Nonlinear Dynamic Behaviour of Hollow Piles Based on Axial Harmonic Loading

Surya Prakash Sharma, Shiva Shankar Choudhary, and Avijit Burman

Abstract The main objective of the current work is to examine the dynamic axial response of three pile group under machine-based harmonic loads. Field tests are carried out under axial harmonic excitations on a group pile with a pile length of 300 cm and an diameter of 11.4 cm in order to accomplish this objective. For various eccentric moments, the frequency versus amplitude responses of the group pile are measured. The field test results of the soil-pile system show non-linear behaviour as their resonant frequencies decrease and their resonant amplitudes disproportionally increase with eccentric forces. The inverse methodology proposed by Novak (1971) is used for the theoretical study. With this methodology, the changes in stiffness, damping, and effective mass of the piles under various eccentric moments are quantified by analyzing the frequency-amplitude response curves of field results. The theoretically back-calculated soil-pile system response curves are compared with the field results, and it is observed that the analytically predicted responses closely match the field responses. It is also found that the values of estimated damping of the pile group increased, while effective mass and average stiffness values decreased with an increase in eccentric moments.

Keywords Axial harmonic excitations · Soil-pile system · Field tests · Frequency-amplitude response

1 Introduction

In recent years, pile dynamics has drawn more attention in geotechnical engineering problems due to its successful application in machinery foundations and dynamic loading like wind or seismic conditions on heavy or large structures. However, numerous researchers are still investigating and researching the impacts of dynamic

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behaviour and characteristics on the nonlinear response of piles with machine foundations. In the case of axial loading, limited research has been carried out for pile group to evaluate the dynamic properties of machine-based foundation systems. A few researchers conducted dynamic vibration tests on piles to examine the nonlinear behaviour of soil-pile systems in terms of frequency-amplitude responses in order to better understand the complex dynamic properties of machine foundations. Some other researchers [1–5], who have worked on pile dynamics, have conducted experiments and done analytical studies on piles to determine the stiffness and damping using a continuum approach method. From the literature, it can be inferred that, in comparison to the experimental findings under machine vibration, the theoretical solutions also indicate a reasonable assessment of nonlinear loading responses. Liu and his co-authors [6] investigated 3D Voigt model stiffness and damping coefficients to evaluate the dynamic pile-soil-pile resistance and, in the case of torsional vibration, the dynamic resistance in order to comprehend the dynamic response of soil-pile interaction in longitudinal vibration. The soil-pile system was studied under dynamic settings by Khalil [7] and from the obtained datasets it was found that the loading frequency significantly influences the dynamic stiffness and damping with generated amplitudes. A fundamental component of machine-based foundation systems, the prediction of dynamic frequency-amplitude response of group piles and its variation due to soil-pile stiffness and damping under dynamic loading needs further exploration because of limited research work. The existing theories, which have hardly ever been examined, require experimental (field or laboratory) verification. Therefore, in this study, machine-induced axial harmonic loading is investigated together with the dynamic properties of a three-pile group, using a nonlinear theoretical approach based on Novak [8] inverse method. The combined set of soil-pile configurations in this method are subjected to harmonic forces, which are generated by a mechanical oscillator and whose amplitude values increase with the square of the frequency. To determine the dynamic parameters of the soil-pile arrangement, the theoretical nonlinear response calculated from Novak's inverse method is compared with field test results. The values of restoring force, damping, and the effective mass of the three-pile group are also calculated from the dynamic response curve.

2 Site Location and Soil Properties

Forced vibration field tests are carried out on the campus of IIT Delhi in India. Various geotechnical tests are carried out on soil samples that are extracted from the borehole to determine their in-situ soil properties. Up to a depth of 6.5 m, two different soil layers are found [0 to 3.5 m (Sand-39%, Silt-43%, and Clay-18%), and 3.5 to 6.5 m (Gravel-3%, Sand-36%, Silt-42%, and Clay-19%)], with the first top layer having an average dry density of 15.33 kN/m^3 and a shear modulus of 1.3×10^4 kN/m^2. In the case of the second layer, the average dry density and shear modulus are found to be 16.72 kN/m^3 and 2.3×10^4 kN/m^2 respectively. From the soil test results, it is found that the soil particles are low in plasticity and represent a clayey silt type of soil.

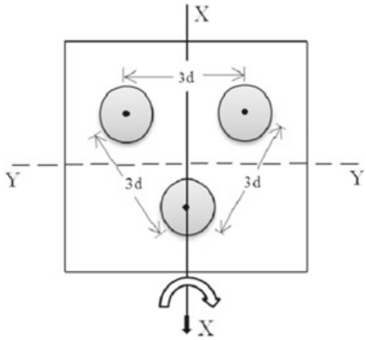

Fig. 1 Schematic diagram of three-pile group

3 Field Testing Setup and Testing Procedure

3.1 Dynamic Axial Loading Tests

Axial harmonic tests are conducted on hollow steel three-pile groups (length of pipe = 300 cm, inner diameter = 11.1 cm, and thickness = 0.3 cm). The schematic diagram of the pile group with rotational forcing direction is shown in Fig. 1. The piles are embedded into the ground by SPT hammer in undersize boreholes which are constructed by a 100 mm diameter hand augur. The bottom end is closed with a circular plate to get the end bearing of the pile.

The axial loading is generated on the pile group with the help of a rotating mechanical oscillator. As per requirement, the axial magnitude of the vibration increases or decreases with the use of an outer valve of eccentricity (θ). This is the part of two counters rotating-mass inside the oscillator which is presented in Fig. 2. The produced eccentric moment ($m.e$) can be represented as follows:

$$m.e = \left(W/g\right).e = \left[2.59\sin\left(\theta/2\right)\right]/g \;\; \text{NSec}^2 \tag{1}$$

where, W and m are the weight and mass of eccentric rotating parts inside the oscillator. e = eccentric distance of the rotating masses, and g = acceleration due to gravity.

The soil-pile responses of the pile group is obtained for four different eccentric moments. For an axially loaded field setup, first an oscillator is resting on a pile-cap

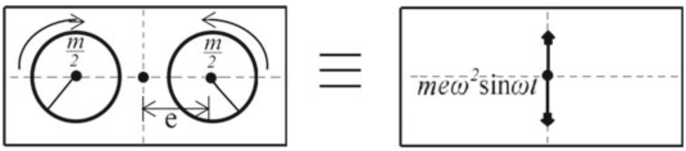

Fig. 2 Rotating masses inside the oscillator with forcing direction

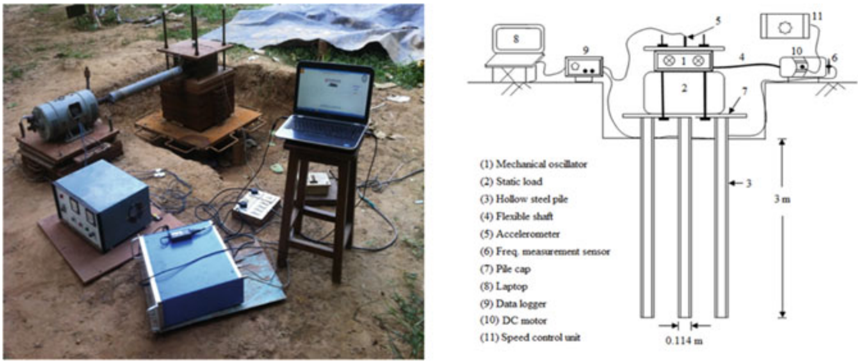

Fig. 3 Complete field test setup and schematic diagram of axial harmonic test

loading system in a horizontal manner so that the harmonic forces are generated in the axial direction. The axial harmonic loading tests are performed for a static load (W_s) of 14 kN (W_s = combined weight of the pile cap, steel plates, and mechanical oscillator). The steel plates are used to bring the dynamic responses of the combined system within the frequency range of 0 Hz to 50 Hz. The nonlinear responses of the combined soil-pile are recorded at varying frequency ranges. The data sets (time vs frequency and time vs acceleration) are transmitted and recorded on the laptop (with software package) through the data acquisition system. To measure the acceleration, an accelerometer is connected to the top and center of the soil-pile setup. To measure the frequency, the wire of the frequency measuring sensor is joined with a DC motor. During dynamic loading tests, the frequency-amplitude responses are recorded. The axial loading field test setup and schematic diagram are presented in Fig. 3.

4 Analytical Study

Nonlinear axial loading can be predicted by many approximate or asymptotic approaches when soil-pile dynamic characteristics of the system are given in terms of frequency, amplitude, loading forces etc. An inverse problem proposed by Novak [8] is one of the analytical approaches based on experimental data sets to measure the nonlinear dynamic responses of piles. In this approach, the machine-based inverse problem method of Novak with a field data set is used for the investigation of frequency-amplitude response curves of pile groups. In this method, steady state oscillation is vibrated by a dynamic force whose axial amplitude of the combined soil-pile system increases with the square of the frequency. In this method, the relationship between backbone curves (Ω) with respect to dynamic nonlinear response curves in terms of undamped natural frequencies is very important to evaluate the nonlinear properties of the soil-pile system. The proposed relationship between both parameters may be expressed as:

$$\Omega = \sqrt{\omega_1 \omega_2} \tag{2}$$

in which ω_1 and ω_2 are the frequencies at the points of interaction through field frequency-amplitude curve. In the case of elastic nonlinearity, the restoring force is linear under harmonic excitation under certain amplitude. If the function of steady amplitudes is assumed to be $F(A)$ during steady excitation, then the square of natural frequencies can be represented as follows:

$$\Omega^2(A) = \frac{F(A)}{Am_{eff}} \tag{3}$$

where, $\Omega(A)$ represents the natural undamped frequencies, m_{eff} represents the effective mass of the soil-pile loading system. Two points (ω_1 and ω_2) on the response curve corresponding to amplitude A_T (resonant amplitude) and the corresponding point on the Ω - curve with ω_T (resonant frequency) are used in the damping calculation formula (Eq. 4). If $A = A_T$ / *SQRT 2* is chosen analogous to the often-used approach in soil-pile system, then the damping is:

$$D = \frac{1}{2}\frac{\omega_2 - \omega_1}{\omega_O}\left[2\left(\frac{\Omega}{\omega_T}\right)^2 - 1\right]^{-1/2} \tag{4}$$

In this case, mass is well known so that the behaviour of the pseudo-nonlinear restoring forces can be determined with the help of Ω-curve.

$$F(A) = Am_{eff}\Omega^2 \tag{5}$$

5 Comparison of Test and Analytical Results

The measured dynamic field response of the pile group is used to back calculate the frequency-amplitude response curves using nonlinear vibration theory. Further, the back-calculated response curves and the field response curves are compared. By intersecting the field response curves with a trace of lines, as illustrated in Fig. 4, the backbone curve is plotted for each of the four response curves, which are obtained from various eccentric moments. The resonant frequencies are found to decrease as eccentric moments are raised, and in the case of amplitudes, the resonant values are discovered to be non-proportional for both back-calculated theoretical and field results. This could be a representation of the nonlinear characteristics of the soil-pile system. The backbone curve pattern shows that the eccentric moments have an impact on the pile group stiffness characteristic. The nonlinear properties of the pile group are listed in Table 1. The tabular findings show that when the vibrating forces increase, the evaluated damping values increase while effective mass and average stiffness values decrease. These trends in the soil stiffness that are decreasing around the pile indicate a reduction in soil resistance. The decreasing pattern of additional effective mass indicates a partial break in the bond between the soil and the pile (or an increase in the soil-pile separation length) with the increase of eccentric moments or excitation forces. It is also observed that the field resonant frequencies and amplitudes are higher as compared to theoretical resonant values. These results may indicate the higher soil-pile stiffness in this theoretical case. However, in the case of field tests, the complete bond between soil and pile is not fully developed or the soil does not return to its natural condition after piles are left to rest for almost two months.

Using the previously described theory, the $F(A)$ and axial displacements are calculated from the measured frequency-amplitude curves of the pile group. For the different eccentric moments, the obtained data sets are used to plot $F(A)$ vs axial displacements (Fig. 5). It is discovered that as eccentric moments increase, the pile group overall stiffness decreases. For various eccentric moments, the values of the soil-pile system effective mass, damping, and stiffness are provided in Table 1.

Theoretical findings show that the nonlinear frequency-amplitude response curves match the outcomes of the field tests conducted under axial loading. Therefore, using

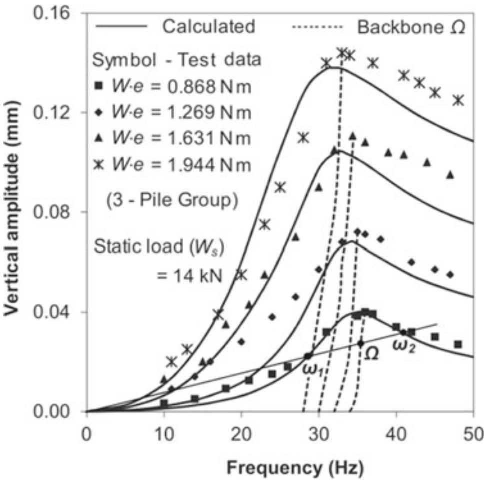

Fig. 4 Comparison between field and analytical response curves of three-pile group

Table 1 Measured dynamic parameter based on theoretical methodology

Eccentric moment (Nm)	Effective mass		Damping	Stiffness (kN/mm)
	Mass, m_{eff} (kg)	Mass coeff., ξ		
0.868	11,348	7.12	0.170	397.71
1.269	9412	5.72	0.175	295.57
1.631	8381	4.98	0.180	210.44
1.944	6579	3.70	0.185	160.23

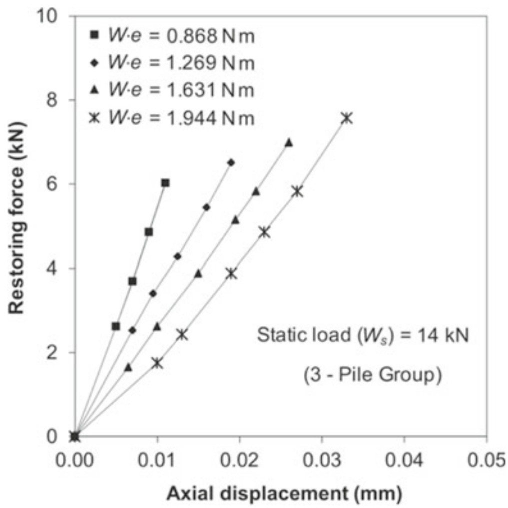

Fig. 5 Measured restoring force versus displacement of pile group

this inverse method and a system with a nonlinear restoring force and linear damping, a comprehensive and straight-forward theoretical investigation is made possible.

6 Conclusions

Under machine-based axial loading testing, the dynamic performance of a three-pile group is examined to understand the behaviour of the soil-pile system. According to the field test and analytical findings, the dynamic properties of the soil-pile system show a nonlinear pattern as their resonance frequencies fall and their amplitudes disproportionally rise with eccentric moments. With the use of the inverse back calculation method established by Novak, the field response curves are used to determine the variation of stiffness, damping, and effective mass at various eccentric moments. According to the theoretical calculation, the pile group stiffness decreases as the eccentric moments are increased. The decreasing behaviour in soil stiffness may occur due to a decrease in soil resistance around the pile. The experimental findings and the back-calculated soil-pile response curves demonstrate the close agreement between theoretical and field test data. Therefore, the comprehensive and straight-forward analytical application can be used through this inverse method as a realistic and versatile solution for dynamic analysis of soil-pile systems.

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