaviour of soil-pile system obtained from FE analysis which is similar to the field test results. 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 3-D 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 3-D finite element model is found to be very efficient for the prediction of dynamic response of full-scale pile in layered soil medium.

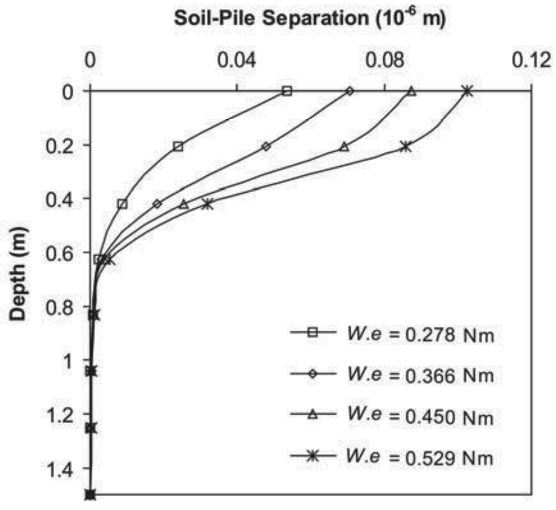

Figure 7. Amount of separation at soil-pile interface (FE Analysis).

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