Tunnelling and Underground Space Technology 73 (2018) 60–70

Contents lists available at ScienceDirect

Tunnelling and Underground Space Technology

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

Experimental study on the structural behaviors of jacking prestressed concrete cylinder pipe

Yao Zhang[b], Zhi-guo Yan[a,b,*], He-hua Zhu[a,b], J. Woody Ju[c]

[a] State Key Laboratory of Disaster Reduction in Civil Engineering, Tongji University, 1239 Siping Road, Shanghai 200092, China
[b] Department of Geotechnical Engineering, Tongji University, 1239 Siping Road, Shanghai 200092, China
[c] Department of Civil and Environmental Engineering, University of California, Los Angeles, CA 90095, USA

ARTICLE INFO

Keywords:
Structural behaviors
JPCCP
Combined load
Internal pressure
External load

ABSTRACT

In this study, full-scale tests were conducted on Jacking Prestressed Concrete Cylinder Pipe (JPCCP) under external load, internal pressure, and combined load in order to evaluate its structural behaviors and possible failure modes. The experimental results indicate that external load plays a critical role in determining the onset of inner concrete core cracking at the invert and crown of a pipe. Once cracking appears in the inner concrete core of JPCCP under external load, the crack propagates rapidly and exhibits significant brittle fracture property. The onset of microcracking first appears in the exterior-reinforced concrete coating at the pipe springline in these three tests. Compared to the inner concrete core, cracks distributed in exterior-reinforced concrete coatings are smaller and narrower, as a result of the restriction imposed by the stirrup. The results of the combined load test show that JPCCP structure transforms from a perfect cycle into a damaged cycle, exhibiting a reduction in section stiffness at the pipe invert as loading increases. When the steel cylinder reaches its yield limit, the prestressing wire at the pipe invert yields soon after, and debonding (delamination) occurs between the steel cylinder and concrete almost simultaneously. Nevertheless, the JPCCP structure features excellent post-cracking capacity after a new equilibrium forms, and it exhibits enhanced ductile properties. Finally, a comparison between test results for JPCCP and Prestressed Concrete Cylinder Pipe (PCCP) is performed to illustrate the failure mode of JPCCP under combined load.

1. Introduction

Prestressed Concrete Cylinder Pipe (PCCP) has been used worldwide over the last few decades as a class of buried pipe (Ge and Sinha, 2014a). It is a popular type of composite structure pipe, and is composed of high-strength prestressing wire, steel, a concrete cylinder, and a mortar coating applied to the exterior of the pipe. In this composite structure pipe, a steel cylinder is embedded in a concrete core, and the outside of the intermediate concrete core is wrapped with a high-strength prestressing wire. This imposes a compressive prestrain in the concrete to balance the effects of the working load, which enhances the cracking resistance of PCCP under working load.

Because of several advantages such as strong permeability resistance, high bearing capacity, and wide applicability, PCCP has been extensively adopted in water transfer and transit project. However, for pipelines that pass through urban roads, railways, rivers, or places with a high volume of human activity, all the existing concrete roads and structures need to be removed when PCCP is installed by the open-cut construction, which can be significantly costly. In addition, PCCP laying may block traffic, interrupt river flow, or cause problems for people in daily life. Therefore, the engineering applications of PCCP by open-cut construction may be limited, which further hinder the popularization and application of PCCP. In order to overcome this problem, an improved PCCP is designed to be used as a jacking pipe, namely Jacking Prestressed Concrete Cylinder Pipe (JPCCP) which has a reinforced-concrete coating applied to the exterior of the pipe instead of the mortar coating applied to PCCP.

To evaluate a new proposed method of design for PCCP pipe, a series of combined load tests involving internal water pressure, external load, and pipe and water weights, were conducted by Zarghamee et al. (1988) and Tremblay (1990). The test results were presented by Zarghamee and Fok (1990), and Zarghamee (1990) to validate a multi-layer ring model of prestressed concrete pipe, and they analyzed its mechanical response and failure mode. Early attempts (Hu et al., 2009; Hu and Liu, 2011, 2012) to evaluate the performance of PCCP focused on the failure mode under external load and internal pressure. As pipes age, failure incidents occur more frequently, which attracts researchers to pursue related studies (Ge and Sinha, 2011a, 2012, 2014a, 2015,

* Corresponding author at: State Key Laboratory of Disaster Reduction in Civil Engineering, Tongji University, 1239 Siping Road, Shanghai 200092, China.
E-mail address: yanzguo@tongji.edu.cn (Z.-g. Yan).

https://doi.org/10.1016/j.tust.2017.11.033
Received 1 September 2016; Received in revised form 25 May 2017; Accepted 26 November 2017
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2016). To alleviate the more serious results of accidents caused by using PCCP, researchers focus their attention on investigations involving the performance of PCCP with broken wires under external load, internal pressure, and combined load, through both experimental study and finite element analysis (Hu et al., 2011; Erbay et al., 2007; Zarghamee and Ojdrovic, 2001; Zarghamee et al., 2002, 2006, 2011; Ge and Sinha, 2011b, 2014b; 2015b; Hajali et al., 2016). In addition, condition assessment technologies and performance predictions of PCCP are also important parts of investigation, which can help ensure the safety of the operational PCCP (Ge and Sinha, 2014a, Holley and Diaz, 2001; Kong and Mergelas, 2005, 2007, 2009; Weare, 2007; Zarghamee and Ojdrovic, 2001; Zarghamee et al., 2006). These results shed light on the structural behavior of pipe structure, which has advanced its application in China. However, there are not any reports available on the investigation about JPCCP as the pressure pipe at home or abroad. There is also no professional code available for designers to refer to. Consequently, JPCCP has to be designed referring to the existing standards, which involves the standard of PCCP and jacking pipe (CECS 140: 2011; SL 702-2015; CECS 246: 2008). Specifically, the load caused by soil and water can be calculated according to the general structure code of jacking pipe (CECS 246: 2008). To avoid possible cracks induced by eccentric jacking load, the longitudinal bar is quantified. The section can be designed based on relative PCCP code (CECS 140: 2011; SL 702-2015). However, the ability of JPCCP to sustain the required operational load (internal pressure and soil pressure) and possible transient load (water hammer effects and vehicle loads) should be further validated. In addition, based on the review of previous research (Ge and Sinha, 2014a), more PCCP tests are needed to study the causes of failure, including laboratory tests and field tests. These kinds of tests are also needed for JPCCP.

Not only does a significant difference exist between the structures of JPCCP and PCCP, but the configurations of the two types of pipes also show a notable change. The differences between PCCP and JPCCP are listed in Table 1, which further require necessary experimental studies on the applicabition of the design of JPCCP. As a novel jacking pipe, the structural behavior of JPCCP should be studied before it is applied in practical engineering. In a companion paper (Gong et al, 2015), the behavior of JPCCP under jacking force with a misalignment angle was analyzed through FEM. In this study, the performance of JPCCP under working load is mainly investigated through experimental tests. Although external load and internal water pressure tests are generally utilized to confirm whether PCCP is qualified or not, they cannot represent the actual field condition which is the basic condition for the design of stiff pipe, and reflect the structural performance and bearing capacity of pipe.

Therefore, to comprehensively investigate the structural properties of JPCCP structure, tests under external load, internal water pressure, and combined loads were carried out for several JPCCP prototype pipes. The structural behaviors and possible failure modes of this kind of pipe are discussed in this study, and the data obtained during testing are carefully collected. The mechanical properties of each structural layer and the strain changes of the pipes under different load conditions are reported.

Table 1
Differences between PCCP and JPCCP.

Item	PCCP	JPCCP
General length	5–6 m	3 m
Configuration	Thin exterior mortar coating	Thick exterior reinforced concrete coating
Pipe type	Buried pipe	Jacking pipe

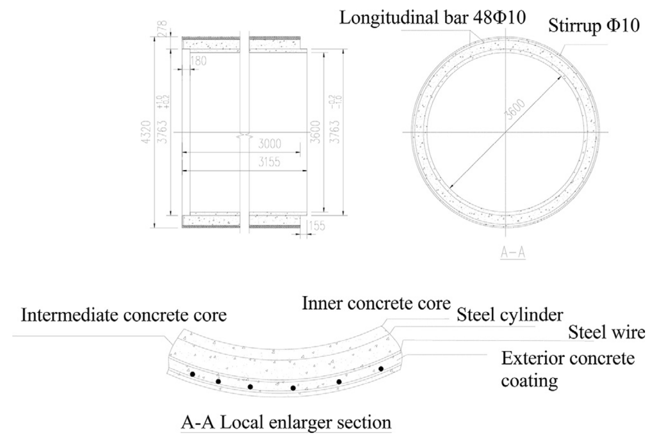

Fig. 1. Structure diagram of JPCCP (Dimension: mm).

2. Test equipment

2.1. JPCCP specimen

The structure of the JPCCP specimen tested in the experiment is shown in Fig. 1. It can be seen that the JPCCP pipe consists of an inner concrete core, a steel cylinder, an intermediate concrete core, prestressing wire, and an exterior-reinforced concrete coating. The characteristics of each part are listed in Table 1. The outer and inner diameters of the JPCCP pipe are 4.32 m and 3.6 m, respectively. The diameter and the spacing of the prestressing wire are both 7 mm. The thickness of the exterior-reinforced concrete coating is 80 mm, and the exterior-reinforced concrete coating is reinforced by longitudinal bars (HRB335) and stirrups (CRB550), whose diameters are both 10 mm. The hoop stirrup with 80 mm space between each hoop stirrup is utilized as configurable bar to facilitate the installation of longitudinal bars. The total number of equally-spaced longitudinal bars along the ring is 48, which is determined by jacking pipe code (CECS 246: 2008). The thickness of the concrete cover for the stirrup bar is 30 mm, which is the nominal thickness over the stirrup. In addition, the thickness of the intermediate concrete core is 200 mm, a summation of the thicknesses of the concrete and the steel cylinder (Q345B, 1.5 mm). While the thickness of the inner concrete core is 80 mm.

The manufacturing procedure of the specimen is shown in Fig. 2. As shown in this figure, the steel cylinder and the bell and spigot are fabricated at the initial stage. After the inner and intermediate concrete core is casted, the test pipes are placed into a steam curing condition until they reach 75% of their yield strength. Then, outside of the intermediate concrete core is wrapped by the high-strength prestressing wire, which allows the inner concrete core to possess a certain compressive prestrain and further resists the effects of the working load. Afterwards, the configurational bar cage is installed. Subsequently, the exterior-reinforcing concrete coating is casted. Finally, all the specimens are put into the standard curing condition for 28 days. When the test started, the actual age of the exterior-reinforced concrete coating of JPCCP pipe was 65 days.

2.2. Load condition and load step

According to the design, the failure loads of JPCCP pipe under external load, internal pressure, and combined load are 2200 kN, 2.1 MPa, and (1300 kN, 1.6 MPa), respectively.

2.2.1. Test under external load (three-edge test)

Based on the load equivalence principle and the mechanical characteristics of piping, concentrated line load is employed in the test. It is notable that soil or water pressure loads on a pipe are distributed loads in reality. Therefore, point loading is not completely representative of

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