Finite Element Simulation of Distressed Prestressed Concrete Cylinder Pipes Embedded in Soils

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Abstract. Durability problems often occur to the prestressed concrete cylinder pipe embedded in aggressive soil environment. The residual performance assessment of damaged pipes is the basis of the maintenance strategy. This study proposes a soil-pipe interaction framework to simulate the limit states of the pipe with path-dependent modelling of each part of the pipe structure, surrounding soil and the contact state between them. Based on the analytical results, the limit states of the pipe can be ranked. Further sensitive analyses showed significance of the nonlinear soil-pipe interactions and the exact deformation is recognized as the aim of the future study.

1. Introduction

Large diameter prestressed concrete cylinder pipes (short as PCCP in the following context) are widely constructed as part of many raw water transfer projects in China. Large PCCP is considered as a better choice of hydraulic structures for the pressurized water conveyance, which could balance the water transportation efficiency, structural safety and building cost. As shown in Figure 1, it consists of a concrete core, a thin steel cylinder, high tensile prestressed wires and a mortar coating. The safety management attracts plenty of public concern.

Fig 1. Typical cross section of PCCP
Durability problems often occur to PCCPs. The coupling effect of mechanical loads and corrosive environment leads to the broken of the prestressed wires and eventually pipe burst[1]. Generally, performance assessment is required for the pipeline served in the aggressive environment. A failure margin analytical method using the risk curves technology is developed to evaluate the residual serviceability and capacity of the distressed pipes[2]. Based on the electromagnetic non-destructive detection results on broken wires[3], the failure risk of the damaged pipes can be assessed.

However, there are many arguments on the accuracy of the failure risk analysis. It is oriented from the simplifications of the analytical methods. Among them, the pipe-soil interaction that has seldom been regarded in the analysis is recognized as one of the key points that should not be neglected for the pipe working performance assessment [4]. Therefore, this study tries to apply nonlinear finite element analysis to simulate the residual performance of the damaged PCCPs embedded in soil and demonstrate the effect of pipe-soil interaction.

2. Analytical approach for damaged PCCPs in soil

2.1. Three-dimensional finite element approach for a PCCP in soil

A three-dimensional finite element approach is applied here for the performance assessment of a PCCP in soil as shown in Fig. 2. Hexahedron solid elements are used for the core concrete, steel cylinder, coating mortar and surrounding soils. Eight-node interfacial elements with no volume are used to simulate the contact state between PCCP and surrounding soils. Truss elements are used for prestressed wires; as the wire wound angle is nearly perpendicular to longitudinal direction of the pipe, only circumferential contribution of the wires is considered in the analysis. To simplify the pre-process, the wire contribution is uniformly distributed along the pipe longitudinal axis, i.e., every truss elements represents ten wires.

Fig. 2. Three-dimensional finite element simulation of PCCP in soils

2.2. Constitutive models for pipe-soil interaction

Path-dependent nonlinear constitutive models [5] are used for core concrete and coating mortar, and soil elements. Steel cylinder is simulated as an elastic-perfect plastic material with von-Mises yielding surface.

As shown in Fig.3, a bilinear open-closure model is used to simulate the normal contact behaviour of the pipe and surrounding soil, in which very small stiffness is applied for contact loss when the interface open while very large stiffness for closure to avoid penetration of different materials.

three stage of finite element analyses are carried out with the “birth and death element” technology. First, the initial strain is input in wire elements while the coating mortar, soil and interfacial elements are set death. Gravity loads is not considered at this stage. Then, the gravity loads are added with the birth of coating mortar, soil and interfacial elements. Finally, the inner pressure is applied. The breakage of wires has to be considered in the last stage. This analysis may not simulate the actual stress history in a pipe, but could successfully catch the residual limit states.
2.3. Simulation of distressed wires
The simulation of the prestressing wires is considered as one of the significant factors that controls the numerical accuracy. Researchers usually employs the equivalent radial pressure [6] to simulate the prestressing effect. However, this does not consider the contribution of wire stiffness to the pipe structure. Without the simulation of broken wires, the stress redistribution among the remaining wires cannot be provided. This study input the initial tensile strain into the wire elements so that the prestressing effect on core concrete and steel cylinder can be automatically computed. Then, the nonlinear mathematic formulation recommended by AWWA code is used to simulate post-yielding behaviour of the wires. To simulate the distressed wires, this study simply sets the whole cycle of the wire as dummy elements in the analysis.

3. Analytical Results

3.1. Simulation of distressed pipes in soils
Finite element analyses were carried out to simulate the residual performance of the damaged PCCPs in soils. Two limit states of damaged PCCPs in soil are computed. The serviceability limit state represents the on-set of longitudinal cracking in core concrete, and ultimate limit state arrives at the yielding of steel cylinder. But it has to be noted that the two limit states are computed based on soil-pipe interaction analysis. Typical curves of the limit states versus the pipe damage are shown in Fig. 4.
Here, the vertical axis denotes the inner pressure while the horizontal axis denotes the number of broken wires. Then, the limit inner pressure of any damage state can be obtained through this figure. The design working pressure and additional water hammer pressure has also been drawn in the figure. According to Fig. 4, the residual limit states of each segment of the pipeline can be obtained with the electromagnetic non-destructive detection data.

3.2. Effect of soil-pipe interactions
Sensitive analyses were also carried out to discuss the effect of pipe-soil interaction. Fig. 5 shows the computed limit states with pure pipe structural analysis. Here, the soil confining pressure is added as face load on the pipe according to the design code. The soil confining pressure based on the design code is a simplified approach; it underestimates the actual soil confinement. It can be found that the pure pipe structural analysis will underestimate the limit states of the pipe.
4. Conclusions
A soil-pipe analytical framework is applied in this study to simulate the residual performance of the PCCPs embedded in soils. Path-dependent nonlinear models of each part of the pipe structure, surrounding soil and the contact state between them are used in the analysis. It employs the “birth and death element” technology and inputs the initial strain in wire elements to simulate the prestressing effects. Based on the in-situ inspection data, finite element analyses are carried out to evaluate residual limit states of an actual damaged pipeline.

Sensitive analyses are carried out to demonstrate the effect of soil-pipe interaction and the cracking damage in core concrete. It implies that the soil-pipe interaction is significant for the evaluation of the limit states.

Since it is unacceptable for the stake holder to excavate soil cover and expose the prestressed wires for the verification of the non-destructive detection, it might be possible to simulate the actual deformation for validations. Therefore, the exact deformation simulation with the complex factors like loading history, wire breakage, creep, temperature and humidity should be studied in future.

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