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Research Paper

Impact of reinforced core on performance and failure behavior of stiffened deep cement mixing piles

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ABSTRACT

The behavior up to failure of stiffened deep cement mixing (SDCM) piles under axial compression is discussed on the basis of finite element simulation and laboratory small-scale model tests. The numerical investigation by means of axial pile load test simulation was carried out using the calibrated parameters and soil profile and properties from previous field tests. The results reveal that the effectiveness of a reinforced core for increasing the ultimate load of the SDCM piles and the associated failure mode mainly depend on the core dimension, core volume ratio and the strength of the deep cement mixing (DCM) socket, whereas the core stiffness has a significant effect only for the case of a relatively long core. These results imply that the core material could potentially be a cheaper, less stiff construction material. For a constant volume of reinforced core, the SDCM piles with a more slender core provide higher ultimate loads and less settlement, particularly at high core-volume ratios. Reduced-scale models were tested under normal gravity to verify the numerical findings. Good agreement was found between the simulation and test results on the influence of the core shape and material on the load-carrying behavior and failure modes of SDCM piles. A series of numerical analyses were extended to establish a guideline for recommending an appropriate size of the core in SDCM piles and to discuss the failure modes with respect to the length of the core. From the developed charts and given strength of DCM socket, the suitable core length and cross sectional dimension can be systematically chosen with known expected failure mode.

1. Introduction

When an earth structure is constructed in a soft ground area, suitable measures are required to enhance the stability and control the settlements of the soft soil. Many methods have been developed to treat soft clay ground; among these, soil improvement by deep cement mixing (DCM) piles has been widely used. This method of stabilization began in Sweden and Japan in the late 1970s. Over the last two decades, the DCM technique has been successfully used for diverse applications including foundations of small buildings, bridges and small dams, retaining structures and mitigation of excessive soil movement [1]. Among various current applications, the DCM piles have been used most often for foundations of road embankments to increase the stability of the native ground and to reduce settlement [2,3].

Under axial loading conditions, the stress along the pile length decreases with depth due to the load transfer to the surrounding soil, so that the maximum compressive stress occurs at the top of the pile (the pile head). The pile failure is therefore governed by the strength of this part. In 2003, Petchgate et al. [4] performed a series of full-scale pile load tests on DCM piles of various actual strengths. The test results revealed that half of the tested DCM piles failed by pile failure. The mode of failure depends on the relative strength of the DCM and the native soil. In order to avoid pile failure, one possible solution is to increase the strength of the DCM pile by increasing the cement content. However, this method is uneconomical because only the top part of DCM piles is subjected to high compressive stress. Moreover, at higher cement contents, the strength of cement-treated clay does not linearly increase with the cement content, and the efficiency becomes inferior with increasing cement content [5,6]. Some innovative solutions have been proposed to solve this problem including T-shaped and stiffened DCM. The "T-shaped, TDM," which is larger in diameter at the top than the lower part, was introduced in China to support embankment loading conditions. Full-scale test results indicated that TDM piles can reduce settlement of embankments as well as

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construction costs [7]. The stiffened deep cement mixing (SDCM) pile was also introduced [8] in China; SDCM piles insert a small concrete pile or any reinforcement into the DCM pile immediately after finishing the DCM pile construction (see Fig. 1a). The tests indicated that SDCM piles can resist higher loads compared to the ordinary DCM piles of the same size and length. SDCM piles are a composite structure of an inserted stiffer core and a deep cement mixed pile or socket, combining the advantages of both components. In the SDCM pile, the DCM socket forms the surrounding outer layer to support the core. The two parts of the composite pile work together by supporting and transferring the vertical load effectively to the DCM pile and to the surrounding soil. The dimensions of the two units should be such that both work together effectively and use the full strength of the surrounding clay soil. This novel method for improving the strength of DCM piles has been given different names by different researchers, such as concrete cored DCM piles, composite DMM columns and stiffened deep cement mixed (SDCM) columns. Some researchers and actual construction projects have used the SDCM piles. The cores can be circular or square concrete piles [9] or steel H-piles [10] with various sizes and lengths. No guideline has yet been developed to recommend the appropriate shape of the core. Increasing the ratio between the length of the core and the DCM pile (L_{core}/L_{DCM}) or the size of the core has a significant impact on the axial ultimate bearing capacity of SDCM piles [9,11]. By full-scale pile load tests, it was found that L_{core}/L_{DCM} of 0.85 can significantly improve the axial bearing capacity 15 times compared to the ordinary DCM pile [9]. However, increasing either the length or size of the core would increase the construction costs due to the need for additional core material that is usually more expensive than the DCM itself. Moreover, by introducing the core, the required strength of the DCM socket may be able to be reduced, resulting in a lower cement content in the DCM. Based on cost considerations, the suitable shape and size of the core must be then considered on the basis of controlled core volume with respect to the strength of the DCM socket, which in turn is relevant to the failure mode of the SDCM.

In this paper, the effect of length and size of the stiffened core under controlled volume and its stiffness on pile bearing capacity are first numerically investigated. Some physical model tests on scaled down SDCM piles under axial loading conditions are conducted to verify the findings from the preliminary numerical analyses. A parametric study on selected influencing factors, i.e., length and size of the stiffened core and the relative stiffness between the DCM socket and the core, is conducted to suggest the appropriate dimensions of the core for various DCM cases. The failure mechanisms observed from both physical model tests and numerical investigations with respect to the SDCM pile bearing capacity are also discussed.

2. Reference case and numerical modeling

2.1. Reference case

Circular DCM piles and SDCM piles 0.6 m in diameter (ϕ) and 7 m long (L) with reinforced concrete cores constructed in soft Bangkok clay from the previous work [12] were chosen as the reference case in this study. The full-scale axial load tests on these composite piles were performed at the Asian Institute of Technology (AIT), in the central plains of Thailand. The site conditions consist of 2.0 m thick weathered crust on top of a 6.0 m thick soft clay layer. A medium to stiff clay layer was found at a depth of 8.0 m, and the water table was found at 1.5 m below the ground surface. The physical properties and soil profile at the test site are shown in Fig. 2. The piles were constructed by wet jet mixing with a cement content of 150 kg/m^3 of soil. Two cross sections, 0.18 × 0.18 and 0.22 × 0.22 m, of square reinforced concrete piles with lengths of 4.0 m and 6.0 m were used as stiffened cores. The installation and details of the SDCM piles are demonstrated in Fig. 1b.

Currently, the materials that have been most often used as core structures are reinforced concrete and steel. The stiffness of those cores is very large compared to that of DCM piles (approximately 100–1000 times stiffer). In addition to these two materials, various types of construction materials are available that may be inferior in terms of stiffness, but are cheaper. Therefore, evaluating the possibility of using less stiff materials as the core is worthwhile. For example, in Thailand, Eucalyptus wood has been widely used in the construction industry because it is cheap, easy to buy, and can be produced in substantial quantities. The properties of the core in preliminary investigations are therefore focused on Eucalyptus wood.

2.2. Numerical modeling

2.2.1. Analysis and boundary conditions

Undrained analyses under two-dimensional axis-symmetric condition were performed to numerically investigate the load-settlement behavior of the SDCM piles during axial loading. Fifteen node hybrid elements were used to model the soil, the core, and the DCM pile. The boundary conditions adopted for the analyses were displacement restraints with roller supports applied on all vertical sides and pin supports applied to the base of the mesh; these conditions were used for all cases throughout the analysis.

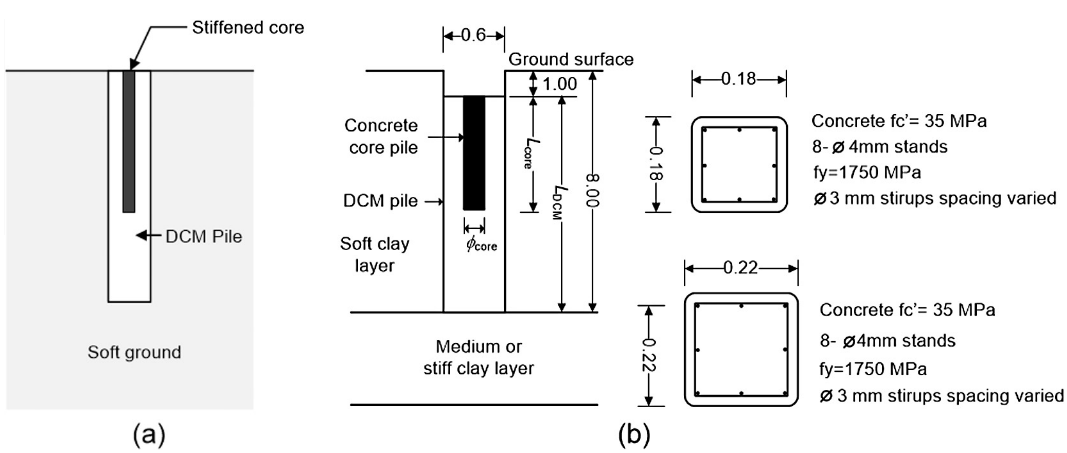

Fig. 1. Schematic of SDCM: (a) general concept of SDCM pile and (b) details of SDCM pile with concrete core (Voottipruex et al. [11]) used as the reference case in this study.