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Displacement aging component-based stability analysis for the concrete dam

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Abstract. The displacement monitoring data series reconstruction method was developed under equal water level effects based on displacement monitoring data of concrete dams. A dam displacement variation equation was set up under the action of temperature and aging factors by optimized analysis techniques and then the dam displacement hydraulic pressure components can be separated. Through the dynamic adjustment of temperature and aging effect factors, the aging component isolation method of dam displacement was developed. Utilizing the isolated dam displacement aging components, the dam stability model was established. Then, the dam stability criterion was put forward based on convergence and divergence of dam displacement aging components and catastrophe theory. The validity of the proposed method was finally verified combined with the case study.

Keywords: concrete dam; monitoring data; displacement effect factor separation; displacement aging component; stability model and criterion

1. Introduction

Concrete Dam is the most widely used dam type so far and there is great development in terms of dam design and construction through practice and research (Zhu *et al*. 2010, Terzi *et al*. 2015, Yang *et al*. 2015a, Roes *et al*. 1972, Yang *et al*. 2015). Dam safety relates to the people's livelihood and the government of every country attaches great importance to the safety of hydraulic structures (Gu *et al*. 2011, Yang *et al*. 2015b, Hong *et al*. 2014, Ji *et al*. 2014, Xue *et al*. 2014). A great number of valuable results have been obtained through the study of the dam safety monitoring theory and method (Lin *et al*. 2014a, Sevim *et al*. 2012, Arefian *et al*. 2016, Akpinar *et al*. 2014, Lotfi *et al*. 2012). Currently, the relevant concrete dam stability analysis mainly uses structural analysis method or model experiments to evaluate the stability of the dam. However, the method of structural analysis (Ren *et al*. 2007, Zhu *et al*. 2014, Chen *et al*. 2016, François *et al*. 2015) of dam stability analysis is performed under certain presuppositions (Lin *et al*. 2014b, Zhang *et al*. 2016) such as the rigid limit equilibrium method, which is inconsistent with the actual situation (Li *et al*. 2013, Zhang *et al*. 2010, Papaleontiou *et al*. 2012, Pehlivan *et al*. 2016). Model experiments also need more improvements with long operating time and high costs. A great number of deformation, seepage and stress monitoring facilities (Ling *et al*. 2013) are arranged on dams for dam safety monitoring which plays a very important role to monitor the dam behavior (Wang *et al*. 2013, Khazaee *et al*. 2014, Abdulrazeg *et al*. 2013, Yang *et al.* 2017). But the ideal method has not been discovered to analyze the stability of the concrete dam utilizing the information obtained from these monitoring instruments and facilities. The aim of this paper is to propose the method of concrete dam stability analysis based on displacement monitoring data which comprehensively reflects structural change behaviors of concrete dam. The main step is that firstly isolate hydraulic components and aging components from dam displacement and then determine the dam stability by the isolated aging displacement. The engineering example verifies the effectiveness of the proposed method.

2. Isolation method of concrete dam displacement hydraulic pressure component δ(H)

A dam and its foundation producing a displacement vector $\vec{\delta}$ at any point could be decomposed into three components along the x, y, z direction in the Cartesian coordinates under water depth *H*, variable temperature *T* and other loads, that is

$$\vec{\delta}(H,T,\theta)=\delta_x(H,T,\theta)\vec{i}+\delta_y(H,T,\theta)\vec{j}+\delta_z(H,T,\theta)\vec{k} \quad (1)$$

In this equation, $\delta_x(H,T,\theta)\vec{i}$, $\delta_y(H,T,\theta)\vec{j}$, $\delta_z(H,T,\theta)\vec{k}$ are displacements respectively along the x, y, z axis

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direction and θ is the aging factor (Wu *et al*. 2000).

Without loss of generality, take $\delta_x(H,T,\theta)$ as an example (hereinafter referred to δ) to study concrete dam displacement hydraulic pressure component isolation method. As shown in Eq. (1), δ is composed of hydraulic pressure components $\delta(H)$, temperature components $\delta(T)$ and aging components $\delta(\theta)$ as

$$\delta = \delta(H) + \delta(T) + \delta(\theta) \tag{2}$$

Besides the influence of water pressure, the displacement of dam is also influenced by the factors such as temperature and aging. Therefore, the factors and the expressions of the statistical model should be scientific selected based on the measured data to determine the coefficient of each factor in the model and the analysis of mechanics and structure theory. The variation of each component is used to estimate the structural state of the dam.

In Akpinar et al. (2014), the equations of $\delta(H)$, $\delta(T)$ and $\delta(\theta)$ of dams for ages can be expressed as

$$\begin{aligned} \delta(H) &= \sum_{i=1}^{n_1} a_i H^i \\ \delta(T) &= \sum_{i=1}^{2}\left(b_{1i}\sin\frac{2\pi it}{365} + b_{2i}\cos\frac{2\pi it}{365}\right) \\ \delta(\theta) &= \sum_{i=0}^{4} c_i \theta^i \end{aligned} \tag{3}$$

In Eq. (3), n_1 takes 3 for gravity dams or 4 for arch dams and t is the cumulative number of days from the very day of dam displacement measured value to the first day of the data series. θ takes $t/100$. a_i, b_{1i}, b_{2i}, c_i are parameters.

At present, automated monitoring is widely used in dam displacement monitoring which can collect practical dam displacements in a short period of time. Assuming actual monitoring displacement series is $\delta_t\left(t = 1, 2 \ldots n\right)$, n is displacement monitoring frequency. Assume $\Delta\delta_t = \delta_t - \delta_{t-1}$, then displacement series $\Delta\delta_t\left(t = 2, 3 \ldots n\right)$ is

$$\Delta\delta_t = \delta_t - \delta_{t-1} = \left(\delta_t(H) - \delta_{t-1}(H)\right) + \left(\delta_t(T) - \delta_{t-1}(T)\right) + \left(\delta_t(\theta) - \delta_{t-1}(\theta)\right) \tag{4}$$

Owing to the close adjacent displacement monitoring periods and the small changes of temperature and aging effects in these periods, $\Delta\delta_t$ is mainly influenced by water level. Therefore, $\Delta\delta_t$ can be expressed as

$$\Delta\delta_t = \delta_t(H) - \delta_{t-1}(H) \tag{5}$$

Hydraulic pressure components $\delta(H)$ can be separated from the dam displacement via Eq. (5). Eq. (5) is utilized for displacement changes in adjacent periods mainly affected by water level. The following method can be adopted to separate hydraulic pressure components when displacement changes in adjacent periods are influenced by the combined effects of water pressure, variable temperature and aging.

In the period of dam displacement monitoring, m different representative water levels are selected. At a fixed water level (the corresponding water depth H_j), the corresponding dam monitoring displacement δ_{ij} can be expressed in Eq. (6).

$$\delta_{ij} = \delta_{ij}(H_j) + \delta_{ij}(T_i) + \delta_{ij}(\theta_i) \quad (i = 1, 2, \ldots n_j;\ j = 1, 2, \ldots m) \tag{6}$$

n_j is the serial number of δ_{ij} when the water depth is H_j. By Eq. (6), the dam displacement reconstruction series difference $\Delta\delta_{ij}$ under water level H_j can be obtained.

$$\Delta\delta_{ij} = \left(\delta_{ij}(T_i) - \delta_{ij}(T_{i-1})\right) + \left(\delta_{ij}(\theta_i) - \delta_{ij}(\theta_{i-1})\right) \tag{7}$$

The total number of difference equations of different water depths are $M = \sum_{i=1}^{m} n_j$ utilizing Eq. (7) and these difference equations are affected only by the variable temperature and aging. Deducting the impact of water depth changes, the dam displacement optimization equation which are only affected by temperature and aging can be obtained via

$$\delta_{T\theta} = \delta(\mathrm{T}) + \delta(\theta) \tag{8}$$

In this equation, $\delta_{T\theta}$ is the dam displacement deducting the displacement caused by the changing water level. The meanings of $\delta(T)$ and $\delta(\theta)$ are the same with those in Eq. (2). Dam displacement hydraulic pressure components $\delta(H)$ are obtained under pressure loads from Eq. (8)

$$\delta(H) = \delta - \delta_{T\theta} \tag{9}$$

Dam displacement hydraulic pressure components $\delta(H)$ are isolated via Eq. (9).

3. Isolation method of concrete dam displacement aging component *δ*(*θ*)

Dam displacement $\delta_{T\theta}$ that deducts the effect of water pressure can be obtained from Eq. (5) and Eq. (8) by the analysis above and dam displacement change equation can be established under the temperature and aging effects via

$$\delta_{T\theta}^{(1)} = \delta^{(1)}(\mathrm{T}) + \delta^{(1)}(\theta) \tag{10}$$

In this equation, $\delta^{(1)}{}_{T\theta}$ is the same with $\delta_{T\theta}$ in Eq. (8). $\delta^{(1)}(T)$, $\delta^{(1)}(\theta)$ are temperature components and aging components expressions by the use of dam displacement $\delta_{T\theta}$ which could be the first results of the dam displacement change analysis.

The following illustrates the dynamic adjustment to temperature effect factors from temperature components $\delta(T)$ taking advantage of the basic idea of dynamic iteration method which makes the adjustment regression equation closer to the actual measurement process lines and components. The specific steps are as follows.

The first step is assuming that $\delta^{(1)}(T)$ is composed of $\delta^{(1)}(T_1), \delta^{(1)}(T_2), \ldots \delta^{(1)}(T_i) \ldots, \delta^{(1)}(T_l)$. $\delta(T_i)$ is dam displacement temperature component under the influence of variable temperature factors T_i. l is the number of variable temperature factors. In order to separate the aging component, take temperature components caused by part or all variable temperature factors in $\delta^{(1)}(T)$ as the known variables in Eq. (10). As the dam displacement temperature component $\delta^{(1)}(T_i)$ deducts the effects of T_i, then

$$\delta_{T\theta}^{(2)} = \delta_{T\theta}^{(1)} + \delta^{(1)}(\mathrm{T}_i) \tag{11}$$

Make use of aging component $\delta(\theta)$ and the remaining temperature component $\delta(T_i)$ (i=1,2,K i−1,i+1,l) from temperature component $\delta(T)$ to establish optimization model of $\delta^{(2)}(\theta)$ to obtain aging component $\delta(\theta)$ and temperature component $\delta(T)$ which deducts effects by temperature factors T_i. The change equation of dam displacement $\delta^{(2)}(\theta)$ can be established as

$$\delta_{T\theta}^{(2)} = \delta^{(2)}(\mathrm{T}_i) + \delta^{(2)}(\theta) \tag{12}$$

The second step is that regard temperature components caused by part or all temperature factors in $\delta^{(1)}(T)$ as the known variables and deduct them from $\delta^{(1)}(\theta)$. $\delta^{(1)}(T_{i-1})$, $\delta^{(1)}(T_{i+1})$ are temperature components deducted T_{i-1}, T_{i+1}, that is

$$\delta_{T\theta}^{(3)} = \delta_{T\theta}^{(1)} - \delta^{(1)}\left(T_{i-1}\right) - \delta^{(1)}\left(T_{i+1}\right) \tag{13}$$

Use all aging factors and other variable temperature factors which deducts T_{i-1}, $T_{i+1}$to establish the optimization model of Eq. (13). Then the expressions of $\delta(T)$, $\delta(\theta)$, $\delta^{(3)}\left(T_j\right)\left(j=1,2\mathrm{K}\ ,l, j\neq i-1, i+1\right)$ and $\delta^{(3)}(\theta)$ are

$$\delta_{T\theta}^{(3)} = \delta^{(3)}(\mathrm{T}_j) + \delta^{(3)}(\theta) \tag{14}$$

Repeat the above analysis process. If small displacement changes and small precision improvement of equation or concussion occurs in temperature factors dynamic adjustment process, part of aging factors in $\delta(\theta)$ can be added in the dynamic adjustment.

In step n, the final dam displacement change process could meet the project accuracy requirements after above n steps of temperature and aging factors dynamic adjustment and optimization analysis, and it is also the optimal equation. The dam displacement $\delta_{T\theta}$ deducting hydraulic impacts can be shown as

$$\delta_{T\theta} = \delta^{(n)}\left(T\right) + \delta^{(n)}\left(\theta\right) \tag{15}$$

It should be noted that in $\delta^{(n)}(T)$, $\delta^{(n)}(\theta)$ in Eq. (15) are including the sum of temperature, aging components of n-1 and n step.

Dam displacement aging components $\delta(\theta)$ can be separated utilizing Eq. (15), that is $\delta(\theta)=\delta^{(n)}(\theta)$.

4. Dam stability displacement discrimination methods

The dam displacement could comprehensively reflect the work state of the concrete dam and dam displacement aging component is the comprehensive reflection of the dam stability (Chugh 2013, Alves *et al*. 2006). The following research on dam stability analysis method (Liu *et al*. 2013) is on the basis of dam displacement aging component $\delta(\theta)$. Without loss of generality, $\delta(\theta)$ can be expressed as Eq. (3) according to the variation rule of dam displacement aging component (Zhu *et al*. 2009), that is

$$\delta\left(\theta\right) = \sum_{i=0}^{4} a_i\theta^i = a_0 + a_1\theta + a_2\theta^2 + a_3\theta^3 + a_4\theta^4 \tag{16}$$

4.1 Dam stability analysis according to convergence and divergence of dam displacement aging component

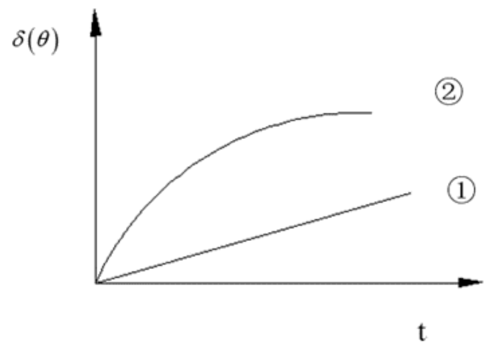

Fig. 1 Change process diagram of the aging component

The aging component reflects the irreversible deformation caused by the creep of concrete and so on which shows the change trend of dam deformation and is an important index to measure the health of dam. Since the dam displacement aging component could comprehensively reflect the dam stability, it is made use to analyze the dam stability (Chelidze *et al*. 2013, Li *et al*. 2016). According to the analysis of dam displacement monitoring data analysis, convergence and divergence of the dam displacement aging component can be determined as follows.

If $\delta(\theta)$ is in stable change or convergence state which is shown in Fig. (1), then the dam structure is in stable condition as

$$\frac{d\delta(\theta)}{d\theta} = 0 \text{, or } \frac{d\delta(\theta)}{d\theta} \neq 0 \text{, but } \frac{d^2\delta(\theta)}{d\theta^2} < 0 \tag{17}$$

Dam is in stable state when Eq. (17) is satisfied.

If the dam displacement aging components $\delta(\theta)$ are in non-convergence state or from positive to negative or from negative to positive, and the actual dam extreme displacement δ_m does not exceed the linear elastic displacement control value δ_{em}, as

$$\frac{d^2\delta\left(\theta\right)}{d\theta^2} \neq 0 \text{, } \delta_m \leq \delta_{em} \tag{18}$$

Then the dam is in basic stable state when Eq. (18) is satisfied.

If the dam displacement aging components $\delta(\theta)$ are in a divergent state or displacement direction have some changes and the actual dam extreme displacements δ_m are greater than δ_{em} without exceeding the elastoplastic displacement control values δ_{nm} as

$$\frac{d^2\delta\left(\theta\right)}{d\theta^2} \neq 0 \text{, } \delta_{em} < \delta_m \leq \delta_{nm} \tag{19}$$

The stability of dam is in abnormal situations when Eq. (19) is satisfied.

If the dam displacement aging components $\delta(\theta)$ are in a divergent state or displacement directions have some changes and the actual dam extreme displacements δ_m are greater than the elastoplastic displacement control values δ_{nm} as

$$\frac{d\delta^2\left(\theta\right)}{d\theta} \neq 0 \text{, } \delta_m > \delta_{nm} \tag{20}$$

Dam is in unstable state when Eq. (20) is satisfied.

4.2 Dam stability analysis by dam displacement aging component according to catastrophe theory

Dam project is in different working conditions under variable loads (Su *et al*. 2013, Shahrbanouzadeh *et al*. 2015). Supposing the dam stability state potential function by dam displacement aging component is

$$F(x)=x^4+ax^2+bx+c \tag{21}$$

Eq. (21) is the dam stability catastrophe model. In this equation, x is the state variable of the dam, a, b are control variables of the dam state, c is the state constant. Conduct a derivation to Eq. (21), then

$$F'(x)=4x^3+2ax+b \tag{22}$$

Solving Eq. (22) to get the critical point of Eq. (21) is also the critical point of dam stability. In terms of the Eq. (21), the number of real roots is determined by the Eq. (23), that is

$$\Delta=4a^3+13.5b^2 \tag{23}$$

Eq. (23) can be used to determine the stability of the dam. Dam is in stable state when $\Delta>0$. Dam is in critical stable state when $\Delta=0$. Dam is in unstable state when $\Delta<0$. Dam displacement aging component $\delta(\theta)$ can be expressed as a polynomial form of θ according to Eq. (16). Define $G=a_3/4a_4$ and $\theta=E-G$, then Eq. (16) can be changed into

$$\delta(\theta)=b_4E^4+b_2E^2+b_1E+b_0 \tag{24}$$

In Eq. (24),

$$\begin{bmatrix} b_4 \\ b_2 \\ b_1 \\ b_0 \end{bmatrix}=\begin{bmatrix} G^4 & -G^3 & G^2 & -G & 1 \\ -4G^3 & 3G^2 & -2G & 1 & 0 \\ 6G^2 & -3G & 1 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 \end{bmatrix}\begin{bmatrix} a_4 \\ a_3 \\ a_2 \\ a_1 \\ a_0 \end{bmatrix} \tag{25}$$

Make $\delta(\theta)=b_4F$, $H=b_2/b_4$, $P=b_1/b_4$, $Q=b_0/b_4$in Eq. (24), then Eq. (24) can be changed into

$$F=y^4+Ky^2+Py+Q \tag{26}$$

The physical meaning of the Eq. (26) is equivalent to Eq. (21). The steady state discriminant of dam stability model illustrated by Eq. (26) is

$$\Delta=4K^3+13.5P^2 \tag{27}$$

Dam displacement aging components are in a stable condition which means that dam is in stable state when $\Delta>0$. Dam is in a stable and non-stable critical state when $\Delta=0$. Dam is in unstable state when $\Delta<0$.

5. Case study

A concrete gravity dam of 158 meters high is in complex geological conditions. A large transverse valley fault near downstream of the dam makes dam riverbed foundation weak. Therefore, the stability of dam on the riverbed is the main problem of the dam project. A large number of safety monitoring instruments are arranged in the dam in order to monitor the safety of the project. The 11th dam section is the crown cantilever. The 11th dam section on the riverbed is one of the most representative dam sections with the layout of orthographic and inverted vertical lines to monitor the dam. Then the measured radial horizontal displacement data from 1/5/1990 to 8/31/2015 of the 11th dam section is utilized to analyze the stability of the dam.

The dam displacement δ can be expressed using Eq. (3) as

$$\delta=\delta(H)+\delta(T)+\delta(\theta)=\sum_{i=1}^{4}a_iH^i+\sum_{i=1}^{2}\left(b_{1i}\sin\frac{2\pi it}{365}+b_{2i}\cos\frac{2\pi it}{365}\right)+\sum_{i=0}^{4}c_i\theta^i+d_0 \tag{28}$$

In this equation, d_0 is the constant term and the meanings of other symbols refer to Eq. (3).

Utilize Eqs. (3)-(9) and the self-designed difference regression program to obtain the expression of water pressure components $\delta(H)$ as

$$\begin{aligned}\delta(H)=&-9.508\times10^{-4}-0.3053H+3.744\times10^{-3}H^2\\&-2.015\times10^{-5}H^3+3.672\times10^{-2}H^4\end{aligned} \tag{29}$$

Utilize Eqs. (10)-(16) and the self-designed dynamic iterative regression program to obtain the expressions of temperature components $\delta(T)$ and aging components $\delta(\theta)$.

$$\delta(T)=0.9674\sin\frac{2\pi t}{365}-0.5164\cos\frac{2\pi t}{365}-1.215\sin\frac{4\pi t}{365}-0.3123\cos\frac{4\pi t}{365} \tag{30}$$

$$\delta(\theta)=0.3212\times10^{-5}+0.9111\theta-0.1019\theta^2+0.0679\theta^3-0.0509\theta^4 \tag{31}$$

Then utilize the isolated displacement aging components in Eq. (31) from displacement data of 11th dam section and the proposed dam displacement discrimination method to evaluate the dam foundation stability against sliding. Specific analysis is as follows.

(1) Analyze the dam foundation stability against sliding according to the convergence and divergence of the dam displacement aging component.

First conduct a derivation to dam displacement aging component component $\delta(\theta)$ of 11th dam section foundation in Eq. (31).

$$\frac{d\ \delta(\theta)}{d\theta}=0.9111-0.2038\theta+0.2037\theta^2-0.2036\theta^3 \tag{32}$$

Eq. (32) would not be identically equaled to 0 with different θ.

Conduct second derivation of $\delta(\theta)$ in Eq. (31).

$$\frac{d^2\delta(\theta)}{d\theta^2}=-0.2038+0.4074\theta-0.6108\theta^2=-0.6108(\theta-\frac{0.2037}{0.6108})^2-0.3150<0 \tag{33}$$

As shown in Eq. (33), $\frac{d^2\delta(\theta)}{d\theta^2}<0$ with different θ. According to the criterion of convergence and divergence for dam displacement aging components, $\frac{d\ \delta(\theta)}{d\theta}\neq0$ but $\frac{d^2\delta(\theta)}{d\theta^2}<0$, Eq. (17) is satisfied. As a result, the displacement aging components of dam foundation are in convergence state. Also the 11th dam section is in stable state.

(2) Analyze the stability of the dam according to

catastrophe theory with dam displacement aging component.

By the general expression of the dam displacement aging component in Eq. (16), define $G=a_3/4a_4$ and $\theta=E-G$, then Eq. (31) is transformed to the following form.

$$\delta(\theta)=b_4E^4+b_2E^2+b_1E+b_0 \tag{34}$$

Utilize Eq. (25) and Eq. (31), the following can be obtained. b_4=0.2944, b_2=0.8582, b_1=-0.0679, $b_0=3.212\times10^{-4}$

Make $\delta(\theta)=b_4F$, $K=b_2/b_4$, $P=b_1/b_4$, $Q=b_0/b_4$, then

$$F=y^4+Ky^2+Py+Q \tag{35}$$

Among them, K=2.9151, P=-0.2306, $Q=1.091\times10^{-3}$.

According to Eq. (27) the stability criterion is

$$\Delta=4K^3+13.5P^2 \tag{36}$$

Since K^3=24.772>0, P^2=0.053>0, Eq. (36) is constant greater than 0. The above analysis illustrates that the dam foundation is stable according to the catastrophe model analysis based on the displacement measured data of the 11th dam section after the year of 1990. This result is consistent with the result of dam foundation stability using the displacement aging component convergence and divergence analysis. That is also consistent with the result of Eqs. (32) and (33).

6. Conclusions

In this paper, the dam displacement measured data is utilized to study the analysis method of the stability of the concrete dam and the effectiveness of the proposed method is verified through the project example. The main conclusions are as follows.

• Put forward the method to separate the dam displacement hydraulic pressure components since the dam displacement information synthetically reflects the operational status of the dam. On the basis, utilize the comprehensive adjustment effect factor method to separate the dam displacement aging components.

• Set up the discriminant method and criterion of the dam stability taking advantage of isolated dam displacement aging components according to the convergence and divergence of aging components. Establish the dam stability analysis model and criterion based on catastrophe theory at the same time.

• Verify the effectiveness of the proposed method through the project example. The proposed method can be applied to the analysis of the stability of crack in concrete dams due to the versatility of the theory and method.

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