Deformation characteristics and a safety monitoring model of high arch dam affected by valley narrowing deformation

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Abstract. Valley narrowing deformation was monitored during the first impoundment period of some high arch dam projects in China, which may affect the working behavior of dams. Dam deformation upstream was one of the most intuitive influences of valley narrowing deformation on arch dam, which makes dam safety evaluation difficult. In this paper, based on detailed monitoring data of a high arch dam project, the temporal-spatial evolution characteristics, and the mutual relationship of valley and dam deformation were analyzed. The influence of valley narrowing deformation on dam deformation was simulated by 3D Finite Element Method (FEM). According to the analysis results, an arch dam deformation safety monitoring model, considering the effect of valley deformation, was established in which the dam deformation was decomposed as water pressure, temperature, valley deformation, and time-effect components. Further, the typical process of valley deformation was analyzed using the proposed model and the decomposed components were separated. Research shows that the safety monitoring model can express the influence of various components on arch dam deformation comprehensively, and monitor the dam deformation quickly and accurately. The proposed model can be used to analyze and predict the arch dam deformation, and evaluate the dam behavior.

1. Introduction
Since the 1980s, numerous 300 m-level high arch dams have been built, such as Ertan (240 m), Xiaowan (295 m), Dagangshan (210 m), Xiluodu (285.5 m), Jinping I (305 m), etc. The arch dam projects of China have been functioning smoothly for many years with leading design and construction levels. After the impoundment of high dams and large reservoir projects, the hydrogeological conditions close to the dam area might change drastically, and the stress state and deformation characteristics of the dam body and foundation will adapt accordingly. For dam foundation, one of the main characteristics of the system adjustment is valley deformation with reservoir bank deformation in the horizontal direction [1,2,3]. For example, at the beginning of the impoundment of the Beauregard arch dam in Italy, the gravity sliding deformation appeared on the left bank mountain, and the valley narrowing deformation contracted by 100–200 mm in 60 years. Due to the excavation of the Gotthard tunnel, 400 m deep at the bottom of the dam foundation, the Zeuzier arch dam in Switzerland occurred significant foundation settlement and valley narrowing deformation [4,5]. The Lijiaxia arch dam, Xiaowan arch dam, and Jinping I arch dam built in China also had different degrees of valley narrowing.
The valley amplitude deformation on the arch dam body acts as the foundation deformation on both banks, adjusting the stress and deformation of the dam \cite{6,7}. Vast monitoring data shows that valley narrowing deformation causes deformation toward upstream of the dam body \cite{8,9,10}, which is different from the conventional deformation and makes the dam safety evaluation difficult. Therefore, there is a pressing need to study the influence of valley deformation on dam deformation.

To address this, the time characteristics, spatial distribution characteristics, and mutual influence of valley deformation and arch dam deformation were analyzed in this paper. In addition, an arch dam deformation monitoring model was established to evaluate the influence of valley narrowing deformation on arch dam deformation.

### 2. Valley deformation and dam deformation monitoring data analysis of an arch dam

#### 2.1. Project overview

An arch dam is a giant hydroelectric power station that focuses on power generation with comprehensive utilization benefits, such as sediment trapping, flood control, and improvement of navigation conditions of river downstream in China. The normal storage level of the reservoir is 600 m, the dead water level is 540 m, the total storage capacity of the reservoir is 12.67 billion m$^3$, the adjusted storage capacity is 6.46 billion m$^3$, and the total installed capacity is 13,860 MW. The dam is a concrete double-curvature arch dam with a crest elevation of 610 m, an excavation elevation of the foundation surface of 324.50 m, a maximum dam height of 285.50 m, a crest length of 681.51 m, and a total of 31 dam sections. The dam concrete was poured in March 2009, the dam diversion bottom outlet was closed to impound water in May 2013, and the normal water level was reached in September 2014.

To monitor the horizontal deformation of the dam, 7 sets of vertical line systems are set up, respectively in the 5$^\text{th}$, 10$^\text{th}$, 15$^\text{th}$, 22$^\text{nd}$, 27$^\text{th}$ dam sections and the grouting gallery on the left and right dam abutment. In the vertical line system, a total of 29 points on the vertical lines are arranged at the elevations of 610 m, 563 m, 527 m, 470 m, 395 m, and 347 m. The dam foundation corresponding to the vertical line is arranged with inverted vertical lines, and a total of 8 inverted vertical line measuring points are arranged. Two inverted vertical lines are arranged in the 15$^\text{th}$ arch dam crown section, one of which is half the anchorage depth of the other.

To monitor the characteristics of the valley deformation of the bank slope, the valley measuring lines are arranged in the upstream and downstream. There are 4 lines in the upstream and 4 lines in the downstream of the dam area, distributed between the elevation of 561 m and 749 m, as shown in Figure 1. The VD08 measuring lines arranged in the downstream are about 150 m deep into the mountain by means of resistance body drainage tunnels.

In the following analysis, the radial deformation of the dam is positive toward downstream and negative toward upstream. The elongation of the valley deformation is positive while the shortening is negative.

#### 2.2. Analysis of valley deformation data

The valley measuring lines started from December 2012, except VD08 measuring line that started from July 2014. To date, vast valley deformation monitoring data has been accumulated.
Time characteristics of valley deformation. The valley deformation process lines toward the upstream and downstream are shown in Figure 2 to Figure 4. It can be seen from the figure that there are the following characteristics in the valley narrowing deformation:

1. The valley deformation of the upstream and downstream starts at the same time during the impoundment. It can be inferred that impoundment is the main cause of valley deformation.
(2) In the early stage of impoundment, there is no obvious correlation between the variation process of valley narrowing deformation and the reservoir water level, and it will not slow down by the fall of water level. After 2016, on the basis of continuous narrowing, the valley deformation showed small periodic fluctuations with the rise and fall of the reservoir water level. The reservoir water level increased while the valley narrowing decreased (expansion trend) and decreased while the valley narrowing increased (shrinking trend).

Spatial distribution characteristics of valley deformation. The deformation values of the valley measuring line in the upstream and downstream are shown in Figure 1. As evident from the figure:
(1) The valley deformation behaves as narrowing deformation, by the end of July 2020, the deformation values were −98.38 mm to −73.80 mm.
(2) The measured values were similar in the upstream and downstream, while the magnitude along the elevation direction is basically the same, and no obvious distribution law was observed.
(3) The deformation values and deformation rate of each measuring line are similar, and the deformation rate is −1.06 mm to −0.80 mm per month.
(4) Figure 4 demonstrates that the cross-river section of VD08 line presents narrowing deformation, no variation in the drainage tunnels, and the measured value changes within ±3 mm. Therefore, it can be inferred that the depth of valley deformation is greater than 150 m.

Convergence analysis of valley deformation. In this paper, the 549 m elevation experienced by the low water level is used as the analysis benchmark, and the valley deformation increment and deformation rates show a rapid decrease trend, as shown in Table 1. Taking the VD04 survey line as an example, the deformation increments at the 549 m water level each time are −7.91 mm, −7.17 mm, −4.81 mm, −4.14 mm, −3.79 mm, which generally shows a decreasing trend. The deformation rate is −0.66 mm/month, −0.60 mm/month, −0.40 mm/month, −0.35 mm/month, and −0.32 mm/month respectively, showing a decreasing overall trend. The annual increment of valley deformation and the annual deformation rates show a rapid decrease trend, and the narrowing deformation tends to be stable.

| Valley deformation lines | VD01 | VD02 | VD03 | VD04 | VD05 | VD06 | VD07 |
|--------------------------|------|------|------|------|------|------|------|
| Increment (mm)           |      |      |      |      |      |      |      |
| 2015~2016                | −8.94| −10.02| −9.7 | −7.91| −9.22| −9.65| −8.31|
| 2016~2017                | −8.92| −6.62| −13.6| −7.17| −7.67| −7.06| −7.44|
| 2017~2018                | −5.75| −5.21| −8.41| −4.81| −4.42| −5.77| −4.18|
| 2018~2019                | −4.28| −4.66| −6.66| −4.14| −3.76| −4.46| −5.51|
| 2019~2020                | −3.93| −3.09| −5.71| −3.79| −2.13| −2.92| −1.51|
| Rate (mm/month)          |      |      |      |      |      |      |      |
| 2015~2016                | −0.75| −0.84| −0.81| −0.66| −0.77| −0.8 | −0.69|
| 2016~2017                | −0.74| −0.55| −1.13| −0.6 | −0.64| −0.59| −0.62|
| 2017~2018                | −0.48| −0.43| −0.7 | −0.4 | −0.37| −0.48| −0.35|
| 2018~2019                | −0.36| −0.39| −0.56| −0.35| −0.31| −0.37| −0.46|
| 2019~2020                | −0.33| −0.26| −0.48| −0.32| −0.18| −0.24| −0.13|

2.3. Analysis of dam radial deformation
Through comparative analysis of the appearance system and the vertical line system, the radial deformation of the vertical measuring point and the appearance measuring point of the bridge behind the dam are consistent in law, trend, and magnitude, verifying that the monitoring results of the dam vertical system are reliable.

Time characteristics of dam radial deformation. Take the deformation of crown cantilever 15° as an example, as shown in Figure 5. It can be seen from the figure that dam radial deformation has the following characteristics:
(1) The radial deformation shows a good correlation with the reservoir water level. Except for the dam foundation, the dam body deformation measurement point will move downstream when the reservoir water level rises and upstream when the reservoir water level falls. When the reservoir water level is
stable, the radial deformation tends to move upstream and the value of correlation coefficient between the measured deformation and the reservoir water level change is 0.85–0.99.

(2) Under the same reservoir water level, the dam deformation appears upstream due to valley deformation.

(3) When the reservoir water level rises or falls to a certain water level, the dam deformation structure is stable and convergent. Under the action of load, the deformation and load distribution will be adjusted inside the dam, which has a certain short time-effect and can converge rapidly.

(4) The dam deformation is synchronous with the periodic variation of water level regulation.

(5) As of July 2020, the maximum dam radial deformation toward upstream is −46.75 mm, appearing at 610 m elevation.

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**Figure 5.** Process line of 15th dam radial deformation.

*Spatial distribution characteristics of dam radial deformation.* Due to the time difference between the embedment of various monitoring instruments, acquisition of initial values, and influence of the early dam construction process, etc., it is objectively difficult to use the deformation to evaluate the structural deformation characteristics. Therefore, it is reasonable to adopt the incremental evaluation. Although the valley deformation has a significant impact on the dam deformation, it still shows a strong regularity for each incremental impoundment process.

Taking the loading and unloading process in 2019 as an example, as shown in Figure 6, during the loading and unloading of reservoir water level, the measured radial deformation variation of different measuring points decreases gradually from the center of the 15th dam section to two banks, and the values of the two banks are close, and the dam body shows deformation coordination.
Convergence analysis of dam radial deformation and its relationship with valley deformation. According to the actual operation mode of the reservoir, the variation time of water level is close, meaning the temperature effect is similar. The 549 m elevation experienced by the low reservoir water level is selected as the analysis standard, as shown in Figure 7. From the variation during six unloading periods, the dam radial deformation generally occurs upstream, and the maximum value appears at the measurement point of the 15th dam section at 610 m elevation. The radial deformation during six unloading process continues to occur upstream because of the valley deformation. The deformation increments are −46.84 mm, −28.35 mm, −35.59 mm, −29.45 mm, −30.80 mm, and −30.18 mm respectively, and the variation of radial deformation toward upstream presents a convergence trends.

3. Research on the influence of valley deformation on arch dam radial deformation
To study the influence of valley deformation on the dam radial deformation, the material parameters of dam and foundation remain unchanged. When valley deformation takes different magnitudes, the three-dimensional finite element method is used to calculate the dam deformation under its own weight and different valley narrowing magnitudes.

3.1. Finite element model
The three-dimensional finite element model is centered on the dam axis. The upstream is about 1700 m, the left and right banks are 2 times the dam height, and the downstream is 2.5 times the dam height. Area below the foundation surface is about 1.5 times the dam height, and the dam crest height is extended to the elevation of 710 m, the size of the three-dimensional finite element calculation model is 2500 × 1500 × 810 m³ (length × width × height), and the overall three-dimensional finite element mesh model of the arch dam and foundation is shown in Figure 8.

The three-dimensional finite element mesh model has a total of 210,000 nodes and 177,000 elements. In the overall coordinate system, the x-axis direction is perpendicular to the river and points to the left bank. The y-axis is the direction against the river and points to the upstream, and the z-axis direction is vertical upwards. The bottom surface of the bedrock is fully constrained in three directions, the four
sides are treated as the normal constrained boundary, and all the air faces of the dam body are free boundaries.

Figure 8. Finite element model.

3.2. Constitutive relationship and calculation parameters
(1) Concrete constitutive relationship
Since the overall stress level of the arch dam body is lower than the proportional ultimate strength of the concrete, the concrete adopts the isotropic linear elastic constitutive relationship.

(2) Constitutive relationship of rock mass
The dam foundation is composed of multiple rock flow layers with strong horizontal and vertical anisotropy. Therefore, the anisotropic linear elastic constitutive model is used to simulate the foundation rock mass. The independent parameters are the deformation moduli $E_1, E_2, E_3$ and $G_{12}, G_{13}, G_{23}$ in 3 orthogonal directions, 3 Poisson’s ratios: $\nu_{12}, \nu_{13}, \nu_{23}$, and 3 shear modulus $G_{12}, G_{13}, G_{23}$. The stress-strain expression is as follows:

\[
\begin{bmatrix}
\varepsilon_{11} \\
\varepsilon_{22} \\
\varepsilon_{33} \\
\gamma_{12} \\
\gamma_{13} \\
\gamma_{23}
\end{bmatrix}
= \begin{bmatrix}
1 / E_1 & -\nu_{21} / E_2 & -\nu_{31} / E_3 & 0 & 0 & 0 \\
-\nu_{21} / E_2 & 1 / E_2 & -\nu_{32} / E_3 & 0 & 0 & 0 \\
-\nu_{31} / E_3 & -\nu_{32} / E_3 & 1 / E_3 & 0 & 0 & 0 \\
0 & 0 & 0 & 1 / G_{12} & 0 & 0 \\
0 & 0 & 0 & 0 & 1 / G_{13} & 0 \\
0 & 0 & 0 & 0 & 0 & 1 / G_{23}
\end{bmatrix}
\begin{bmatrix}
\sigma_{11} \\
\sigma_{22} \\
\sigma_{33} \\
\sigma_{12} \\
\sigma_{13} \\
\sigma_{23}
\end{bmatrix}
\]

Since the rock flow layer is transversely isotropic, the actual strike of the rock layer is taken into account in the calculation. Let $E_1=E_3=E_p, E_2=E_n, \nu_{12}=\nu_{13}=\nu_{23}=\nu_{pp}, G_{13}=G_{23}=G_n$, where $p$ and $t$ represent transverse and longitudinal directions of the transversely isotropic elastic body, and assume that $\nu_{12}=\nu_{23}=\nu_{13}=\nu$, the stress-strain expression is as follows:

\[
\begin{bmatrix}
\varepsilon_{11} \\
\varepsilon_{22} \\
\varepsilon_{33} \\
\gamma_{12} \\
\gamma_{13} \\
\gamma_{23}
\end{bmatrix}
= \begin{bmatrix}
1 / E_p & -\nu / E_p & -\nu / E_t & 0 & 0 & 0 \\
-\nu / E_p & 1 / E_p & -\nu / E_t & 0 & 0 & 0 \\
-\nu / E_p & -\nu / E_p & 1 / E_t & 0 & 0 & 0 \\
0 & 0 & 0 & 1 / G_p & 0 & 0 \\
0 & 0 & 0 & 0 & 1 / G_p & 0 \\
0 & 0 & 0 & 0 & 0 & 1 / G_p
\end{bmatrix}
\begin{bmatrix}
\sigma_{11} \\
\sigma_{22} \\
\sigma_{33} \\
\sigma_{12} \\
\sigma_{13} \\
\sigma_{23}
\end{bmatrix}
\]

Where, $G_p = E_p / (2(1+\nu))$.

(3) Material parameter
According to the material test results and field acoustic test, the parameters of dam and foundation materials are depicted in Table 2.
Table 2. Material parameters

| Rock grade       | Unit weight (kg/m³) | Modulus of deformation(Gpa) |
|------------------|---------------------|-----------------------------|
|                  |                     | Horizontal | Vertical |
| I                | 2850                | 36         | 17        |
| II               | 2850                | 36         | 17        |
| III1             | 2850                | 20         | 14        |
| III2             | 2850                | 15         | 12        |
| Fault            | 2600                | 1          | 0.6       |
| Fault (Grouting treatment) | 2600 | 6       | 6       |
| Concrete         | 2400                | 44         | 44        |

3.3. Loading mode of valley deformation

According to the analysis of valley monitoring data, the mode of adding deformation loads on the left and right sides of the integrated model at the same time is adopted, as shown in Figure 9. To verify the rationality of the loading mode under the action of a deformation load of 10 cm on both sides (loaded by 5 cm on the left and right sides), the variation of the valley measurement line is sorted out.

The results show that under the same deformation load on both sides, the high elevation valley measuring line narrows slightly larger than the low elevation, but the difference is small. Within 150 m of the drainage tunnel on both sides, the mountain deformation is small, about 0.8 mm. It can be concluded that the mode of adding deformation loads on both sides of the integrated model can be approximately used in the dam valley deformation.

3.4. Calculation results

Under the action of valley narrowing deformation of 0 mm, −30 mm, −60 mm, −100 mm, −150 mm, and −200 mm, the dam radial deformation is shown in Figure 10. It can be seen from the chart:

(1) The valley narrowing deformation will generally cause the dam to deform upward along the river, which will reduce the impoundment radial deformation.

(2) The effect of valley narrowing deformation on the dam radial deformation at high elevation measuring points is greater than that of low elevation, and the elevation direction is approximately linear.
4. Safety monitoring model of dam radial deformation

Valley narrowing deformation is closely related to engineering geological characteristics and water level characteristics. The variation of the seepage field, stress field, and temperature field in the wider dam area are caused by the reservoir impoundment, and all of them will cause valley narrowing deformation. Therefore, there is a need to explore the deformation mechanism of the valley deformation, which has become an urgent problem in the field of hydropower engineering technology.

4.1. Establishment of monitoring model. In addition, an arch dam deformation monitoring model that considers the effect of valley deformation must be proposed.

As per the causes, the deformation of a point in an arch dam may consist of water pressure component $\delta_H$, temperature component $\delta_T$, valley deformation component $\delta_V$, time-effect component $\delta_\theta$, and the constant $C_{on}$ under the influence of valley deformation, that is:

$$\delta = \delta_H + \delta_T + \delta_V + \delta_\theta + C_{on}$$

(1)

where, the constant term $C_{on}$ represents the constant caused by factors, such as different selected initial values of the calculated and monitored deformation.

Water pressure component. Under water pressure, the dam will generate elastic deformation, called the hydraulic deformation component. It can be derived from material mechanics and elastic mechanics that the water pressure component $\delta_H$ at any point of the dam is related to the upstream water depth $H$, and described by a polynomial as:

$$\delta_H = \sum_{i=0}^{S} a_i H^i$$

(2)

where, $a_i$ is the structure coefficient.

$H$ is the upstream water depth.

$S$ is the number of factors, 4 for the arch dam.
Temperature component. Temperature load is one of the main factors affecting arch dam deformation. Dam deformation caused by temperature is called temperature deformation component. According to the elastic mechanics, under the action of variable temperature, the relationship between the deformation of any point of the dam and the variable temperature value of each point is linear, and the dam temperature has not reached the stable temperature field after the construction of the arch dam. Therefore, in this paper, the typical temperature measurement points are selected to represent the overall temperature field of the dam, which is described by a polynomial as:

\[ \delta_T = \sum_{i=1}^{m_i} b_i T_i \]  

where, \( m_i \) is the number of typical thermometers, \( b_i \) is the regression coefficient, and \( T_i \) is the measured value of thermometer.

Valley deformation component. As the foundation deformation, the valley deformation will cause dam deformation, called the valley deformation component. When the mechanical parameters are determined, the finite element method is used to calculate the deformation at any point of the dam under different valley narrowing magnitudes, that is, the deformation generated under the valley deformation, as shown in Figure 10. The deformation at any point can be obtained by polynomial fitting as follows:

\[ \delta_V = \sum_{i=0}^{m_v} s_i V^i \]

where, \( s_i \) is the fitting coefficient, and \( m_v \) is the number of powers.

Time-effect component. The deformation of concrete dams under load actions will generate an irreversible component that develops over time, called the time-effect component. The time-effect factor usually adopts exponential function \( \delta_\theta = d \left[ 1 - \exp(-d_1 \theta) \right] \), hyperbolic function \( \delta_\theta = d_1 \theta / (d_2 + \theta) \), polynomial \( \delta_\theta = \sum d_i \theta_i \), logarithmic function \( \delta_\theta = d \ln \theta \), logarithmic function with additional periodic term, linear function, etc. or a combination of any of them.

Here, \( d \) is the regression coefficient, \( \theta \) is the time factor, usually taken as \((1+\tau)/100\), \( \tau \) is the cumulative time from the date of data measurement to the date of monitoring.

Model expression. Taking polynomial and logarithmic function as the time-effect components as an example, a comprehensive expression of the deformation monitoring model is established combining the above four parts:

\[ \delta = \sum_{i=0}^{1} a_i H^i + \sum_{i=1}^{m_t} b_i T_i + \sum_{i=0}^{m_v} s_i V^i + d_1 \theta + d_2 \ln \theta + C_{im} \]  

4.2. Model application

The radial deformation of the perpendicular measuring point at 610 m elevation of the 15th dam section is selected as the analysis object. In order to eliminate the influence of the dam weight and the arch closure during the construction period of the model, all data from the first impoundment to the normal water level so far are selected as statistical regression samples. It is necessary to determine the expression of temperature and valley components to complete the model expression.
To describe the influence of dam foundation and dam body temperature on deformation, the high, middle, and low temperatures of the reservoir water temperature, air temperature, foundation, and arch crown are selected as temperature statistical factors:

$$\delta r = \delta r(T_{T16-1}, T_{T-25}, T_{T16-31}, T_{J8-2}, T_{J27-3}, T_{J15-11}, T_{J15-29}, T_{J15-53}, T_{J15-40}, T_{J15-42})$$

$$= b_1 \times T_{T16-1} + b_2 \times T_{T-25} + b_3 \times T_{T16-31} + b_4 \times T_{J8-2} + b_5 \times T_{J27-3} + b_6 \times T_{J15-11} + b_7 \times T_{J15-29} + b_8 \times T_{J15-53} + b_9 \times T_{J15-40} + b_{10} \times T_{J15-42}$$

(7)

where, $T_{16-1}$ is the thermometer number, $J8-2$ is the joint meter number.

It can be seen from Figure.10 that the impact of valley narrowing deformation on the measuring point deformation can be represented by the valley narrowing deformation from the 1st to the 2nd power. In order to display the impact more intuitively, the power of 1 is selected, that is, the value of $m_i$ in formula (5) is 1. The VD04 survey line, closest to the dam axis and directly acting on the arch dam, is selected as the representative value of the valley deformation. With fixed mechanical parameters, the relationship between the dam radial deformation at the measuring point and the valley deformation according to the curve fitting can be described as follows:

$$\delta \delta = 0.84 VD_{04}$$

(8)

Combining the above deformation components, the mixed model expression of arch dam deformation measurement points is obtained, as shown in Equation (9):

$$\delta = X \sum_{i=0}^{4} a_i H_i^1 + b_i \times T_{T16-30} + b_2 \times T_{J15-5} + b_3 \times T_{J15-20} + b_4 \times T_{J15-35} + b_5 \times T_{J15-41} + b_6 \times T_{J15-11} + b_7 \times T_{J15-29} + b_8 \times T_{J15-53} + b_9 \times T_{J15-40} + b_{10} \times T_{J15-42} + d_1 \theta + d_2 \ln \theta + C_{on}$$

(9)

Taking the radial deformation at 610 m of 15th dam section as an example, the regression coefficients, constant terms, complex correlation coefficients, and standard deviations of the radial deformation statistical model are obtained with the stepwise regression analysis method, as shown in Table 3. The actual measured value, model calculated value, and the process line of each component are shown in Figure 11.

### Table 3. Regression coefficients

| $a_1$ | $a_2$ | $a_3$ | $a_4$ | $b_1$ | $b_2$ | $b_3$ | $b_4$ | $b_5$ | $b_6$ | $b_7$ | $b_8$ | $b_9$ | $b_{10}$ | $c$ | $d_1$ | $d_2$ | $C_{on}$ |
|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| 2.41E-02 | -1.33E-04 | 2.15E-07 | 0 | -0.32 | -0.27 | 1.33 | 0.06 | -1.54 | 0 | -1.54 | 0 | -1.09 | 0.07 | 0 | 0 | -47.66 |

![Graph of reservoir water elevation and radial deformation at 610 m of 15th dam section](image)
Figure 11. The process of the measured value and calculated value of radial deformation at the typical measurement point.

The following can be learned from the chart:

1. The accuracy of radial deformation statistical model is maintained at a high level. The value of multiple correlation coefficients is 0.99. It shows that the regression effect of the statistical model on the dam radial deformation is ideal.

2. The water pressure component shows that the reservoir water level rises and the dam radial deformation moves downstream. The temperature component shows that the temperature rises and the dam radial deformation moves upstream. The valley deformation component shows that the dam valley narrows and the dam radial deformation moves upstream.

3. The valley deformation has a significant influence on the radial deformation of each measuring point. In this paper, the load range from the first normal water level to the normal water level in 2019 is used as the calculation boundary, and the absolute value of each component is used as the calculation unit to calculate the proportion of each component, namely:

$$\omega_i = \frac{|\delta_i|}{|\delta_H| + |\delta_T| + |\delta_V| + |\delta_i|} \quad (10)$$

Where, $\omega_i$ is the proportion of each component. $i$ represents water pressure, temperature, valley deformation and time-effect, $|\cdot|$ is the absolute value.

The proportion of each component calculated for the above research example is shown in Table 4. The following views can be obtained from the table:

1. The horizontal dam deformation is affected by water pressure more significantly. As the reservoir water level rises, the dam downstream deformation increases. As the reservoir water level decreases, the dam downstream deformation decreases. The water pressure component in the upper part is greater than the lower part.

2. Temperature is also one of the factors affecting the dam deformation. As the temperature increases, the dam downstream deformation decreases or the upstream deformation increases. While the temperature decreases, the dam downstream deformation increases or the upstream deformation decreases. The temperature component in the table includes the temperature deformation caused by the dam body temperature rise since the first normal water level.

3. The valley deformation is a special factor affecting the arch dam deformation. The valley narrowing deformation causes the downstream deformation to decrease or the upstream deformation to increase.

4. It can be seen from the statistical model that the time-effect factors of dam deformation are not obvious. Generally speaking, the initial time-effect of a hydropower station is more obvious. As the operating time extends, the time-effect gradually stabilizes and tends to zero. According to the analysis, the reason for the insignificance of the time-effect factors in the statistical model is not that there is no time-effect on the arch dam deformation, but the correlation between the time-effect and the valley deformation factor is better, and the time-effect factors are incorporated into the valley deformation factor.
Based on this monitoring model, a comprehensive study on the deformation analysis of the arch dam during the first impoundment period and the previous loading and unloading stages of the hydropower station has been conducted. Many research achievements have been acquired on the dam deformation working state at each stage. The research results have been applied to the monitoring and evaluation of the impoundment process at each stage, and the safe engineering operation during the whole impoundment process has been guided and ensured.

5. Conclusion
The arch dam belongs to hyperstatic structure. The stress and deformation of the dam are extremely sensitive to the foundation deformation, which means the valley deformation has a great impact on the safety of the arch dam. Taking a certain project as the research object, this paper analyses the deformation characteristics and safety monitoring model of high arch dam affected by valley narrowing deformation. The results show that the valley narrowing deformation has significant influence on the deformation of arch dam, causing it to deform upstream. The annual increment of valley deformation shows a rapid decreasing trend, followed by the new balance of hydrogeological conditions after reservoir impoundment. The simulation analysis indicates that the influence of valley narrowing deformation on the dam deformation can be approximated as a linear relationship. The proposed deformation monitoring model can track and monitor the arch dam deformation quickly and accurately, which is convenient to analyse and predict the dam deformation under the influence of valley deformation, as well as to evaluate the dam working safety status. It is suggested that valley deformation monitoring should be done as soon as possible in high arch dam construction.

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