Deformation Monitoring Indexes of High Concrete Arch Dam Considering Time-varying Effect

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Abstract. Deformation is the most intuitive reflection of comprehensive behavior of concrete dams, and it is of great significance to determine the deformation monitoring indexes for dam abnormality identifying. In this paper, deformation monitoring indexes of arch dam were determined in the form of causal components, and the time-varying effect caused by the degradation of dam material properties was considered. The hydraulic component in monitoring index was determined into three grades by water density overloading method, and the appearances of dam heel yield depth coming up to the curtain axis, the catastrophes of dam body yield volume ratio and dam radial displacement, were respectively taken as the abnormal symbols. The temperature component was determined for two operation conditions, with respect to the measured high and low temperature periods. As for the time effect component, it was initially calculated by FEM with the environmental damage-considered rheological constitutive models, and fitted by the combination of exponential function and periodic function. A case study was performed to give more detailed introductions for determining the proposed deformation monitoring indexes. Research results show that the components of temperature and time-effect occupy a large proportion in monitoring index of arch dams.

1. Introduction
Dam safety behaviors are usually monitored by various types of instrument. To ensure dam safety, it is necessary to timely detect and analyze dam abnormal symptoms according to the monitoring data, in which monitoring quantity should not exceed its allowable value, namely, the monitoring index. The frequently used methods for determining monitoring index are confidence interval method, typical low probability method and structural analysis method [1]. The confidence interval method is based on monitoring models, such as the statistical model, hybrid model, deterministic model and artificial intelligence algorithm-integrated machine learning model [2-5]. Among these models, the HST (hydraulic, seasonal, time effect) causal factors-based statistical model and hybrid model, as well as artificial intelligence models with HST factors as system input, such as the support vector machine (SVM) and the artificial neural network (ANN), etc., are most classical and frequently used in practical engineering [6-7]. The reliability of monitoring index obtained by the typical low probability method mainly depends on the selected subsample. As for the frequently used subsample of annual extreme value series, it will result in fewer sampling samples when the monitoring data year is shorter, and other larger values in a year are neglected. To overcome this problem, Su et al. [8] determined the larger values, which exceed a certain threshold in the measured time series, as subsample. Gu and Wang [9] took the time effect component separated by monitoring models as warning information, and deformation monitoring index for dam instability was determined at its catastrophe moment. Lei et al.
[10] established the overall deformation entropy monitoring index for the spatial displacement field of high concrete arch dams. However, these two methods are all based on mathematical statistic, the reliability of determined monitoring indexes seriously depends on the load information contained in the existing monitoring data. Thus, these monitoring indexes can only be used to judge whether the measured deformation is normal or not, rather than make a reasonable judgment on the safety condition of dam structure.

The physical concept of deformation monitoring index determined by the structural analysis method is clear, but its reliability mainly depends on the simulation of critical state during dam failure. Numerical simulation at present are commonly conducted by the finite element method (FEM) and the discontinuous deformation method (DDA), etc., with implement measures of strength reduction and overloading [11-13]. However, during the long-term operation of concrete dams, the degradation of material properties will affect dam resistance ability to deformation, so that dam deformation abnormal symptoms and the development law of time effect deformation may also change. Therefore, the time-varying effect caused by the degradation of dam material properties should be taken into account when determining the deformation monitoring index of arch dams. Aiming at this problem, based on the structural analysis method and mathematical model theory, a time-varying effect-considered three grade monitoring indexes determination method for concrete arch dams was proposed in this paper.

2. Deformation behavior and abnormal symbols of high concrete arch dams

Geo-mechanical model tests of some high arch dams in China show that the failure of arch dams with good geological conditions are mainly caused by the large distribution of tension cracking or compression-shear yielding of dam concrete [12-13]. During the progressive failure process, dam heel cracks firstly under the tension action, and tension cracking zones increase with the development of dam load. These cracks further lead to the compression-shear yielding of dam concrete at the middle and low elevation parts of dam body, especially the dam toe. Then, concrete cracking or yielding zones expand from foundation plane to the upper part of dam body, so that the successive appearances of horizontal and vertical cracks, which finally weaken the beam effect and arch effect of arch dams, respectively. Dam concrete yield zones gradually penetrate to the whole dam body, and it leads to the dam failure eventually.

![Displacement vs. Load](image)

Figure 1. Deformation variation characteristics of concrete arch dam.

Dam structural behavior in the aforementioned progressive failure process can be roughly divided into three stages of elastic, elastic-plastic and instability failure, as shown in figure 1. (1) Elastic stage of OB: during this stage, the upstream faces of dam heel and arch abutment crack locally, and the adjustment of dam stress field leads to the increase of compressive stress on the downstream faces of dam toe and arch abutment. Before the critical point of B, dam deformation basically maintains a linear relationship with the load, and dam body maybe in a complete elastic working stage for some cases. (2) Yield deformation stage of BC: with the increase of dam load, compressive stress increases significantly at the downstream dam body and leads these areas into yielding stage, so that dam deformation and load no longer maintain a linear relationship. (3) Failure stage of CD: if dam load exceeds a certain extent, the cracking zone, crushing zone and yield zone of dam body, and dam
deformation, develop sharply. Meanwhile, according to the implementation rules of concrete dam safety inspection, dam safety statuses are divided into three categories of normal, abnormal and dangerous. Therefore, monitoring indexes of arch dams can be determined into three grades, with respect to the aforementioned three safety statuses.

From the causal perspective, deformation of concrete dams can be mainly attributed to three aspects of hydraulic pressure, temperature and time effect. The deformation caused by hydrostatic pressure usually accounts for a larger proportion. Meanwhile, tremendous hydrodynamic pressure will be generated when dam subjects to earthquake and reservoir bank landslide. Thus, to obtain the aforementioned three abnormal characteristic points, the nonlinear relationship between dam deformation and load can be studied by increasing the hydrostatic pressure. The temperature load of arch dam varies with the annual periodic cycle of air temperature, and the annual temperature extremes are basically the same. Considering the inconsistency of dam deformation direction in temperature rising stage and dropping stage, the temperature deformation component in monitoring index should be determined in two conditions, with respect to the highest and lowest dam temperature field, respectively. As for the time effect deformation, its irrecoverable and recoverable items vary with dam service time and load, respectively. Thus, it is better to use the viscoelastic-plastic FEM to simulate the time effect deformation under dam actual operation condition, and then its monitoring index can be determined according to the fitted time function of the simulated value. Therefore, two additive models in the form of causal components were established as shown in equations (1) and (2), and according to these models, three grade monitoring indexes for dam later operation stage can be determined.

For high temperature period:

\[
\begin{align*}
\delta_{iH} &= \delta_{iH}^1 + \delta_{T_{\text{max}}} + C \left[ 1 - e^{-rt} \right] + \sum_{i=t}^{n} D_i \sin \left( \frac{2\pi it}{365} \right) + K_i \cos \left( \frac{2\pi it}{365} \right) \\
\delta_{sH} &= \delta_{sH}^1 + \delta_{T_{\text{max}}} + C \left[ 1 - e^{-rt} \right] + \sum_{i=t}^{n} D_i \sin \left( \frac{2\pi it}{365} \right) + K_i \cos \left( \frac{2\pi it}{365} \right)
\end{align*}
\]

For low temperature period:

\[
\begin{align*}
\delta_{iL} &= \delta_{iL}^1 + \delta_{T_{\text{min}}} + C \left[ 1 - e^{-rt} \right] + \sum_{i=t}^{n} D_i \sin \left( \frac{2\pi it}{365} \right) + K_i \cos \left( \frac{2\pi it}{365} \right) \\
\delta_{sL} &= \delta_{sL}^1 + \delta_{T_{\text{min}}} + C \left[ 1 - e^{-rt} \right] + \sum_{i=t}^{n} D_i \sin \left( \frac{2\pi it}{365} \right) + K_i \cos \left( \frac{2\pi it}{365} \right)
\end{align*}
\]

Where \( \delta_{iH}, \delta_{sH}, \text{ and } \delta_{sL} \) are the first, second and third grade of deformation monitoring indexes. \( \delta_{T_{\text{max}}} \), \( \delta_{T_{\text{min}}} \) are hydraulic deformations with respect to the three characteristic points as shown in figure 1. The \( \delta_{T_{\text{max}}} \) and \( \delta_{T_{\text{min}}} \) are temperature deformations with respect to the highest and lowest temperature field of arch dam body. \( C, r, D_i \) and \( K_i \) are fitting coefficients in the FEM calculated time effect deformation of \( \delta_{tC} \).

3. Determination methods for time-varying effect-considered deformation monitoring index

To obtain the relationship between dam deformation and load as shown in figure 1, it is necessary to simulate the progressive failure process of arch dams, and it is commonly conducted by increasing water density. According to the current Chinese specifications for seismic design of hydraulic structures marked as NB 35047-2015 [14], a gravity dam section of unit width, with the maximum dam height of 160 m, was taken as an example, and the earthquake hydrodynamic pressure and inertial force were calculated as shown in table 1. As can be seen, the equivalent water density overloading coefficient, \( k \), comes up to 1.73 when the peak acceleration of earthquakes reaches to 0.56 g (the design earthquake peak acceleration of Dagangshan arch dam in China). As for the actual situation, extreme external loads caused by strong earthquakes or landslides may be more serious than this.
Table 1. Equivalent water density overloading coefficients of a 160 m high gravity dam.

| Peak acceleration of earthquakes | 0.1g | 0.2g | 0.4g | 0.56g |
|----------------------------------|------|------|------|-------|
| Static water pressure of upstream $P_s$ ($10^7$ N) | 11.6 |      |      |       |
| Earthquake hydrodynamic pressure $P_{th}$ ($10^7$ N) | 0.38 | 0.76 | 1.51 | 2.12  |
| Earthquake inertial force $P_{Dg}$ ($10^7$ N) | 1.13 | 2.26 | 4.51 | 6.32  |
| Overloading coefficient of water density $k = \frac{(P_s + P_{th} + P_{Dg})}{P_s}$ | 1.13 | 1.26 | 1.52 | 1.73  |

$a g$ is the gravitational acceleration, and the normal water depth of upstream reservoir is 154 m.

According to the typical characteristics in the progressive failure of arch dams, three key control standards were put forward by some researchers [12]. The first standard, $k_1$, is used for curtain safety control, and defined as the water density overloading coefficient when plastic yield zone of crown cantilever dam heel extends to the curtain axis. The second control standard, $k_2$, is used for structure abnormality identification, and defined as the overloading coefficient when the yield volume of dam body concrete increases abruptly. The last standard, $k_3$, is defined with respect to the limit failure state of arch dams, and determined at the catastrophe moment of dam displacement. Thus, according to these three control standards, the hydraulic components of $\delta_{th}$, $\delta_{th}$ and $\delta_{th}$ in the three grade deformation monitoring indexes can be determined.

Based on the aforementioned analyses, to determine the deformation monitoring index of arch dams and consider the dam material property degradation-induced time-varying effect, the determination process can be implemented as follows:

Step 1: According to dam recent deformation monitoring data, invert the equivalent elastic modulus, $E_i$, of dam concrete and foundation rock. Then, the damage degree, $D$, can be represented as follows:

$$D = \frac{E_0 - E_i}{E_0} \quad (3)$$

Where $E_0$ is the initial elastic modulus.

Step 2: Conduct the three dimensional elasto-plastic FEM overloading simulation. During this process, the required mechanical parameters of cohesion and friction angle should be respectively adjusted as $c_i = (1 - D)c_0$ and $\varphi_i = (1 - D)\varphi_0$, where $c_0$ and $\varphi_0$ are their initial values. Then, dam deformations, with respect to the aforementioned three control standards of $k_1$, $k_2$ and $k_3$, can be determined as the hydraulic components of $\delta_{th}$, $\delta_{th}$ and $\delta_{th}$.

Step 3: As for the temperature component, the highest and lowest temperature field of arch dam body should be firstly obtained according to the measured value of dam body thermometers, and the $\delta_{t_{\text{max}}}$ and $\delta_{t_{\text{min}}}$ in deformation monitoring index are respectively calculated with respect to these two temperature loads by FEM.

Step 4: Use the environmental damage-considered rheological constitutive model of dam concrete and foundation rock as shown in figure 2, calculate the time effect deformation of arch dam under the actual load condition [15]. Then, fit the calculated time series with the combination of exponential function and periodic function, and this fitting function can be determined as the time effect component in equations (1) and (2).

![Figure 2](image_url)

Figure 2. The environmental damage-considered rheological constitutive models.

A flow chart for determining the time-varying effect-considered deformation monitoring indexes of high concrete arch dams is shown in figure 3.
Establishing the FEM model of high concrete dam

Determining the monitoring indexes for dam different safety grades

Conducting the inversion analysis of the equivalent elastic modulus of dam concrete and foundation rock, and calculating the damage degree

FEM simulation

The measured high and low temperature field of dam body

Hydraulic component

Time-effect component

Viscoelastic or viscoelastic-plastic rheological constitutive model

Water density overloading method

Dam safety evaluation indicator \( k_1, k_2, k_3 \)

Fig. 3. Flow chart of determining monitoring index for arch dams considering time-varying effect.

4. Case study

The Xiaowan arch dam is located on Lancangjiang River of Yunnan Province, China. The maximum dam height is 294.5 m. After the completion of dam concrete pouring and transverse joints grouting in June, 2010, dam reservoir began to store water from the elevation of 1166 m to 1240 m. The FEM model is shown in figure 4.

According to the measured data of dam radial displacement during the water storage period, inversion analysis of the equivalent elastic modulus of dam concrete has been conducted firstly through the hybrid monitoring model, with a result of 27.2 GPa, which is close to its design value. Therefore, mechanical parameters of cohesion and friction angle used in the FEM overloading simulation are taken as their design values.

The overloading simulation process was implemented after the initial simulation of dam concrete pouring and reservoir water impoundment. To obtain the curtain safety control standard, \( k_1 \), the overloading process with the coefficient between 1.0 and 2.0 was simulated with an interval of 0.2 times of water density. After that, the water density interval was defined as 0.5 times. When the...
overloading coefficient, $k$, came up to 8.5, the FEM simulation was not converged. The relationship between the relative yield depth of crown cantilever dam heel and overloading coefficient is shown in figure 5. As can be seen, the yield zone of dam heel reaches the centerline of impervious curtain when $k = 1.4$, with a relative depth of 31%. Thus, the curtain safety control standard, $k_1$, of Xiaowan arch dam is determined as 1.4.

![Figure 5. Relationship between dam heel relative yield depth and overloading coefficient.](image)

The relationship between yield volume ratio of dam body and overloading coefficient is shown in figure 6. It can be seen that the yield volume ratio increases abruptly when the overloading coefficient is more than 2.0, so that the structure abnormality control standard, $k_2$, for this dam is determined as 2.0.

![Figure 6. Relationship between dam yield volume ratio and overloading coefficient.](image)

The relationship between radial displacement at different elevations of crown cantilever and overloading coefficient is shown in figure 7, and evolution laws of other dam sections are basically the same. As can be seen, dam displacements are basically linear with overloading coefficient before it reaches 4.0, and increase nonlinearly after that. Therefore, the limit state control standard for dam failure is determined as 4.0.

![Figure 7. Relationship between radial displacement of crown cantilever and overloading coefficient.](image)

Based on the aforementioned analyses, three control standards were determined for this arch dam,
with the water density overloading coefficients of 1.4, 2.0 and 4.0, respectively. As for the crest of crown cantilever dam section marked as 22#, the hydraulic components in three grade monitoring indexes of dam radial displacement are 23.2 cm, 33.9 cm and 83.3 cm, respectively.

According to the measured values of thermometers embedded at different elevations of dam body, the current temperature loads, corresponding to the joint closure temperature, were calculated as shown in table 2. It can be seen that the average temperature changes at high and low temperature periods are all positive, indicating that dam body is in an overall state of temperature rise. Reasons are that dam concrete is still hydrated and the heat dissipation is not over yet. Then, temperature deformations with respect to these two loads were calculated by FEM. For the crest of 22# dam section, the radial displacements are -5.3 cm and -4.0 cm at high and low temperature periods, respectively.

Table 2. The measured temperature loads of Xiaowan arch dam (unit: °C).

| Elevation (m) | 1245 | 1210 | 1170 | 1130 | 1090 | 1050 | 1010 | 970 | 965 | 950.5 |
|--------------|------|------|------|------|------|------|------|-----|-----|-------|
| Average temperature change | High | 6.91 | 7.17 | 7.63 | 5.8  | 6.69 | 9.56 | 9.66 | 8.34 | 8.45  | 8.98  |
| Low          | 6.43 | 5.92 | 5.83 | 5.21 | 5.84 | 8.81 | 9.28 | 8.31 | 8.37 | 8.75  |
| Equivalent linear temperature difference | High | 1.05 | 4.51 | 7.14 | 9.53 | 10.28 | 7.12 | 2.27 | -1.38 | -1.84  | -2.57  |
| Low          | 1.63 | 1.18 | 3.72 | 8.77 | 8.78 | 3.75 | 1.56 | -0.93 | -1.39 | -2.05  |

This dam was designed with an annual regulation reservoir. Thus, after the first impoundment to the normal water level of 1240 m, the later upstream reservoir water level was assumed to be annually recycled between 1240 m and 1180 m (the dead water level). The FEM calculated time series of radial time effect displacement at the crest of 22# dam section is shown in figure 8. Then, it was fitted by the combination of exponential function and periodic function as follows:

\[
\delta_t = 2.46 \left(1 - e^{-0.0035t}\right) + 0.16\sin \frac{2\pi t}{365} - 0.82\cos \frac{2\pi t}{365}
\]

Figure 8. Time series of radial time effect displacement at the crest of 22# dam section.

Based on the form of causal components, the three grade monitoring indexes of radial displacement at the crest of 22# dam section were determined by the accumulation of their hydraulic component, temperature component and time effect component, as shown in table 3. It must be noted that these indexes were determined with respect to the current physical and mechanical parameters and the measured temperature field, so it should be adjusted regularly according to the changes of dam later actual operation conditions.

Table 3. Monitoring indexes of crest radial displacement of 22# dam section (Unit: cm).

| Grade | Hydraulic component | Temperature component | Time effect component | Monitoring index |
|-------|---------------------|-----------------------|----------------------|------------------|
|       |                     | high                  | low                  | high             | low             |
| \(\delta_1\) | 23.2                |                       |                      | 17.9 + \(\delta_0\) | 19.2 + \(\delta_0\) |
| \(\delta_2\) | 33.9                | -5.3                  | -4.0                 | 28.6 + \(\delta_0\) | 29.9 + \(\delta_0\) |
| \(\delta_3\) | 83.3                |                       |                      | 78.0 + \(\delta_0\) | 79.3 + \(\delta_0\) |
5. Conclusion
Aiming at the time-varying effect caused by the degradation of material properties during the long-term operation of arch dams, based on the structural analysis method and mathematical model theory, a time-varying effect-considered three grade monitoring indexes determination method for concrete arch dams was proposed in this paper. The following conclusions are drawn:

1) The appearance of dam heel yield depth coming up to the curtain axis, and the catastrophes of dam body yield volume ratio and dam displacement, can better represent the progressive failure characteristics of arch dam, and are in accord with the mechanical definition of critical failure states for monitoring indexes of concrete arch dams.

2) The temperature component and time effect component account for a large proportion in deformation monitoring index. The proposed causal components-represented monitoring index can better adapt to dam different service conditions, and is beneficial to improve its accuracy. It is recommended that these monitoring indexes should be adjusted regularly according to the changes of dam later actual operation conditions.

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