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Field investigation of the performance of composite foundations reinforced by DCM-bored piles under lateral loads

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HIGHLIGHTS

- Composite DCM-BP columns formed by DCM piles and core bored piles were introduced.
- Performance and advantage of the DCM-BP under lateral loads were studied.
- Effect of cement-soils on the bearing capacity of the DCM-BP was analyzed.
- Bending moments and lateral resistances of the DCM-BP and CBP were compared.

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ABSTRACT

The DCM-bored pile (DCM-BP) is a new kind of composite foundation formed by inserting a core-bored pile into a deep cement mixing (DCM) column socket, and the DCM-BP has only been used in a few projects to date. Unlike the conventional bored pile (CBP), the performance of the DCM-BP is enhanced by the surrounding cement-soil materials, which should result in a large change compared to that of the CBP. In this paper, a series of full-scale load tests on the DCM-BP were conducted to investigate the performance of the DCM-BP under lateral loads compared with that of the CBP. The lateral bearing characteristics of the DCM-BP and its advantages are presented in this study. Based on the test results, the DCM-BP displays a greater bearing capacity than that of the CBP, with much smaller lateral displacement under the same lateral load. Comparisons of the bending moments and lateral resistances of the DCM-BP and CBP were also analysed in detail. It is concluded that the DCM-BP has considerable advantages over the CBP because the DCM-BP improves the surrounding lateral resistance and enhances the performance of the core bored pile.

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1. Introduction

Pile foundations over layered clays with low strength and high compressibility are easy to cause large deformations or structural failures, especially subjected to lateral loads. Bored piles with mature technology and high bearing capacity have been used worldwide for high-rise buildings, bridge foundations and retaining structures. But when encountering soft clays, it also shows impotence with poor bearing capacity and excessive deformation problems [1,2]. In recent years, the Deep Cement Mixing (DCM) technology was developed to improve the engineering properties of soft clays, initially in supporting embankment loading conditions [3,4]. Although DCM pile has many advantages, e.g. presented by Han et al. (2002) [5], Shen et al. (2003, 2008) [6,7], and Bhadriraju et al. (2008) [8], invalidation caused by pile failure can occur especially when subjected to lateral loads [9]. Moreover, the DCM pile cannot be used as high bearing foundations due to its low strength and stiffness [10]. To mitigate these problems, some innovative solutions have been proposed including T-shaped piles [11–13], stiffened DCM piles [14–19], and different types of composite foundations [20,21]. The composite foundation technology has been proved to be effective to improve the bearing capacity of native pile foundations [20], which usually inserts a concrete core pile or any reinforcement into the DCM pile after finishing the DCM pile construction. In past 10 years, the composite foundations have been extensively used in China, and some studies are conducted. For instance, Dong et al. (2004) [14] studied the bearing capacity and settlement of concrete-cored DCM piles in soft ground; Zheng and Gu (2005) [22] reported the development and

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practice of a composite Deep Mixing Method (DMM) pile in ground improvement in China; Li et al. (2009) [20] analyzed the load-bearing mechanisms of the composite foundation of plain concrete reinforced cement-soil mixing piles (MC piles); Ren et al. (2010) [23] and Liu et al. (2010) [21] performed full-scale model tests on load transfer mechanisms and influence factors for jet grouting soil-cement-pile strengthened piles; Voottipruex et al. (2011) [18] studied the performance of a composite foundation formed by concrete core piles and DCM piles using FEM approach; Wang et al. (2014) [24] carried out plate load tests on the composite foundation reinforced by concrete-cored DCM piles. Li et al. (2015) [25] proposed a calculation method for the vertical bearing capacity of the DCM-prefabricated pipe piles in sands. However, the conventional composite foundations mainly refer to precast concrete core piles, and limited field tests are available to demonstrate the composite DCM-BP column and its lateral bearing characteristics. The DCM-BP formed by DCM piles and core bored piles is a new composite structure, which has only been used in a few projects to date. As shown in Fig. 1, the DCM-BP is composed of a core bored pile and an external DCM pile socket, where the high strength bored pile is designed to bear external loads, and DCM pile socket acts to transfer the stress into the surrounding soil by cement-soil interface. For this smart design, the bearing capacity of the native bored piles can be reinforced by DCM pile, and the construction cost of large diameter bored piles is avoided.

At present, there are very few studies on the performance of composite DCM-BP columns. This paper presents the results of an actual full-scale instrumented test that was carried out to examine the performance of the DCM-BP under lateral loads. The results are also compared to the behavior of the conventional bored pile (CBP).

2. Project site and subsoil profile

The full-scale tests were performed in the Suzhou city of Jiangsu province of eastern China, as shown in Fig. 2. Due to near Taihu Lake area, the geological formations of Quaternary deposits in this location are mainly Lagoon of Taihu Lake. The engineering features of the subsoil are extremely poor. Both in situ and laboratory tests were performed for site characterization studies before installation of the DCM-BP and CBP piles. In situ piezocone penetration (CPTU) tests were conducted using the digital equipment from Southeast University of China [26,27]. All the tests were conducted in accordance with the international standards [28,29]. The groundwater table (GWT) at the test site was recorded at a depth of about 1.0 m–1.5 m from the ground surface. A representative profile of the CPTU sounding is presented in Fig. 3. It can be found that the subsoil strata in the test site mainly consists of soft to stiff clayey soils and silty clay soils with weak strength and stiffness characteristics. The detailed soil properties are shown in Table 1. To ensure the safety of constructions and reduce the project cost, the DCM-BP and the CBP were used to reinforce the natural foundation in this area. The CBP and the core bored pile of the DCM-BP are both installed with 0.7 m diameter and 18 m length. The DCM pile socket is constructed by wet jet mixing with 1.5 m diameter and 22 m length.

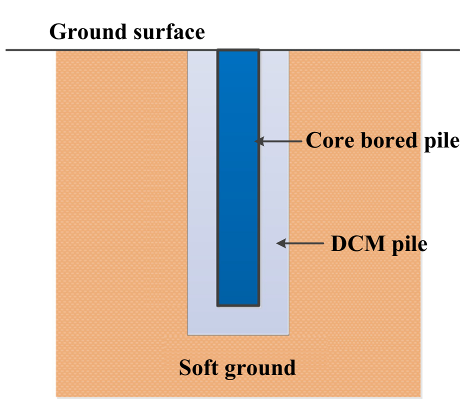

Fig. 1. Schematic of the DCM-BP column.

3. DCM-BP installation and instrumentation

The DCM-BP was constructed by inserting a core bored pile into the centre of the DCM pile after finishing the DCM pile installation (see Fig. 4a). The insertion time should be controlled to within 7 d after finishing the DCM pile. The DCM piles in the test were constructed by wet jet mixing with a water to cement ratio of 1:1.5 by weight. The mass ratio of cement to soil for DCM is 1:5. The bored piles are the cast-in-place type with slurry wall protection, and their details are shown in Fig. 4b. The reinforcement and concrete conditions in the CBPs and the core bored piles of the DCM-BP columns are the same. For DCM-BP columns, the main load is borne by the core bored pile and passes to the DCM pile before transferring to the surrounding soils. The DCM pile forms a surrounding outer layer to enhance the stiffness and strength of the core bored pile. Both piles work together to resist external forces and ensure the overall stability of the composite foundation.

To monitor lateral responses of the DCM-BP and the CBP, steel stress gauges and pressure cells were used to measure the bending moments and lateral resistances of the core bored piles along their depth. Before installation of the bored piles, these steel stress gauges and pressure cells were first attached to the steel cage and then lowered down into drill holes together. Briefly, the steel stress gauges were directly welded onto the steel reinforcement, and the pressure cells were fixed through some designed cloth bags enclosed in the steel cage. The detailed layout and installation of the sensors are shown in Fig. 5. A total of 17 pairs of steel stress gauges and 17 pairs of pressure cells were distributed on the bored pile body at a vertical interval of 1 m each. In this test, the same sensor configuration is arranged on the CBP shafts.

To comprehensively investigate the differences of the DCM-BP and CBP lateral bearing characteristics under different soil conditions, a secondary loading approach for the test piles after ground excavation was adopted. In the test site, an upper 6-m-deep soil layer was excavated for construction of a double basement after pile installations. The test piles were moved above the ground surface again when the 6-m-deep soil layer was removed. The secondary load test was conducted at the excavation surface. To protect the sensor wires used for the secondary load test, the iron pipes shown in Fig. 6a were designed to prevent wires from being destroyed. The iron pipes protecting the wires were placed into the borehole along with the steel cage and were maintained near the later excavation line after the installation was finished. Fig. 6b presents a section of a test pile in a 6-m-deep soil excavation line where the sensor wires have been drawn out of the iron pipes.

4. Lateral load tests

Two lateral load tests on a DCM-BP and its adjacent CBP under the same soil conditions were conducted in accordance with JGJ106-2014, *Chinese technical code for testing pile foundations* [30]. The two tests were conducted at the initial ground surface and after the 6-m-deep soil excavation, respectively. In this study, the lateral load for the DCM-BP test was applied on the surface of the external DCM column. The flexural rigidity of the CBP and the core bored pile of the DCM-BP were both $EI = 4.03 \times 10^5$ kN m^2. The test process was performed using a displacement-controlled approach. Fig. 7 shows a schematic of the lateral loading arrangements and the field

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