Theoretical Study of the Reinforcement of Pre-stressed Concrete Cylinder Pipes with External Pre-stressed Strands

Lijun Zhao and Tiesheng Dou

Abstract Reinforcement of the pre-stressed concrete cylinder pipes with external pre-stressed strands is an effective way to enhance a prestressed concrete cylinder pipe's ability to bear the design hydraulic pressure. A theoretical derivation is studied, and this formula derivation could be used to determine the cross-sectional area per unit length. This derivation determine the cross-sectional area and target tensile strength of steel strands in order to meet the requirements of ultimate limit states, serviceability limit states, and quasi-permanent limit states. The theoretical results agree well with the experimental results. This paper could provide technical supports for the application of the external reinforcement of PCCPs with strands.

Keywords Pre-stressed concrete cylinder pipe · External pre-stressed strands · Theoretical study · Breaking wires

1 Introduction

The pre-stressed concrete cylinder pipe (PCCP) has strong bearing capacity and it is economically affordable because of the efficiencies in construction and reductions in fabrication costs. However, it is necessary to reinforce the deteriorate pipe because the wire-breakage may lead to the rupture of the pipe. This study introduced the theoretical derivation and determined the pre-stress loss of steel strands hooped on PCCPs. To estimate pre-stress losses, the normal stress between the strands and the pipe was considered as a trigonometric distribution instead of uniformly. The cross-sectional area per unit length of the pre-stressed strands was determined to meet the requests of ultimate limit states, serviceability limit states, and quasi-permanent

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limit states. The load response of the deteriorate pipe during the whole procedure was analyzed.

2 Theoretical Research

2.1 Determination of Pre-stress Loss, $\sigma_{st,l}$

The pre-stress loss contains two parts, which is instantaneous loss and long-term loss [1–3]. Instantaneous loss exists during the tensioning operation and long-term loss exists after the tensioning procedure. Long-term pre-stress losses included pre-stress losses [1, 4] including shrinkage and creep losses of concrete, and long-term relaxation losses of pre-stressed steel strands. This part gives out the calculation method of the friction resistance between the surface of the pipe and the pre-stressed strands.

The retraction length, l_{re}, and its corresponding angle, θ_{re}, can be given $l_{re} = \sqrt{\frac{\Delta l_{re} E_{st} r_{st}}{\mu \sigma_{st}}}$, where E_{st} is the elastic modulus of the pre-stressed strand (N/mm^2), σ_{st} is the tension stress of the strand (N/mm^2), r_{st} is the calculated radius of the strand hooped on the pipe (m) and μ is the average friction coefficient between the pre-stressed strands and the outer surface of the PCCP. The value of Δl_{re} differed with the type of anchor.

The pre-stress loss caused by the friction resistance, σ_{l1}, was induced by bending and deviation. The radial compressive stress, σ_r, was caused by pre-stressed strands which located between the strand and the pipe. And the extrusion friction occurred. The bending loss accounted for a large proportion of the total friction loss.

Based on the assumption of a rigid body, we assumed that the pressure between the pre-stressed strand and the PCCP would not show uniform distribution [5]. It was not accurate enough to consider the contact stress as uniformly distributed under normal contact pressure. And when the two elastic bodies began to contact each other, elastic deformation occurs.

The scope of the bending loss was relevant to the retraction length, l_{re}. The assumption was made that the normal stress between the strands and the PCCP would show a trigonometric distribution [6] (Fig. 1).

The equation is given as $p_{(\alpha)} = p_0 \cos^2\left(\frac{\pi}{\theta}\alpha\right)$,

where $\cos^2\left(\frac{\pi}{\theta}\alpha\right) = \begin{cases} 0 & \alpha = \frac{\theta}{2} \\ 1 & \alpha = 0 \\ 0 & \alpha = -\frac{\theta}{2} \end{cases}$.

A forces in the z-direction could reach a balance (Eqs. 1 and 2). Therefore, the normal stress was calculated by Eq. 3.

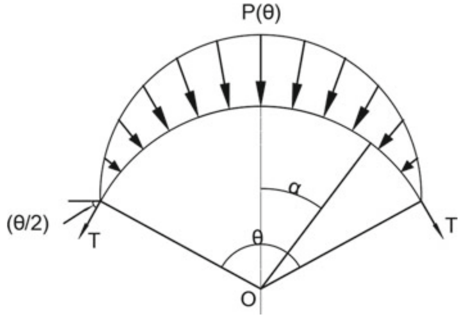

Fig. 1 Distribution of the normal stress

$$T \cdot \sin\left(\frac{\theta}{2}\right) + (T + dT) \cdot \sin\left(\frac{\theta}{2}\right) + 2\int_0^{\frac{\theta}{2}} p_{(\alpha)} \cdot \cos\alpha \, dl = 0 \tag{1}$$

$$p_0 = \frac{\sin\frac{\theta}{2}}{\int_0^{\frac{\theta}{2}} \cos^2\left(\frac{\pi}{\theta}\alpha\right)\cos\alpha \, d\alpha} \times \frac{T}{R} \tag{2}$$

in which $\int_0^{\frac{\theta}{2}} \cos^2\left(\frac{\pi}{\theta}\alpha\right)\cos\alpha \, d\alpha = \left(\cos^2\left(\frac{\pi}{\theta}\alpha\right)\sin\alpha\right)\Big|_0^{\frac{\theta}{2}} + \frac{\pi}{\theta}\int_0^{\frac{\theta}{2}} \sin\alpha \sin\left(\frac{2\pi}{\theta}\alpha\right) d\alpha$

$$p_{(\alpha)} = \left(2 - \frac{\theta^2}{2\pi^2}\right) \cdot \cos^2\left(\frac{\pi}{\theta}\alpha\right) \cdot \frac{\sigma_0}{R} \tag{3}$$

The pre-stress loss which was related to the bending loss, F, during the tensioning procedure is depicted in Eq. 4.

$$F = 2\int_0^{\frac{\theta}{2}} \mu p_{(\theta)} \cdot dl = \mu\theta\sigma_0\left(1 - \frac{\theta^2}{4\pi^2}\right) \tag{4}$$

Errors in the positioning and installation of the pipe induced the friction between the force rib and the pipe material. And the contact friction formed. The deviation loss was related to the contact friction. In comparison to the bending loss, the deviation loss owned a small proportion of the total friction loss. The total pre-stress loss caused by the friction resistance was calculated as $\sigma_{l1} = c_1 F$, where c_1 is the correction coefficient, usually in the range of [1, 1.3] [7].

2.2 Calculation of Area of Pre-stressed Steel Strands

The cracking of PCCPs under combined loads mainly occurs at three dangerous sections [8–10] (1) the 6-o'clock orientation of the inner surface of the concrete core, (2) the 12-o'clock orientation of the inner surface of the concrete core, and (3) the 3-o'clock or 9-o'clock orientation of the outer surface of the concrete core. The cross-sectional area per unit length of the pre-stressed steel strands can be determined under the assumption of a complete loss of pre-stress of pre-stressing wires.

The combined loads acting on the pipe included the vertical earth pressure at the 12 o'clock orientation of the pipe, $F_{sv,k}$, lateral earth pressure, $F_{ep,k}$, ground pile load, the weight of the pipe, G_{1k}, the weight of fluid in the pipe, G_{wk} and variable load.

The value of $F_{sv,k}$ and $F_{ep,k}$ is calculated according to Marston theory and Rankine's earth pressure theory [11], separately. The variable load can be regarded as the ground stacking load and its standard value is defined as $q_{mk} = 10$ kN/m. $G_{1k} = \pi r_G(D_i + h_c)h_c$, where D_i is the inner diameter of the pipe (m); h_c is the thickness of concrete core (m), r_G is the gravity density of the pipe (kN/m^3). G_{wk}, can be calculated by $\mathrm{G_{wk}} = \frac{\mathrm{r_W}\pi D_\mathrm{i}^2}{4}$, where $\mathrm{r_w}$ is the gravity density of the fluid in the pipe (kN/m^3).

The design requests for calculation of ultimate limit states under the external soil load, the weight of pipe, the weight of the fluid, and other variable loads were carried out [12, 13]. The area of the pre-stressed strands of ultimate limit states should be calculated by $\mathrm{A_{st}} \geq \frac{\lambda_\mathrm{y}}{\mathrm{f_{pyk}}}\left(\mathrm{N^l} + \frac{\mathrm{M^l_{max}}}{\mathrm{d_0}} - \mathrm{A_{sc}f'_{yy}}\right)$, where λ_y is the comprehensive adjustment factor of the PCCP. f_{pyk} is the design strength of pre-stressed strands (N/mm^2). Therefore, the area of pre-stressed strands should be calculated by $\mathrm{A_{st}} \geq \left(\sigma_\mathrm{ss} - \mathrm{K}\gamma\mathrm{f_{ty}}\right)\frac{\mathrm{A_n}}{\sigma'_\mathrm{st}}$, where σ_{ss} is the maximum tensile stress at the edge of the pipe at the bottom. Meanwhile, checking calculation of mortar at the 3 or 9 o'clock orientation of the pipe should be conducted under different limit states.

3 Applications

Parameters of the design and materials were given in the former article [14]. $\Delta \mathrm{l_{re}} = 6$ mm (Obtained from the full-scale test). Given $\mu = 0.1$, the calculated radius of the strand hooped outside the pipe, r_{st}, and l_{re}, is $r_{st} = 1.1726$ m and $l_{re} = 3.61$ m, respectively. The corresponding angle of the retraction length, θ_{re}, is π, which is in accordance with the value of θ. The correction coefficient is 1.01 and the pre-stress loss caused by friction resistance, σ_{l1}, can be calculated as $\sigma_{l1} = 278.860$ N/mm^2. The total pre-stress loss of pre-stressed wire is 490.74 N/mm^2.

According to the Marston theory, the vertical earth pressure at the top of the pipe, $F_{sv,k} = 164.245$ kN/m. And the lateral earth pressure is calculated based on the Rankine's earth pressure theory, $F_{ep,k} = 25.026$ kN/m. Weight of the pipe, $G_{1k} = 29.157$ kN/m. Weight of water in the pipe, $G_{wk} = 31.416$ kN/m.

Fig. 2 The strengthened pipe after tensioning

The area of pre-stressed strands should meet the requirement of $A_{st} \geq \left(\sigma_{ss} - K\gamma f_{ty}\right)\frac{A_n}{\sigma_{st}^{l}} = 2257.64\ \text{mm}^2/\text{m}$. The area of pre-stressed strands is $A_{st} = 2258\ \text{mm}^2/\text{m}$.

$\left(\alpha_m \varepsilon_{mt} E_m = 17.44\ \text{N/mm}^2\right) > \left(\sigma_{ss}^{l} = 9.57\ \text{N/mm}^2\right)$, indicating that the area of pre-stressed strands can reach the tensile request of the mortar coating under the states of serviceability limit.

$\left(\alpha_m^{'} \varepsilon_{mt} E_m = 13.95\ \text{N/mm}^2\right) > (\sigma_{ss}^{l} = 8.31\ \text{N/mm}^2)$, indicating that the area of pre-stressed strands can reach the tensile request of the mortar coating under the states of quasi-permanent limit.

Above all, it is reasonable of the calculation result of the area of pre-stressed strands, which is $A_{st} = 2258\ \text{mm}^2/\text{m}$. The predictions of the results by the equations agrees well with the test results [14]. The strengthened pipe with external strands was capable of sustaining the design internal hydraulic pressure and the pipe do not leak (Fig. 2). The rationality of the theory in this study was testified by the effective reinforcement effect with external pre-stressed strands.

4 Conclusion

A theoretical research was studied aiming at the determination of the appropriate cross-sectional area per unit length of pre-stressed strands in this paper.

(1) The pre-stress loss of pre-stressed strands contains several types. The formula derivation in this study provides a reliable method to determine the effective pre-stress of the strands.
(2) The stress of the concrete core under different limit states was calculated. And the condition of the mortar coating under different limit states is then verified, and the appropriate cross-sectional area per unit length of pre-stressed strands is finally determined.

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