Theoretical and Applied Mechanics Letters 5 (2015) 69–73

Contents lists available at ScienceDirect

Theoretical and Applied Mechanics Letters

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

Letter

Difficulties and measures of driving super long piles in Bohai Gulf

Shuwang Yan [a,*], Jia Li [a], Liqiang Sun [a], Guomin Sun [b]

[a] School of Civil Engineering, Tianjin University, Tianjin 300072, China

[b] China Offshore Oil Engineering Co., Tianjin 300461, China

ARTICLE INFO

Article history:
Received 23 October 2014
Accepted 28 December 2014
Available online 26 February 2015
*This article belongs to the Solid Mechanics

Keywords:
Super long pile driving
Refusal
Excessive pore pressure
Hydraulic fracture
Finite element analysis
Prevent measures

ABSTRACT

Long piles of the ocean oil platform are usually manufactured as the integration of several segments, which have to be assembled one by one during installation. During pile driving, excessive pore pressure will build up in such a high level that hydraulic fracturing in the soil round the pile may take place, which will cause the soil to consolidate much faster during pile extension period. Consequently, after pile extension, the soil strength will recover to some extent and the driving resistance will increase considerably, which makes restarting driving the pile very difficult and even causes refusal. A finite element (FE) analysis procedure is presented for judging the risk of refusal by estimating the blow counts after pile extension, in which the regain of soil strength is considered. A case analysis in Bohai Gulf is performed using the proposed procedure to explain the pile refusal phenomenon.

Oil platforms with six or eight legs have been normally adopted in Bohai Gulf, China [1]. The leg piles with diameters of 2 m or more need to be driven to about 100 m below the seabed [2]. Such long piles have to be manufactured by segments before installation, because of transportation and hoisting difficulties. The segments of the pile will be assembled during installation, in which a successive segment will be attached to a formerly penetrated one by welding (Fig. 1). Each pile extension work often takes one day or even a longer time.

During this period, the excessive pore pressure in the soil around the pile, which was built up during pile driving, will be dissipating [3,4]. Consequently, the soil strength will regain to some extent, which makes restarting the successive penetration very difficult and even causes refusal [5]. It is usually very costly and time-consuming to deal with pile refusal problems. This matter has been encountered quite often in Bohai Gulf and puzzled the designers for years.

In order to avoid pile refusal after pile extension, it is essential to conduct accurate and rigorous pile drivability analysis, based on which comprehensive construction schemes, procedures, and correlative management system should be established. Accurate prediction of the driving response is also important to estimate the capacity of a pile and to select a suitable hammer system.

In this paper, the buildup and dissipation characteristics of excessive pore pressure in the soil is discussed. According to the engineering experience and theoretical analysis, it is proved that the accumulated high pore pressure will cause fracturing of soils around the pile. The developed fissures will greatly increase the consolidation ratio during pile extension time and make the soil strength to recover, which will make restarting driving difficult. The finite element (FE) procedure is established to estimate the risk of pile refusal after pile extension, in which a suitable fatigue factor, which is related to the degree of consolidation of the soil, is chosen to consider the regain of soil strength. A case is analyzed by using the proposed procedure to explain the pile refusal phenomenon.

Figure 2 shows a typical pile driving records of the platform WHPE in Bohai Gulf, which is one of the refusal cases in this area.

From the record charts it can be seen that, when the pile is driven continuously, for example, from 22 m to 47 m, the blow counts for every 30 cm penetration are increasing smoothly, indicating that the pile is penetrated without difficulty. This may be due to several factors. (1) The structure of the soil around the pile has been disturbed so that the soil resistance decreases. (2) Excessive pore pressure in the soil has accumulated to a high level so that the effective confining stress on the soil–pile interface reduces. (3) The soil–pile interface has been polished by the repeated relative movement.

The first and second factors will cause both tip bearing resistance and the normal stress acting on the soil–pile interface to decrease. The third factor will diminish the interface frictional coefficient. Since the shaft frictional force is the product of the effective normal stress and the frictional coefficient, it will decrease

* Corresponding author.
E-mail address: yanshuwang@tju.edu.cn (S. Yan).

http://dx.doi.org/10.1016/j.taml.2015.02.006

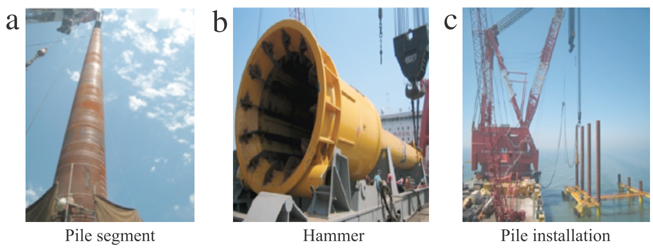

Fig. 1. Pile installation of oil platform in Bohai Gulf, China.

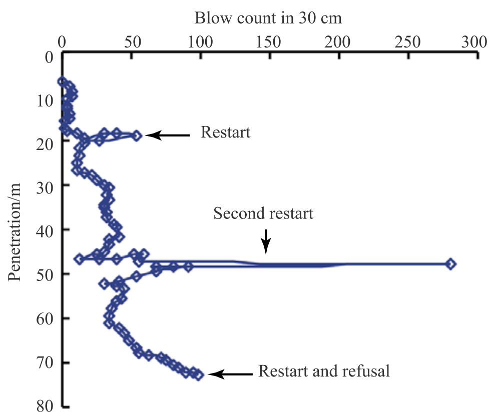

Fig. 2. Pile driving records of the platform WHPE.

with pile driving sharply. The total penetration resistance is the sum of the tip bearing resistance and the shaft frictional force on the soil–pile interface. Therefore, penetration resistance is greatly decreased from the initial state. It is obvious that without the resistance reduction induced by these influencing factors, driving a pile would become very difficult or even impossible.

In the commonly used FE programs for drivability analysis, such as TNO and GRLWEAP [6,7], a so called fatigue factor, $\beta (\beta \leqslant 1)$, is consistently introduced to cover all these three influencing factors. In the analysis, the soil resistance is multiplied by β to calculate the blow counts versus penetration. There are several assumed distribution types for β. The most commonly used is the following one:

$$\beta = \begin{cases} \left(\dfrac{X}{Y-5} \right)^2, & X \leqslant Y-5, \\ 1, & Y-5 < X \leqslant Y, \end{cases} \tag{1}$$

where β is the fatigue factor, Y is the designed penetration, and X is the specified pile tip penetration. The β value is increased from zero to 1 along with the pile tip penetration 5 m above the designed pile tip penetration. For the last 5 m penetration, the fatigue effect can be neglected. Engineering experiences have shown that this type of β distribution is good for predicting the blow counts for driving a pile continuously, otherwise it will give fault results. The reason will be discussed hereinafter.

During pile driving, great energy is generated by the driving hammer. Some portion of the energy does the direct work to overcome the penetration resistance, and some other portion of the energy is transferred to the surrounding soils and changes their properties, among which excessive pore pressure will be accumulated. At the same time, the penetration of the pile will push the soil mass aside, which will apply additional pressure to the soil around the pile and induce more excessive pore pressure. Hwang et al. [4] performed a very detailed theory to estimate this part of excessive pore pressure in situ test on pile driving, and found the calculated data agreed well with the published results obtained by other researchers [8]. The comparison is shown in Fig. 3, in which

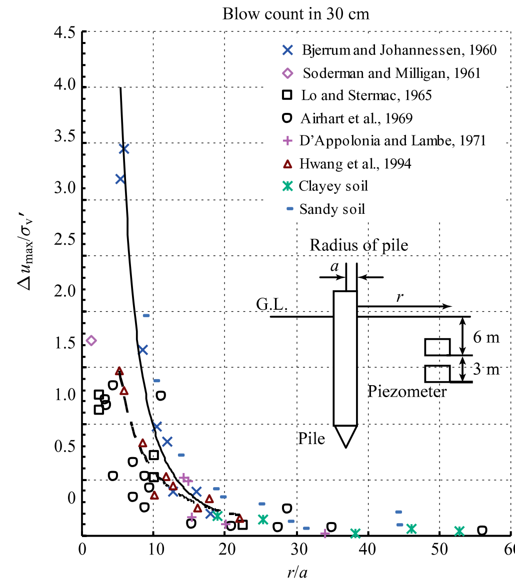

Fig. 3. Variation of normalized maximum excess pore pressure ratio with distance to pile driving.

the maximum excessive pore pressure, Δu_{max}, is normalized by the effective overburden, σ_{vo}', and the distance away from the pile, r, is normalized by a, the radius of the pile. It can be seen from Fig. 3 that near the pile the ratio of the accumulated pore pressure Δu_{max} to the effective overburden σ_{vo}' can reach 1.5 for sandy soil; for clayey soil, the ratio can reach 3 or more. With the increase of distance away from the pile, the accumulated pore pressure becomes lower and lower. The excess pore pressure buildup may be induced by several reasons, including: (1) soil expansion because of pile penetration, (2) soil disturbance caused by the relative movement of the pile and the soil interface, and (3) dynamic energy induced by the pile driving.

Research results have shown that when the excess pore pressure is increased to a high level, the hydraulic fracturing phenomenon will occur [9]. By applying high water pressure to the drilling hole, fracturing of the soil or rock wall of the drilling hole will take place. During this process, many fissures will be developing in the soil or rock near the wall, which will greatly increase the permeability of the soil or rock. Vaughan [10] put forward a formula to predict the hydraulic fracturing of clayey soils based on specially designed in situ experiment

$$u > m\sigma_v' + |\sigma_t|, \tag{2}$$

where m is between 1 and 2, depending on the stress distribution, u the pore pressure, σ_v' the overburden, and σ_t the tension strength of the soil, which is quite small comparing with the overburden and can be neglected in calculation.

For the circumstances of pile driving, as shown in Fig. 3, near the pile ($r/a \leqslant 7$) the ratio u_{max}/σ_v' is much greater than $m = 2$. Introducing the values into Eq. (2), it can be judged that hydraulic fracturing must have been taking place within this area.

During pile driving, the pore pressure will both generate and dissipate, and the accumulated pore pressure is the offset result of the two adverse processes. The pore pressure generating rate is always greater than the dissipating one. From Fig. 3 it can be seen that the accumulated pore pressure is much smaller in sandy soils than that in clayey soils, because of the difference in dissipation rates between clayey soils and sandy soils. Once pile driving ceases, the accumulating process will stop while the dissipating process continues and the soil around the pile will undergo consolidation, which will decrease the excessive pore pressure and increase in effective stress in the soils.