

Research for different crack width calculation methods of concrete-lined steel pressure pipe

Chuang Xu¹ and Yang Li²

¹ Hubei University of Technology, Hubei Wuhan, 430068, China

² Hubei University of Technology, Hubei Wuhan, 430068, China

E-mail: 742653174@qq.com

Abstract. Based on a certain threshold to ensure the durability of structure, the concrete-lined steel pressure pipes used in the structure of large hydropower station widely are allowed to exist in concrete cracking under the action of a certain hydraulic pressure. According to the 1:2 large scale experiment model and the measured data of Three Gorges Hydro-power Station, the existing different methods for calculating crack width were compared and improvements and crack control measures were raised.

1. Introduction

Steel lined reinforced concrete penstock, as a new type of structure, first originated from the Former Soviet Union and was introduced into the structure of some large hydropower station in China since the late 1970 s, commonly known as “penstock on downstream dam surface”. Changing the traditional layout of penstock inside dam, this kind of structure adopted the new arrangement that the pressure pipelines are located on the downstream surface of concrete dam, and widely used in water diverting device of large hydropower station. With the gradually increasing of hydropower station scale, the diameter of the pressure piping is becoming bigger and bigger, even more than ten meters ^[1]. This kind of structure considering the joint bearing capacity of concrete and steel lining, greatly improves the mechanical behavior of structure. But the external concrete wall cracks easily under the action of a certain hydraulic pressure. In order to give full play to the mechanical properties of steel, it is generally allowed that the concrete cracks under a certain limit for crack width. The durability of pressure piping is related to the size of wall crack width. The crack width is so large that rainwater will seep into pipes to rust steel and the invasion of carbon dioxide in the air will cause concrete carbonation, which will reduce the durability of concrete and its service life ^[2]. Owing to the fact that the exceptional crack forms of steel lined reinforced concrete pressure pipeline are different from the general beam slab truss component, thus it is unreasonable that these formulas for calculating crack width, affirmed by the test of member structures, are applied to the pipeline by related criterion ^[3-5] and even if barely used, its calculation accuracy is poor. Therefore not a few academics study the cracking model and mechanical characteristics of penstock on downstream dam surface by scaling down the actual engineering model, and put forward more reasonable formulas ^[6-10] for calculating crack width. Although there are a lot of rationality hypothesis of these formulas, its calculation accuracy has been greatly increased.

2. The existing methods for calculating crack width



2.1. *The Method of Zhe-ren Dong* ^[6]

The Method of Zhe-ren Dong is to calculate the ring to the total length of steel lined reinforced concrete pipe with radial cracks firstly; After deducting the ring to the limiting deformation of concrete, and then finding the number of structural cracks, the average crack width W can be calculated; Then multiply W by the amplification coefficient β obtained from experimental data to get maximum crack width W_{\max} ; According to steel lined reinforced concrete pressure pipeline structure model test data of the Yisa river II hydropower station in Yunnan Province, the β can be taken as 1.3. This method, taking into account the circumferential deformation of structure, strain of concrete and deformation of reinforced, has a distinct physical concept. And it is practical that the method should minimize the error between the calculated value and the true value.

2.2. *The modified Method of Zhe-ren Dong (Semi-empirical Method)* ^[8]

On the basis of Zhe-ren Dong Method, three ideas were put forward to improve the method, and then it was put forward that the modified method called Semi-empirical Method for calculating crack width. According to Semi-empirical Method: 1. For the overhanging portion instead of the whole outer edge of the pipe is where deflection occurs, so the deformation of the part connected with dam body is not considered when radial crack widths are summed up. 2. When calculating the number of cracks, in the inner radius of the pipe, the cracks are less than actual ones; in the outer fringe radius, the number is more proper. 3. The amplification coefficient of crack width, concluded from the test of the structural model of ground pen-stock, made by reinforcement concrete with steel, of Yisa River II Hydro-power Station in Yunnan Province is not proper. While another amplification coefficient, concluded from the test of the large-scale pen-stock structure on downstream dam surface of Three Gorges Hydro-power Station, is this, $\beta=1.8$, which is more consistent with the actual one.

2.3. *The calculation method of the crack width established on the basis of stress and strain* ^[9-10] (Stress Method)

This formula of crack width derived from the basis of the stress and strain, is characterized by idealized concrete, and it thinks that the cracks are evenly spaced. And the formula also thinks that when the load increases, the quantity of crack is constant, only the width of the crack increases, and no new cracks appear. At center of the specimen, the average crack width W is equal to the difference of elongation between steel and concrete which lie between two cracks, and because of the tensile strain of concrete is very small, negligible. Due to uneven distribution of mass concrete, it will be impossible for crack spacing to keep equidistant completely, and taking into account the fact that the tensile deformation of concrete has a significant influence on steel strain. Therefore, regarded as the standard to measure if it exceeds allowable value, the maximum crack width is the double of average crack width.

2.4. *The method for calculating average crack width established on the basis of deformation compatibility* ^[11] (Integral Method)

Ignoring the deformation of concrete, on the basis of deformation compatibility, a scholar put forward the solving method of average crack width and found the function that can express the stress of steel bar $\sigma_{s,1}$ preferably. And the function is integral in math and accordant to the test data of the tensile steel stress, so the average crack width can be calculated by integral expression. Due to the fact that the cracks of pressure pipeline are radial distribution along the radial direction generally under the action of hydraulic pressure, so the steel stress is distributed in terms of trigonometric function in this case ^[12]. According to the large scale model experimental data of Yisa River II Hydro-power Station in Yunnan Province and the 1:2 scale model experimental data of Three Gorges Hydro-power Station, the amplification coefficient of maximum crack width take the average, about 1.35. For pressure piping equipped with multi-layer steel, this method can calculate the steel bar stress at any fracture cross-section layer and its corresponding crack width, but also reflects the reinforcement

stress, concrete cover thickness, steel protective layer thickness on the influence of crack width, and conforms to the general law.

3. Engineering illustration

Now through to the analysis of 1:2 large scale structure model, the steel lined reinforced concrete pressure pipeline of Three Gorges Hydro-power Station, the maximum crack width was measured. According to the above formulas for calculating crack width, the maximum crack width of outer pipeline was calculated, and the measured maximum crack width has been compared with the calculated.

3.1. The calculation condition ^[2]

The design value of hydraulic pressure $P = 1.21\text{MPa}$, the pipeline of inside radius $R = 3100\text{mm}$, the pipeline of outside radius $R' = 4100\text{mm}$, the axial length of pipe $L = 1000\text{m}$, the elastic modulus of concrete $E_c = 0.285 \times 10^5\text{MP}$, the elastic modulus of steel $E_s = 2.02 \times 10^5\text{MP}$, the standard value of concrete compressive strength $f_{tk} = 1.75\text{MPa}$. For steel disposition, see table 1.

Table 1. The steel disposition of 1:2 large scale structure model, the steel lined reinforced concrete penstock of Three Gorges Hydro-power Station.

	Steel disposition	A_{si}/mm^2	R_i/mm	Remark
i=0	The thickness, 16mm		3108	steel lining
i=1	5Φ28	3079	3164	The inner steel
i=2	5Φ32	4021	3932	middle layer reinforced
i=3	5Φ36	5090	4032	outer steel

3.2. The result of calculation

According to the above formulas for calculating crack width, different maximum crack widths of outer pipeline can be calculated and the calculated results with measured results are listed in table 2.

Table 2. The comparison between calculated value and measured by diverse formulas.

		ΣW	L_{cr}	W	β	W_{max}	Measured value W_{max}	The error of W_{max}
Zhe-ren Dong Method		11.7	408.91	0.289	1.3	0.377	0.27	39.5%
Semi-empirical Method		8.534	408.91	0.186	1.8	0.334	0.27	23.8%
Stress Method			676.28	0.323	2.0	0.646	0.27	139.1%
Integral Method			371.09	0.205	1.35	0.277	0.27	2.6%

Contrasting the calculated crack widths, which are by 4 different calculated methods, with the measured crack widths, it is obvious to see that the result calculated by the modified Zhe-ren Dong Formula confirms more to the actual width than the result by the original formula. There is a certain inaccuracy. So the formula needs to be further improved. The crack width calculated by the method based on stress and strain (Stress Method) has a huge margin of error compared with the measured width. It might relate to the assumptions---idealized concrete and evenly spaced crack width. So this formula needs to be improved a lot. From the chart, it can be seen that the crack width, calculated by the method for average crack width based on deformation compatibility (Integral Method) only has a 2.6% margin of error with measured one, almost the same. So the Integral Method is more suitable to

calculate crack width of concrete-lined steel pressure pipe.

3.3. Crack limits and controls

In [3] and [5], the different limits of crack width are set according to different environmental categories, and the maximum crack width should not exceed 0.3mm. In the actual project, the cracks of penstock on downstream dam surface are generally beyond the design limit. The reason is that the crack limits in the specification are calculated based on the beams and slabs and there are differences in the form and characteristics of the concrete-lined steel pressure pipe. The above experimental methods, based on the geometric scaling model of the actual construction of penstock on downstream dam surface, are proposed in the indoor experimental conditions based on the pipeline model. Compared with the crack width calculation formulas in the specification affirmed by the test of member structures, the above methods are more consistent with the measured situation. However, due to the indoor experimental conditions (such as working environment, load combination, construction quality, etc.) have a certain difference with the actual situation. In the calculation, the models are idealized, and the actual situations are supposed reasonably. In the calculation, the existing methods for calculating crack width are assumed that the pipeline is an axial force component, without considering the temperature effect, and the load is short-term load. In order to consider the influence of these factors and improve the calculation accuracy, an amplification factor is used to calculate the maximum crack width, so a certain deviation between the calculated result and the actual situation is reasonable.

From the analysis [13-16] of stress changes of steel lining, steel and concrete at all levels of loads, it can be concluded that the inner hydraulic pressure is mainly undertaken by steel lining before crack occurs. After deformation occurs from steel lining to the inner wall of concrete, the pressure is mainly undertaken by steel lining and outer-packed concrete. Before crack occurs, the stress of concrete decreases from inside to outside, and the stress of steel lining is the maximum. After crack occurs, the stress of the steel lining near cracks suddenly increases. Then inner water pressure is mainly undertaken by steel until it yields. The durability of structure depends on width of cracks and the width of cracks depends on the number of steel. Taking all factors into account, it is suggested to choose ordinary steel and reduce thickness of concrete cover appropriately. When the reinforcement ratio is equal, proper thinner steel can be selected to reduce the spacing of bars and ribbed bars can be used to improve bond performance. Such measures should be taken to reduce the width of crack. In addition, it is more important to raise the level of construction quality and take right structural measures to improve the cracking of structural components, and using the prestressed concrete structure can effectively reduce crack width. When total amount of steel is equal, adjustment of reinforcement method and enclosing of distribution of outer reinforcement can be done to control the maximum crack width.

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