Reliability research analysis on crack control standard for steel lined reinforced concrete penstocks

Jiazhi Kang, Yang Li, Jiangkun Zhang, Qiuhong Wang *

School of Civil Engineering and Environment, Hubei University of Technology, Wuhan, Hubei, 430068, China

*Corresponding author e-mail: 574157322@qq.com

Abstract. In view of the insufficiency of research about steel lined reinforced concrete penstocks in hydropower station crack control standard, the Monte Carlo method was combined with the crack width calculation formula of Dong Zhe-ren method to establish a reliability calculation method. According to the engineering example and model test parameters, the reliability index of the crack control standard for steel reinforced concrete penstocks in China were calculated, and the main influence factors were concluded. Studies indicates that the reliability level of crack control for steel lined reinforced concrete penstocks is of medium level or slightly lower. The influence of crack width limit, cover thickness and the effective reinforcement ratio on reliability level of crack control standard is significant.

1. Introduction

Steel-lined reinforced concrete penstock is a type of pipe commonly used in the large and medium-sized dam-type hydropower station, and has been applied in Dongjiang, Lijiaxia, Three Gorges Hydropower station [1].

Besides withstanding and transmitting the radial pressure, the outsourced concrete also prevents the steel liner from being exposed directly to the air, thus avoiding the influence of temperature difference and acid rain erosion, greatly improving the safety and durability of the pipeline. However, according to the previous research and practice, steel-lined reinforced concrete pipe in the bearing process, varying degrees of cracking will generally appear in the external reinforced concrete [2]. In China, there are two guiding norms in the design of pressure piping: nbt35056-2015 "Design code for Penstock of Hydropower Station" [3] and SL281-2003 "design code for Penstock of Hydropower Station" [4]. On the calculation of the maximum crack width of steel lined reinforced concrete penstock outside in serviceability limit state, the "NBT35056-2015" specification stipulates that it should be based on the standard combination and considered long-term effect, use the relevant provisions of industry standard DL 5057-2009 "Design Code of hydraulic Concrete Structure" [5] The SL281-2003 stipulates that the crack width calculation formula given by the SL/T191-1996 "design Code of hydraulic concrete Structure"[6] should be used. Because the pressure pipe is different from the general beam-bar members, the crack development form has certain particularity, if the calculation formula of crack width based on the beam-plate member is used to calculate the crack width of the pressure pipe, there will be a great difference between the measured value and the calculate value. At the same time, the research material on reliability of the existing steel-lined reinforced concrete pipe crack control standard is less. In view
of this, combined with Dongjiang prototype, tight water beach prototype, Li Jia Xia and other engineering data, analyses and compare with the existing steel-lined reinforced concrete pipe crack control standards for reliability, the conclusions can provide references for the revision of the relevant norms of China.

2. Comparison of two formulas for calculating crack width
   The crack width calculating formula in DL/T5057-2009 is using the standard load combination and taking into account the long-term load effects, the uneven strain of steel the elongation of concrete, and the non-uniformity of crack width. According to DL/T5057-2009 "Hydraulic Concrete Structure Design Code" the concrete member crack width formulas are given by:

   \[ \omega_{\text{max}} = \alpha_{\text{cr}} \psi \frac{\sigma_{sk} - \sigma_0}{\sigma_s} L_{\text{cr}} \]  (1)

   \[ \psi = 1 - 1.1 \frac{f_{sk}}{\rho_{te} E_s} \]  (2)

   \[ L_{\text{cr}} = \left( 2.2 c + 0.09 \frac{d}{\rho_{te}} \right) u \]  (3)

   Where \( \alpha_{\text{cr}} \) is the coefficient that takes into account the force characteristics of the component and \( \alpha_{\text{cr}} = 2.45 \) for the axial tension component; \( \psi \) is the strain non-uniformity coefficient of the longitudinal tensile strain of the crack; \( \sigma_{sk} \) is the stress in the longitudinal direction of the component which is calculated according to the standard combination N/mm²; \( \sigma_0 \) is the initial stress of the bar N/mm²; \( E_s \) is the modulus of elasticity of the bar N/mm²; \( f_{sk} \) is the standard value of the axial tensile strength of the concrete N/mm²; \( \rho_{te} \) is the effective reinforcement rate of the longitudinal tensile bar; \( L_{\text{cr}} \) is the average crack spacing in mm; \( c \) is the distance between the outer edge of the outermost longitudinally stretched bar and the bottom edge of the tension zone in mm, 20mm < \( c \) < 65mm;

   At present, the SL/T 191-1996 specifications has been replaced by SL 191-2008 "Hydraulic concrete structure Design Code"[7]. Therefore, the study is carried out with taking SL 191-2008 as its object. The calculation formula for the crack width given in SL 191-2008 is calculated according to the load standard combination and the long-term combination of the load effect and the load characteristics are considered. The influence of the protective layer thickness on crack width is also appropriately reduced. According to SL 191-2008 "Code for Design of Hydraulic Concrete Structures" the limit state checking formula of steel pipe-lined reinforced concrete pipe crack width is:

   \[ \omega_{\text{max}} = \alpha \frac{\sigma_{sk}}{E_s} \left( 30 + c + 0.07 \frac{d}{\rho_{te}} \right) \]  (4)

   Where \( \alpha \) is the comprehensive influence coefficient considering the force characteristics of the member and the long-term load effect, \( \alpha= 2.7 \) for the axial tension member; \( \sigma_{sk} \) is the tensile stress in the longitudinal direction of the member according to the standard combination N/mm²; \( c \) is the distance between the outer edge of the longitudinal tensile reinforcement and the bottom edge of the tension zone in mm; \( d \) is the diameter of the reinforcement in mm; \( \rho_{te} \) is the effective reinforcement ratio of the longitudinal tensile reinforcement.

   As can be seen from the comparison between the two codes: both of the hydraulic codes adopt the standard load combination and consider the long-term load effect, but there are some discrepancies in formula setting and calculation parameters. When calculating the crack width according to DL/T 5057-2009, there are considering the initial stress of the member under long-term action, and the expansion coefficient influenced by the force characteristics of the member and long-term effect. In this case, the value taken according to the SL 191-2008 specification is slightly larger than DL/T 5057-2009.
3. Reliability Calculation Method of Steel Lined Reinforced Concrete Crack Control Standard

For the serviceability limit state, crack width of concrete members specified in the code should be used as the resistance and the maximum crack width of steel lined reinforced concrete pipe under load should be taken as load effect. The ultimate state formula of crack width checking is:

\[ Z = \omega_{\text{max}} - \omega_{\lim} \]  

(5)

Where \( \omega_{\text{max}} \) is the maximum crack width in mm; \( \omega_{\lim} \) is the allowable value of crack width in mm.

Since the formulas for calculating the crack width proposed by the two hydraulic codes are both based on the rod members, there are some differences with the actual crack conditions of the steel lined reinforced concrete pipe. Therefore, when carrying out reliability calculation and analysis, the Dong Zheren formula based on the force characteristics of the pipeline and the orthotropic method \[8\] is introduced which makes it more realistic to simulate the crack width of actual steel lined reinforced concrete pressure pipe under the action of internal water pressure. Specific Dong Zheren formulas are as follows:

\[ \omega_{\text{max}} = \beta \bar{\omega} \]  

(6)

\[ \sum \pi (U_{\text{out}} - R_{\text{out}} \varepsilon_{\text{max}}) \]  

(7)

\[ L_c = 2 \left( c + \frac{s}{10} \right) + K_1 K_2 \frac{d}{\mu} \]  

(8)

\[ \bar{\omega} = \frac{\sum W}{N} = \frac{(U_{\text{out}} - R_{\text{out}} \varepsilon_{\text{max}}) L_c}{r} \times \frac{360}{360 - \theta} \]  

(9)

Where \( \beta \) is the crack width magnification factor; \( \bar{\omega} \) is the average crack width of the pipe in mm; \( U_{\text{out}} \) is the radial displacement at the outer edge of the pipe structure in mm; \( R_{\text{out}} \) is the radius of the outer edge of the pipe structure in mm; \( \varepsilon_{\text{max}} \) is the ultimate tensile strain of the concrete; \( L_c \) is the average crack spacing in mm; \( K_1 \) is the coefficient of bond of steel \( K_1 = 0.4 \) (deformed steel) \( K_1 K_2 = 0.8 \) (smooth steel); \( \mu \) is the ratio of reinforcement and \( \theta \) to reflect the dam or bedrock angle in degree.

When simulating the crack width of steel-lined reinforced concrete pipe, most of the parameters in Eq. (6) ~ (9) can be regarded as random variables. The detailed statistical parameters are shown in Table 1.
Table 1. Statistical properties of basic variables

| design variable          | Distribution Type       | Mean value coefficient | Coefficient of variation |
|--------------------------|-------------------------|------------------------|--------------------------|
| Steel lining thickness   | Normal distribution     | 1.00                   | 0.016                    |
| radius                   | Normal distribution     | 1.00                   | 0.0068                   |
| Section height           | Normal distribution     | 1.00                   | 0.02                     |
| Section width            | Normal distribution     | 1.00                   | 0.02                     |
| Protective layer thickness| Normal distribution     | 0.85                   | 0.03                     |
| Reinforced bar diameter  | Normal distribution     | 1.00                   | 0.0175                   |
| Steel cross-sectional area| Normal distribution     | 1.00                   | 0.01                     |
| Concrete ultimate tensile strain| Normal distribution | 1.00                   | 0.25                     |
| Concrete Elastic Modulus| Normal distribution     | 1.00                   | 0.10                     |
| Steel elastic modulus    | Normal distribution     | 1.00                   | 0.06                     |
| Calculation mode uncertainty| Normal distribution   | 0.924                  | 0.8195                   |

In the calculation of the crack width of steel lined reinforced concrete pipe by using the above hydraulic code, the crack width of the axial-tensile member is calculated by using the negative condition [9]. At the same time, the average stress of the pipe circumferential reinforcement crack is calculated by the boiler formula, and the formula is as follows:

$$\sigma = \frac{Pr}{t}$$  \hspace{1cm} (10)

Where $\sigma$ is the tensile stress on the ring bar in MPa, in this paper $\sigma = \sigma_{sk}$; $P$ is the water pressure in the pipe in MPa; $r$ is the inner radius of the steel liner in mm; $t$ is the thickness of the steel liner in mm. The current hydraulic concrete structure design specifications cracks control standard reliability calculation and calibration. The concrete idea is as follows (1) According to the calculation formula of the crack width of the two specifications based on the principle that the calculated crack width value is equal to the crack width limit according to formula (1) ~ formula (3) or (4) and (10) the water pressure $P$ in steel-lined reinforced concrete pipe under the limit state is determined. (2) Using Monte-Carlo method combining the statistical distribution rules of each design parameter to generate $n$ random numbers of design parameters. (3) Calculate the limit of water pressure $P$ according to Dong Zheren formula (6) ~ formula (9) to generate $nZ$, find the number of times $Z < 0$, take the ratio of this number of times to the total times of simulated as failure probability thus the reliability index $\beta_w$ can be deduced.

4. Case study

4.1. Example and design parameters
Select the Three Gorges Hydropower Station 1:2 model, the Isa River 1:1 model Dongjiang prototype, Jinhuitian prototype, Lijiaxia prototype as the calculation object. The specific parameters are in Table 2.
Where \(t_0\) is the thickness of the steel lining in mm; \(t_i\) is the thickness of the hoop reinforcement in the \(i\)-th layer in mm; \(R_0\) is the radius of the pipe at the inner wall of the steel lining in mm; \(R_i\) is the radius of the \(i\)-th reinforcement relative to the pipe in mm; \(d_i\) and \(n_i\) distribution for the \(i\)-th layer of steel diameter and numbers; \(C\) is the thickness of the protective layer; \(E_s\) is the steel elastic modulus; \(E_c\) is the concrete elastic modulus; \(S\) is the spacing of steel bars along the axis of the pipe in mm; \(\theta\) is the central angle of the connecting area between the dam and the pipe section relative to the pipe axis. In order to analyze the reliability of the formula of crack width under different width limits. The crack limits under different environmental conditions were selected as the limit cracks which were 0.15 mm 0.2 mm 0.25 mm 0.3 mm and 0.4 mm.

**Table 2. Reliability calculation model parameters**

| parameter | Three Gorges 1:2 model | Isa River 1:1 model | Dongjiang prototype | Jinshuitan prototype | Li Jiaxia prototype |
|-----------|------------------------|---------------------|--------------------|----------------------|---------------------|
| \(t_0\)   | 16                     | 22                  | 16                 | 18                   | 24                  |
| \(R_0\)   | 3100                   | 500                 | 2600               | 2250                 | 4000                |
| \(R_1\)   | 3164                   | 564                 | 2800               | 2420                 | 4100                |
| \(R_2\)   | 3932                   | 861                 | 3000               | 3170                 | 4300                |
| \(R_3\)   | 4032                   | 4500                | 5200               |                      |                     |
| \(R_4\)   |                        |                     |                    |                      | 5400                |
| \(d_1\)   | 28                     | 28                  | 36                 | 32                   | 32                  |
| \(d_2\)   | 32                     | 32                  | 32                 | 25                   | 32                  |
| \(d_3\)   | 36                     | 36                  |                    | 25                   |                     |
| \(d_4\)   |                        |                     |                    |                      | 32                  |
| \(n_1\)   | 5                      | 9                   | 4                  | 5                    | 5                   |
| \(n_2\)   | 5                      | 8                   | 4                  | 5                    | 5                   |
| \(n_3\)   | 5                      |                     | 5                  |                      |                     |
| \(n_4\)   |                        |                     | 5                  |                      |                     |
| \(C\)     | 50                     | 50                  | 82                 | 67.5                 | 84                  |
| \(E_s\)   | 205                    | 207                 | 200                | 200                  | 200                 |
| \(E_c\)   | 29                     | 28                  | 29.44              | 28                   | 28                  |

4.2. Reliability Analysis

By using the established maximum random crack width model, the above case was simulated by MATLAB. The parameters of the component were taken as the parameters in Table 2 and the influence of different crack limits on the reliability index \(\beta_w\) was compared. Combining the five examples, the reliability is checked to be based on DL / T 5057-2009 and SL 191-2008 respectively. Figure 1 shows the results of two standard crack control standards under different crack width limits reliability index.

(1) For the same code, there are significant differences in the reliability indicators of crack control in the five cases. Taking DL / T 5057-2009 as an example, when the crack limit is 0.15mm, the reliable index corresponding to Dongjiang prototype is 2.5 higher than Jinshuitan Prototype.
(2) From the overall reliability level, when the crack width limit is 0.3mm, the mean value of the reliability standard of crack control obtained by DL/T 5057-2009 specification is 0.364 for five examples. The mean value of crack control standard reliability index obtained by SL191-2008 norms is 0.127; DL/T 5057-2009 standard crack control standards reliability index is slightly higher than SL191-2008 specifications. The target reliability index of the structural component under the serviceability limit states should be 0~1.5 according to the degree of reversibility. This shows that at present China's steel-lined reinforced concrete pressure pipe crack control standard safety level overall slightly lower but within the allowable range.

(3) DL/T 5057-2009 norms and SL191-2008 norms crack control reliability indicators are reduced with the crack limit increases. As the crack limit increases from 0.15mm to 0.4mm, it corresponds to 5 cases of Three Gorges Hydropower Station 1:2 model, Ixa River 1:1 model Dongjiang prototype, Jinhuitan prototype and Lijiaxia prototype. DL/T 5057-2009 standard crack control standard reliability index drop value was 0.804. SL191-2008 standard crack control standard reliability index drop values were 0.526. The main reason for the decrease of the reliability index is that: the stress of the steel is increasing with the increases of crack limit which leads to the increase of the internal water pressure and the possibility of the maximum crack width exceeding the limit.

5. Conclusion
According to the calculation formulas and parameters given in DL/T 5057-2009 and SL 191-2008 of the two hydraulic specifications, the Monte Carlo method and Dong Zheren crack width calculation formula was combined to establish a method of reliability calculation. Both specifications on the reliability of crack control standards were calculated and analyzed and compared. The main conclusions are as follows:

(1) When the crack limit is 0.3mm, the average value of cracks control standard reliability obtained by the DL/T 5057-2009 specification is 0.364; the average value of crack control standard reliability obtained by the specification of SL191-2008 is 0.127; the crack control standards reliability index calculated by DL/T 5057-2009 is slightly higher than by SL191-2008. At present, the reliability setting level of crack control for steel lined reinforced concrete pipe is overall slightly lower in China but in a allowable range.

(2) When the crack limit increases from 0.15 mm to 0.4 mm, the reliability index of crack control in both codes is decreasing. The decrease of reliability index of crack control in DL/T 5057-2009 is 0.804. The decrease of reliability of crack control in SL191-2008 is 0.526.

Acknowledgments
This work was financially supported by “Science and technology research projects for youth talent of Hubei Provincial Department of Education” (BSQD13043) and NSFC Natural Science Foundation of China (51508171). The author would like to express his gratitude to their support to current research.

References
[1] Yang Ping Shi Changzheng Wu Hegao.Effects of pipeline layout of gravity dam on seismic performance J. The Yangtze River 47(2016) 59-63, 96.
[2] Shi Changzheng Wu Hegao. Damage and bearing behavior of steel-lined reinforced concrete pipe downstream of dam face of hydropower station J. Journal of Tianjin University 47(2014) 1081-1087.
[3] NB / T35056-2015. Design Code for Penstock of Hydropower Station S. Beijing China Electric Power Press 2015.
[4] SL281-2003. Code for design of penstocks for hydropower stations S. Beijing China Electric Power Press 2003.
[5] DL / T 5057-2009. Code for Design of Hydraulic Concrete Structures S. Beijing National Energy Administration of the People's Republic of China 2009.
[6] SL / T 191-1996. Code for Design of Hydraulic Concrete Structures S. Beijing National Energy
Administration of the People's Republic of China 1996.

[7] SL 191-2008. Code for Design of Hydraulic Concrete Structures S. Beijing Ministry of Water Resources People's Republic of China 2008.

[8] Dong Zheren Dong Fuping Lu Yihui. Mathematical model of concrete crack width in steel-lined reinforced concrete penstock J. Hydraulic Power Generation 5(1996) 39 -42.

[9] Study on Crack Width of Steel-lined Reinforced Concrete Pipe Based on Test J. Water Resources and Hydropower 43(2017) 59-64.