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Concrete Creep Strain Monitoring and Analysis of Prestressed Hydraulic Tunnel

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Based on the actual engineering monitoring data, the concrete creep change during the operation period of the prestressed hydraulic tunnel is analyzed, and it’s calculated theoretically by using the existing concrete creep prediction model which has a wide range of application. The results of the study indicate that, within six months after the project enters the operating period, the strain changes generated by the concrete strain meter tend to be stable, and the strain increment at this time can be considered as the creep strain of the concrete. The calculation results of the CEB-FIP model can better match the measured results of the actual hydraulic tunnel structure. Therefore, in the absence of actual engineering data, the CEB-FIP model is recommended to analyze the creep effect of the hydraulic tunnel structure.

1. Introduction

The creep of concrete is an important parameter in the design of prestressed concrete structures and the analysis of prestressing effects. The problem of creep in prestressed concrete structures has always been the focus of scholars at home and abroad. In recent years, scholars have attempted to estimate the creep strain after the concrete structure has been put into service by establishing an ideal concrete creep prediction model. Yang (Yongqing et al., 2015) established a combined creep model for predicting creep of concrete under actual environmental temperature and humidity conditions based on the creep coefficient of concrete under constant temperature and humidity conditions, and found that the combined creep model gives results closer to the experimental results than the current creep models; Cao (Guohui et al., 2014) determined that the creep coefficient inside the concrete cylinder was smaller than the creep coefficient outside the concrete cylinder through long-term creep tests, and modified the CEB-FIP (1990) model according to the results of creep coefficient tests at different loading ages. (Xie et al., 2013) obtained the result that there was a large deviation between the experimental value and the predicted value of the model by simulating creep tests of early-age shotcrete under the construction environment. Therefore, for now, the concrete creep prediction models are still applied in the laboratory, due to limitation of certain laboratory conditions (such as temperature, relative humidity, small test pieces), and the different factors considered by models proposed by different researchers, the influence of the creep on the structures in actual projects cannot be completely simulated, the calculation results of the prediction model do not agree well with the actual situation, so each concrete creep prediction model needs to be verified by actual measured data in actual projects.

Although many important achievements have been made in the long-term monitoring of the structural creep of prestressed concrete hydraulic tunnels in China, Kang (Jingfu et al., 2013) analyzed the concrete creep of prestressed hydraulic tunnel structures only in the prestressed tensioning stage, and they found that the creep of the prestressed concrete in the tensioning stage is linear with the stress and the load-keeping time. However, it is worth noting that hydraulic tunnels are mainly used for water conveyance and drainage projects, the relative humidity of their working environment is over 90%, and the average temperature is 5-30°C. The hydraulic tunnel lining structure is large in size, which is very different from the laboratory conditions, and we haven’t seen any published literatures that applied concrete creep prediction models to hydraulic tunnels yet.

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Therefore, it is necessary to study prestressed hydraulic tunnels under humid conditions in combination with examples of domestic hydraulic tunnel projects to determine the concrete creep prediction model suitable for this structure.

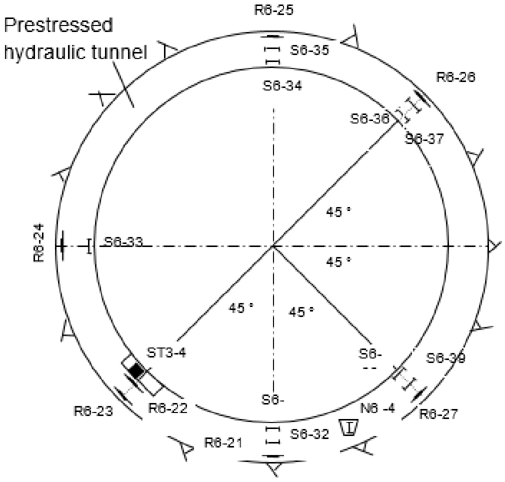

Figure 1: Lining structure and instrument layout of downstream observation section

Based on the measured data of a constructed prestressed hydraulic tunnel project, this paper studies the true response of hydraulic tunnel structures under the action of concrete creep in a humid environment according to the long-term system monitoring of the structural response during its operation period, which provides a reference for concrete creep calculations of similar projects in the future.

2. Overview of a constructed project

The Xiaolangdi sediment tunnel is the first hydraulic tunnel project in China to adopt unbonded prestressed concrete lining with circular anchored tendons. In order to study the mechanical properties and deformability of this new type of structure, not only a 1:1 structural model test was conducted before the start of construction, but also the steel stress meter, concrete strain meter, zero stress-strain meter and other permanent observation instruments are buried in three typical casting sections, aiming to understand the working performance of lining structures through a large amount of important data obtained from the construction phase to the operation phase of the Xiaolangdi sediment tunnel project. The prestressed concrete lining section has an inner diameter of 6.5 m and a lining thickness of 0.65 m. The prestressed concrete lining is casted in sections, the length of each section is 12.05m, and the anchor cable spacing is 0.5m. In each bundle, the cable anchor consists of 8 7Φ5 unbonded prestressed steel strands, which are placed in circles by double loops and fixed in the anchorage grooves. The standard strength of the steel strand is 1867 MPa and the nominal diameter is 15.7 mm. The anchorage groove is arranged in two rows alternately in the lower half circle, forming an angle of ±45° with the vertical center line of the lining. This paper selects the 3# sediment tunnel downstream (ST3-B) instrument observation section as the research object. The typical section form and instrument layout of the instrument observation section are shown as Figure 1, in which, S is a vibrating wire concrete strain meter, R is a steel stress meter, N is a zero stress-strain meter, and ST is an anchor cable dynamometer.

3. Monitoring results and analysis of creep strain of lining concrete of prestressed hydraulic tunnel

For the concrete strain meter buried in the Xiaolangdi sediment tunnel, its reading ε_s is composed of the instrument initial reading ε_{in}, concrete free strain ε_0, creep strain ε_c, and elastic strain ε_e, that is: $\varepsilon_s = \varepsilon_{in}+\varepsilon_0+\varepsilon_c+\varepsilon_e$. The free strain ε_0 of concrete can be directly read from the zero stress-strain meter. Due to the large amount of measured data, and for convenient visual analysis, only the concrete strain meter at the clock positions in the inner side of the middle section of the ST3-B instrument observation section are selected as representatives, and the strain curve after deducting the initial reading of the instrument ε_{in} is shown in Figure 2.

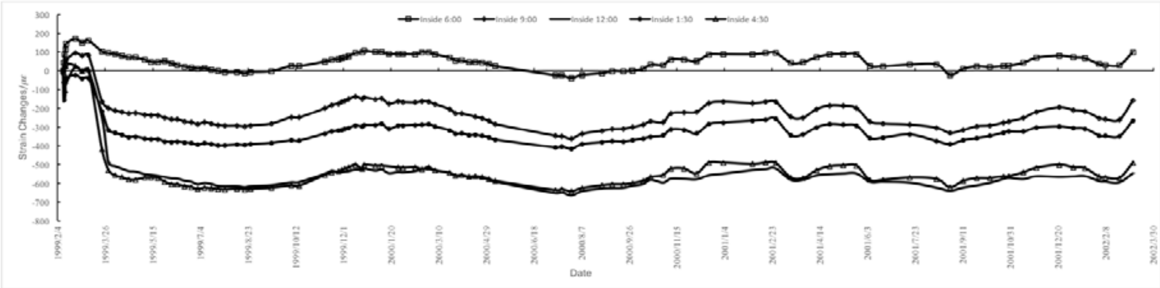

Figure 2: Strain change of concrete strain meters in ST3-B inner side

It can be clearly seen from Figure 2 that the change trend of each curve is basically the same, except that the strain change amplitude of each strain meter is different. The development rule of strain readings in the figure shows that the creep development of the lining concrete of the Xiaolangdi sediment tunnel takes about half a year after the tensioning of the anchor cable, and the compressive strain reading continuously increases, after that, basing on this, the strain reading varies with temperature and internal water pressure. According to the analysis, the continuous increase in strain readings may come from two aspects: first, generated by the grouting in the joints between the lining concrete and the surrounding rock increases the compressive strain to a certain extent, second, generated by the creep development of the concrete. From a conservative perspective, it is assumed that joint grouting is not considered to increase the compressive strain.
In order to obtain the measured data of creep strain, nearly one year's sample data of the Xiaolangdi sediment tunnel is selected from the beginning of the operation period until water entering the sediment tunnel, that is from March 24, 1999 to March 6, 2000. In this way, the influence of the internal water pressure on the concrete strain meter can be ignored. Then calculate the strain change of each concrete strain meter, and then subtract the free strain caused by temperature, humidity and other changes. Finally, the strain change of the sediment tunnel from the tensioning period until entering the operation period is obtained. The actual measured data of the concrete strain meter in the inner side of the lining at 1:30 clock position direction is taken as an example for calculation. The calculation results are shown in Table 1.

Table 1: Strain changes of lining concrete and anchor cables during operation period

		S6-36					ST3-4	
Observation Date	Days of After Pulling	Strain Changes /με	Elastic Strain /με	Loss of Prestress /με	Creep /με	Creep Coefficient	Strain Changes /με	Percentage of Prestress Loss of Cable/%
1999/3/23	0	-331.9	-285.9	0.0	0.0	0.076	-530.9	100.0
1999/3/24	1	-324.4	-275.2	10.7	-25.0	0.091	19.8	-3.7
1999/3/25	2	-326.4	-274.1	11.8	-28.1	0.103	22.0	-4.1
1999/3/26	3	-327.2	-273.3	12.6	-29.7	0.109	23.4	-4.4
1999/3/29	6	-355.6	-271.4	14.5	-60.0	0.221	26.9	-5.1
1999/4/12	20	-374.0	-268.1	17.8	-81.7	0.305	33.0	-6.2
1999/4/26	34	-382.0	-267.1	18.8	-88.9	0.333	35.0	-6.6
1999/5/6	44	-387.5	-266.2	19.7	-94.1	0.353	36.5	-6.9
1999/5/20	58	-387.0	-265.3	20.6	-93.3	0.352	38.2	-7.2
1999/11/11	233	-361.3	-250.6	35.3	-115.5	0.461	65.5	-12.3
1999/12/22	274	-346.0	-257.1	28.8	-96.6	0.375	53.4	-10.1
2000/1/17	300	-370.4	-263.9	22.0	-115.4	0.437	40.8	-7.7
2000/3/6	349	-369.2	-262.4	23.5	-131.9	0.503	43.6	-8.2

The strain change of the concrete strain meter in Table 1 is the strain after deducting the initial reading of the strain meter and the free strain, that is: $\varepsilon_c+\varepsilon_e=\varepsilon_s-\varepsilon_{in}-\varepsilon_0$ (after the data of the concrete strain meter of the same section is sorted, draw them in Figure 3). The value of the elastic strain is determined based on the percentage of prestress loss of the anchor cable. Through the analysis of Table 1, it can be seen that the strain change of the lining concrete in nearly one year after the completion of tensioning of the anchor cable is mainly due to creep. The creep strain of lining concrete increases rapidly with time, it is especially obvious on the first day, and gradually stabilized after one month. At the same time, the prestress loss of the anchor cable increases with time, which means that the effective prestress of the anchor cable gradually reduces, the change law is similar to the creep change of the lining concrete, the change is most obvious on the first day, after one month, the effective prestress of the anchor cable tends to be stable.

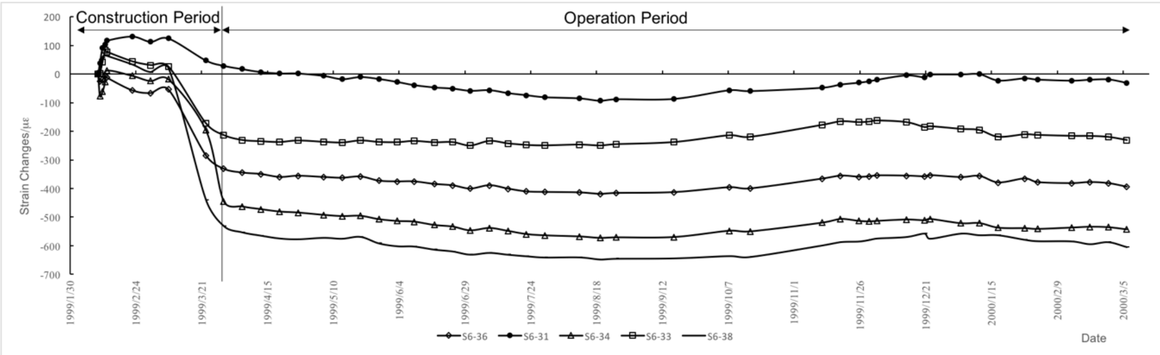

Figure 3: Change of readings of concrete strain meters in the inner side of ST-3B end

From Figure 3, it can be clearly seen that the strain change trend of the concrete strain meters in the same section is basically the same, but the strain change amplitude of each instrument is different. Moreover, since the Xiaolangdi sediment tunnel entered into the operation period, the strain change still has a tendency to increase in the first half of the year. The strain has increased rapidly at the beginning, and then stabilized slowly and smoothly into a straight line. Since the effects of temperature and internal water have been eliminated, it can be conservatively considered that the strain increment at this time is the creep strain of the concrete.

4. Concrete creep prediction model and analysis

At present, domestic and foreign experts have put forward many concrete creep prediction models, among which the CEB-FIP series model, ACI series model, BP series model, BS series model, and GL2000 model have great influences and are widely used. Literatures conducted detailed evaluation and verification of the above several prediction models, the results show that, from the view of calculation accuracy, the B3 model and GL2000 model have the most accurate predictions of creep, followed by the CEB-FIP (1990) model. The accuracy of the ACI209 model is the lowest; in addition, the GL2000, CEB-FIP (1990), and B3 models are more prominent in the uniformity of the distribution of model prediction results. However, the calculation of the B3 model is quite complicated, so its application in practical engineering is limited. Therefore, this paper will use GL2000 model and CEB-FIP (1990) model to analyze the creep effect of the prestressed hydraulic tunnel, the formulas for the creep coefficient of the two models are as follows:
(1) Formula for the creep coefficient of the GL2000 model:

$$\phi(t,t_0)=\frac{1}{E_{cmt0}}+\frac{\phi_{28}}{E_{cm28}}; \quad (1)$$

$$\phi_{28}=\phi(t_c)\left[2\left(\frac{(t-t_0)^{0.3}}{(t-t_0)^{0.3}+14}\right)+\left(\frac{7}{t_0}\right)^{0.5}\left(\frac{t-t_0}{t-t_0+7}\right)^{0.5}+2.5(1-1.086h^2)\left(\frac{t-t_0}{t-t_0+0.15(V/S)^2}\right)^{0.5}\right]; \quad (2)$$

(2) Formula for the creep coefficient of the CEB-FIP (1990) Model:

$$\phi(t,t_0)=\phi_0\beta_c(t-t_0); \quad (3)$$

$$\phi_0=\phi_{RH}\beta(f_{cm})\beta(t_0); \quad (4)$$

$$\beta_c(t-t_0)=\left[\frac{(t-t_0)/t_1}{\beta_H+(t-t_0)/t_1}\right]^{0.3}; \quad (5)$$

$$\phi_{RH}=1+\frac{1-RH/RH_0}{0.46(h/h_0)^{\frac{1}{3}}}; \quad (6)$$

$$\beta(f_{cm})=\frac{5.3}{(f_{cm}/f_{cm0})^{0.5}}; \quad (7)$$

$$\beta(t_0)=\frac{1}{0.1+(t_0/t_1)^{0.2}}; \quad (8)$$

$$\beta_H = 150\left[1+\left(1.2\frac{RH}{RH_0}\right)^{18}\right]\frac{h}{h_0}+250 \leq 1500. \quad (9)$$

Where: $\phi(t, t_0)$ is the concrete creep coefficient when the age of loading is t_0, and the calculation considers the age to be t; $\phi_0(\phi_{28})$ is the nominal creep coefficient; $\phi(t_c)$ is the drying reduction coefficient before the loading, where t_c is the drying age (d), takes 28d; volume surface ratio V/S takes 682.5mm; E_{cm28} is the elastic modulus of the concrete when the age is 8d, takes 32500Mpa; E_{cmt0} is the elastic modulus (Mpa) when the loading age is t_0; t is the age of the concrete (d) at the time of calculation; t_0 is the age of the concrete at loading (d), takes 36d; RH [same as h in formula (2)] is the average annual relative humidity of the environment, takes 0.96; β_c is the creep development coefficient with time after loading; in formula (6) h is the theoretical thickness of the component (mm), takes 1430mm, h_0 takes 100mm; RH_0 takes 100%; f_{cm} is the average cubic compressive strength (Mpa) of concrete with intensity level of C20-C50 at the age of 28d, $f_{cm}=0.8f_{cu,k}+8$Mpa, where $f_{cu,k}$ is the compressive strength standard value (Mpa) of concrete cubes with age of 28d and a guarantee rate of 95%, takes 40.1Mpa; f_{cm0} takes 10Mpa; t_1 takes 1d.
The creep coefficient of the measured data is based on the definition of the CEB-FIP standard specification, i.e., creep coefficient = creep strain/elastic strain, and the calculation process is the same as Table 1. Because the hydraulic tunnel is different from the buildings in the natural environment, its relative humidity is larger, therefore, when building a model, the relative humidity takes an annual average of 96%. Other parameters of each model are taken from relevant parameters of the Xiaolangdi sediment tunnel. The above two kinds of concrete creep prediction models are used for calculation, and the calculation results are shown in Figure 4.

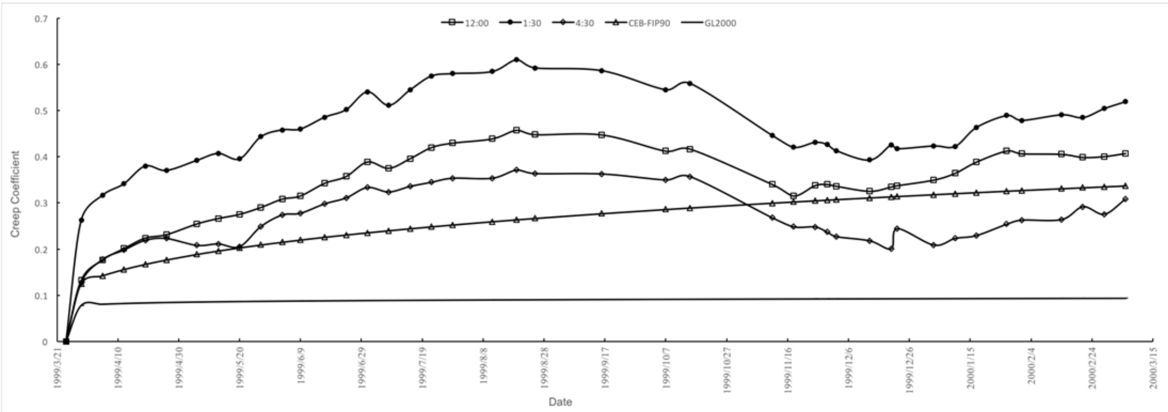

Figure 4: Comparison of creep coefficient of ST3-B concrete

It can be seen from Figure 4 that the theoretical creep coefficient calculated by the CEB-FIP model and the GL2000 model can basically reflect the creep course of the hydraulic tunnel in a humid environment. Although the GL2000 model has a higher calculation accuracy, the theoretical values calculated by it is larger than the actual measured values. In comparison, the calculated results of the CEB-FIP model agree well with the measured values, and the general errors do not exceed 30%, indicating that the temperature, humidity, and other factors considered in this paper can be better applied to the creep analysis of hydraulic tunnels in a humid environment. However, the error of the creep coefficient measured by the instrument in the direction of 1:30 of the inner side of the lining is the greatest, which may be due to the fact that the temperature history and construction deviations considered in this paper fail to reflect the actual situation. Therefore, in the absence of actual data, CEB-FIP model is recommended to analyze the creep effect of hydraulic tunnel structures.

5. Conclusions

(1) After Xiaolangdi 3# sediment tunnel entered the operation period for six months, the strain change generated by the concrete strain meter tends to be stable, and the strain increment at this time can be considered as the concrete creep strain.
(2) The CEB-FIP model and the GL2000 model can basically reflect the creep course of hydraulic tunnels in a humid environment. In contrast, the CEB-FIP model can better reflect the true response of the hydraulic tunnel

structure under the influence of creep, therefore, in the absence of actual engineering data, the CEB-FIP model is recommended for the analysis of the creep effect of hydraulic tunnel structures.

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