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Pseudo-static low cycle test on the mechanical behavior of PHC pipe piles with consideration of soil-pile interaction

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ABSTRACT

Pre-stressed high-strength concrete (PHC) pipe piles have been widely used in the pile foundations of buildings and bridges which are usually designed elastic based on the capacity design principle. However, when the PHC pipe pile comes to the foundations of Integral Abutment Jointless Bridges (IAJBs), limited ductility might apply in order to accommodate the relatively large deformation demand under the effect of temperature fluctuations or earthquake. The conventional design methods for PHC pipe piles remain in doubt. This paper focuses on low cycle pseudo-static tests on 4 PHC pipe-pile models with various pre-stress levels to gain insight into their mechanical behaviors with consideration of soil-pile interaction. Medium sand was employed in the tests. The details of the experiments are introduced, including design of the models, instrumentation and loading scheme. The testing results indicate that the damages of the PHC pipe piles are mainly concentrated at 4D to 8D of embedded depths. Moreover, the pre-stress level and reinforcement ratio have a significant influence on the failure mode of PHC pipe piles, especially on the distribution of internal force and moment along piles. It is found that the interaction effect of pile-soil strengthens with the pre-stress level which is beneficial to the seismic performance. Furthermore, the backbone of the PHC pipe piles model has four stages: elastic, elastic-plastic, plastic hardening, and failure. It is concluded that PHC pipe piles perform favorably plastic and ductile behavior, and their failure modes are flexural (bending) not brittle (shear). Finally, the PHC pipe pile has an appreciable energy dissipation and deformation capacity, and hence can be used for pile foundations in IAJBs.

1. Introduction

Integral Abutment Jointless Bridge (IAJB) is composed of a continuous deck connected rigidly to abutments, thereby eliminating the expansion joints. It has many advantages over bridges with expansion joints in terms of favorable integrity and low maintenance costs, which has been widely used in Europe and North America. However, the design of IAJB is relatively complicated due to the elimination of the expansion joint. Its pile foundations require high flexibility to accommodate the girder's thermal expansion and contraction as well as earthquake action. H-shape steel piles are often selected to support integral abutment in North America and Europe [1–3] since they are of high strength and large deformation capacity, while concrete piles are rarely used and lack of researches [4,5].

In recent years, IAJBs are also popularized in China and a number of IAJBs have been constructed [6]. In these bridges, concrete piles are often employed to support integral abutment based on the consideration of economy and engineering experience. Without the conduct of comprehensive experiments and analytical studies on the concrete piles, these bridges would be in a risk of failure when subjected to large earthquake or even rapid temperature fluctuations. In addition, concrete piles are weaker in strength and deformability than H-shape steel piles. But when carefully designed and detailed, they can also present high nonlinearity and ductility, like conventional reinforced concrete bridge columns. Therefore, concrete pile should not be disregarded for the application in IAJBs without clear evidence of its deficiency. What's more, the design methods of bridge piles in current Chinese specifications are of linear elasticity and small deformation, which cannot meet the demands for nonlinearity and large deformation of piles in IAJBs. All of above, the experimental and analytical studies on concrete pile

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are extremely needed before its application to the pile foundations in IAJBs [7].

Pre-stressed high-strength concrete (PHC) pipe pile is a new type of pile, usually made from C80 cement and pre-stressed strands. Compared with traditional piles, pre-stressed high-strength concrete pipe piles have been extensively applied in building structures due to their advantages of high-speed construction, easy drivability and high strength, which could satisfy the requirements of IAJBs' foundation. However, limit researches have been focused on this type of pile, especially for its failure mechanism during large lateral displacement, leaving this applicability in doubt. In the past decades, researchers mainly focused on the vertical mechanical properties and bearing capacities of PHC pipe-piles, while only a small amount of them were on the lateral mechanical properties and bearing capacities. Chen et al. [8] conducted lateral static tests on three AB type of PHC pipe-piles with 400 mm diameter. It was found that the deformations of the tested PHC pipe-piles were mainly concentrated at 1.7–2.0 m (4–5 times pile diameters) below the ground surface. Zhou et al. [9] conducted lateral static experiments on two PHC pipe piles with 400 mm diameter and 36 m long. Shi et al. [10] performed static tests on 56 PHC pipe-piles in-situ and presented the lateral bearing capacities of PHC pipe-piles with 400 mm, 500 mm and 600 mm diameters in soft soil area of Fuzhou city. In addition, lateral static-load experiments and finite element analyses on PHC pipe-piles were conducted by Lv [11]. All of above tests were monotonous that focused on the lateral static resistance rather than pile-soil interaction. However, PHC pipe-piles are often subjected to seismic loading which is a lateral cyclic loading. Monotonous lateral static-load experiments on one single pile cannot reflect the soil-pile interaction and seismic performance of PHC pipe-piles.

At present, a number of researches on dynamic response of various pile foundations in soft soil condition have been conducted and the corresponding bearing capacities of the piles were obtained [12–16]. However, the studies on seismic behavior of PHC pipe-piles are rarely conducted. Chung et al. [17] conducted low cycle experiments on PHC pipe-piles to investigate the relationship of the energy dissipation capacity with the amount of reinforcement, and the test results indicate that the ratio of reinforcement has a large influence on the capacity. Park et al. [18] conducted field tests on the prototype piles and performed FEM analysis to study the influences of temperature on the behavior of PHC pipe-piles. Rong et al. [19] conducted low cycle pseudo-static tests on PHC pipe-piles. It was found that the ductility and deformability of PHC pipe-piles decreased with the increase of pile diameter and pre-stress tendons could improve the seismic behavior of PHC pipe piles. Wang et al. [20] conducted low cycle loading tests on four PHC pipe-piles and monotonic flexural loading tests on two PHC pipe-piles to analyze failure modes, hysteretic performances, ductility, bearing capacities and load–displacement curves of piles. Nevertheless, the soil was not considered in these tests, so the soil-pile interaction could not be considered. Soil-pile interaction of laterally loaded piles under temperature effects or earthquake impacts is a complicated phenomenon [21–25], in which separation between soil and pile plays a significant influence on the lateral bearing capacity of pile foundation. In this paper, pseudo-static low-cyclic tests on 4 PHC pipe piles in medium sand were conducted in the Structure Laboratory of Fuzhou University to study their failure modes and seismic behaviors. Details of the experiments, including design of models, instrumentation, and loading scheme were discussed. A method was presented to directly measure the displacements of the embedded portion of pile by displacement transducers in order to study the soil-pile interaction. The observations of damage for the models, strains, displacements and bending moment distributions along the embedded depth, and the hysteretic loops and backbone curves for the pile are presented to identify its failure mechanism and evaluate its energy dissipation as well as deformation capacity.

2. Experimental design

2.1. Pile models [26]

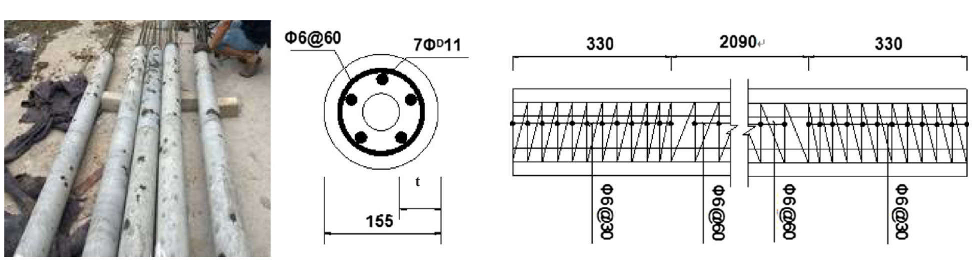
In these experiments, 4 PHC pipe-piles were designed and fabricated according to the Chinese Code for Building Pile Foundations in terms of the similar principle of pile diameters '*D*'. Their geometrical scales are 0.31(155 mm/500 mm) [26] and they are labeled as PHC-1 to PHC-4 respectively. All of these models are 2.75 m long, and 155 mm in diameters. The thickness of pipe is 52.5 mm for PHC-1 to PHC-3 and 40 mm for PHC-4 respectively. The transverse reinforcement in these models is 6 mm in diameter and its spacing (S) is 30 mm within 330 mm at both ends while changes to 60 mm along the rest of the pile. 11.10 mm diameter (7-wires standard) steel strands were selected as the pre-stressed tendon. The pre-stress strands resulted in reinforcement ratio of 1.5% in PHC-1 to PHC-3 and 2.5% in PHC-4. The pre-stress forces of PHC-1 to PHC-4 are 0, 0.25λ, 0.5λ and 0.57λ respectively where λ is the pre-stressing force (λ = 243 kN) for the steel strands. 5 prestress tendons were used for each pile. It was noted that no pre-stress was applied to PHC-1, which was designed as a reference to evaluate the influence of pre-stressing level. Pre-stress was applied by hydraulic jack, while strain gages and force sensors were utilized to monitor the pre-stress force. The process of applying pre-stress and cross-section of the models are shown in Fig. 1a and b, respectively. The basic information of these models is summarized in Table 1.

High-strength concrete was used to construct the pile in order to increase the strength of PHC pipe-piles. For this purpose, the C80 concrete was employed. It has a compressive strength of 82.1 MPa and an elastic modulus of 3.95×10^4 MPa that were measured after 28 days. The yield strength of each pre-stress strand is 142kN and the tensile yield strength of transverse reinforcement is 300 MPa.

The sand from Min River in Fujian Province, China, where a number of IAJBs were constructed, was employed in these tests. Its average SPT blow counts of the sand was 11. According to ASTM Standards [27], it is classified as the medium sand. The parameters of sand are shown in Table 2.

2.2. Soil container and soil parameters

The boundary condition is a critical factor for the experiment to study soil-pile interaction. Theoretically, the larger the soil box, the



(a) Pre-stressing (b) Reinforcement drawing

Fig. 1. PHC pipe pile models.