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A numerical and experimental study of hollow steel pile in layered soil subjected to vertical dynamic loading

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ABSTRACT

This paper presents an investigation of the nonlinear behaviour of single piles subjected to varying levels of vertical dynamic load. A good number of tests are performed for the understanding of the dynamic behaviour of single hollow steel piles embedded in layered soil. Experimental results are validated with results obtained from a nonlinear numerical analysis using commercially available Finite Element Method (FEM) based software. The results of numerical analysis and experimental investigations showed that the length of pile has significant influence on resonant frequency and amplitude of the pile foundation. It has also been found that the slippage of pile from the surrounding soil considerably affects the resonance frequency and amplitude of the soil–pile foundation system.

1. Introduction

One of the primary objectives of the design of the pile foundation subjected to dynamic load is to limit the vibration amplitude to a permissible value. At resonance foundation experiences large vibration amplitudes. Hence the estimation of resonant frequency of soil–pile system is a very important task. It is well known that the response of pile foundations under dynamic excitation is a complex phenomenon involving nonlinearities in material behaviour and complex interaction between the soil and pile.

In the early development some approximate solutions such as equivalent cantilever model [1] and lumped mass-spring-dashpot model [2] were adopted in analysis for the simplification of the complex soil–pile system subjected to dynamic load. Later, a continuum approach [3] was developed using a Winkler soil model considering soil as visco-elastic continuous medium and pile as massless rigid cylinder. Many researchers adopted 3D-FEM to analyze nonlinear dynamic response of the soil–pile system considering both material nonlinearity and complex soil–pile interaction [4,5].

Many researchers conducted field tests with small-scale prototype piles [6,7] as this type of testing is less demanding than full scale tests in terms of equipment, cost, and effort. Some earlier work performed by the same research group includes static and dynamic vertical load test on full-scale single pile in the field and validation of the test results with that obtained from 2D-FEM analysis [8]. Subsequently, experimental and theoretical investigations were conducted on small-scale single and group piles in the field under vertical and horizontal excitation [9–11]. They performed a parametric study introducing length of separation of pile from the adjacent soil. The present investigation is the continuation of a previous research work on horizontal response of single pile in the field [12]. In this investigation it is attempted to study the dynamic behaviour of single piles under vertical vibration by experimental and numerical investigation. Relevant issues of soil nonlinearity, slippage between the soil and the pile are also addressed.

2. Experimental investigation

The experimental set-up and test procedure are as described in Bhowmik et al. [12]. The only two differences in the experimental set-up from previous investigation are: (i) the mechanical oscillator was oriented in such a way that the produced dynamic force acts in the vertical direction; and (ii) two piezoelectric acceleration

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pickups were attached vertically on top of the plate over the static mass by means of magnetic shoe attached to it to record the vertical displacement amplitude. The site conditions are the same as in Bhowmik et al. [12]. Fig. 1 shows the location of vertical vibration pick-ups and all other geometric details of the loading.

2.1. Experimental results

The average of vertical amplitude of soil–pile system recorded from two vibration pickups is used for the investigation. Resonant frequencies and amplitudes obtained from the tests are presented in Table 1 for all pile lengths and dynamic load intensities. It can be seen from Table 1 that as the exciting moment increases the resonant amplitude increases but resonant frequency decreases. Similar trends also are observed for all other lengths of pile. Further, Table 1 shows that with the increase of pile length (L/d ratio from 10 to 20) resonant frequency increases (from 14.4 Hz to 20.38 Hz) whereas resonant amplitude decreases (from 5.8×10^{-5} m to 4.4×10^{-5} m), while other parameters being constant.

3. Finite element modelling of pile foundation system

A finite element model using general purpose commercial software Abaqus has been developed to validate the dynamic behaviour of the pile as obtained from the experimental investigation. The detail geometry and the method of discretization were similar to that of previous work [12]. The location of the point where vertical vibration amplitudes were noted and all other geometric details are shown in Fig. 1. Vertical amplitudes were noted at a point on the top of the foundation. The point lies in the same vertical plane which passes through the centre of gravity of the machine and foundation. Vertical displacement values of the outer surface of the pile and adjacent soil surface at different depths were estimated to find out the slippage in soil–pile interface.

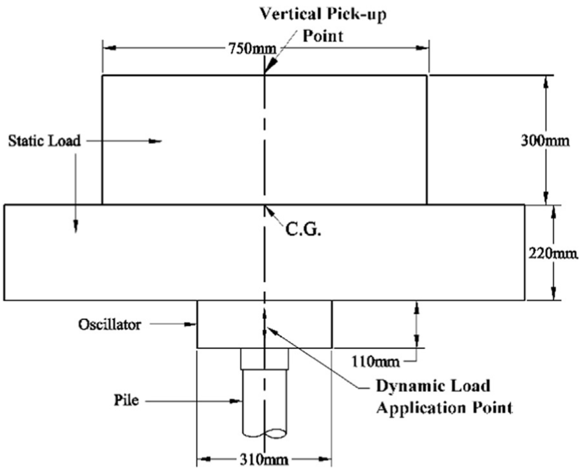

Fig. 1. Detailing of pile cap and point of vibration pick-up.

The detailed material properties and other modelling issues (assumptions, calibration, convergence studies etc.) are as described in [12]. Table 2 presents the assumed hardening properties based on the stress–strain curve obtained from the Unconfined Compression Strength (UCS) tests, as described in [12] for all three soil layers. Damping ratio of the soil was assumed to be 0.05 for all soil layers. The elastic modulus and Poisson's ratio of steel were considered 2×10^{11} N/m^2 and 0.3 respectively. The boundary of the soil mass is modelled using infinite elements as reported by Lysmer and Kuhlemeyer [13] to simulate absorbing boundary conditions. The steps of the analysis are as described in [12].

3.1. Numerical results

Dynamic analysis was carried out by FEM using the procedure described above for three single piles with diameter of 100 mm each and length 1.0, 1.5 and 2.0 m (L/d=10, 15 and 20). Four different exciting moments ($w_e \cdot e$) to produce dynamic load of different magnitudes were considered for each pile. Fig. 2 presents frequency versus amplitude curves for 2.0 m long pile under different exciting moments from the FEM analysis and from experimental investigation. It can be seen from the figure that the vertical dynamic responses show very similar characteristics with those found in the experimental investigation. Resonant frequencies and amplitudes obtained from the numerical studies for similar conditions and for all pile lengths are presented in Table 1 along with test results. It can be seen from Table 1 that with the increase of pile length resonant frequency increases whereas resonant amplitude decreases for a particular exciting moment as it was observed in the experimental results. For example resonant frequency increased from 12.355 Hz to 22.04 Hz and resonant amplitude decreased from 0.0468 mm to 0.0417 mm with the increase of L/d from 10 to 20, other conditions being constant.

Fig. 3(a) through (c) shows the vertical deformation contour diagram for three different lengths of pile at the position of maximum downward displacement of the pile head during oscillation while vibrating at vertical resonant frequency. Red colour (or lighter shade) indicates the zone of least deformation while blue (or darker shade) shows maximum deformation. It can be seen from the figures that larger vertical deformation takes place in shorter pile than in case of longer pile. Furthermore, as the length of the pile decreases it behaves more like a rigid body. Very

Table 1
Experimental and numerical results.

Study	**Exciting moment (N m)**	**L/d=10**		**L/d=15**		**L/d=20**	
		f_{ve} (Hz)	**A_{ve} (m)**	**f_{ve} (Hz)**	**A_{ve} (m)**	**f_{ve} (Hz)**	**A_{ve} (m)**
Experimental	0.125	14.40	5.800E−05	17.05	5.100E−05	20.38	4.400E−05
	0.248	13.95	1.160E−04	16.50	1.070E−04	20.27	8.800E−05
	0.366	13.50	1.580E−04	16.03	1.520E−04	19.63	1.355E−04
	0.477	12.33	2.180E−04	15.17	2.050E−04	19.27	1.860E−04
		f_{vn} (Hz)	**A_{vn} (m)**	**f_{vn} (Hz)**	**A_{vn} (m)**	**f_{vn} (Hz)**	**A_{vn} (m)**
Numerical	0.125	12.36	4.681E−05	15.68	4.762E−05	22.04	4.171E−05
	0.248	12.35	9.187E−05	15.68	9.407E−05	22.04	8.259E−05
	0.366	12.30	1.349E−04	15.60	1.387E−04	22.03	1.219E−04
	0.477	12.23	1.733E−04	15.55	1.745E−04	22.00	1.578E−04

f_{ve}=Experimental resonant frequency, A_{ve}=Experimental resonant amplitude, f_{vn}=Numerical resonant frequency, and A_{vn}=Numerical resonant amplitude.