Steel and Composite Structures, *Vol. 36, No. 5 (2020) 521-531*
DOI: https://doi.org/10.12989/scs.2020.36.5.521

An analytical approach of behavior change for concrete dam by panel data model

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(*Received May 11, 2020, Revised July 23, 2020, Accepted August 13, 2020*)

Abstract. The behavior variation of concrete dam is investigated, based on a new method for analyzing the data model of concrete dam in service process for the limitation of wavelet transform for solving concrete dam service process model. The study takes into account the time and position of behavior change during the process of concrete dam service. There is no dependence on the effect quantity for overcoming the shortcomings of the traditional identification method. The panel data model is firstly proposed for analyzing the behavior change of composite concrete dam. The change-point theory is used to identify whether the behavior of concrete dams changes during service. The phase space reconstruction technique is used to reconstruct the phase plane of the trend effect component. The time dimension method is used to solve the construction of multi-transformation model of composite panel data. An existing 76.3-m-high dam is used to investigate some key issues on the behavior change. Emphasis is placed on conversion time and location for three time periods consistent with the practical analysis report for evaluating the validity of the analysis method of the behavior variation of concrete dams presented in this paper.

Keywords: panel; concrete dam; behavior variation; data model; conversion time and location

1. Introduction

Concrete dams are special steel and composite structures, serving to retain flood water. Their safety is related to national security and social stability. As their behaviors deteriorate up to certain degree, there will be state conversion. Concrete dam behavior conversion mainly refers to the mechanical behavior, statistical properties and dynamic characteristics in current state, which differ significantly from the previous state. The behavior evolution law of concrete dams is caused by concrete dam behavior conversion, which further leads to the abnormal security status of the entire concrete structure (Adanur et *al.* 2016, Aslani *et al.* 2016, Su *et al.* 2015, Zhang *et al.* 2019). Therefore, it can be used to analyze, evaluate and summarize the previous evolution law of concrete dam behavior and timely identify the current state of concrete dam behavior conversion. The future principles of development and security status of concrete dam will be suggested based on the behavior conversion evolution. Hence, the aim of this paper is to study the identification method of concrete dam behavior conversion. As we all know, there are usually one or more conversion points during the process of concrete dam behavior fault. In order to effectively identify the concrete dam behavior conversion, a large number of monitoring instruments are usually set to monitor the effect values of concrete dams, which can objectively reflect the variation of the concrete dam structural properties. The behavior variation will be caused by abnormal change of effect values (Bayagoob *et al.* 2010, Katariya *et al.* 2020).

In order to determine the occurrence time and location of faults, based on the variation of in-situ monitoring data effect values, Gu Chongshi *et al.* analyzed the basic principle of dam and rock foundation stability by utilizing catastrophic theory, and established the criterion of dam behavior conversion (Altunisik *et al.* 2017, Christopher *et al.* 2020). Bao Tengfei *et al*. explored the variation law of crack opening degree, and put forward the criterion of concrete dam crack stability and behavior variation. Li Xuehong *et al*. proposed the fault diagnosis model of concrete dam cracks based on wavelet analysis and catastrophe theory, and reconstructed the phase plane of aging deformation through phase space reconstruction technology, thereby determining the fault occurrence time of concrete dam cracks (Agouzal *et al.* 2008, Chen *et al.* 2016, Jaan *et al.* 2019). Li *et al.* also proposed the fault diagnosis criterion of different concrete dam cracks based on statistical theory (Li *et al.* 2009, Burenkova *et al.* 2020, Zhang *et al.* 2017). A method was put forward by Lai Daoping *et al*. to determine whether the dam behavior conversion based on dam in-situ monitoring data by means of fractal dimension.

However, all of above methods are with some limitations, such as rough accuracy of conversion points identification, and can only diagnose conversion occurrence

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ISSN: 1229-9367 (Print), 1598-6233 (Online)

time.

For solving above problems, the panel data diagnosis model of concrete dam behavior fault is proposed which can determine the occurrence time and position of concrete dam behavior fault.

2. Method

Wavelet method was once used to isolate the aging components from the monitoring effect values facing concrete dam behavior fault problems, and concrete dam behavior fault is identified by the phase plane space method. The modeling principle of this method is as follows.

2.1 Analytical model of concrete dam behavior variation

In order to identify the appearance of concrete dam behavior variation, the aging components are usually used by wavelet theory from the monitoring effect values.

In the wavelet analysis, the discrete wavelet transform of the measured signal can be described as

$$W_f(\mathrm{j},\mathrm{k}) = \langle f, \psi_{\mathrm{j,k}} \rangle = 2^{-\frac{j}{2}} \int_R f(t)\overline{\psi(2^{-j}t-k)}dt \qquad (1.1)$$

If the subspace W_{j+1} and V_j satisfy the relation as follows

$$V_j = W_{j+1} \oplus V_{j+1}, W_{j+1} \perp V_{j+1} \qquad (1.2)$$

Then W_{j+1} is the orthogonal complement space of V_j , and the relation can be obtained

$$V_0 = W_1 \oplus V_1 = W_1 \oplus W_2 \oplus V_2 = W_1 \oplus \ldots \oplus W_j \oplus V_j \qquad (1.3)$$

Concrete dam monitoring data is series of measured digital signal. Known from $V_{j-1} = W_j \oplus V_j$, the projection of the signal at V_i is its low-frequency part, written as A_j , the projection of the signal at W_i is its high-frequency part, written as D_j . By analogy, the signal can be decomposed step by step.

Concrete dam monitoring data can be decomposed by utilizing wavelet to roughly remove high-frequency parts affected by water pressure, temperature variation, random factors and errors. And, then the remaining low-frequency parts can be approximately recognized as the aging components of the concrete dam monitoring data.

The phase space of the isolated aging components is reconstructed:

$$\dot{\delta}_\theta = f(\delta_\theta, \alpha) \qquad (1.4)$$

In equation: δ_θ is the aging component of concrete dam monitoring data, $\dot{\delta}_\theta$ is the changing rate of aging component, α is the parameter.

$\dot{\delta}_\theta$ and δ_θ characterize the motion state at any time in Eq. (1.4), which is recognized as phase, $\dot{\delta}_\theta$ and δ_θ are phase points, and $(\delta_\theta, \dot{\delta}_\theta)$ is phase plane. To reconstruct phase plane, variation process of $(\delta_\theta, \dot{\delta}_\theta)$ can be present with δ_θ as the abscissa and $\dot{\delta}_\theta$ as the ordinate. Concrete dam behavior conversion can be identified roughly by phase plane.

The panel data analysis method of concrete dam behavior conversion is further explored to provide the theoretical basis for the effective identification of behavior fault during the dam service facing at the shortage of wavelet phase plane analysis model, and for the convenience of methods analysis and comparison.

Instruments of monitoring deformation, stress, strain and seepage are often set in the dam body, foundation and reservoir basin. A comprehensive monitoring system is formed based on these monitoring points to monitor the dam surface, interior, foundation and reservoir basin. Through long-term monitoring, a matrix X_{it} composited by monitoring effect values and a series of monitoring values D_{it} can be obtained. Panel data model is with the analysis function of both the cross-section data model and the time series model (Diao *et al*. 2011, Hartford *et al*. 2004), the general form of concrete dam panel data model is described as

$$X_{it} = \begin{bmatrix} x_{11} & x_{12} & \cdots & x_{1t} \\ x_{21} & x_{22} & \cdots & x_{2t} \\ \vdots & \vdots & \ddots & \vdots \\ x_{i1} & x_{i2} & \cdots & x_{it} \end{bmatrix} D_{it} = \begin{bmatrix} D_{11} & D_{12} & \cdots & D_{1t} \\ D_{21} & D_{22} & \cdots & D_{2t} \\ \vdots & \vdots & \ddots & \vdots \\ D_{i1} & D_{i2} & \cdots & D_{it} \end{bmatrix}$$

$(i = 1, 2, \cdots N\ ,\ \ t = 1, 2, \cdots T)$

$$D_{it} = \beta_i X_{it} + \alpha_i + \gamma_{it} \qquad (1.5)$$

In equation: i is number of monitoring points; t is monitoring time series; D_{it} contains two dimensional information: cross-sectional dimension N and temporal dimension T ; α_i is a variable which only varies with individuals; η_t is a variable which only varies with time; γ_{it} is a variable which varies with time and individuals.

The general form of concrete dam panel data model can be divided into three modes according to different parameters:

Mode 1: $D_{it} = \beta_i X_{it} + \alpha_i + \gamma_{it}$ (Variable coefficient panel data model)

Mode 2: $D_{it} = \beta X_{it} + \alpha_i + \gamma_{it}$ (Variable intercept panel data model)

Mode 3: $D_{it} = \beta X_{it} + \alpha + \gamma_{it}$ (Fixed intercept and fixed coefficient panel data model)

F test can be utilized to determine the parameter types then to choose the suitable mode of concrete dam panel data model.

Above all, modelling process of concrete dam panel data model is exhibited as follows.

(1) The processed monitoring data is substituted into the general form of concrete dam panel data model.

(2) The suitable mode of concrete dam panel data model is selected by F test.

(3) The parameters are estimated and the modelling is completed.

2.2 Diagnosis method of behavior fault of concrete dam

In above chapter, the traditional wavelet phase plane analysis model is studied. And on this basis, the panel data model of concrete dam is established in order to identify concrete dam behavior fault. The traditional wavelet phase plane analysis model can only roughly identify concrete dam behavior fault, and the analysis accuracy depends on the accuracy of aging components, which are isolated from effect values by wavelet. The panel data model of concrete dam, established in this paper, can identify the occurrence time and location of concrete dam behavior variation. It is independent with effect values and overcomes the shortcomings of traditional fault identification methods. In order to facilitate comparison of different methods, the following research focuses on panel data model to identify concrete dam behavior fault on the basis of wavelet phase plane analysis model.

(1) Wavelet phase plane model to identify concrete dam behavior fault

The aging component changes from steady increase to nonlinear increase, as shown in Fig. 1 as behavior variation is occurred during concrete dam in service. The phase plane is reconstructed by derivative reconstruction method, as shown in Fig. 2. It can be seen in Figs. 1 and 2, in period $t_0 \sim t_A$, the raising velocity $\dot{\delta}_\theta$ of aging component δ_θ decreases gradually while the raising velocity of aging component increases gradually during period $t_A \sim t_1$. At the point t_A, there is a sudden change in the raising law of aging component, which is the behavior conversion occurrence time during the concrete dam in service. In phase plane, t_A is performed as the second derivative of aging component $\ddot{\delta}_\theta$ at that time is zero, which orbital phase produces an inflection point, as can be seen in Eq. (1.6).

$$\begin{cases} \dot{\delta}_\theta = \dfrac{d\delta_\theta}{dt} \geq 0 & t_0 \leq t \leq t_1 \\ \ddot{\delta}_\theta = \dfrac{d^2\delta_\theta}{dt^2} < 0 & t_0 \leq t < t_A \\ \ddot{\delta}_\theta = \dfrac{d^2\delta_\theta}{dt^2} = 0 & t = t_A \\ \ddot{\delta}_\theta = \dfrac{d^2\delta_\theta}{dt^2} > 0 & t_A < t \leq t_1 \end{cases} \tag{1.6}$$

In equation: δ_θ is aging component of concrete dam monitoring data; $\dot{\delta}_\theta$ is the first derivative of aging component; $\ddot{\delta}_\theta$ is the second derivative of aging component.

The panel data model is a new statistical method developed in recent decades. The panel data model is also firstly used for analyzing the behavior change of composite concrete dam. It is for pooled time series and cross section data. It can overcome the problem of time series analysis by multicollinearity and provide more information, more changes, less collinearity, more freedom and higher estimation efficiency. And unit root test, co-integration analysis and practical application promotion of the panel data model are ones of the most advanced fields.

As the aging component of concrete dam monitoring data satisfies the judgment criteria listed in Eq. (1.6), the moment t_A is considered as the occurrence time of concrete dam behavior conversion.

(2) Panel data model to identify concrete dam behavior variation

In previous sections, the behavior variation occurrence time can be identified through wavelet phase plane model. However, the accuracy of this method is dependent on the accuracy of aging component isolated by wavelet. Therefore the behavior occurrence can only be roughly identified. In order to solve above problems, in this paper, panel data model is introduced, which can identify the occurrence time and location of concrete dam behavior occurrence.

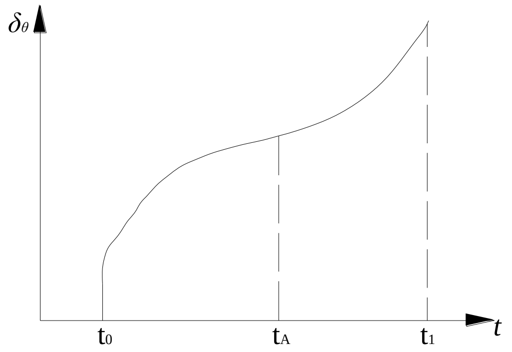

Fig. 1 The diagram of typical aging component of concrete dam behavior conversion

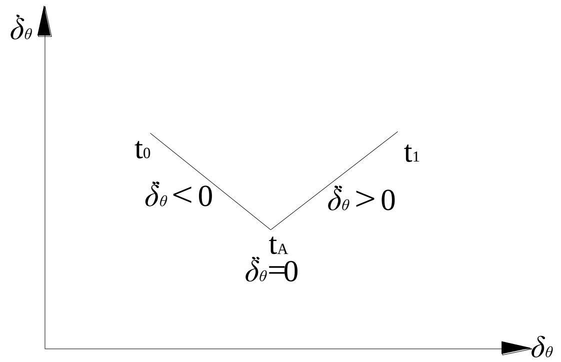

Fig. 2 The phase plane of typical aging component of concrete dam behavior conversion

In actual project, it is difficult to determine the occurrence time of concrete dam behavior conversion. When the moment of behavior fault is unknown, the problem of identifying the behavior fault by panel data model is transformed into change-point problem of panel data model. As there is any change in the distribution of panel data model sequence, at an unknown time, it is changed to another law marked the time for the behavior conversion occurrence. Therefore, concrete dam behavior conversion occurrence can be tentatively identified by use of change-point theory (Rezaiee-Pajand *et al.* 2013, Shariatmadar *et al.* 2011). The in-situ monitoring data is selected to study panel data model identification method of concrete dam behavior conversion.

Firstly, change-point (behavior conversion point) panel data model is established as

$$\begin{cases} D_{it} = \beta_i x_{it} + w_{it} & i = 1,2,\cdots N, t = 1,2,\cdots k_0 - 1 \\ D_{it} = \beta_i x_{it} + \beta_i ' v_{it} I(t \ge k_0) + w_{it} & i = 1,2,\cdots N, t = k_0 ... \mathrm{T} \\ w_{it} = \alpha_i + \gamma_{it} & i = 1,2,\cdots N, t = 1,2,\cdots T \end{cases} \quad (1.7)$$

In equation: $I(.)$ is indicative function, D_{it} is endogenous variable of monitoring data effect value, x_{it} and v_{it} are exogenous variables, $v_{it} = Rx_{it}$, R is a known matrix, vector β_i and β_i' are coefficients to be estimated, α_i is effect variable which is fixed or random, k_0 is behavior fault point, γ_{it} is disturbance.

(3) Behavior conversion point estimation of fixed effect panel data model

If α_i in Eq. (1.7) is fixed, Eq. (1.7) can be defined as behavior fault point panel data model of fixed effect. Then the estimate method of behavior fault point k_0, coefficients β_i and β_i' will be studied. Since no restrictions are on model coefficients and the intercept is also fixed, the model can be estimated utilizing the least squares method. The sum of residual squares ESS1 and ESS2 of coefficients β_i and β_i' are respectively calculated as

$$ESS_1 = \sum_{i=1}^{N} \sum_{t=1}^{k} (D_{it} - \hat{\beta}_i(k) x_{it})^2 \quad (1.8)$$

$$ESS_2 = \sum_{i=1}^{N} \sum_{t=k+1}^{T} (D_{it} - \hat{\beta}_i '(k) x_{it})^2 \quad (1.9)$$

The sum of residual squares RSS(k) is the sum of ESS1 and ESS2 as (Zhang *et al.*)

$$RSS(k) = \sum_{i=1}^{N} \sum_{t=1}^{k} (D_{it} - \hat{\beta}_i(k) x_{it})^2 + \sum_{i=1}^{N} \sum_{t=k+1}^{T} (D_{it} - \hat{\beta}_i '(k) x_{it})^2 \quad (1.10)$$

The estimation of behavior fault point is defined as

$$\hat{k}_{NT} = \arg\min RSS(k) \quad (1.11)$$

In equation: N is the location of concrete dam behavior fault, T is the occurrence time of concrete dam behavior fault.

Substituted the obtained $\hat{k}_{NT}$ to estimate the gradient coefficients $\hat{\beta}_i(k)$ and $\hat{\beta}_i '(\mathrm{k})$ as

$$\hat{\beta}_i(k) = \frac{\sum_{i=1}^{N} \sum_{t=1}^{k} D_{it} x_{it}}{\sum_{i=1}^{N} \sum_{t=1}^{k} x^2{}_{it}} \quad (1.12)$$

$$\hat{\beta}_i '(k) = \frac{\sum_{i=1}^{N} \sum_{t=k+1}^{T} D_{it} x_{it}}{\sum_{i=1}^{N} \sum_{t=k+1}^{T} x^2{}_{it}} \quad (1.13)$$

(4) Behavior conversion point estimation of random effect panel data model

Eq. (1.7) can be defined as behavior fault point panel data model of random effect as α_i is random. In order to estimate behavior fault point, Eq. (1.7) can be written as the following vector matrix form:

$$\begin{cases} \mathbf{D} = \mathbf{X}\boldsymbol{\beta} + \mathbf{w} \\ \mathbf{D} = \mathbf{X}\boldsymbol{\beta} + \mathbf{V}\boldsymbol{\beta}' + \mathbf{w} \\ \mathbf{w} = \mathbf{L}\boldsymbol{\alpha} + \boldsymbol{\gamma} \end{cases} \quad (1.14)$$

In equation: $\mathbf{L}$ is Kronecker product of e_T and I_N , e_T is T-dimensional unit vector, I_N is N-dimensional unit matrix, Assuming that x_{it} and w_{it} are independent and identical distribution (i.i.d), $E(\mathbf{w}) = 0$, $E(\mathbf{ww}') = \mathbf{U}$.

Since α_i is random, it is not possible to use the least squares estimation like the fixed effect panel data model, as the coefficients cannot be estimated unbiased, therefore generalized least square method is adopted to estimate the random effect panel data model, then the gradient coefficients are estimated as (Khazaee *et al.*)

$$\begin{pmatrix} \hat{\boldsymbol{\beta}}_k \\ \hat{\boldsymbol{\beta}}'_k \end{pmatrix} = \begin{pmatrix} \sum_{i=1}^{N} \mathbf{X}_i '\mathbf{U}^{-1}\mathbf{X}_i & \sum_{i=1}^{N} \mathbf{X}_i '\mathbf{U}^{-1}\mathbf{V}_k^{(i)} \\ \sum_{i=1}^{N} \mathbf{V}_k^{(i)} '\mathbf{U}^{-1}\mathbf{X}_i & \sum_{i=1}^{N} \mathbf{V}_k^{(i)} '\mathbf{U}^{-1}\mathbf{V}_k^{(i)} \end{pmatrix}^{-1} \begin{pmatrix} \sum_{i=1}^{N} \mathbf{X}_i '\mathbf{U}^{-1}\mathbf{D}_i \\ \sum_{i=1}^{N} \mathbf{V}_k^{(i)} '\mathbf{U}^{-1}\mathbf{D}_i \end{pmatrix} \quad (1.15)$$

The sum of squared residuals is defined as

$$SSR(k) = (\mathbf{D} - \mathbf{X}\hat{\boldsymbol{\beta}}_k - \mathbf{V}_k \hat{\boldsymbol{\beta}}'_k)' \mathbf{U}^{-1} (\mathbf{D} - \mathbf{X}\hat{\boldsymbol{\beta}}_k - \mathbf{V}_k \hat{\boldsymbol{\beta}}'_k) \quad (1.16)$$

The selection criteria of the behavior conversion point is defined as

$$\hat{k}_{NT} = \hat{k}_0 = \arg\min RSS(k) \quad (1.17)$$

In equation: N is the location of concrete dam behavior conversion, T is the occurrence time of concrete dam behavior conversion.

(5) Estimate multiple behavior conversion point by panel data model

In actual project, there may be multiple behavior fault points among monitoring data, which the number of behavior fault points are unknown (Hu *et al.*, Dempster *et al.* 1967). The previous analysis is based on the case that there is only a single behavior fault point. This method could be used to solve above problem and avoid the defect

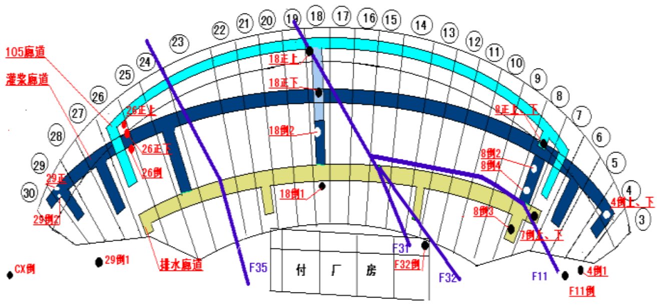

Fig. 3 Measure points layout of the concrete dam

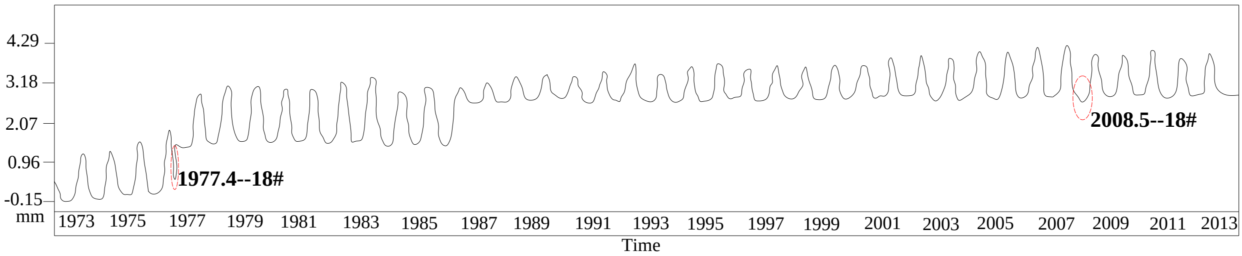

Fig. 4 Measured data of crack opening for No.18

of previous method. Therefore, utilizing panel data model to estimate multiple behavior fault point is studied.

Multiple behavior fault points are generated in time dimension, which time series T are divided into multiple segments, each segment contains a behavior fault point. Suppose that there are j behavior fault points $\{k_1,\ldots,k_j\}$, $k_0=0, k_{j+1}=T$, then multiple behavior conversion point panel data model can be described as

$$\begin{cases} D_{it}=\beta x_{it}+\alpha_i+\gamma_{it} & t=k_{m-1}+1,\ldots,k_m \\ D_{it}=\beta x_{it}+\beta'^{(m)}v_{it}+\alpha_i+\gamma_{it} & t=k_m+1,\ldots,k_{m+1} \end{cases} \tag{1.18}$$

In equation: $i=1,\ldots,n$, $m=1,\ldots,j$.

For each time segment, it can still be regarded as the problem of estimating the single behavior fault point. The sum of squared residuals is calculated to single estimate behavior fault point $\hat{k}_m$ in each segment. By analogy, the estimation of multiple behavior conversion points $\{k_1,\ldots,k_j\}$ can be defined as

$$\{\hat{k}_1,\ldots,\hat{k}_j\}=\arg\min_{\{k_1,\ldots,k_j\}} RSS(\{k_1,\ldots,k_j\}) \tag{1.19}$$

3. Case study

A concrete gravity arch dam with concentric circular radius is selected as a project example based on above theory. The dam top elevation is 126.3 m, the maximum dam height is 76.3 m, the dam top arc length is 419 m, the dam top width is 8 m, and the maximum dam bottom width is 53.5 m. There are 28 dam zones from left to right, and the geological conditions of the dam site are complex. Owing to the phase concrete rapidly increases and the pouring interval is short, the contraction and deformation of the second-phase concrete is strongly restrained by the first-phase concrete, which causes cracks near the 105 m elevation, top of the first-phase concrete. The crack extents from No.5 dam zone to No.28 dam zone, more than 300 meters long and 5 m deep, which weakens the rigidity of the dam and affects the integrity of the dam. Therefore, first of all, it is necessary to determine whether the concrete dam occurs behavior fault, and to analyze the location and the occurrence time of behavior fault. In order to monitor the security of the project, a large number of health monitoring instruments are buried in the dam, and the distribution of measuring points are shown in Fig. 3. The time series is selected from January 1st, 1 973 to October 30th, 2013. The data of measured deformation points and the 105m elevation crack monitoring points of No.18 dam zone are collected to analyze whether behavior fault occurs during the dam in service.

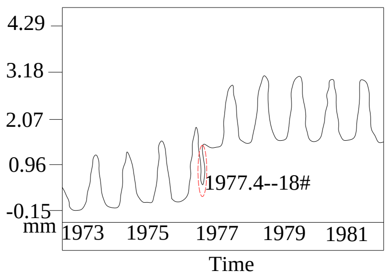

Fig. 5 The detailed measured data during 1973~1971

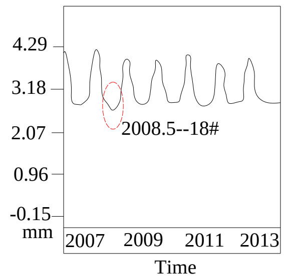

Fig. 6 The detailed measured data during 2007~2013

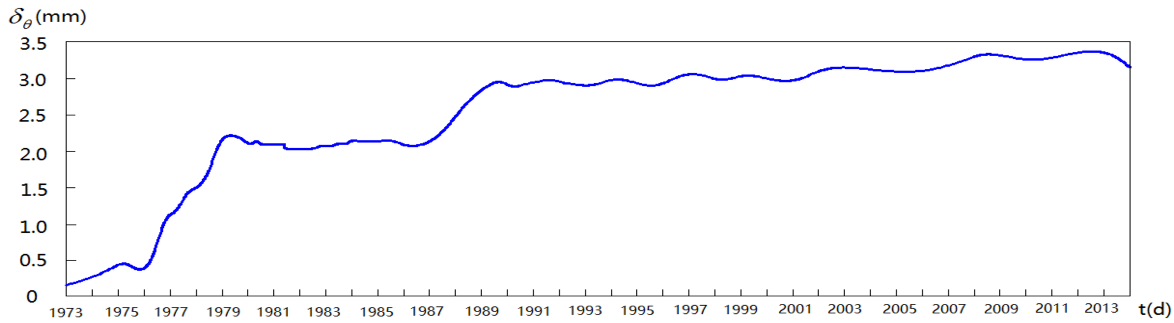

Fig. 7 The line chart of typical measure point crack opening aging component

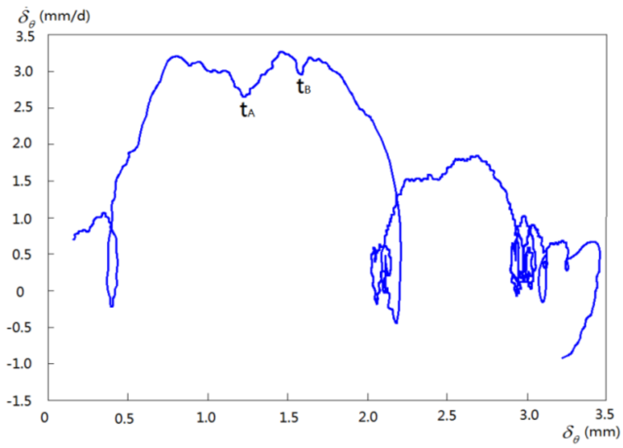

Fig. 8 Phase plane of aging component of crack opening

(1) Wavelet phase plane identification model of concrete dam behavior conversion

In order to judge concrete dam behavior variation, the traditional wavelet phase plane identification model is introduced, the specific steps are as follows.

First of all, in-situ crack monitoring data of concrete dam is isolated by use of wavelet. Filter out the high frequency parts of crack monitoring data, and the remaining low frequency parts are used as aging components, which can be seen in Eqs. (1.1)-(1.3). Since the variation of the 105m elevation horizontal crack generally reflects the structural behavior variation of the dam, the crack measured data of 105m elevation in No.18 dam zone is taken as an example for analysis. Curve of measured crack opening values is shown in Figs. 4-6. The variable process line of aging component isolated from crack monitoring data by wavelet is shown in Fig. 7.

It can be seen from Fig. 7 that the variation tendency of the crack opening aging component produces a certain fluctuation, which aging component isolated by wavelet generates two great changes in 1977 and 1987.

As shown in Fig. 7, phase plane of aging component is reconstructed by phase space theory, where the horizontal axis is the aging component δ_θ and the vertical axis is the variable rate of the aging component $\dot{\delta}_\theta$.

It can be seen from Fig. 8 that phase plane of aging component produces inflection points at t_A and t_B. The

Table 1 Fixed effect model of concrete dam deformation panel data

Fixed-effect model						
Fixed-effects (within) regression				Number of obs	=61,720	
Group variable: _j				Number of groups	=20	
R-sq: within	= 0.1834			Obs per group : min	=3086	
between	= 0.0000			avg	=3086.0	
overall	= 0.0262			max	=3086	
				F(10,61688)	=1385.05	
corr(u_i, X)	= 0 (assumed)			Prob > F	=0.0000	
var	Coef.	Std.Err.	z	P>|z|	[95%Conf.Interval]	
x_1	-0.043429	0.018308	-2.37	0.018	-0.079313	-0.0075456
x_2	-0.000802	0.0072855	-0.11	0.912	-0.079313	0.013478
x_3	0.000871	0.0009775	0.89	0.373	-0.0010454	0.0027863
x_4	0.000053	0.000041	1.29	0.196	-0.0000273	0.0001333
x_5	-0.443264	0.0051323	-86.37	0.000	-0.4533232	-0.4332047
x_6	-0.270816	0.0065632	-41.26	0.000	-0.2836801	-0.2579525
x_7	-0.199294	0.0050283	-39.63	0.000	-0.2091495	-0.1894387
x_8	-0.090028	0.005404	-16.66	0.000	-0.10062	-0.0794364
x_9	0.000186	8.00e-06	23.23	0.000	0.0001703	0.0002017
x_{10}	-0.715675	0.0356895	-20.05	0.000	-0.7856261	-0.6457231
_cons	-0.898810	0.0295981	-30.37	0.000	-0.9568226	-0.840798
sigma_u	2.4684639					
sigma_e	0.87735078					
rho	0.88784237			(fraction of variance due to u_i)		

variation characteristics of the curve near t_A and t_B are similar to the typical variation characteristics of concrete dam behavior fault shown in Fig. 3, therefore, t_A and t_B can be considered as behavior variation point. According to the corresponding in-situ monitoring data, the occurrence time of behavior fault are April 7th, 1977 and May 11th, 1978. Based on the monitoring data of 105 m elevation crack in No.18 dam zone and analysis of corresponding environmental quantities, the crack opening has increased at the end of 1976, until April 1977 the crack opening generally enlarges. Therefore, it is reasonable to identify the behavior fault point on 7 April 1977 by use of wavelet phase plane identification model. After April 1977, the increase of crack opening becomes stable without significant change, while the behavior fault point May 11th, 1978 identified by the model cannot find the corresponding conclusion in the analysis of in-situ monitoring data. In addition, the crack aging component isolated by wavelet takes place a great change in 1987, and the crack opening generally enlarges. However, there is no inflection point on the corresponding phase plane plot shown in Fig. 8.

(2) Panel data model to identify concrete dam behavior variation

For analysis and comparison, the panel data model proposed is used to identify concrete dam behavior conversion. The monitoring data of deformation measuring points IP4_1, IP4_2U, IP4_2D, IP7U, IP7D, PL8U, PL8D, IP8_2, IP8_3, IP8_4, PL18U, PL18D, IP18_1, IP18_2, PL26U, PL26D, IP26_1, IP29_1, PL29_1 and IP29_2 are selected. Since the variation effect of crack at 105 m elevation has been reflected in dam deformation, the behavior conversion of crack is not analyzed specifically. Firstly, concrete dam panel data model is established f by substituting the monitoring data as follows

$$D_{it} = \beta_i X_{it} + \alpha_i + \gamma_{it} \quad (i = 1,2,\cdots N, t = 1,2,\cdots T) \tag{2}$$

In equation: hydraulic pressure, temperature, and aging, the most important factors affecting the deformation of concrete dam, are characterized by H , T , θ respectively, then $X_{it} = \left(H_t^1, H_t^2, H_t^3, H_t^4, T_{1,t} \cdots, T_{m,t}, \theta_t, \ln\theta_t\right)'$; $\beta_i = (a_1, a_2, \ldots, a_l)$ is coefficient to estimate; l is number of factors, α_i is effect value(fixed or random), γ_{it} is random error which mean is 0, variance is σ^2 and satisfies independent and identical distributions.

Construct fixed effect panel data model as shown in Table 1, $(x_1, x_2, \ldots, x_{10})$ representing the factors.

Then Hausman test is used to test whether the model

Table 2 Hausman test

var	(b) fe	(B) re	(b-B) difference
x_1	-0.0434293	-0.0434293	3.01e-11
x_2	-0.0008016	-0.0008016	1.50e-11
x_3	0.0008705	0.0008705	2.12e-12
x_4	0.000053	0.000053	8.94e-14
x_5	-0.443264	-0.443264	-7.50e-13
x_6	-0.2708163	-0.2708163	-9.22e-13
x_7	-0.1992941	-0.1992941	3.52e-13
x_8	-0.0900282	-0.0900282	1.88e-13
x_9	0.000186	0.000186	-1.92e-15
x_{10}	-0.7156746	-0.7156746	6.62e-12
b = consistent under Ho and Ha, obtained from xtreg			
B = inconsistent under Ha, efficient under Ho, obtained from xtreg			

Table 3 Random effect model of concrete dam deformation panel data

Random effects model						
Random-effects GLS regression				Number of obs		=61,720
Group variable: _j				Number of groups		=20
R-sq: within		= 0.0000		Obs per group : min		=3086
between		= 0.0000		avg		=3086.0
overall		= 0.0262		max		=3086
				Wald chi2(10)		=13850.50
corr(u_i, X)		= 0 (assumed)		Prob > chi2		=0.0000
var	Coef.	Std.Err.	z	P>|z|	[95%Conf.Interval]	
x_1	-0.0434293	0.018308	-2.37	0.018	-0.0793123	-0.0075463
x_2	-0.0008016	0.0072855	-0.11	0.912	-0.0150809	0.0134778
x_3	0.0008705	0.0009775	0.89	0.373	-0.0010453	0.0027863
x_4	0.000053	0.000041	1.29	0.196	-0.0000273	0.0001333
x_5	-0.443264	0.0051323	-86.37	0.000	-0.453323	-0.4332049
x_6	-0.2708163	0.0065632	-41.26	0.000	-0.2836798	-0.2579527
x_7	-0.1992941	0.0050283	-39.63	0.000	-0.2091493	-0.1894389
x_8	-0.0900282	0.005404	-16.66	0.000	-0.1006198	-0.0794366
x_9	0.000186	8.00e-06	23.23	0.000	0.0001703	0.0002017
x_{10}	-0.7156746	0.0356895	-20.05	0.000	-0.7856247	-0.6457245
_cons	-0.8988103	0.6603789	-1.36	0.173	-2.193129	0.3955085
sigma_u	2.4684285					
sigma_e	0.87735078					
rho	0.88783951			(fraction of variance due to u_i)		

can be modeled utilizing the random effect panel data model. Hausman test is shown in Table 2.

The selected monitoring data can be modeled by the random effect panel data model after testing. The random effect panel data model is shown in Table 3.

Concrete dam behavior conversion can be identified by utilizing the established random effect panel data model. The specific steps are as follows. Panel data model is analyzed by F test to determine the occurrence of behavior conversion. The result shows that the model is not stable, as the coefficient β in F test alters at some moments, indicating that behavior conversion occurs.

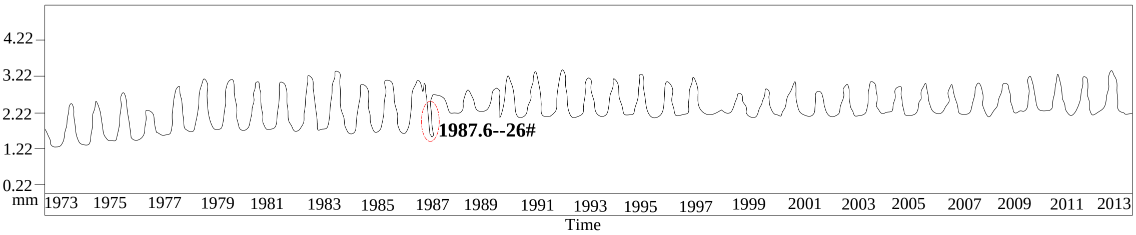

Fig. 9 Measured data of crack opening for 26#

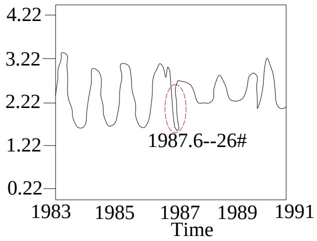

Fig. 10 Measured data of crack opening during 1983~1991 for 26#

Then the occurrence moments of behavior conversion are judged by utilizing multiple behavior variation point panel data model. That is, the time series from January 1st, 1973 to October 30th, 2013 are divided into multiple segments, and each segment contains a behavior fault point. For each segment, it can still be regarded as the problem of estimating the single behavior variation point, the specific estimation method can be seen in Eq. (1.18), Eq. (1.19). By analogy, the behavior fault analysis results are as follows.

The first segment is from January 1st, 1973 to January 1st, 1985. The behavior fault point is identified by use of the established random effect panel data model, and the sum of squared residuals is calculated by Eq. (1.16). The moment of the minimum sum of squared residuals is taken as the occurrence time of behavior variation, then the estimation occurrence time of behavior fault is April 7th, 1977, and the behavior fault location is No.18 dam zone. Since the deformation of concrete dam represents macro variation of dam behavior, the deformation data of nearby measuring points have effect on each other, therefore, the identified behavior fault location is not necessarily exact. However, it can be used as an auxiliary method to find the behavior variation location.

According to the analysis report of the in-situ monitoring data, the concrete dam suffers the load of high temperature-low water level and low temperature-high water level. The continuous occurrence of unfavorable load combinations causes large deformation, and instability expansion of cracks, which generally enlarges after April 1977.

The second segment is from January 1st, 1985 to January 1st, 2000. The behavior fault point is identified by use of the established random effect panel data model, then the estimation occurrence time of behavior fault is June 1st, 1987, and the behavior fault location is No.26 dam zone (Figs. 9 and 10).

According to the analysis report of the in-situ monitoring data, deformation and crack opening of the concrete dam enlarges significantly in 1987 due to epoxy grouting in the spring of 1987.

Since the grouting restricts the closure of the crack, the measured value of the crack opening is increased, which the reinforcement measures lead to the crack opening enlarged.

The third segment is from January 1st, 2000 to October 30th, 2013. The behavior fault point is identified through the establishment of random effect panel data model. The estimation occurrence time of behavior variation is May 19th, 2008, and the behavior variation location is No.18 dam zone. According to the analysis report of the in-situ monitoring data, the reservoir maintains a relatively high level since 2005, especially in 2008. Wenchuan earthquake on May 12th, 2008 has certain effect on the hole water level. The crustal stress variation caused by the earthquake leads to rapid rise and fall of the hole water level. Therefore, the average crack opening values in 2008 are enlarged.

Through comparative analysis, the occurrence time of behavior variation identified by the traditional wavelet phase plane method is April 7th, 1977 and May 11th, 1978. In which, behavior fault point April 7th, 1977 is identified simultaneously by the traditional wavelet phase plane method and the behavior variation panel data model, which is concordant with the conclusion of the in-situ monitoring data analysis report. For the behavior fault point May 11th, 1978, as shown in Fig. 8, since water pressure component and aging component are highly correlated, the aging component isolated by wavelet is not necessarily exact, resulting that the identified behavior fault point cannot find the corresponding conclusion in the analysis report. Therefore, concrete dam behavior variation can be only roughly identified by traditional wavelet phase plane method.

The occurrence time and location of concrete dam behavior variation identified by panel data model respectively exhibit as follows: Segment 1: the time is April 7th, 1977, and the location is No.18 dam zone. Segment 2: the time is June 1st, 1987, and the location is No.26 dam zone. Segment 3: the time is May 19th, 2008, and the location is No.18 dam zone. All of them are concordant with the conclusion in the analysis report, further verifying the effectiveness of behavior fault panel data estimation model proposed in this paper.

4. Conclusions

The monitoring data is the most intuitive factor for reflecting the safety of the structure. The outside effects of various environments or loads could be separated from the monitoring data, such as, aging component, water pressure component, temperature component, and so on. The proposed method, panel data model, is also served for analyzing the monitoring data. Therefore, the basic research for monitoring data is the most important for the safety analyses for the structures.

The panel data method is a new method during recent years. Its extensive application is still an area to be studied. Further, there are fewer applications of the panel data method in dam area while the normal method is wavelet analysis with lots of defects. After a pilot study, the panel data method is certified to be useful for behavior variation research. And, there will be more applications for this finding.

There must be defect for any method or technology. The proper method is only for specific question. No method is called the best one for solving one problem. Therefore, there will be better method for the behavior variation based on our present research for future study.

With the development of public consciousness and basic subjects, there will be more requirements and understandings for the same question, which will prompt the further development of new methods or theories. Science always develops in such a spiral way.

The present study employed an exploratory research of panel data model faced composite concrete dam, using change-point theory, phase space reconstruction technique and time dimension method. An existing composite concrete dam has been investigated to gain temporal and spatial behavior change. The following conclusions can be drawn from the study:

1. The principle, advantages and disadvantages of traditional wavelet phase plane identification method of concrete dam behavior fault is discussed. To overcome the deficiency of traditional method, the panel data model identification method is proposed.
2. The wavelet phase plane method is analyzed to identify of concrete dam behavior fault. The aging component is isolated from the monitoring data by wavelet. On this basis, the behavior fault is recognized by phase panel method. However, the disadvantage is obvious which is overdependent on the accuracy of wavelet isolating aging component.
3. In order to overcome the shortcomings of traditional methods, the behavior fault panel data model is established by combining cross-section data and time series data, to characterize concrete dam behavior fault from spatio-temporal dimension comprehensively.
4. Behavior fault panel data identification model is proposed, which can determine the occurrence time and locations of different-type behavior fault points. On this basis, multiple behavior fault point identification method is put forward. The effectiveness of the proposed method is verified by an actual case.
5. Modeling process of concrete dam behavior change based on panel analysis has been given. Evidence of behavior variation, consistent with the actual data from 76.3-m-high arch dam, has shown that, times and positions are April 7th, 1977 and May 19th, 2008 located in 18# and June 1st, 1987 located in 26#.
6. Multi-turning point model of concrete dam behavior data is also proposed for the service of concrete dams, for several turning points during the time dimension. It can be regarded as the singular point estimation problem of the single-point model for the behavior data of concrete dam in service for each time segment.

Acknowledgments

This work was supported by the National Natural Science Foundation for Young Scientists of China (Grant No.51909173), the State Key Program of National Natural Science of China (Grant No.51739003), National Key R&D Program of China (2019YFC1510801, 2016YFC0401601), fundamental Research Funds for the Central Public Welfare Research Institute (No.Y119002), the Fundamental Research Funds for the Central Universities (Grant No. 2016B04114), basic Research Project Funded of National Key Laboratory (Grant No. 520003812), national Natural Science Foundation of China (51979093, 51739003, 51909173，51979093, 51779086).

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