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

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ABSTRACT

The present study aims at investigating the nonlinear behavior of single hollow pile in layered soil subjected to varying levels of horizontal dynamic load. A finite element model has been developed using commercially available FEM based software. Mohr–Coulomb plasticity model is used to simulate the soil plasticity whereas the pile-material is idealized as elastic. Numerical results are validated comparing with the experimental results. The experimental investigations were carried out in the field located at IIT Kharagpur. Two types of motion: horizontal and rocking are studied. The effects of various influencing parameters, namely, exciting moment, length and diameter of the pile etc. on the nonlinear dynamic response of piles are investigated. It is found that separation of pile from the surrounding soil considerably affects the resonance frequency and amplitude of the pile foundations.

1. Introduction

Pile foundations are widely used for heavy structures to support large static as well as dynamic load where shallow foundations are unsuitable. Structures like high rise buildings, bridges, chimneys, nuclear power reactors and offshore structures are often subjected to dynamic loads coming from seismic activity, operation of heavy machinery, traffic movement, wave action etc. One of the primary objectives of pile foundation is to minimize the vibration amplitude to a permissible limit. Due to the interaction between pile and the adjacent soil it offers resistance through generation of stiffness and damping of the soil–pile system during vibration. So the study of soil–pile interaction is becoming more and more popular to ascertain more accurate design of continuously evolving complex and heavy structures.

Many theories have been developed for the dynamic analysis of pile foundation. In the early development, the soil–pile system was idealized as a massless equivalent cantilever and the theory of subgrade reaction was used for dynamic analysis of piles by Hayashi et al. [1] and Prakash and Sharma [2]. Lumped mass–spring–dashpot model was used in the analysis of pile foundations by Barkan [3] and Maxwell et al. [4]. Later, few researchers namely Novak [5], Novak and El Sharnouby [6] and El Naggar and Novak [7] developed a number of solutions for the dynamic analysis of pile foundation assuming that the behavior of soil is linear elastic or viscoelastic in nature and the soil is fully bonded to the pile. Prakash and Jadi [8] suggested reduction factors for shear modulus of soil and radiation damping for improving theoretical predictions. These approximate solutions help us to understand the basic mechanism of dynamic pile–soil interaction. However in reality both separation and slippage can occur at the contact surface between the soil and the pile and analysis become much more complex to incorporate those factors. The finite element method (FEM) is a very powerful computationally efficient method to analyze nonlinear dynamic response of soil–pile system considering both material nonlinearity and complex soil–pile interaction due to separation and slippage. A few investigators used a 3-D finite element model to obtain the pile response under dynamic loading considering the effects of material and interface nonlinearities on the dynamic behavior of single and group piles: Lewis et al. [9] and Maheshwari et al. [10,11]. Padron et al. [12,13] applied coupled BEM–FEM model to study dynamic response of pile foundation. Maheshwari and Sarkar [14] performed a 3D FEM analysis of a soil–pile–structure system in liquefiable soil simulating soil plasticity using modified Drucker–Prager model. Sarkar and Maheshwari [15] investigated the effect of separation and sliding and soil plasticity on nonlinear dynamic behavior of single pile and pile groups in liquefiable soil.

Though there are a number of methods available for analyzing the dynamic response of piles and pile groups, very little validation had been done so far using field test. Full scale field tests were

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conducted on both single and group piles for both vertical and horizontal vibrations by Blaney et al. [16] and Manna and Baidya [17]. Dynamic load tests were conducted on small scale prototype pile by El Sharnouby and Novak [18], Burr et al. [19] and Manna and Baidya [20]. Boominathan and Ayothiraman [21] conducted dynamic tests on small scale piles in laboratory.

The response of soil–pile system under high amplitude dynamic loading producing large vibration amplitude is a complex phenomenon because of associated soil nonlinearity. Complex pile–soil interaction involving both slippage and separation makes the problem even more complex. A very few attempts have been made by the past investigators [7–9,15] to study the effect of separation between pile and soil on the dynamic response of the pile. Also a few attempts were made to quantify the separation length. However, experimental verification on separation length and effects of it on the dynamic response of the pile foundation is scanty. Therefore there is a need of establishing some guidelines for estimating the pile separation length under different modes of vibration with a good degree of accuracy. In the present investigation it is aimed to study the dynamic behavior of single piles by numerical investigation under coupled vibration by FEM. Relevant issues of nonlinearity, separation and slippage between the soil and the pile are also addressed. Finally through a systematic experimental investigation, results obtained from the FEM are validated.

2. Finite element analysis

A finite element model using general purpose software Abaqus has been developed to study the dynamic behavior of a single pile in layered soil. The pile used was a free head hollow steel pile.

2.1. Geometric configuration of the model

Fig. 1 shows the basic configuration of the finite element model. Three different pile lengths (1.0 m, 1.5 m and 2.0 m) were considered with the outer diameter of pile of 0.1 m and wall thickness of 5 mm in each case. The soil mass surrounding the pile was assumed to be cylindrical in shape with radius equal to 1 m (10 times the diameter of the pile) in the model. The soil up to 1 m depth (10 times the diameter of the pile) below pile tip of the longest pile was considered. The pile was considered completely hollow, devoid of any soil inside it. Three soil layers were considered as shown with different shades in Fig. 1. Outside the main soil mass, a 0.3 m thick layer of infinite soil mass was considered to create a boundary layer which would not reflect any shear wave in the soil medium. A static load of 10 kN was used on top of the pile as shown in Fig. 1. The elements were more closely spaced near the pile compared to the outer region of the soil mass. The pile mass and soil mass were discretized using continuum solid elements using mainly 8-noded hexahedral elements (C3D8R) along with a small number of 6-noded wedge elements (C3D6). The outer layer of the soil mass was modeled using a single layer of solid infinite elements (CIN3D8). The properties of infinite elements were as reported by Lysmer and Kuhlemeyer [22]. The dynamic response of the infinite elements was formulated on the basis of one dimensional wave propagation theory, considering plane body waves traveling orthogonally to the boundary. The boundary was kept at a distance far enough from the region of interest. The amplitude of response adjacent to the boundary was so small that the medium responds in a linear elastic fashion. The values of damping at the boundary that are built into the infinite element in Abaqus are formulated in such a way that the infinite elements transmit all normally impinging plane body waves.

2.2. Material modeling

The soil mass was idealized with nonlinear elasto-plastic material property. Mohr–Coulomb plasticity model was used to model the soil plasticity. The pile was considered to be elastic. Soil properties used in the model were the closest simulation of the properties determined during experimental investigation. Different laboratory tests namely, Atterberg's Limit tests, Sieve Analysis, Unconfined Compression Strength (UCS) test and Unconsolidated Undrained (UU) Triaxial test were carried out on soil samples. Soil properties obtained from different laboratory tests are summarized in Table 1. Hardening property was idealized for different soils using the stress–strain curve obtained from the unconfined compression tests. Initially up to cohesion value the respective soil was considered to be elastic and after that plasticity was developed. The elastic moduli were estimated from the initial slope of the stress–strain curve obtained from the unconfined compression tests. Table 2 shows a typical hardening property of soil considered for layer 3 in the model.

2.3. Material property calibration

A numerical model analysis of UCS test using the same software and same material properties was carried out on standard soil sample of 76 mm height and 38 mm diameter. The results were compared with physical laboratory test results in Fig. 2. The results were found to be in good agreement with those obtained from laboratory tests. The stress–strain curves of UCS test presented in Fig. 2 are from a soil samples collected from layer 3.

2.4. Interaction properties at soil–pile interface

Interaction properties were defined with surface to surface interaction for top and middle layer, whereas node to surface interaction was considered for the bottom layer. Tangential behavior was considered to be governed by penalty interaction with angle of wall friction taken as 2/3 of angle of internal friction of the corresponding soil. Normal behavior was defined by hard contact pressure–overclosure relationship. Separation between soil and pile after the contact was allowed for all three layers. Cohesive behavior with default value was considered for the interaction of the bottom layer, as this layer predominantly consists of medium stiff clayey soil. Measurement of depth of separation was estimated by plotting the horizontal displacements of the points located on the outer surface of pile and adjacent soil surface at the interface on the same vertical plane on which the horizontal dynamic load was acting. Maximum separation length was estimated during oscillation at resonant frequency at a time in the last loading cycle of the simulation when horizontal displacement of the pile was maximum.

2.5. Numerical model test

Numerical model tests were carried out for studying the dynamic characteristics of piles with three different lengths to diameter (L/d) ratios. A hollow closed end steel pile with 100 mm outer diameter and 5 mm wall thickness was considered for this analysis. Four different exciting moments ($m_e e$) were used for each pile to induce dynamic load of different magnitudes. The analyses were carried out in three steps. First, gravity load was applied in downward ($-Z$) direction only in soil mass. Then the soil–pile interaction was introduced and gravity load was applied to overburden mass and the pile. Both of these steps used static general analysis procedure. In the next step implicit dynamic analysis procedure in time domain was used with the maximum time increment (Δt) versus time period (T) ratio, $\Delta t/T=1/8$ (for all frequencies). Dynamic external load was applied at the center of oscillator which was 155 mm above the pile top to simulate the conditions of the field test described later in this paper. Analysis