A monitoring model for the stress on a super-high arch dam during pre-impoundment construction

Jingtai Niu, Xiang Luo, Zhiping Deng, Yang Zhang, Yingjia Guo and Zhiqiang Wang

ABSTRACT

This paper presents a proposed model for monitoring the stress on a super-high arch dam during construction. Using mathematics, mechanics, and dam engineering principles, the mathematical expressions of the self-weight component of the dam prior to and following the sealing of the bottom of the arch were derived. The visco-elastoplastic constitutive model of dam concrete during construction was identified and used to develop a stress monitoring model for a super-high arch dam. Based on in-situ stress monitoring data collected during the construction of a super-high arch dam, the stress monitoring model was applied to a super-high arch dam accounting for future impoundment, and the key components of the monitoring model were isolated. The results show that the model has high fitting accuracy and incorporates an appropriate selection of factors affecting dam stress. The hydrograph of each component conforms to the structural characteristics of super-high arch dams during construction. This model overcomes the limitations of applying the complete self-weight of the dam body on the cantilever beam and was validated using data from a super-high arch dam construction project. Thus, this paper provides evidence for a safety monitoring model for super-high arch dams during construction.

Key words | dam construction, monitoring model, stress, super-high arch dam

HIGHLIGHTS

- Presents a proposed model for monitoring the stress on a super-high arch dam during construction.
- The visco-elastoplastic constitutive model of dam concrete during construction was identified.
- The stress monitoring model was applied to a super-high arch dam accounting for future impoundment.
- Shows that the model has high fitting accuracy.
- Incorporates an appropriate selection of factors affecting dam stress.

INTRODUCTION

With the increasing number of super-high arch dams being constructed, safety has become a major focus in dam engineering research (Zhu 2009). Super-high arch dams store water and generate electricity in advance when built to specific heights (Zhou et al. 2011). Due to the effects of self-weight, water pressure, and concrete hydration heat during construction, the dam body and foundation bear a substantial load after dam impoundment. Whether the dam can withstand the stress of the first impoundment and continued construction after impoundment is critical to the overall safety of the dam. Therefore, research on the safety monitoring of super-high arch dams during construction...
construction that considers the pre-impoundment stage is urgently needed (Ma et al. 2019).

The construction and initial impoundment of the dam are associated with more frequent accidents compared with other dam operations. Thus, there is a greater failure probability and greater risk of events that directly affect the safety of the structure at these stages (Zhang et al. 2016; Deng et al. 2018). At present, an increasing number of experts are examining the safety monitoring research regarding the construction and initial impoundment of super-high arch dams. For example, Luo et al. (2015) studied the influence of the initial impoundment process on the deformation and stress of the dam body through finite element analysis. Liang Guohe et al. (Barla et al. 2010; Liang et al. 2016) summarized the temporal and spatial distribution laws of the deformation of the dam body and the reservoir bank rock mass, focusing on the problem of the significant river valley amplitude contraction associated with the first impoundment of super-high arch dams. Tatin et al. (2015) investigated the influence of water temperature and temperature gradients on the structural thermal effect by introducing a water temperature component to their analysis model. Li et al. (2017) examined the autogenous volume deformation and stress state of dam concrete and determined the distribution law of the dam stress state. Li et al. (2014) added dam height and temperature components to a traditional model and used this to construct a dam deformation regression model. Zhou et al. (2015) predicted the long-term working behavior of dam structure using finite element analysis by separating the self-weight components, which improved the accuracy of the model.

These studies have presented in-depth investigations of the stress distribution laws and monitoring models of super-high arch dams and have demonstrated some important results. However, there are some limitations of the previous work. For example, previous models have not considered some important factors in super-high arch dam construction. First, there is a time delay between pouring the dam and sealing the arch during dam construction, which results in the formation of a complete system after transverse joint grouting. Second, the self-weight of the dam body in the subsequent phases of construction will contribute to the load distribution of the arch beam. Therefore, the self-weight of subsequent pouring cannot be directly used as an influencing factor in the stress monitoring model. In order to elucidate the stress law changes of super-high arch dams during construction, this study aimed to consider the actual working conditions of the dam during pre-impoundment construction. In this work, prototype monitoring data from multi-source temporal and spatial monitoring, such as the amount of environmental stress, was comprehensively considered. This data was integrated with results from previous studies of mechanical characteristics and numerical analysis to develop a stress monitoring model for the pre-impoundment stage of super-high arch dam construction. Finally, the model was validated using a case study of stress monitoring analysis in super-high arch dam construction.

**DEVELOPMENT OF A STRESS MONITORING MODEL FOR SUPER-HIGH ARCH DAM PRE-IMPOUNDMENT CONSTRUCTION**

For a super-high arch dam prior to impoundment, the dam structure and internal stress of the dam vary with the pouring elevation and sealing height (Lin et al. 2019). Due to the sealing arch and future impoundment, the dam bears an increasing dead load and variable water pressure as the elevation of the dam changes. The stress distribution of the arch beam in the dam can be adjusted by sealing arch grouting (Fan et al. 2018). In line with the nature of load application during construction, a temperature load is applied to the lower part of the arch. Owing to the thick dam body, the influence of boundary heat transfer on the temperature of the central section of the dam body is slow, and the internal concrete exhibits a rise in temperature beyond the sealing arch (Yang et al. 2012; Zhou & Zhang 2015).

Given the variable loads on the dam and the internal temperature changes during this stage of construction, the traditional concrete dam safety monitoring model is insufficient for super-high arch dams during pre-impoundment construction. Thus, to evaluate the safety of the dam during this phase of construction, it is critical to understand the law of internal stress variation along the dam body considering external load factors comprehensively. Below, this paper reports and analyzes the factors affecting the stress on super-high arch dams during pre-impoundment construction.
construction and selects different factors to determine the stress variation at different construction periods. To determine the stress distribution characteristics of the upper portion of the dam after sealing the bottom of the arch, the influence of self-weight, temperature load, water level, and creep effect on the stress of the dam are analyzed in the proposed model.

**Mathematical expression of the concrete self-weight component**

The concrete self-weight component prior to sealing the arch

At the beginning of construction, concrete is poured layer by layer; thus, the self-weight is the main factor affecting the vertical normal stress of the horizontal section of the arch dam. According to the understanding of dam mechanics and the principles of dam construction, the mathematical expression for the self-weight component is herein derived.

A crown cantilever of unit thickness was considered as the study object (Figure 1). The self-weight of the concrete and the vertical normal stress at \( e_h \) – the horizontal section of the measuring point \( P \) – increase with dam height. In general, the maximum and minimum normal stresses appear on the up- and downstream edges of the dam, respectively. The calculation of point \( P \) is based on the stress values of two points, \( C \) and \( D \). Assuming that the vertical normal stress of the horizontal section at a point is linearly distributed, the stress at points \( C \) and \( D \) is calculated by the eccentric compression formula for material mechanics, as follows:

\[
\begin{align*}
\epsilon_C &= \frac{W}{T_2} + \frac{6M}{T_2^2} \\
\epsilon_D &= \frac{W}{T_2} - \frac{6M}{T_2^2}
\end{align*}
\]  

(1)

In Equation (1), \( \epsilon_C \) and \( \epsilon_D \) are the vertical normal stresses of the up- and downstream edges, respectively, of the horizontal section at point \( P \), \( W \) is the concrete self-weight above the horizontal section of point \( P \), \( M \) is the moment of the concrete self-weight above the horizontal section from \( P \) to the centroid of the section, and \( T_2 \) is the thickness of the dam at \( P \).

Integrating the configuration parameters of the arch dam, the vertical normal stress \( \epsilon_C \) and \( \epsilon_D \) can be calculated by Equation (1).

In Equation (2), \( \rho_c \) is the concrete density, \( Z \) is the over-

\[
\begin{align*}
\epsilon_C &= \frac{\rho_c z_2}{2} \left( \frac{T_1 + T_2}{T_2} + 3T_1 \rho_c z_2 \left[ (a_1 \varepsilon_1 - a_2 (\varepsilon_1^2 + 2 \varepsilon_1 \varepsilon_2)) / ZT_2^2 + (T_2 - T_1) / 2T_2^2 \right] \right) \\
\epsilon_D &= \frac{\rho_c z_2}{2} \left( \frac{T_1 + T_2}{T_2} - 3T_1 \rho_c z_2 \left[ (a_1 \varepsilon_1 - a_2 (\varepsilon_1^2 + 2 \varepsilon_1 \varepsilon_2)) / ZT_2^2 + (T_2 - T_1) / 2T_2^2 \right] \right)
\end{align*}
\]  

(2)

all height of the dam, \( z_1 \) is the un-poured height of the dam, \( z_2 \) is the distance from the horizontal section of the measuring point \( P \) to the top of the poured section of the dam, \( T_1 \) is the thickness of the top of the poured dam, \( a_1 \) and \( a_2 \) are the configuration parameters of the arch dam, and the other parameters are the same as for Equation (1) as described above.

Therefore, the vertical normal stress at the measuring point is

\[
\begin{align*}
e_h &= T_2 (\epsilon_D - \epsilon_C) / L + \epsilon_C \\
&= \frac{\rho_c z_2}{2T_2} \left( \frac{T_1 + T_2}{L} + 3T_1 \rho_c z_2 (L - 2T_2) \right) \left( (a_1 \varepsilon_1 - a_2 (\varepsilon_1^2 + 2 \varepsilon_1 \varepsilon_2)) / ZT_2^2 L + (T_2 - T_1) / 2T_2^2 L \right)
\end{align*}
\]  

(3)
In Equation (3), $L$ is the horizontal distance from the measuring point to the surface of the upstream dam, $r_c, a_1, a_2, Z, L$ and $T_2$ are constant for a fixed measuring point, and the other parameters are as described above.

Substituting $Z_1 = Z - Z_2$ into Equation (5):

$$
\varepsilon_h = -\frac{r_c}{2T_2 L}(\alpha z_1^3 + \beta z_2^3 + \gamma z_3 + T_2 z_3) - \frac{3r_c}{2T_2^2 L}(L - 2T_2)
$$

$$(\frac{\alpha_1}{\alpha_2} + \frac{\beta_1}{\beta_2} + \gamma)(a_2 + \alpha)z_2^2 + (a_1 + \beta)z_2 + a_2z^3 - a_1z - T_2 + \gamma)
$$  \hspace{1cm} (4)

Therefore, the expression of the self-weight component prior to sealing the arch is

$$
\sigma_H(t, L) = \sum_{i=1}^{5} a_i H^i
$$  \hspace{1cm} (5)

The concrete self-weight component after sealing the bottom of the arch

In contrast to the self-weight of the dam with an unsealed arch, the self-weight component of the super-high arch dam once the bottom of the arch is sealed is affected by the structure of the dam body as well as additional construction stages and procedures in the upper portion of the dam. With the dam joint grouting, impoundment, and other construction procedures still to be implemented, the stress resulting from the self-weight of the portion of the dam below the sealed arch is fixed and does not need to be further adjusted. However, the upper portion of the dam that continues to rise after the sealing of the bottom of the arch must be adjusted for deflection. Therefore, the entire weight of the arch dam cannot be applied to the cantilever beam when the stress of the dam is calculated. Accordingly, the expression of the self-weight component of newly poured concrete after the sealing of the arch differs from that for the unsealed arch.

The pouring height $H$ and the sealing height $h$ are used to perform displacement adjustment based on the arch-cantilever method for the concrete poured after sealing. The stress generated by the self-weight of the cantilever beam at the height of the sealed arch is fixed prior to sealing the arch and represented as $\sigma_0$. Therefore, the expression of the self-weight component for the concrete poured after sealing the arch is

$$
\sigma_{\text{new poured}}(H, h, t) = \sum_{i=1}^{5} a_i (H - h)^i
$$  \hspace{1cm} (6)

The expression of the self-weight component of stress in the upper portion of the dam after sealing the bottom of the arch is the sum of the stress generated by the self-weight before sealing the arch and the stress of the newly poured concrete self-weight after sealing the arch, as follows:

$$
\sigma_{G}(H, h, t) = \sigma_0 + \sum_{i=1}^{5} a_i (H - h)^i
$$  \hspace{1cm} (7)

Temperature component

A thermometer inside the arch dam can be used to collect temperature data from an arch dam during construction. The temperature stress was calculated using previously reported temperature data (Li et al. 2015) and can be expressed as:

$$
\sigma_T(t) = \sum_{i=1}^{m_2} b_i T_i
$$  \hspace{1cm} (8)

In Equation (8), $T_i$ is the temperature change of the $i$th thermometer (equal to the instantaneous value minus the initial value), and $m_2$ is the number of the thermometer. The temperature of the dam interior changes with the harmonic change of the surrounding water and air temperatures (Gu & Wu 2006). Therefore, when there are no thermometers in the dam or the thermometers fail, the temperature component can be expressed as

$$
\sigma_T(t) = \sum_{i=1}^{m_2} (b_{i1} \sin 2\pi t/365 + b_{i2} \cos 2\pi t/365)
$$  \hspace{1cm} (9)

In Equation (9), $i = 1$ represents an annual cycle whereas $i = 2$ represents a semiannual cycle, $i$ is generally 1 or 2, $b_{i1}$ and $b_{i2}$ are the regression coefficients, and $t$ is the cumulative number of days from the start of monitoring.
Water pressure component

In general, the water pressure component of stress can be expressed by an \( n \)th-order polynomial of the water level \( H_1 \). For a gravity dam, \( n = 3 \) whereas \( n = 4 \) for an arch dam or multiple arch dam. Accordingly, the water pressure component of stress can be expressed as:

\[
\sigma_{11}(H_1, t) = \sum_{i=1}^{4} a_i H_1^i
\]  

(10)

where \( a_i \) is the regression coefficient for \( i = 1-4 \).

Aging component

The stress state of a concrete dam is constantly changing during construction, and the development of a stress change trend relates both to the magnitude and effect time of the stress. The expression of the stress–aging component can be obtained by determining the relationship between stress and strain using the mechanical constitutive model of concrete. In this model, the internal stress and strain of dam concrete are related to time, but the internal change mechanism is a black box (Xia et al. 2008). The combination of mechanical models of the elements facilitates understanding of the theoretical stress and strain characteristics for dam concrete (Nguyen 2015). However, the selection of a constitutive model suitable for dam concrete is a challenging problem that requires an urgent solution as currently only combined mechanical models of the elements exist.

Fifteen types of combined mechanical models of the elements can be used to express the behavior of different viscoelastic–plastic materials. The combination mechanical models of elements for a cohesive–elastic–plastic material can be accurately determined by the identification of a mechanical constitutive model, as shown in Table 1 (Sun 2007). Extensive engineering practice has shown that the concrete of a dam will undergo viscoelastic–plastic deformation including elastic strain, viscous strain, and plastic strain when subjected to prolonged stress. Therefore, a mechanical constitutive model for dam concrete was constructed according to the creep characteristics of dam concrete and the loading and unloading curves of concrete specimens under different stress levels. From this model, the corresponding constitutive equation was established and the expression of the stress–aging component was determined.

(1) At a low stress level, \( \sigma \leq \min(\sigma_{s1}, \sigma_{s2}) \), \( \sigma_{s1} \) and \( \sigma_{s2} \) are defined as the plastic yield stress in the unified mechanical constitutive model. Field observations and laboratory tests show that the dam concrete first demonstrates instantaneous linear elastic strain under loading followed by creep deformation until a stable value is achieved.

At any time, the total strain of the concrete is

\[
\varepsilon = \varepsilon_e + \varepsilon_c(t) = \frac{\sigma}{E} + \sigma \cdot C(t, \tau)
\]

(11)

In Equation (11), \( \varepsilon_e \) is the elastic deformation, \( \varepsilon_c(t) \) is the creep deformation, and \( C(t, \tau) \) is the creep degree, which represents the creep under unit stress and describes the creep characteristics of the material. The creep degree \( C(t, \tau) \) can be expressed as:

\[
C(t, \tau) = C[1 - e^{-\lambda(t-\tau)}]
\]

(12)

In Equation (12), \( c \) is the general volume of creep, and \( \lambda \) is the speed of creep development.

Thus, Equation (11) can be rewritten as:

\[
\frac{d\varepsilon_c}{dt} = a\sigma + b\varepsilon_c
\]

(13)

In Equation (13), \( a \) and \( b \) are material parameters of the concrete.

Equation (13) is consistent with the constitutive equation of a viscoelastic body and shows that the creep performance of concrete behaves according to visco-elastic rheology, which can be reversed by the hysteresis effect. Therefore, the attenuated rheological strain of the concrete is equal to the lag rebound strain.

(2) At a high stress level, \( \sigma \geq \max(\sigma_{s1}, \sigma_{s2}) \), the concrete will undergo a process of accelerated rheology similar
to rock. The accelerated rheological stage appears earlier than the low stress level in the stress curve. Therefore, the rheological curve of concrete integrates both attenuated rheology and stationary creep.

According to the rheological characteristics of concrete at different stress levels, the attenuated rheological deformation of dam concrete is equal to the lag rebound strain at high or low stress levels. Therefore, the Nishihara model was adopted as a constitutive model of dam concrete, as this model can comprehensively describe the deformation of dam concrete under various loads (Figure 2).

![Figure 2](https://iwaponline.com/ws/article-pdf/20/8/3604/813453/ws020083604.pdf)

**Figure 2** | Constitutive model of mechanical composite elements of concrete dam.
The constitutive equation for dam concrete is

\[
\begin{align*}
\sigma \leq \sigma_2 & \quad \varepsilon = \frac{\sigma}{E_{MC}} + \frac{\sigma}{E_{KC}} \left[ 1 - \exp \left( \frac{E_{KC}}{\eta_{KC}} \frac{t}{t_0} \right) \right] \\
\sigma > \sigma_2 & \quad \varepsilon = \frac{\sigma}{E_{MC}} + \frac{\sigma}{E_{KC}} \left[ 1 - \exp \left( -\frac{E_{KC}}{\eta_{KC}} t \right) \right] + \frac{\sigma - \sigma_2}{\eta_{NC}}
\end{align*}
\]  

(14)

In Equation (14), \(\sigma_2\) is the plastic yield stress, \(E_{MC}\) is the elastic modulus, \(E_{KC}\) is the viscoelastic modulus, \(\eta_{KC}\) is the viscosity coefficient, and the other parameters are as described above.

The right side of Equation (14) includes instantaneous deformation and creep deformation. Considering that the dam concrete has just been poured and the stress level is unlikely to reach the yield limit, \(\sigma \leq \sigma_2\); creep deformation can therefore be expressed as:

\[
\varepsilon_c = \frac{\sigma}{E_{KC}} \left[ 1 - \exp \left( -\frac{E_{KC}}{\eta_{KC}} t \right) \right]
\]  

(15)

Equation (15) can be rewritten as:

\[
\sigma = \varepsilon_c E_{KC} \left[ 1 - \exp \left( -\frac{E_{KC}}{\eta_{KC}} t \right) \right]^{-1}
\]  

(16)

Equation (16) defines the creep stress as a function of \(t\) and \(\varepsilon_c\), and \(E_{MC}, E_{KC}, \eta_{KC}\) are constant. Therefore, Equation (16) can be rewritten as:

\[
\sigma_c(t) = c_1 (1 - e^{-\gamma_2 t})^{-1}
\]  

(17)

The stress monitoring model at the stage of ongoing dam construction following the sealing of the bottom of the arch is the sum of the self-weight, water pressure, temperature, and aging components. The comprehensive expression for stress monitoring of the super-high arch dam is therefore as follows:

\[
\sigma_2(H, h, H_1, T, t) = \sigma_0 + \sum_{i=1}^{5} a_i (H - h)^i + \sum_{i=1}^{m_1} b_i T_i + \sum_{i=1}^{4} c_i H_1^i + d_1 (1 - e^{-\gamma_2 t})^{-1}
\]  

(18)

or

\[
\sigma_2(H, h, H_1, T, t) = \sigma_0 + \sum_{i=1}^{5} a_i (H - h)^i + \sum_{i=1}^{m_1} b_i T_i + \sum_{i=1}^{4} c_i H_1^i + d_1 (1 - e^{-\gamma_2 t})^{-1}
\]  

(19)

CASE STUDY

In order to validate the effectiveness and accuracy of the monitoring model described above, section 16 of a super-high arch dam was selected for analysis as a case study. The validation used the in-situ strain monitoring data from the S616-4 measurement point at the heel of the dam section collected from December 2009 to December 2015.

Engineering and monitoring features

The dam used for model validation is a double-curvature concrete arch dam with a maximum height of 285.5 m, total storage capacity of 12.67 billion m\(^3\), regulating storage capacity of 6.46 billion m\(^3\), and a total installed capacity of 1,386 MW. The first block of dam concrete was poured on March 27, 2009. Gemel arch grouting began in September 2010 and was completed in November 2013. The last block of dam concrete was poured on March 6, 2014. Water storage began in early December 2011 and reached five characteristic water levels of 440 m, 540 m, 560 m, 580 m, and 600 m with a normal water level of 600 m being reached on August 26, 2014. A number of thermometers are arranged next to the strain gauges inside the dam. The actual temperature, construction, measured stress, and water storage data are shown in Figure 3.

The profile of the radial monitoring of the No. 16 dam section is shown in Figure 4. The strain monitoring system is arranged in alignment with the six arches and three beams. The strain gauges are oriented from upstream to downstream to monitor the changes in stress on the corresponding surfaces and the dam interior.
Model construction and analysis

The stress monitoring model described in the section for the upper portion of the dam after sealing the bottom of the arch was used. As mentioned above, this model considers the self-weight, water pressure, temperature, and aging components of stress on the dam. A corresponding calculation program was developed using MATLAB, and the coefficients were solved by a nonlinear regression method and nonlinear fitting.

In the case study dam, the upper portion of the dam following sealing of the arch was constructed between October 2010 and September 2013. According to the analysis described in the section above on the concrete self-weight component after sealing the bottom of the arch, the expression of the self-weight component is given by Equation (7). As there are a number of thermometers arranged inside the super-high arch dam, the temperature stress was calculated using measured data according to Equation (8). The water pressure component was calculated using Equation (10). Given that the concrete of the super-high arch dam is young during construction, the aging deformation process predominantly accounts for the concrete creep effect. According to the analysis of the concrete constitutive model of the dam body in the section above on the aging component, the Nishihara model was selected for the concrete constitutive model; thus, the expression of the aging component was calculated using Equation (17). Equation (18) was used to describe the overall stress monitoring model. Based on the stress data converted by the deformation method, the fitting coefficients shown in Table 2 were obtained by the least squares method. The self-weight component, water pressure component, temperature component, and aging component were determined separately. The fitting of the stress monitoring model and the hydrograph of each component are shown in Figure 5.

Table 2 and Figure 5 show that the fitting correlation coefficient of the stress monitoring statistical model reaches 0.986; thus, the fitting accuracy is relatively high, indicating that the proposed model can effectively describe the stress development process and provide technical guidance for the stress and safety monitoring of super-high arch dams during construction.

In order to quantitatively evaluate the influence of the considered factors individually, the annual variation of the stress at measuring point S616 in 2012 was taken as an example, as this year had the greatest variation in water level. The annual variation of each component was

![Figure 3](image-url) | Hydrograph of temperature construction, construction, and water storage.

![Figure 4](image-url) | Radial monitoring profile of No.16 dam.

<table>
<thead>
<tr>
<th>$a_0$</th>
<th>$a_1$</th>
<th>$a_2$</th>
<th>$a_3$</th>
<th>$a_4$</th>
<th>$a_5$</th>
<th>$b$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.36511</td>
<td>0.06350</td>
<td>-0.00221</td>
<td>1.96E-05</td>
<td>-7.25E-08</td>
<td>9.80E-11</td>
<td>0.02654</td>
</tr>
<tr>
<td>$c_1$</td>
<td>$c_2$</td>
<td>$c_3$</td>
<td>$c_4$</td>
<td>$d_1$</td>
<td>$r_1$</td>
<td>$R^2$</td>
</tr>
<tr>
<td>-0.02157</td>
<td>0.00057</td>
<td>-4.58E-06</td>
<td>1.32E-08</td>
<td>5.07723</td>
<td>-0.04586</td>
<td>0.986</td>
</tr>
</tbody>
</table>
separated according to the stress monitoring model, and the results are shown in Table 3.

The hydrograph of the self-weight component in Figure 5 indicates that the self-weight of the concrete has the most significant influence on the stress on the dam, and the weight of the concrete above the plane of the measuring point increases with the height of the dam, as does the compressive stress at the measuring point. However, due to the effects of the arch cantilever, the compressive stress generated by the self-weight gradually decreases and the hydrograph of the self-weight component gradually plateaus during the process of gemel arch grouting. In general, the effect of the self-weight of the dam concrete on stress is greater than the effect of temperature or creep. The variation range of the self-weight component accounts for approximately 28.7% of the overall variation in stress on the dam.

The hydrograph of the temperature component in Figure 5 indicates that temperature has some effect on the stress on the dam, as the stress on the dam has a relatively strong correlation with the temperature change. The stress and temperature at the measured point of the dam heel show consistency. This phenomenon is consistent with the known change law of concrete stress at the dam heel. The variation in the temperature component accounts for approximately 2.1% of the overall variation in stress on the dam.

The hydrograph of the water pressure component in Figure 5 shows that the hydrograph of the water pressure component is very consistent with the hydrograph of

![Figure 5](image-url)  
*Figure 5 | The fitting of the stress monitoring model and the hydrograph of each component.*

<table>
<thead>
<tr>
<th>Annual variation range of total stress (MPa)</th>
<th>Self-weight component</th>
<th>Temperature component</th>
<th>Water pressure component</th>
<th>Creep component</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.656 (absolute)</td>
<td>0.442</td>
<td>0.031</td>
<td>0.939</td>
<td>-0.124</td>
</tr>
</tbody>
</table>

Table 3 | Separation table of annual variation range of stress (MPa)
water storage. The second stage of water storage for the studied dam began in May 2013, with the water level rising from 440 m to 540 m. The water pressure component of stress increased accordingly after May 2013, consistent with the change law of the water pressure component. The variation of the water pressure component accounts for approximately 61.1% of the overall variation in stress.

Finally, the hydrograph of the aging component in Figure 5 indicates that the creep effect of concrete increases gradually during construction. The creep rate decreases with time, and the change in stress on the dam gradually plateaus in line with the hydrograph of the measured stress. The stress change laws are reflected by the aging component, which accounts for approximately 8.1% of the overall variation in stress on the dam.

CONCLUSION

Using mathematics, mechanics, and dam engineering principles and methods, a stress monitoring model for a super-high arch dam in the pre-impoundment stage of construction was developed based on the analysis of prototype observation data. The main contributions of this study are summarized as follows:

(1) The mathematical expressions of the self-weight component both prior to and following the sealing of the bottom of the arch were derived considering the characteristics of a super-high arch dam in the pre-impoundment phase of construction and the effect of arch seal grouting on self-weight stress. The expression of the stress of a concrete dam’s aging component was determined based on rheological theory. Furthermore, the stress monitoring model considered the contribution of the temperature component of stress on the dam.

(2) The proposed stress monitoring model was applied to a constructed super-high arch dam as a case study, and the components of the monitoring model were isolated. The analysis showed that the model has a high fitting accuracy and considers an appropriate selection of components. The hydrograph of each component conforms to the observed structural characteristics of the super-high arch dam during construction. Thus, this model overcomes the previous limitation of considering the application of the complete self-weight of the dam on the cantilever beam. The validity of the proposed stress monitoring model has been verified for a super-high arch dam. Thus, this paper provides evidence for the potential of safety monitoring models of super-high arch dams during construction.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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