Soil Dynamics and Earthquake Engineering 94 (2017) 109–115

Contents lists available at ScienceDirect

Soil Dynamics and Earthquake Engineering

journal homepage: www.elsevier.com/locate/soildyn

Experimental and theoretical study on the nonlinear response of full-scale single pile under coupled vibrations

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ARTICLE INFO

Keywords:
Full-scale pile
Layered soil
Coupled vibration
Nonlinear response
Continuum approach
Boundary zone parameters

ABSTRACT

In this study, an attempt is made to investigate the complex nonlinear behaviour of a reinforced concrete full-scale single pile of 22.0 m length and 0.45 m diameter subjected to machine induced coupled i.e. horizontal and rocking vibrations. The forced vibration tests were conducted in the field to determine frequency-amplitude responses of the single pile for different eccentric moments. The continuum approach of Novak was used to determine the nonlinear responses of the single pile after incorporating precise values of soil-pile separation lengths and boundary zone parameters. The analytical responses were compared with the experimental responses and it was found that the analytical resonant frequencies and amplitudes were within a reasonable range with the coupled vibration test results. Variation of stiffness and damping of the single pile with frequency were also presented using continuum approach analysis.

1. Introduction

Pile foundations are broadly used to support various vibration producing structures like different type of machine foundations, off-shore structures, wind turbines etc. But designers often face problems to predict the nonlinear soil-pile response due to lack of guidelines. Many theories are developed to evaluate the frequency-amplitude responses of pile foundations under machine induced vibrations. However, determinations of the actual nonlinear responses of the pile foundations are still found very difficult under coupled vibrations using the existing theories because of the limited information about the various influencing parameters. Therefore, more detailed study is necessary to understand the role of these parameters in the nonlinear behaviour of soil-pile system under rotating machine induced coupled vibrations.

Among the different available theoretical methods for prediction of the dynamic response of pile foundations, the continuum approach analysis is most widely used in practice. Novak [1] introduced an approximate continuum approach analysis for piles under dynamic loading by considering wave propagation through soil medium along transverse direction. A direct solution in terms of closed form formulas were developed by Novak and Nogami [2] using continuum approach to evaluate the stiffness, damping and pile displacements for horizontal vibration. An approximate analytical solution was proposed by Novak and Aboul-Ella [3] for determination of the stiffness and damping of single piles embedded in layered soil. Novak et al. [4] derived the linear complex dynamic soil stiffness for this model [3] assuming plane strain case of cylindrical soil medium under harmonic wave motion. To include the effect of soil nonlinearity, Novak and Sheta [5] revised the complex soil reaction by considering a cylindrical soil boundary zone around the pile characterized by lower shear modulus and higher damping as compared to the outer soil region. Later, Han and Sabin [6] proposed a soil model with parabolic variation of boundary zone shear modulus of soil to provide non-reflective wave interface. Sinha et al. [7] performed parametric study of different soil models using continuum approach of Novak [2] and found that the soil model of Novak and Sheta [5] was very efficient to determine the nonlinear responses of single piles under machine induced vibrations.

Experimental investigation of piles is an unavoidable component to verify the efficiency of theoretical methods. Gle and Woods [8] conducted steady state dynamic lateral load tests on full-scale pipe piles and the dynamic lateral responses were compared with the solution of a two degree of freedom soil-pile system. Blaney and O'Neill [9] conducted lateral vibration tests on a full-scale steel single pile and the experimental responses were compared with the responses obtained from an equivalent-liner plane strain solution. Similar kind of study was also conducted by Sy and Siu [10] on a full-scale expanded base single concrete pile and well agreement was found between the

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http://dx.doi.org/10.1016/j.soildyn.2017.01.012
Received 20 July 2014; Received in revised form 15 September 2016; Accepted 15 January 2017
0267-7261/

experimental and analytical response curves for different modes. Puri and Prakash [11] conducted vibration tests on a full-scale single concrete pile and the test responses were compared with analytical responses obtained using different methods developed based on continuum approach. El Marsafawi et al. [12] conducted field experiments on pile groups under harmonic loading in a clay site to investigate the efficiency of various linear-elastic plane strain theories. Manna and Baidya [13] performed dynamic tests on full-scale concrete piles and the test results were compared with the results of a two-dimensional axisymmetric finite element model. Elkasabgy and El Naggar [14] performed dynamic field tests and continuum approach analysis on full-scale steel single helical as well as driven piles to investigate the performance characteristics of the piles under dynamic loading.

It is found from the literature review that the dynamic test results on full-scale piles under coupled vibration are rarely presented. Effect of input parameters i.e. boundary zone parameters and soil-pile separation lengths used in Novak's continuum approach analysis have not been studied in details so far. Hence in the present study, coupled vibration tests were performed on a full-scale single pile (l/d =49, l and d are the length and diameter of the pile respectively) embedded in layered soil medium to determine the frequency-amplitude responses for different eccentric moments. The continuum approach of Novak was used to predict dynamic responses of the single pile using various boundary zone parameters and soil-pile separation lengths. The variations of stiffness and damping of the single pile with frequency were also investigated in this study.

2. Site investigation

The dynamic pile tests were conducted in the site located at I.I.T. Kharagpur Extension Centre, Block No.- HC, Plot-7, Sector-III, Salt Lake City, Kolkata, India [13]. Standard penetration tests (SPT) were performed at different depths of the soil up to a depth of 30 m to obtain SPT-N values which are shown in Fig. 1. Both disturbed and undisturbed soil samples were collected from different boreholes for laboratory testing. Water table was encountered during the site investigation at 1.25 m depth below ground level. Laboratory experiments such as natural moisture content, Atterberg's limits test, particle size distribution, specific gravity, direct shear test and triaxial test were carried out on selected soil samples. Based on laboratory and field observations, the vertical soil profile of the site is divided into six different soil layers as per Unified Soil Classification System which is shown in Table 1. It is observed from the laboratory test results that the soil layers are mainly comprised of fine grain soils. Shear wave velocity of soil was evaluated from the following correlations [15] which were proposed specially for the zone of testing location i.e. Kolkata, India.

$$V_s = 77.11N^{0.39} \quad \text{for clay (Layer 2 and Layer 3)} \tag{1}$$

$$V_s = 58.02N^{0.46} \quad \text{for silt (Layer 4 and Layer 6)} \tag{2}$$

$$V_s = 54.82N^{0.53} \quad \text{for silty sand (Layer 1 and Layer 5)} \tag{3}$$

The field SPT-N values considered to evaluate the shear wave velocity of soil for different soil layers are listed in Table 1. The values of the calculated shear wave velocities are also presented in Table 1.

3. Coupled vibration test

3.1. Construction of the test pile

The test pile was constructed in the field by bored cast in-situ method. The diameter and length of the pile were 0.45 m and 22.0 m respectively. The boring operation was carried out by rotary type drilling rig using direct mud circulation method. The borehole was lined with a casing throughout the depth of the pile. Then reinforcements were placed into the hole with a clear cover of 40 mm in all directions. As the water table was found at 1.25 m below the ground level, the under water concreting (Grade of concrete - M25) was done using Tremie method [16].

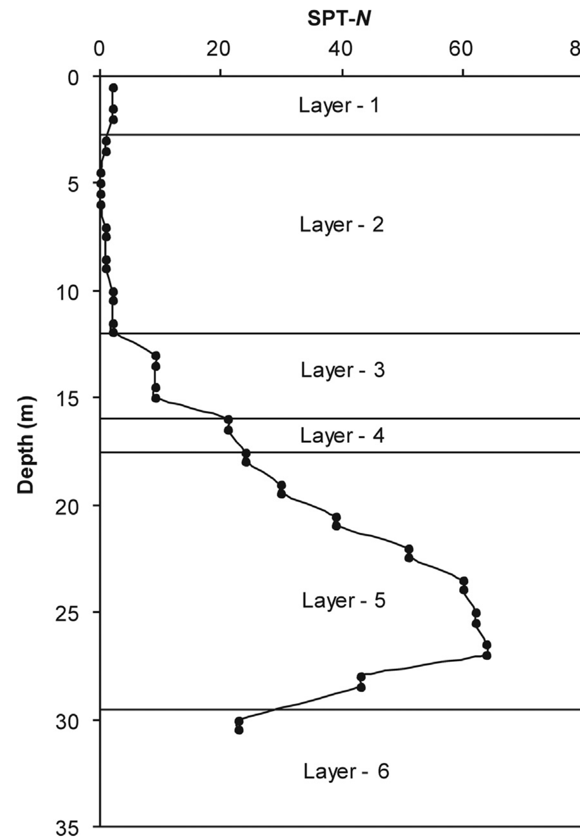

Fig. 1. SPT-N values with depth.

Table 1
Properties of soil layers.

Layers	Unit wt. (kN/m^3)		SPT-N	Shear wave velocity (m/s)	Type of soil
	Dry	Saturated			
Layer–1	12.7	17.8	2	79	Silty sand (SM)
Layer–2	12.5	17.9	1	77	Inorganic clay with high plasticity (CH)
Layer–3	14.6	18.9	11	196	Inorganic clay with low plasticity (CL)
Layer–4	14.5	18.8	21	235	Inorganic silt and fine sand (ML)
Layer–5	15.0	20.0	44	407	Silty sand (SM)
Layer–6	13.0	18.8	25	255	Inorganic silt and very fine sand (ML)

3.2. Forced vibration test

A Lazan type mechanical oscillator with two counter rotating eccentric masses was used to produce the harmonic excitation force on the pile. The eccentric moment ($W.e$) of the oscillator is given by

$$W.\ e = 0.9 \sin\left(\frac{\theta}{2}\right)\ (Nm) \tag{4}$$