Computers and Geotechnics 104 (2018) 13–21

Contents lists available at ScienceDirect

Computers and Geotechnics

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

Research Paper

Wave propagation and ground vibrations due to non-uniform cross-sections piles driving

Omid Tavasoli[a,*], Mahmoud Ghazavi[b]

[a] Department of Civil Engineering, East Tehran Branch, Islamic Azad University, Tehran, Iran
[b] Department of Civil Engineering, K. N. Toosi University of Technology, Tehran, Iran

ARTICLE INFO

Keywords:
Field testing
Pile driving
Ground vibration
Pile geometry
Finite difference method

ABSTRACT

Piles are normally installed into the ground using appropriate hammers which cause different environmental problems such as noise, air pollution and ground vibration. In this paper, the ground vibrations due to the drivability of cylindrical, tapered and semi-tapered piles are investigated using field testing and numerical analysis and the results are compared and discussed. It is concluded that the application of non-uniform cross-section piles increase the driving process efficiency, reduce energy consumption and decrease the noise pollution by reducing the operation time. This, the application of tapered piles should be considered in practice from the viewpoint of allowable ground vibrations.

1. Introduction

Despite the benefits of pile driving technique, this process has serious environmental problems and disadvantages such as air and noise pollution and ground vibrations caused by hammer impacts. Other problems, for instance, the possibility of swelling, penetration or lateral displacement of surrounding soil occur during this process and three types of waves including spherical, cylindrical and superficial waves create in the ground due to hammer impacts [1]. Spherical waves propagate from the tip of the pile, while cylindrical waves move laterally from the shaft and surface waves reproduce through refraction of the waves at a critical distance from the pile in the ground [1,2]. When the hammer strikes the pile head, tension waves with a certain frequency and amplitude propagate in the pile and then release into the surrounding soil. The main effects of emission of these tension waves during pile driving are wave propagation in the pile, pile-soil interaction along the pile shaft and toe, wave propagation within the ground and dynamic soil-structure interaction due to dynamic response of adjacent foundations and the development of vibrations in structures.

Dynamic effects of pile driving on surrounding medium depend on various factors including driving system and hammer specification, the pile geometry, pile materials, soil specifications, nearby structure types, soil-structure interaction, and the distance between the vibrating piles and nearby structures. One most important factor affecting the vibrations is the pile impedance which is directly related to the geometry and shape of the pile. Another important factor is the energy of driving hammer which always is known as an effective factor. However, there is ambiguity in defining this energy. Each hammer has a nominal energy which transfers to the pile-soil system and adjacent structures. The transferred energy ratio is defined as the energy transmitted through air, anvil, pile pad, hammer pad, and so on. The soil properties have important role in the amount of wave dissipation. Such properties affect damping characteristics which depend on the type of soil, grain size distribution, hardness, moisture content and temperature [2].

Analyses of uniform shaped piles during pile driving have been investigated comprehensively in the literature (Smith [3]; Chow and Smith [4]; Coutinho et al. [5]; Mabsout and Tassoulas [6]; Mabsout et al. [7]; Ghazavi et al. [8]). Axial load-carrying characteristics of tapered piles have been studied in the literature by Wei and El-Naggar [9], static loads, harmonic vibrations and the kinematic response of such piles under earthquake loading was also evaluated by Ghazavi [10–12] and Ghazavi and Ahmadi [13,14], Rybnikov [15] and Sakr et al. [16] which reported that the tapered pile had a better performance than a cylindrical pile. The behavior of piles with varying sections during driving was investigated by Ghazavi and Tavasoli [17], using pile-soil modeling by finite difference method, and concluded that the change in the geometry of the pile section has a direct effect on the rate of pile's residual set and velocity. Tavasoli and Ghazavi [18] performed numerical analysis and real tests on the drivability of pre-casted cylindrical and tapered piles with open and closed-ended conditions. They reported that in closed or open-ended pile cases, the tapered pile had a final penetration more than a cylindrical pile, and

* Corresponding author.
E-mail address: o.tavasoli@iauet.ac.ir (O. Tavasoli).

https://doi.org/10.1016/j.compgeo.2018.08.010
Received 8 June 2018; Received in revised form 6 August 2018; Accepted 12 August 2018

when the end of the pile is open, the pile efficiency is greater than the closed-ended piles. The behavior of driven tapered piles into cohesive soils using the theoretical method based on cavity expansion method (CEM) was assessed by Sormeie and Ghazavi [19] in conjunction with wave equation, indicating that tapered piles are driven easier than cylindrical piles of the same length and volume.

Comprehensive studies have been carried out about waves propagation caused by uniform-section piles during driving by the use of laboratory, numerical and analytical methods. A common method for recording vibrations is to perform field tests and measure the peak particle velocity (PPV) during pile driving. In such way, soil damping properties may be determined in the field and use in the relationships between the vibration amplitude and the distance from the pile driving. This helps to avoid or reduce the probable damage to nearby structures. Also, numerical analyses may be used to estimate the vibration severity on surrounding structures before pile driving. Valuable studies were performed on evaluating the attenuation properties of vibrations to protect structures from unlikely damage by Wiss [20], Woods and Jedele [21] and Uromeihy [22]. The prediction of time-dependent vibration velocity due to impact and vibratory piles by Ramshaw et al. [23], Selby [24] and Madheswaran et al. [25] who used harmonic numerical method. They evaluated vertical peak acceleration which was in close agreement with the field data, but the predicted radial peak acceleration was 20% greater than that of field measurement. A numerical analysis to predict the free field vibrations in terms of PPV due to vibratory and impact pile driving was presented by Masoumi et al. [26,27]. They analyzed the soil effects on the ground vibration for the case of a soft layer on a stiffer half space by considering linear and non-linear constitutive behavior of the soil in the vicinity of the pile and concluded that the results of near-field vibrations were satisfactory, but the far-field vibrations were overestimated. Serdaroglu [28] developed the impact pile driving vibrations in saturated cohesive soils with considering a non-linear finite-element model and several soil layers with different damping ratios to minimize the reflection of stress waves at the boundaries. The results presented that this model underestimated the measured peak vertical and radial velocities. Ekanayake et al. [29] represented a numerical study based on vibratory driving of closed-ended piles to replicate the wave propagation during vibratory pile driving and analyzed the effect of wave propagation on the surrounding ground. They showed that the material damping was an important parameter contributing to wave attenuation around the driven pile in addition to the geometric damping. Khoubani and Ahmadi [30] investigated the penetration of piles from the ground surface to the desired depth with considering plastic deformations in the soil adjacent to the pile and large slip frictional contact between the pile and the soil on the amplitude of vibrations. They concluded that the PPV at the ground surface does not occur when the pile toe is on the ground surface and the particle velocity reaches a maximum value at a critical depth of penetration. Liyanapathirana and Ekanayake [31] mentioned that the ground vibrations during urban construction activities had a major concern due to severe damages to adjacent structures caused by vibrations. The stated vertical wave barriers with different types of fill materials were installed in the ground to minimize the detrimental effects of ground vibrations on surrounding structures. They examined the efficiency of expanded polystyrene geofoam in-filled wave barriers on ground vibration attenuation during vibratory pile driving in different soil types with the three-dimensional finite element model. Biswas et al. [32] analyzed the complex nonlinear behavior of a reinforced concrete full-scale single pile subjected to machine induced coupled horizontal and rocking vibrations to determine frequency-amplitude responses of the single pile for different eccentric moments. Additionally, In order to investigate the seismic soil-pile-structure interaction and dynamic response of piles embedded in an elastic half-space and under transverse loadings, numerical and analytical analyses were carried out by Pak and Jennings [33] and Guin and Banerjee [34]. Ahmadi and Eskandari [35] and Eskandari et al. [36] used analytical and numerical methods for analyses of dynamic response of a rigid foundation with a transversely isotropic half-space under a buried inclined time-harmonic load, considering the superposition technique. All above studies reveal that wave propagation due to dynamic loading on either shallow or deep foundations is significant and thus should be broadly investigated using various methods. To this aim, the current research focuses on wave propagation within the soil mass due to the drivability of piles into the ground.

To the best knowledge of the authors, the effect of pile geometry and shape on wave propagation form the pile during driving to the surrounding soil has not yet been studied. The present study aims to provide information due to pile geometry effects on wave propagation from the pile-soil system during driving of cylindrical, tapered and semi-tapered piles. To this aim, wave propagation and ground vibrations during non-uniform shaped piles driving have been investigated by performing field tests and three-dimensional numerical analysis based on finite difference method. Upon such investigation, the soil particle velocity and displacement due to the propagation of waves generated into the ground have been reported.

2. Field testing on ground vibration due to pile driving

In this section, the wave propagation and ground vibrations due to the drivability of non-uniform cross-sections piles are investigated by conducting field tests on various pile geometries.

Tapered and semi-tapered steel piles with various geometries but of the same length and volume were prefabricated and used, as shown in Fig. 1. Each steel pile has 250 cm length and 5 mm thickness. A 15 cm of the end of each pile was sharpened in order to penetrate the pile into the ground easily. The cylindrical pile (pile C) has an outer diameter of 162 mm. The outer diameters of fully tapered pile (pile T) are 212 mm and 115 mm at its head and tip, respectively. The cylindrical-tapered pile (pile C-T) consists of two lengths. The top cylindrical part has 100 cm length and 172 mm outer diameter. The lower tapered part has 150 cm length and its top and end diameters are 172 and 121 cm, respectively. The tapered-cylindrical pile (pile T-C) consists of two parts. Its 100 cm top tapered part has 226 cm outer diameter at its head and 140 cm outer diameters at its end. Its lower cylindrical part has 150 cm length and 140 mm outer diameter. All test piles have 2.5 m length. The length to diameter ratio of each pile is greater than 10 ($D_f/D_p > 10$ and $L_p/D_p > 10$), where D_f, D_p and L_p are respectively the depth of foundation and the diameter and length of pile. Thus, they are assumed to be deep foundations. Moreover, these filed tests are only real available tests which were performed on non-uniform cross-section piles. Thus, the obtained results may be extended to real piles and used in practice.

Prior to field testing, five boreholes were drilled to a depth of 25 m with a square array of four boreholes at the sides and one borehole in the center to explore the soil specification and parameters on soil bed

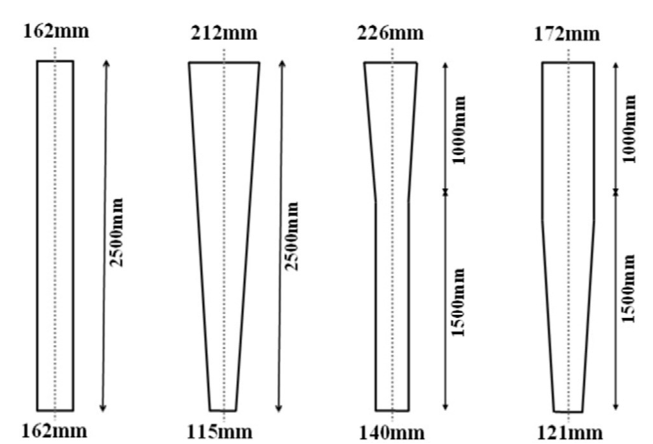

Fig. 1. Geometry of pre-casted steel piles.