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Research Paper

Load-settlement behaviour of bored piles with loose sediments at the pile tip: Experimental, numerical and analytical study

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ABSTRACT

An elevated raft technique is proposed for cast-in-place bored piles, where loose sediments and excavation debris at the pile tip can be compressed by the applied load from the superstructure. The axial load-settlement (i.e., *P-S* curve) behaviour of bored piles with debris is evaluated by a series of model-scale laboratory experiments. Numerical simulation is conducted using a two-dimensional axisymmetric model for comparison. An analytical model is then proposed to capture the whole *P-S* curve in three segments: (a) the contribution of skin friction, (b) increased settlement associated with the compression of debris, and (c) the development of tip resistance.

1. Introduction

When the soil layer at shallow depth cannot provide sufficient resistance to support the superstructure, pile foundation is normally used to transfer the load to a greater depth. The skin friction mobilized on the pile shaft and the pile tip resistance will act together to counteract the applied load. Cast-in-place bored pile is one of the most developed and widely used piling techniques, which can be employed in any ground conditions, including soils and rocks [1]. However, bored holes need to be cleaned carefully to ensure minimum sediments and excavation debris at the pile tip; otherwise, the pile resistance will be influenced significantly by the quality of the construction [2]. Vibrating wire strain gauges can be used near the tip of a single pile to evaluate the base settlement in the field [3–7], but the costs will be a problem for a massive piling project.

Softened zones in the bedrock near the pile tip cannot be detected with certainty. For underwater pile installations, piling quality can be easily compromised due to the difficulty in inspecting deflects at the pile tip. Therefore, for lifeline projects of bridges, Walter et al. [8] suggested to design bored piles based on shaft resistance only, aiming at a conservative design. However, the conservative design sometimes is not financially viable. Alternatively, researchers proposed some techniques to improve the performance of bored piles, such as socketed piles [9,10], disconnected settlement reducing piles [11], and pile-based post-grouting [12]. However, these approaches will increase the complexity in the design and construction of bored piles. An elevated raft technique is proposed in this investigation as schematically shown in Fig. 1. When loose sediments exist at the pile tip, a bored pile could experience a certain settlement subjected to loading before the end bearing capacity is mobilized. The settlement of the pile actually corresponds to the compression of residual debris, before which the pile resistance primarily consists of skin friction. To compensate the bottom debris compression, a margin space can be reserved below the raft. That is, in the design stage, to pre-elevate the raft at a value of ΔS equivalent of the debris compression. For pile groups, the debris compression of individual piles can be compared, and the maximum value can be used to pre-elevate the raft. After the debris is compressed upon loading from the superstructure, the raft will reach the original design elevation, and the pile gains desired base resistance.

The pile bearing issue due to surrounding and bottom debris has been identified by researchers. Gavin and Lehane [13] conducted a series of laboratory and field tests on model piles, and demonstrated that the pile tip resistance can only be mobilized once the pile settles to eliminate the softened zone below the pile. Zhang et al. [14] stated the inclusion of ‘mudcake’ between the pile and the borehole wall could result in decreased resistant and increased settlement for bored piles. Similar field tests on bored piles with debris have been conducted by Dai et al. [12] and Liu et al. [15]. However, all of the existing tests count on continuous pile loading to the point where the pile settlement initiated to increase suddenly, rather than to the point of the bottom debris being fully compressed. This is less applicable and time consuming.

An alternative, but efficient, solution is to use numerical method to predict the load-settlement curve and determine the compression

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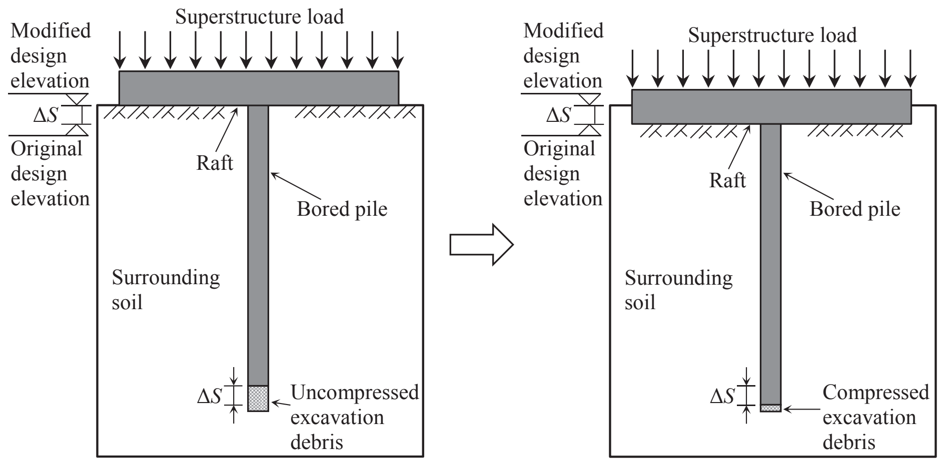

Fig. 1. Schematics of the elevated raft technique to compress the sediment and excavation debris left at the pile tip.

compensation. Different numerical modelling techniques [16–20] have been employed to study the axial load-settlement behaviour of piles. However, no computational effort has been made to capture the axial behaviour of bored piles after the zone of loose sediments at the pile tip is fully compressed. Hence, all developed empirical calculations of load transfer functions [21–29] in the past cannot account for the influence of debris on the full axial load-settlement behaviour of bored pile.

In this investigation, a series of experimental, numerical and analytical studies is presented to support the conceptual elevated raft technique to fully utilize the resistance of bored piles with debris at the pile tip. Model-scale laboratory tests are conducted on Perspex (Plexiglass) piles without and with debris at the pile tip. The applied load is continued to capture the full load-settlement response for piles. A two-dimensional (2D) axisymmetric numerical model is subsequently calibrated against experimental measurements. An analytical load-settlement model with three segments is proposed to characterize the response of bored piles with debris. Finally, an illustrative case study is presented, where a defected pile with loose sediments at the pile tip is tested until the full regain of pile resistance is achieved. Field measurements of load-settlement behaviour of bored piles with debris are compared with analytical calculations.

2. Laboratory experiments

2.1. Test chamber

Due to the cost associated with field or large-scale laboratory tests, model-scale experiments are often conducted to study the behaviour of piles. For example, Matsui et al. [30] measured the earth pressures acting on laterally loaded piles with a maximum diameter of 40 mm in a steel plate container box of 0.6 m long by 0.3 m wide by 0.3 m deep. Onuselogu and Yin [31] designed a reinforced concrete chamber with a length of 2.1 m, a width of 1.65 m and a depth of 1.05 m to test the response of Perspex piles with an external diameter of 30 mm. Cao et al. [11] studied the soil-pile-raft interaction for square hollow aluminum piles with dimensions of 9.5 mm by 9.5 mm buried in a reinforced concrete trench of 0.8 m deep and 1.7 m by 0.24 m in plan. Suleiman et al. [32] tested the axial response of pervious concrete piles with a diameter of 102 mm embedded in a soil box with dimensions of 1.5 m by 1.5 m by 2.25 m (deep). Overall, the ratio of the shorter size of the chamber over the pile size varies from 7.5 to 55. In this study, a strong box with dimensions of 0.8 m by 0.8 m and 1.5 m is assembled in a large-scale buried infrastructure test pit as illustrated in Fig. 2. With the pile diameter of 20 mm, the ratio between the box dimension over the pile size is calculated as 40, which is close to the upper bound of the range in previous studies. Therefore, it is believed that the axially loaded behaviour of bored piles will not be influenced by the boundary effects. Temporary concrete walls with steel frames are used, since this enables to alter the configuration of the container as needed for other tests [33].

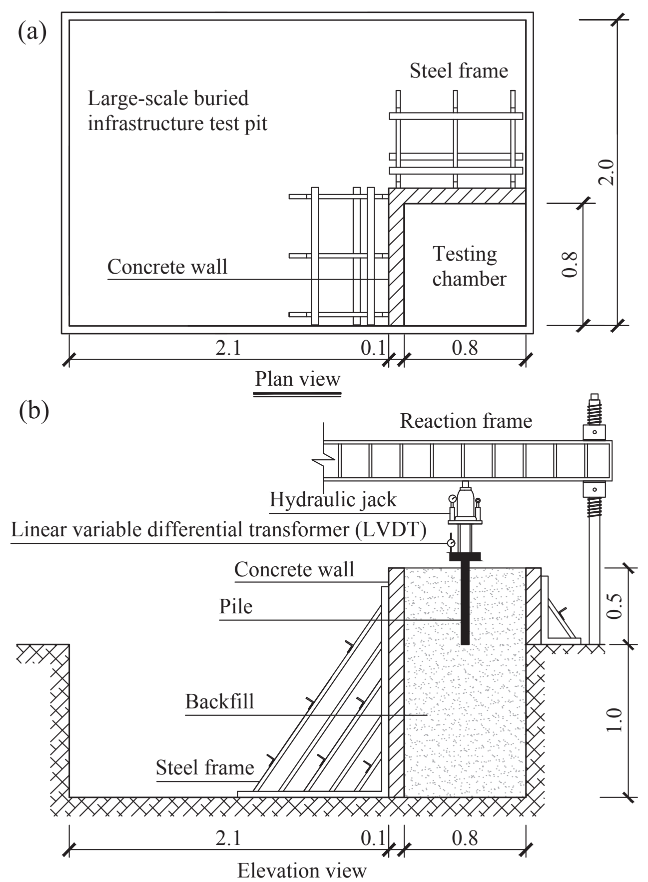

Fig. 2. Schematics of the test box: (a) plan view, and (b) elevation view (Note: Units are meters).

Although the size of the chamber is believed to be sufficient, a friction treatment system is implemented on the sidewalls to further eliminate the boundary effects. Silicone grease is smeared between two layers of polyethylene sheets, where the base layer is fixed on top of the sidewalls and the second layer can slide against the base layer [34]. The arrangement of double layered sheets can reduce the soil-wall friction angle substantially from 26.5° [35] to approximately 5° [36].