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Observed displacement data-based identification method of deformation time-varying effect of high concrete dams

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The long-term safety of high concrete dams has become the focus and central issues of public attention. Deformation is an actual comprehensive reflection of concrete dams. Especially the deformation time-varying effect, is a key index for evaluating the structural behavior, health status, and their evolution of a concrete dam in long-term service. In this paper, causing factors of the deformation time-varying effect of concrete dams were analyzed, and the time-varying effect was divided into two parts, which are the inherent time-varying effect and the time-varying effect caused by the change of dam structural performance. Then, based on the observed dam displacement and the wavelet multi-resolution analysis, causal models for identifying the later deformation time-varying effect and the identification process were proposed. Finally, the efficiency and rationality of the proposed method were verified by two actual concrete dams with runoff reservoir and regulatory reservoir.

high concrete dam, deformation, time-varying effect, causing analysis, identification method

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1 Introduction

Concrete dams during operation not only need to bear dynamic and static cyclic loads and sudden disasters, but also suffer a lot from the erosion and corrosion due to the harsh environments [1,2]. Therefore, the structural performance of concrete dams is a nonlinear dynamic evolution process with the interaction of dam material and structure under the cooperation of multiple factors [3]. The evolution of structural performance of concrete dams could change their original load-bearing systems, which probably leads to the deviation of design condition and the cracking of concrete dams [4–6].

Deformation time-varying effect of concrete dams is generated during the dynamic evolution process, and it can be fundamentally interpreted by the inherent rheological property and the performance degradation of both dam concrete and foundation rock caused by aging effect [7]. Subjecting to external excitations, the deformation time-varying effect is the occurrence sign of tendency change even mutation of dam structural performance [8,9]. Aiming at this problem, research topics are mainly focused on the irreversible displacement of dam body caused by cracking, alkali-aggregate reaction (AAR), freezing-thawing, leakage dissolution, creep of dam concrete and bank slope rock mass, etc. [10–12]. Based on the joint element, Zhang et al. [13] simulated the influence of multi-defects on long-term working performance of Chencun arch dam, and it demonstrated that the increase tendency of dam crest deformation towards the upstream direction is related to the axial cracks on dam crest. Lu et al. [14] studied the reason for the phenomenon of "two peak values in one year" in both vertical and horizontal displacements at the

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*Corresponding author: (email: shaowei2006nanjing@163.com) crest of Fengman concrete gravity dam, which was demonstrated to be caused by the frost heave deformation of dam concrete. With the help of three dimensional finite element model of the dam-foundation system, the long-term AAR was also demonstrated to be a causing factor for the irreversible displacement of concrete dams, and it was mainly interpreted by the gradual increase of the volume of the mass concrete and the accompanied cracks [15,16]. Liu et al. [17] and Yu et al. [18] found that the main reason for valley contraction of high concrete arch dams was the creep deformation of bank slope, and this phenomenon would lead to an increase of the compressive stress at dam heel and the tensile stress at dam toe, as well as the irreversible displacement of dam body towards the upstream direction.

Except for the irreversible dam displacement, the deformation time-varying effect of concrete dams is also reflected by the evolution of recoverable deformation capacity of dam body. The main discussion object is the elastic modulus of dam concrete, which can be used to identify the structural damage of concrete dams [19]. However, not only the varying of external loads, such as the upstream reservoir water level, air temperature, etc., but also the inherent rheological property and the property evolution of dam materials could lead to the varying of concrete dam deformation. So, the aforementioned evolution raw is mostly hidden by the irregularity of environmental loads. For the traditional dam health monitoring methods, we usually can only detect the irreversible dam displacement, or identify the time-varying behavior by comparing the relationship between the monitored and the forecasted dam displacements [20–22]. It is very difficult to identify the deformation time-varying effect caused by the structural performance change of concrete dams.

Based on the multi-scale characteristics of long term monitoring signals of bridges, the deflection monitoring signal is separated in the frequency domain into several components, and according to the frequency characteristics of influencing factors, these components are respectively determined to be caused by live loads, daytime temperature variations, abrupt temperature drops, seasonal temperature fluctuations and dead loads [23,24]. Structural health monitoring signals of concrete dams also have the multi-scale characteristics, both the environmental quantities and the effect quantities. Therefore, time-frequency analysis can also be introduced into the identification of deformation time-varying effect of concrete dams, not just the separation of irreversible dam deformation [25]. In practical terms, the time-varying effect caused by the structural performance change of concrete dams can be identified by the evolution of relationship between components of environmental quantity and effect quantity with the same frequency characteristic. In this paper, based on the observed displacement data, an identification method for the deformation time-varying effect of high concrete dams is systemically studied and proposed.

2 Deformation time-varying effect of high concrete dams and its causing factors

Engineering examples show that the structural deformation behavior of concrete dams is varying during operation. This is mainly represented by dam deformation in two aspects. First, the unrecoverable time-dependent deformation exists. Second, the recoverable deformations under the same environmental load are not the same in different service periods.

Time series of the crest vertical displacement of a concrete gravity dam in the northeast of China are shown in Figure 1. It can be seen that dam crest elevates over time. While, monitoring results show that the abnormal upward deformation mainly results from dam body. In addition to the common thermal expansion and contraction of dam concrete, which respectively lead to the rise and settlement of dam crest in summer and winter, the frozen and thaw of water in concrete crack groups of the upper dam body make dam crest rise in February and subside in April of each year. Therefore, the combination of these two actions leads to the displacement variation rule of “two peak values in one year”. However, during the process of frozen-thaw cycles, local damage appears on dam body, and due to the existence of residual deformations, dam crest does not completely sink back to its

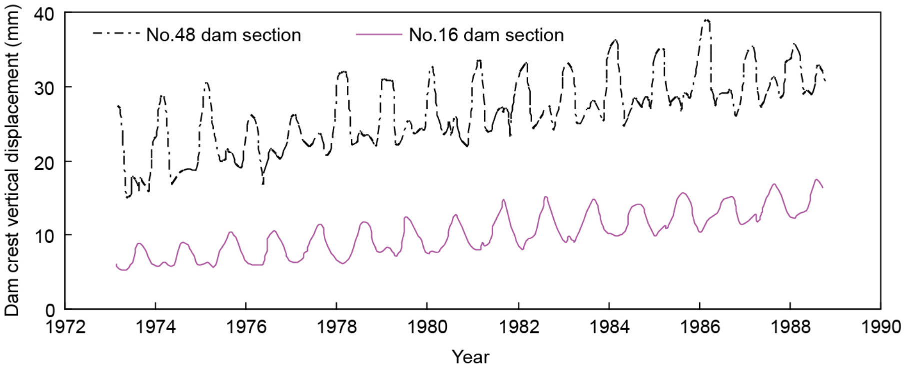

Figure 1 (Color online) Time series of crest vertical displacement of a concrete gravity dam.

original elevation. The abnormal upward tendency of dam crest makes this dam different from other concrete dams.

Due to the complex interaction between material and structure in the service performance evolution of concrete dams, the deformation time-varying effect is caused by various factors, such as the inherent rheological property and the property evolution of dam materials, dam cracks caused by loads or some other reasons, dam reinforcements during operation, and even the tendency changes of boundary conditions or external loads of some individual concrete dams at a particular stage. Among all these causing factors, material property is a key factor to determine the structural performance. Firstly, deformations of dam concrete and foundation rock under constant load are all developed over time. Besides, dam material properties, such as the elastic modulus, thermal expansion, strength, viscosity, etc., are usually varying during dam long-term operation, which will lead to the change of dam structural performance. As for those destructive cracks, the cracking process is relatively fast, and the location and cracking degree are uncertain. Therefore, their influences on the sudden change of dam structural performance should be studied particularly. Causing factors for the deformation time-varying effect of concrete dams can be mainly interpreted by the inherent rheological property and the property evolution of dam materials.

The time-dependent component represented by the combination of linear function and logarithmic function in mathematical monitoring models mainly reflects the unrecoverable dam deformation caused by dam concrete and foundation rock. It is the tendency component of deformation time series. In addition to the unrecoverable deformation, the inherent rheological property of dam materials also produces a certain degree of recoverable time-dependent deformation. These two time-dependent deformations are both caused by the rheological property, so they are together defined as the inherent time-varying effect of concrete dam deformation. Evolution of dam material properties during operation will lead to the structural performance change of concrete dams, which will be finally reflected by the deference of variation amplitude of dam recoverable deformation in the process of reservoir water level fluctuation and air temperature periodic variation. For example, under the periodic cyclic load of constant amplitude, the aging of dam concrete will lead to the degradation of its mechanical properties, and the variation amplitude of dam displacement corresponding to its base value will increase. This phenomenon is gradually appeared during the long-term operation, so it is defined as the time-varying effect of deformation that caused by the structural performance change of concrete dams. Under the assumption of the same variation rule of environmental loads for each year, schematic diagrams of the deformation time-varying effects of concrete dams are shown in Figure 2.

3 Identification method of deformation time-varying effect of concrete dams

Cause analysis of the deformation time-varying effect shows that the inherent rheological property and the property evolution of dam materials are the main factors causing the change of concrete dam structural performance. The inherent time-varying effect can be represented by the form of exponential function with additional periodic terms and separated from the observed dam deformation by mathematical models. With regard to the later time-varying effect, due to the slow development of dam structural performance change caused by the property evolution of dam materials, it is gradually revealed in the long-term operation of concrete dams. Although the change of dam environment loads has a certain periodicity, the complex actual load combination makes it difficult to obtain the assumed evolution rule of annual variation amplitude between peak and valley values of dam displacement as shown in Figure 2. It is mostly hidden by the irregularity of environment loads. Since the effect quantity and its influencing factor have the same frequency, the displacement wavelet component corresponding to the component of its influencing factor could be obtained. Then, the deformation time-varying effect of concrete dams caused by the structural performance change can be identified by studying the changing rule of the

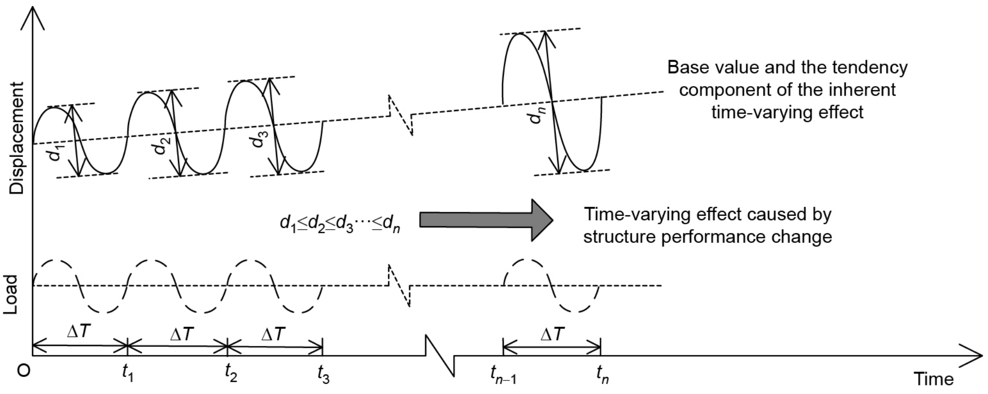

Figure 2 Schematic diagrams of deformation time-varying effects of concrete dams under the periodic environmental load of constant amplitude.

correlation between the two wavelet components.

3.1 Wavelet multi resolution-based component extraction of concrete dam deformation

Concrete dam deformation is mainly consisted of hydraulic pressure component, temperature component and time-dependent component. Under design loads, numerical simulation and geomechanical test show that dam concrete is in a state of viscoelasticity, so the hydraulic pressure component and temperature component mainly belong to the elastic deformation, and can be respectively used to represent the integral stiffness and thermal expansion of concrete dams. Therefore, the elastic component of dam deformation can be used to excavate dam recoverable deformation ability. On the basis of this, the structural performance change of concrete dams can be evaluated.

The monitored dam deformation is a comprehensive value, each effect component can only be separated by mathematical models or signal separation methods. The reservoir water level and air temperature usually have a certain variation frequency. The frequencies of deformation components are correspondingly the same with their influencing factors, which would be generally independent with each other in the frequency domain.

Wavelet multi resolution analysis is a signal processing method in the time-frequency domain, and the time sequence signal can be decomposed into components with different frequency characteristics. Therefore, according to the same frequency of effect component and its influencing factor, deformation wavelet components of each influencing factors can be respectively determined. The deformation time-varying effect caused by the structural performance change of concrete dams can be identified as well by the evolution law of the correlation between the two wavelet components of influencing factor and dam deformation.

The basis content of wavelet multi resolution analysis is the decomposion of the original signal at different resolution levels by means of orthogonal transformation, and the low frequency component of the upper resolution level can be decomposed again according to the actual needs [26]. The total frequency band of the original signal f_0 is defined as V_0. After the first decomposition, V_0 will be divided into two subspaces, which are the low frequency subspace V_1 and the high frequency subspace W_1. Therefore, for j times decomposition, V_j and W_j are the low and high frequency subspaces of V_{j-1} and respectively used to represent the profile and the detail of spatial signals. According to the law of orthogonal transformation, W_j is the orthogonal complementation of V_j in the upper low frequency subspace V_{j-1}, and it can be represented as $V_j \oplus W_j = V_{j-1}$. Therefore, as for the wavelet multi resolution analysis, V_0 can be approximated by a limited number of subspaces as follows:

$$\begin{aligned} V_0 &= V_1 \oplus W_1 = V_2 \oplus W_2 \oplus W_1 = \cdots \\ &= V_N \oplus W_N \oplus W_{N-1} \oplus \cdots \oplus W_2 \oplus W_1. \end{aligned} \tag{1}$$

Therefore, for a function $f \in L^2(R)$, if $c_j \in V_j$ and $d_j \in W_j$ are respectively determined as the approximation and corresponding error of f at the resolution level of 2^{-j}, the decomposition diagram can be obtained from eq. (1) as follows and shown in Figure 3.

$$\begin{aligned} f_0 &= c_1 + d_1 = c_2 + d_2 + d_1 = \cdots \\ &= c_N + d_N + d_{N-1} \cdots + d_2 + d_1 \\ &= c_N + \sum_{j=1}^{N} d_j, \end{aligned} \tag{2}$$

where f_0 is the original signal; c_j and d_j are the low and high frequency components decomposed from c_{j-1} of the upper resolution level, respectively.

As for the discrete sampling sequence $f(n)$, $n=1,2,\ldots,N$ of a continuous signal $f(t)$, if $c_0(n)=f(n)$ is used to represent the approximation of the original signal at the resolution level of $j=0$, the discrete dyadic wavelet transform for $f(t)$ can be derived as follows:

$$\begin{cases} c_{j+1}(n) = \sum\limits_{k\in Z} h(k-2n)c_j(n), \\ d_{j+1}(n) = \sum\limits_{k\in Z} g(k-2n)c_j(n), \end{cases} \tag{3}$$

where c_j and d_j are the profile and the detail of spatial signal at the resolution level of $j=0$, respectively; $h(k-2n)$ and $g(k-2n)$ are conjugate filter coefficients determined by wavelet function $\psi(x)$.

Then, scaling function $\varphi(x)$ and wavelet function $\psi(x)$ can be completely determined by the two-scale relation as follows:

$$\varphi(x) = \sum_{k=-\infty}^{\infty} h(k)\varphi(2x-k), \tag{4}$$

$$\psi(x) = \sum_{k=-\infty}^{\infty} g(k)\varphi(2x-k), \tag{5}$$

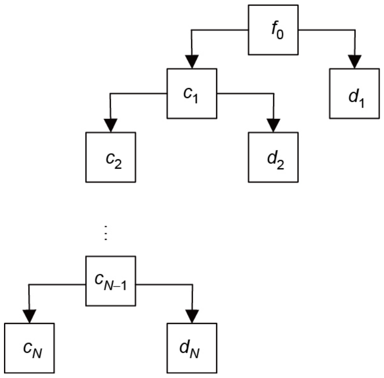

Figure 3 The decomposition diagram of wavelet multi-resolution analysis.

where $h(k)=\left\langle \frac{1}{\sqrt{2}}\varphi\left(\frac{x}{2}\right), \varphi(x-k)\right\rangle$, $g(k)=(-1)^k h(1-k)$.

After j times decomposion, the discrete signal $f(n)$ is finally decomposed as d_1, d_2, …, d_j, c_j, which contain the information of different frequency bands from high frequency to low frequency.

3.2 Causal models for deformation components of concrete dams

Displacement of concrete dams, δ, can be divided into three parts and represented by mathematical model as follows:

$$\delta=\delta_H+\delta_T+\delta_\theta=\sum_{i=1}^{n}a_iH^i+\sum_{i=1}^{m}b_iT_i+\delta_\theta, \tag{6}$$

where δ_H, δ_T and δ_θ are hydraulic pressure component, temperature component and time effect component, respectively.

The reservoir water level and air temperature generally change around the average value, so the following relative deformation relationship can be established:

$$\begin{aligned}\varDelta\delta &= \delta-\bar{\delta}\\ &=\sum_{i=1}^{n}a_i(H^i-\bar{H}^i)+\sum_{i=1}^{m}b_i\left(T_i-\bar{T}\right)+\left(\delta_\theta-\bar{\delta}_\theta\right),\end{aligned} \tag{7}$$

where $\bar{\delta}$ and $\bar{\delta}_\theta$ are average values of dam displacement and its time effect component; $\bar{H}$ and $\bar{T}$ are average values of reservoir water depth H and air temperature T; n is the highest degree of polynomials used in hydraulic pressure component, which is determined as 3 and 4 for gravity dam and arch dam, respectively; T_i is the average air temperature that i days before.

The high frequency wavelet component of the decomposed displacement time series is a relative value caused by the change of influencing factors that corresponding to their mean values. Therefore, according to eq. (7), relationships between wavelet components of dam displacement and its influencing factors with the same frequency can be established. The change of deformation ability of concrete dams can be evaluated by the evolution of relationship parameters.

As for the displacement wavelet component caused by the fluctuation of reservoir water level, to establish the relationship between variations of dam displacement and reservoir water depth, dam displacement fields under different water depths should be firstly simulated by finite element method (FEM), and the base state is determined corresponding to the multi-year average upstream reservoir water depth $\bar{H}$.

$$\Delta\delta'_H=\sum_{i=1}^{n}a'_i(H^i-\bar{H}^i), \tag{8}$$

where $\Delta\delta'_H$ is the FEM calculated displacement variation with a reservoir water depth of H corresponding to $\bar{H}$; a'_i are fitting coefficients.

Considering the structural performance change of concrete dams during operation and the deviation of elastic modulus between the initial assumed value and the actual value, a time-varying adjustment coefficient $X(t)$ is introduced as follows:

$$\Delta\delta_H=X(t)\Delta\delta'_H=X(t)\sum_{i=1}^{n}a'_i(H^i-\bar{H}^i), \tag{9}$$

where $\Delta\delta_H$ is the displacement wavelet component which has the same variation frequency with reservoir water level. If the variation period of reservoir water level is more complex, it can also be decomposed, and relationship models should be established by wavelet components of reservoir water level and dam displacement with the same frequency.

The temperature field of concrete dams is generally consisted of initial temperature, hydration heat temperature, periodic temperature and the random component. Among which, the hydration heat temperature is mainly produced in the early operation stage and gradually eliminated later. The deformation temperature component reflected in the monitoring data is mainly caused by the periodic variation of air temperature. Therefore, for the displacement wavelet component caused by the periodic environmental temperature load, the evolution of temperature deformation ability of concrete dams can be evaluated according to the linear relationship between temperature deformation and dam concrete temperature.

The lag time interval Δt spent in the heat conduction process that from dam surface to internal concrete should be taken into consideration to comprehensively evaluate the evolution of dam temperature deformation ability. In order to obtain the most reasonable lag time interval, the correlation coefficient between wavelet components of temperature displacement and air temperature should be gained firstly. Then the lag time can be determined by finding the maximum correlation for the assumed Δt_i (i is the assumption number) and the above correlation coefficient. Therefore, the temperature variation between the air temperature $T_{\Delta t}$ that monitored Δt days before the monitoring time of dam displacement and the annual mean temperature $\bar{T}$ can be directly introduced as the factor of periodic temperature displacement component as follows:

$$\Delta\delta_T=b\left(T_{\Delta t}-\bar{T}\right), \tag{10}$$

where $\Delta\delta_T$ is the displacement wavelet component which has the same variation frequency with air temperature; b is fitting coefficient related to the temperature expansion coefficient of dam concrete.

Generally, air temperature has obvious seasonal period, but the reservoir water level varies from dam to dam. For the decomposed displacement wavelet component, if the frequency characteristics show that this component only contains the hydraulic pressure component or temperature component, the causal model can be directly established by eqs. (9) or (10). Otherwise, this displacement wavelet component is commonly caused by hydraulic pressure and air temperature as follows:

$$\Delta\delta = \Delta\delta_H + \Delta\delta_T = X(t)\sum_{i=1}^{n} a'_i(H^i - \overline{H}^i) + b(T_{\Delta t} - \overline{T}). \qquad (11)$$

3.3 Implementation process

Based on the wavelet multi-resolution analysis and the established causal models, identification method of deformation time-varying effect of high concrete dams can be implemented as follows:

(1) Determine the used typical measurement points of dam displacement. The radial (or stream direction) relative displacement of plumb line measurement points on the upper dam body corresponding to the foundation plane can better reflect the overall structural performance of concrete dams, so it is considered in most cases.

(2) Pretreatment of the observed time series of dam displacement, temperature and reservoir water level. It is mainly focused on the data integrity, continuity and outliers, and the monitoring time interval in one time series should be adjusted to the same.

(3) Wavelet multi-level decomposition of the pretreated time series, and calculate the normalized power spectrums for all these decomposed high frequency components of the used time series.

(4) The decomposed high frequency component of dam displacement with obvious periodicity is determined to be used in the identification analysis. According to the same periodicity of effect quantity and influencing quantity, its influencing factors can be determined from these high frequency components that decomposed from the time series of air temperature and reservoir water level.

(5) According to eqs. (9)–(11), establish causal models for each year.

(6) Analyze the evolution law of adjustment coefficients of temperature deformation and hydraulic pressure deformation.

4 Case study

Two concrete dams are analyzed here to identify the deformation time-varying effect that caused by dam structural performance change. These two dams operate with runoff reservoir and regulatory reservoir, respectively.

4.1 Concrete dam of runoff hydropower station

For concrete dam whose reservoir water level changes slightly, its hydraulic pressure component is mainly performed as the base value of dam deformation time series. It is the temperature deformation that considered as the obvious cyclical component. Therefore, using the decomposed high frequency displacement wavelet component which has the same frequency with air temperature, the deformation time-varying effect caused by dam structural performance change can be identified according to the evolution of relationship between dam temperature deformation and air temperature.

A concrete arch dam with the maximum dam height of 155 m is selected as an example. The normal and dead reservoir water levels are respectively 2180 and 2178 m. It belongs to the incomplete daily regulation reservoir. The construction process began in April, 1988, and fully completed in December, 2002. Water storage began in December, 1996, and the dam was poured to the crest on May 16, 1999. After several times of impoundment, the reservoir was impounded to the normal water level on January, 2002, and the reservoir water level changed no more than 2 m since then.

Time series of the 4th, 5th and 6th high frequency components of the radial displacement at the dam crest of arch crown beam and the air temperature are shown in Figure 4. It can be seen that dam deformation changes with obvious annual periodicity and is mainly represented by the decomposed 5th high frequency component. The year periodic variation process of dam crest radial displacement is negative correlation to air temperature, which demonstrates the temperature deformation law of concrete arch dam that dam body inclines towards the upstream direction when temperature rise, towards the downstream direction when temperature drop. According to the normalized power spectrums of the aforementioned time series as shown in Figure 5, it can be seen that the 5th high frequency component of the decomposed crest displacement has the same unique frequency with air temperature, so this displacement component can be determined as the temperature deformation.

The relationship between temperature lag time and the correlation coefficient between the 5th high frequency component of dam displacement and air temperature is shown in Figure 6. As can be seen, the comprehensive lag time interval between the changes of dam temperature field and air temperature is about 56 d. Therefore, the variation ΔT_{56} between the air temperature T_{56} that monitored 56 d before the monitoring time of dam displacement and the annual mean temperature $\overline{T}$ is determined as the influencing factor for the decomposed 5th high frequency component of dam displacement. The relationship is established as follows:

$$\delta_5 = b\Delta T_{56}. \qquad (12)$$

The relationship between the 5th high frequency component and the temperature variation ΔT_{56} from 2004 to 2009 is shown in Figure 7. Under the same temperature variation, the temperature deformation in the temperature rise stage is slightly less than that of the temperature drop stage. Piecewise fitting based on the monitoring data of each year shows that the model coefficients of b are −0.519, −0.526, −0.538, −0.547, −0.552, and −0.544 for these six years. The negative coefficients indicate that the radial displacement at the crest of arch crown beam is negative correlation to air temperature,

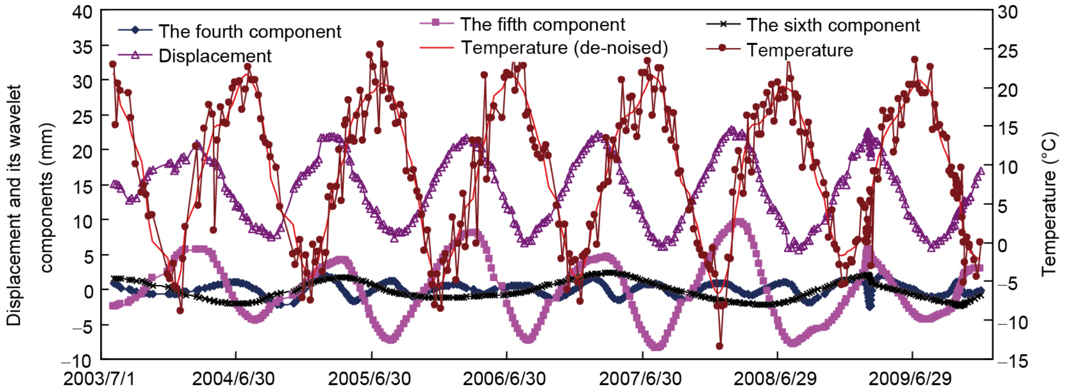

Figure 4 (Color online) Time series of temperature and wavelet components of dam crest radial displacement.

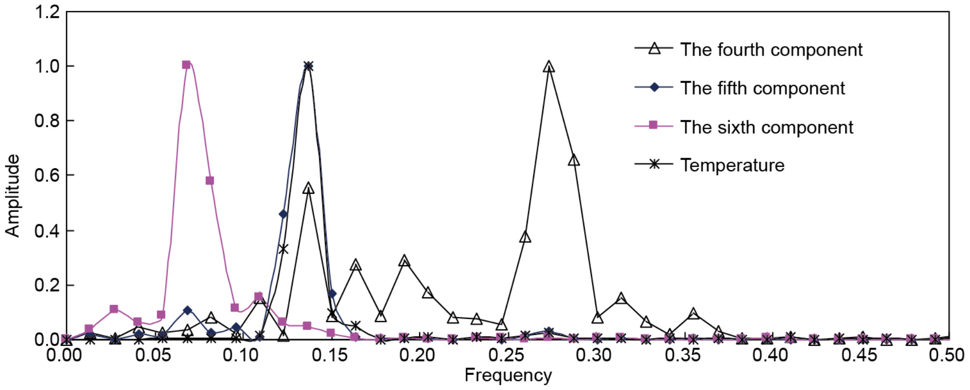

Figure 5 (Color online) Normalized power spectrums of temperature and wavelet components of displacement.

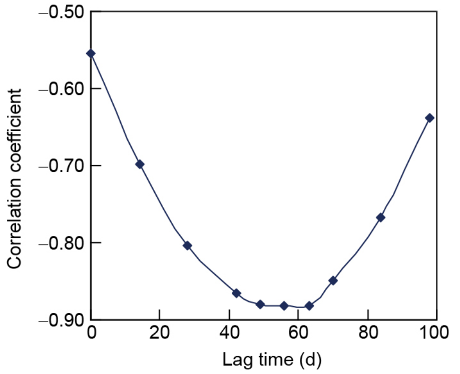

Figure 6 Relationship between lag time and the correlation coefficient between the 5th high frequency component of dam displacement and air temperature.

which is in accordance with the actual condition of temperature deformation of concrete arch dams. Besides, the absolute value of the proportion coefficient b is gradually increasing within these years, which means the increasing of dam temperature deformation ability. As a result, the difference between the peak and valley value of dam temperature displacement will gradually become larger when the air temperature is exactly the same in each year. Considering the temperature deformation ability of concrete dams is mostly determined by the thermal expansion of dam concrete, the increase of the absolute value of dam temperature deformation coefficient indicates that the integer structural performance of this concrete dam is changed during operation. One cause may be that the water content of concrete in local or global dam body has changed. The water thermal expansion coefficient is about 210×10^{-6}/°C, which is far greater than that of dam concrete. Research results show that the thermal expansion coefficient of dam concrete reaches the maximum when the water content is about 50% to 80%, so the change of water content of concrete dams will affect the thermal expansion deformation more or less.

4.2 Concrete dam with regulatory reservoir

A roller compacted concrete gravity dam with the crest elevation of 179 m and the maximum dam height of 113 m is analyzed here. The dam reservoir belongs to the incomplete annual regulation reservoir. The construction process began in April, 1998 and fully completed in December, 2001. Water storage began on December 18, 2000. Under the comprehensive load action of environmental temperature and hydraulic pressure, dam deformation changes complicatedly. Time series of the stream direction displacement at the crest of the highest dam section is shown in Figure 8. To study its deformation time-varying effect, wavelet decomposition of dam

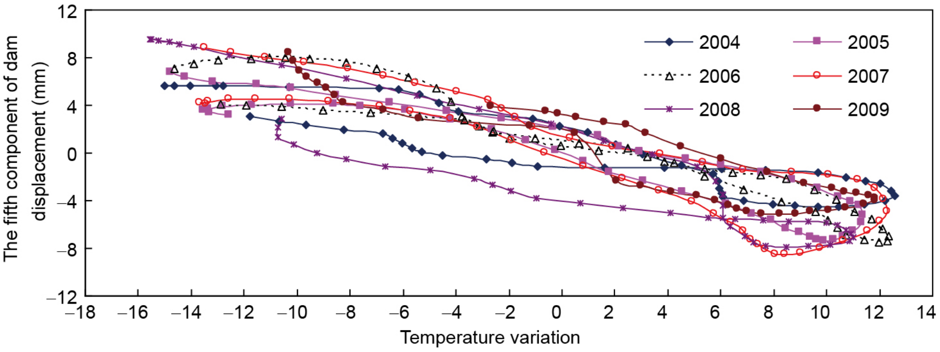

Figure 7 (Color online) Relationship between the 5th high frequency wavelet component of dam displacement and temperature variation from 2004 to 2009.

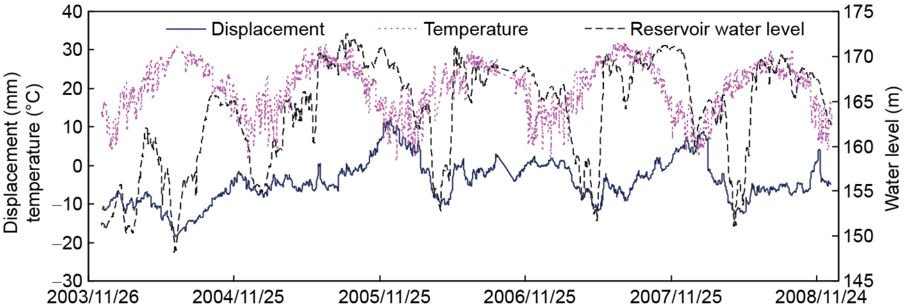

Figure 8 (Color online) Time series of dam crest stream displacement, reservoir water level and temperature.

displacement and its influencing factors should be conducted firstly, and then wavelet components with the same frequency characteristic can be used to establish the relationship between effect-quantity and influencing factors.

The periodicities of high frequency components of dam displacement, reservoir water level and air temperature at the same decomposition layer are almost the same. The normalized power spectrums of the 8th high frequency wavelet components are shown in Figure 9. As can be seen, the dominant frequency is 0.0027. Taking into account the monitoring interval of once every day, the cycle period is about 370 d. The 8th high frequency component of radial displacement is the dam deformation under the comprehensive annual periodic effects of air temperature and hydraulic pressure. Time series of the 8th high frequency wavelet components are shown in Figure 10.

Due to the dam reservoir water level changes from 146 to 173 m, 12 groups of water level are determined to calculate the deformation hydraulic pressure component by FEM. They are respectively 173 m (the normal water level), 170, 167.5, 165, 162.5, 160, 157.5, 155, 152.5, 150, 147.5 and 146 m. The multi-year average reservoir water level in the analysis period is 162.75 m, and the corresponding water depth is 96.5 m. When reservoir water level fluctuates around this base value, the relationship between the variations of hydraulic pressure component of dam crest radial displacement $\Delta\delta'_H$ and water depth by FEM is shown in Figure 11 and expressed as eq. (13).

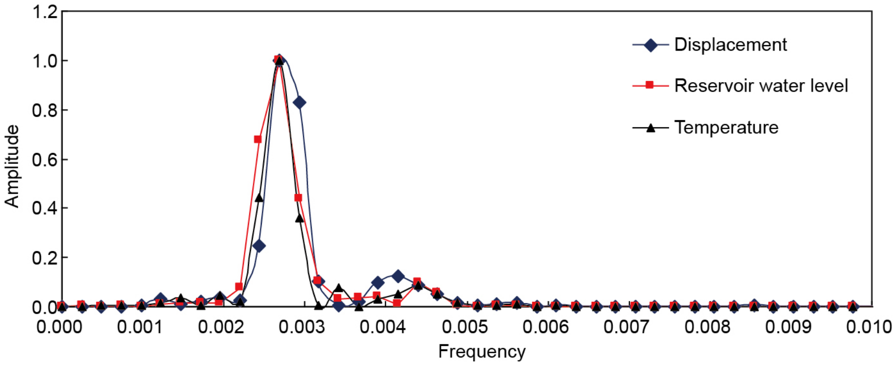

Figure 9 (Color online) Normalized power spectrums of the 8th high frequency wavelet components of stream displacement, temperature and reservoir water level.

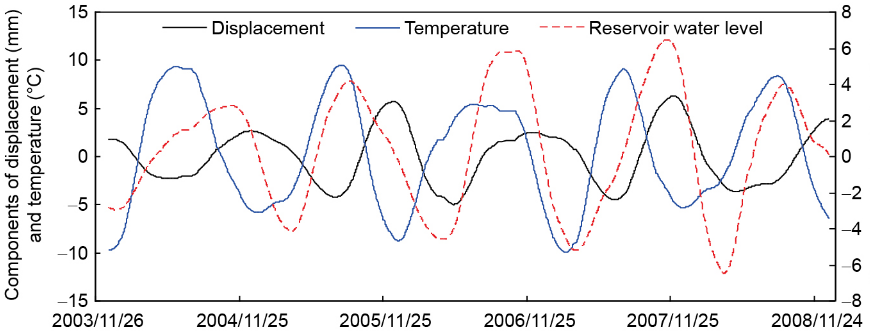

Figure 10 (Color online) Time series of the 8th high frequency wavelet components of stream displacement, temperature and reservoir water level.

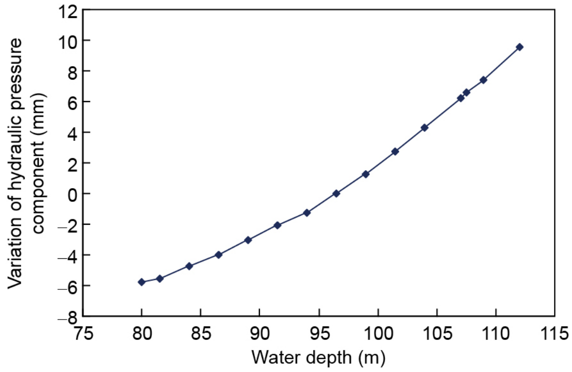

Figure 11 Relationship between the variation of water pressure component and water depth by FEM.

$$\Delta\delta'_H = 7.53\times10^{-4}(H-96.5) -3.3\times10^{-3}(H^2-96.5^2)+4.01\times10^{-5}(H^3-96.5^3). \tag{13}$$

According to eq. (11), piecewise models can be established for the 8th high frequency component of dam crest radial displacement. Regression coefficients are shown in Table 1. The negative coefficients in temperature component represent the upstream direction dam deformation at the rise stage of air temperature, which accords with practice. The slightly increase tendency of adjustment coefficients of water pressure component and temperature component indicates the slowly variation of integer stiffness and temperature expansion of concrete dam body during this operation stage.

Statistical models are commonly used to separate the influences of different factors, and then to observe anomalies. The most common statistic method in dam engineering is called HST (hydrostatic, season, time) model. To illustrate the rationality of the proposed method, adjustment coefficient X of water pressure component is also calculated by the HST model. The hydrostatic component δ_H calculated by FEM is fitted as follows:

Table 1 Fitting coefficients of the 8th high frequency wavelet components of dam crest stream displacement from 2004 to 2008

Adjustment coefficients	Hydraulic pressure component X	Temperature component b
2004	1.195	−0.489
2005	1.193	−0.494
2006	1.211	−0.497
2007	1.224	−0.502
2008	1.227	−0.507

$$\delta_H = 0.1095H-0.0047H^2+4.5211\times10^{-5}H^3. \tag{14}$$

The HST model is established as shown in eq. (15), and the separated components of hydrostatic, temperature and time-dependent are shown in Figure 12.

$$\begin{aligned}\delta &= X\delta_H+\delta_T+\delta_\theta\\ &= 1.2234(0.1095H-0.0047H^2\\ &\quad +4.5211\times10^{-5}H^3)-3.8999\sin\frac{2\pi t}{365}\\ &\quad +1.4985\cos\frac{2\pi t}{365}-0.3094\sin\frac{4\pi t}{365}\\ &\quad -0.9756\cos\frac{4\pi t}{365}-0.0206\theta+0.0471\ln\theta,\end{aligned} \tag{15}$$

where t is the cumulative days from the initial monitoring date, which is the first day of January of 2004 for this analysis; θ is the cumulative days divided by 100.

The adjustment coefficient X of water pressure component in the HST model is 1.2234, which is very close to the values calculated by the method proposed in this paper. As for the longer monitoring period is required for the HST model, it is difficult to reflect the time-varying effect of X, which is also the advantage of the proposed method.

5 Conclusions

In order to study the time-varying problem of structural deformation behavior of concrete dams in the long-term service period, observed displacement data-based identification method of the deformation time-varying effect is proposed on the base of causing factors analysis. The main results are as follows:

(1) The time-varying effect is consisted of two parts, which are the inherent time-varying effect and the time-varying effect caused by dam structural performance change.

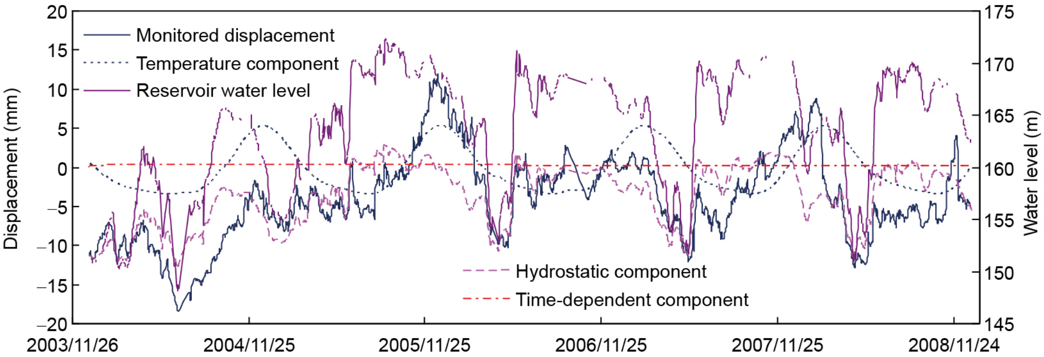

Figure 12 (Color online) Time series of dam crest stream displacement and its components separated by HST model.

(2) Causal models for the high frequency components of dam displacement decomposed by the wavelet multi-resolution analysis is suitable to be used in identifying the change of dam recoverable deformation ability.

(3) Except for the unrecoverable time-dependent deformation, the recoverable deformation increases slowly during dam operation. It should be carefully dealt in the studying of dam long-term deformation.

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