RESEARCH ARTICLE

A statistical model of deformation during the construction of a concrete face rockfill dam

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Summary
Monitoring data collected during dam construction are important in complete series of monitoring data. These data play a significant role in dam safety monitoring and the analysis of structural conditions. The traditional statistical model of the deformation of a concrete face rockfill dam (CFRD) with filling height and time factors is associated with serious multicollinearity issues during the construction phase. This study uses the Longbeiwan CFRD as an engineering model, and the internal settlement of the dam is the research focus. The traditional statistical model of deformation includes internal settlement data from the construction period and the filling height factor. Subsequently, the filling height component of the statistical model is established, and an improved statistical model is proposed with additional factors not included in the traditional statistical model. The model analysis indicates that the improved statistical model can effectively eliminate or reduce multicollinearity issues between the filling height and time factors in the traditional statistical model. The model analysis also provides a new and reasonable modeling approach for quantitatively analyzing deformation monitoring data during CFRD construction.

KEYWORDS
concrete face rockfill dam, deformation, monitoring, multicollinearity, statistical model

1 | INTRODUCTION

A concrete face rockfill dam (CFRD) is a type of dam that uses rockfill as the support structure and an upstream surface concrete face as the anti-seepage structure. CFRDs are effective because of their adaptability to poor topographical, geological, and climatic conditions. In addition, they have excellent safety features and economic efficiency. Currently, CFRDs are one of the most commonly used and cost competitive dam types.[1,2]

Deformation and seepage control are two key technical problems in CFRD construction. Deformation (such as that of the surface, interior, and foundation of dams) and various joint deformations can be monitored using various technologies.[3] For example, the horizontal displacement of the dam surface can be monitored by line of sight or torsion, whereas the surface settlement (vertical displacement) of the dam can be monitored using the geometric method. Moreover, the horizontal displacement of the rockfill body can be monitored by a meter or inclinometer, whereas the
A large or uneven deformation (especially internal deformation) of a CFRD can cause cracks in the panel and the breakage of the waterstop between the panels, which is one of the sources of major defects in CFRDs.\[1\] Therefore, further analysis of deformation monitoring data has significant theoretical significance and applicational value in ensuring dam safety.

Currently, deformation monitoring and data analyses of CFRDs mainly rely on qualitative analysis methods,\[6–8\] such as analyzing the trends of deformation over time through drawing process lines, determining the variable range of deformation based on statistical characteristics, and analyzing spatial deformation using scattergrams. However, quantitative analysis results based on mathematical models are not sufficient.

In mathematical models, analyses of the deformation monitoring data of a CFRD can mainly be classified into three categories. The first category includes traditional methods of statistical modeling, deterministic modeling, and mixed modeling.\[9–12\] In this category, the factors that influence deformation are generalized into water pressure, temperature, and aging factors.\[13,14\] The second category involves finite element calculations combined with monitoring data analysis. First, rock creep is simulated, and material parameter inversion is conducted. Then, the deformation behavior can be analyzed.\[15,16\] The third category uses modern mathematical methods, such as artificial neural networks and gray time series modeling, to model CFRD deformation. These new concepts and methods can improve CFRD deformation analysis and deformation prediction.\[17–20\]

Mathematical models of CFRD deformation monitoring are mainly associated with data observation during the run-up period when the impoundment of the sluice is complete. Such models generally disregard deformation during construction. However, a few monitoring models consider deformation during construction and preset model factors, but they neglect in-depth analysis of the characteristics of deformation during construction. Therefore, the mathematical model cannot make realistically and effectively analyze deformation characteristics. Nevertheless, dam monitoring data include monitoring data during construction and operation. To identify the basic monitoring effects during construction, monitoring data during the construction period are an important part of the time series of dam monitoring data, which is of special significance for analyzing structural dam behavior and implementing dam safety monitoring. Thus, this study presents a deformation model for CFRDs on the basis of the traditional statistical model of deformation monitoring but considering deformation during the construction period. In this study, the Longbeiwan CFRD is considered in the engineering model, and the internal settlement of the rockfill is the research focus. The improved statistical model provides a novel and reasonable modeling approach for the quantitative analysis of the deformation monitoring data of CFRDs.

2 | LONGBEIWAN PROJECT INTRODUCTION

The Longbeiwan Hydropower Project is located in the upper and middle reaches of the Guandu River, Zhushan County, Hubei Province, China. This large-scale hydroelectric power station project comprises a dam, spillway, and power generation system, as shown in Figure 1. The normal water level of the reservoir is 520.00 m; the designed flood level is 521.85 m; the flood level is 523.89 m; and the reservoir capacity is 466 million m$^3$ with a multi-year regulating function.

The dam in Figure 1 is a CFRD. The main dam height is 520 m, and the height of the top of the rockfill dam is 524.30 m. The maximum dam height is 158.30 m; the upstream slope is 1:1.4; and the average value of the variable downstream slope is 1:1.5. The rockfill and secondary rockfill zones are dolomite and excavation material, respectively. The bottom of the upper toe plate has an anti-seepage curtain. This diversion type hydropower station has an installed capacity of approximately 2 × 90 MW.

The construction of the Longbeiwan Hydropower Project began at the end of 2009, and the dam body was filled with rockfill at the end of April 2012. On March 30, 2014, the dam body was filled to the top of the rockfill body at an elevation of 520.00 m. On October 12, 2014, the dam began water storage, and on April 25, 2015, the highest water level of 502.55 m was reached. The processes of dam filling and dam water storage are shown in Figures 2 and 3, respectively. To monitor the internal settlement characteristics of the rockfill body of the Longbeiwan CFRD, a water pipe settlement instrument was installed such that pile 0 + 263 m had monitoring section elevations of 410, 435, and 460 m and pile 0 + 167 m had monitoring section elevations of 435 and 460 m. The layout for each water pipe settlement instrument had four to seven measuring points, and 0 + 263-m section was the main monitoring section, as shown in Figure 4. The main monitoring section, 0 + 263 m, was arranged as follows: seven measuring points numbered TA1-1
FIGURE 1  Longbeiwan hydropower station hub

FIGURE 2  Process line of dam filling height change for a typical Longbeiwan concrete face rockfill dam section

FIGURE 3  Process line of upstream water level change at Longbeiwan hydropower station

FIGURE 4  Longbeiwan concrete face rockfill dam internal settlement monitoring points on 0 + 263 section arrangement diagram
to TA1-7 were located at an elevation of 410 m; five measuring points numbered TA2-1 to TA2-5 were located at an elevation of 435 m; and four measuring points numbered TA3-1 to TA3-4 were located at an elevation of 460 m.

3 | THE TRADITIONAL STATISTICAL MODEL OF DEFORMATION MONITORING

3.1 | The structure of a traditional statistical model of deformation monitoring

On the basis of the literature\(^9,21\) and existing dam engineering knowledge and experience, the internal CFRD deformation at any point in time \(t\) is affected mainly by the comprehensive influence of the rockfill filling height, upstream and downstream water level changes, dam body temperature, and time factors. Therefore, the traditional statistical model in monitoring internal CFRD deformation mainly consists of a filling height component \(\hat{y}_h(t)\), upstream water pressure component \(\hat{y}_{Hu}(t)\), downstream water pressure component \(\hat{y}_{Hd}(t)\), temperature component \(\hat{y}_T(t)\), and aging component \(\hat{y}_\theta(t)\). The general expression of the model is as follows:

\[
\hat{y}(t) = a_0 + \hat{y}_h(t) + \hat{y}_{Hu}(t) + \hat{y}_{Hd}(t) + \hat{y}_T(t) + \hat{y}_\theta(t).
\] (1)

1. Filling height component \(\hat{y}_h(t)\)

The settlement at any monitoring point in the CFRD during the construction period is mainly related to the compressive stress directly generated by the overlying rockfill bodies at the measuring point, which is mainly a function of the rockfill height \(h\) at the measuring point. The compressive stress produced by rockfill bodies is related to the characteristics of the rockfill material (such as the rock mass density \(\gamma\) and deformation modulus \(E_d\)). By using the Duncan model to simulate the deformation modulus of the rockfill, we find that the filling height component \(\hat{y}_h(t)\) of the settlement at any point in the internal rockfill of the CFRD is proportional to the \(\alpha\)th power of the filling height \(h\) above the point. Thus, \(\hat{y}_h(t) = f(h) = \sum h^\alpha\), in which \(\alpha\) generally equals 0.25, 0.5, 0.75, or 1.0. Thus, the filling height component \(\hat{y}_h(t)\) can be expressed as follows:

\[
\hat{y}_h(t) = f(h) = \sum_{i=1}^{r} a_i h^{(i)} = a_1 h^{0.25} + a_2 h^{0.5} + a_3 h^{0.75} + a_4 h^{1.0}.
\] (2)

2. Upstream water pressure component \(\hat{y}_{Hu}(t)\)

After the impoundment of the rockfill dam face, the water pressure is gradually transferred to the rockfill through the panel. Therefore, the settlement at any monitoring point in the rockfill dam during the operation of the rockfill dam is not only related to the upstream water level but also to the rockfill material characteristics. The Duncan model is also used to simulate the deformation modulus of the rockfill, and we find that the upstream water pressure component \(\hat{y}_{Hu}(t)\) at any point in the internal rockfill of the CFRD is proportional to the \(n\)th power of the upstream water depth \(H_u\) above the point. Thus, \(\hat{y}_{Hu}(t) = f(H_u) = \sum H_u^n (n = 1–4)\), the upstream water pressure component \(\hat{y}_{Hu}(t)\) can be expressed as follows:

\[
\hat{y}_{Hu}(t) = f(H_u) = \sum_{i=1}^{n} b_i H_u^i(t) = b_1 H_u + b_2 H_u^2 + b_3 H_u^3 + b_4 H_u^4.
\] (3)

Similarly, the downstream water pressure component \(\hat{y}_{Hd}(t)\) can be expressed as follows:

\[
\hat{y}_{Hd}(t) = f(H_d) = \sum_{i=1}^{m} c_i H_d^i(t) = c_1 H_d + c_2 H_d^2 + c_3 H_d^3 + c_4 H_d^4,
\] (4)

where \(H_u\) denotes the upstream water depth and \(H_d\) denotes the downstream water depth.
3. Temperature component $\hat{y}_T(t)$

The expression of the temperature component is related to the dam temperature field. If sufficient measuring points $p$ exist to describe the dam temperature field, the temperature component $\hat{y}_T(t)$ can be expressed as follows:

$$\hat{y}_T(t) = f(T) = \sum_{i=1}^{p} d_i T_i(t),$$  \hspace{1cm} (5)$$

where $T_i(t)$ is the $i$th temperature factor for the measured temperature of the temperature measuring point $i$ at time $t$.

However, the complete state of the dam body temperature field cannot be obtained because temperature monitoring instruments are rarely installed in the CFRD section. At this point, the change in temperature is mainly affected by outside temperature changes because the dam body temperature field approaches the quasi-steady temperature field. Therefore, external temperature changes can reflect the changes in the internal dam temperature field indirectly due to the lag effect that exists between the internal temperature of the dam body and external temperature changes. Thus, a period of several days prior to settlement observation can be used to average temperature factors because the influence of the internal settlement temperature change has a lag effect. Subsequently, the temperature component $\hat{y}_T(t)$ can be expressed as follows:

$$\hat{y}_T(t) = f(T) = \sum_{i=1}^{p} d_i T_{(i(k_1−k_2)}(t),$$  \hspace{1cm} (6)$$

where $T_{(i(k_1−k_2)}(t)$ is the $i$th temperature factor of the average temperature in the period from $k_1$ to $k_2$ days before the observation.

4. Aging component $\hat{y}_\theta(t)$

The aging component is a type of irreversible deformation in a certain direction over time. This component mainly reflects the influence of the dam-filling material rheology, dam foundation overburden, and bedrock creep on the internal settlement of the dam body due to relatively complex causes and mechanisms. According to existing research results, the aging component combined with the constitutive relationship between a CFRD and filling material is generally described using logarithmic, exponential, exponential decay, hyperbolic, or linear functions. When establishing the statistical model, the aging component generally uses the time factors shown in Equation 7 as the subset of time factors:

$$I_1 = \ln(t_1 + 1), \hspace{0.5cm} I_2 = 1-e^{-t_1}, \hspace{0.5cm} I_3 = t_1/(t_1 + 1),$$
$$I_4 = t_1, \hspace{0.5cm} I_5 = t_1^2, \hspace{0.5cm} I_6 = 1/(1 + e^{-t_1}).$$  \hspace{1cm} (7)$$

where $t_1$ denotes the time calculation parameters relative to the benchmark date, which generally takes the form $t_1 = (\text{observation sequence number} − \text{base date number})/365$.

Therefore, the aging component $\hat{y}_\theta(t)$ can be represented as follows:

$$\hat{y}_\theta(t) = f(t) = \sum_{i=1}^{s} e_i I_i(t),$$  \hspace{1cm} (8)$$

where $a_0$ is the regression constant; $a_i$, $b_i$, $c_i$, $d_i$, and $e_i$ are the regression coefficients and $r$, $n$, $m$, $p$, and $s$ are the corresponding numbers of factors according to the actual engineering scenario.

The theoretical basis for the statistical monitoring model is regression, including multiple regression analysis and stepwise regression analysis.
3.2 Problems that exist in the traditional monitoring and statistical models

Regression analysis uses the least squares method for an unbiased estimation of the regression coefficients. The least squares method is based on the absence of a close relationship with the hypothesized model factors. When a certain degree of linear or approximately linear relationship exists between the model factors, the established statistical model will have serious issues in determining the multicollinearity among factors. These problems include the inability to effectively decompose each component, difficulty in determining the actual states of monitoring effects, and the distortion of the actual states of monitoring effects.

As shown in Equation 9, the structure of the traditional statistical model contains the following factors: filling height, upstream and downstream water levels, temperature, and aging. In Equation 2, the filling height component is a function of the filling height \( h \), and \( \hat{y}_h = f(h) \). The filling height \( h \) is a function of time \( t \), namely, \( h = f(t) \). In Equations 7 and 8, the aging component is a function of time \( t \), namely, \( \hat{y}_\theta = f(t) \). The \( t \) in the filling height and aging factors overlaps when deformation is considered during construction. Because the filling height factor is similar to a limitation factor in form, multicollinearity exists between the filling height and aging factors.

This study introduces the variance coefficient of expansion to further analyze the multicollinearity problem between the embankment height and time. The expansion coefficient variance VIF\(_i\) of factor \( x_i \) is as follows:

\[
VIF_i = (1-R^2_i)^{-1},
\]

where \( R^2 \) is the multiple determination coefficient relative to \( x_i \) when other factors \( x_j (j \neq i) \) are used in regression analysis.

A large VIF reflects high multicollinearity relative to \( x_i \) when other factors \( x_j (j \neq i) \) are used in regression analysis. When \( 0 < VIF < 10 \), no multicollinearity exists between factors; when \( 10 \leq VIF < 100 \), some multicollinearity exists between factors; and when \( 100 \leq VIF \), high multicollinearity exists between factors.

The internal deformation of filling and aging at the 410-m measuring point during construction of the Longbeiwan CFRD (December 9, 2012–March 31, 2014) were calculated using the traditional model. The values of the expansion coefficient variance between filling and aging are shown in Table 1.

Table 1 shows that the values of the expansion coefficient variance between filling height and time factors are greater than 10 at all points at 410 m. Thus, stronger multicollinearity exists between filling height and aging factors at each measuring point.

4 THE IMPROVED STATISTICAL MODEL OF DEFORMATION MONITORING

4.1 The improved basic concept

Because of the multicollinearity between the filling height and time factors in the traditional statistical model of internal CFRD settlement, finding the right method of eliminating or reducing the effect of multicollinearity in modeling is necessary.

In Equation 9, various factors of influence exist and follow these basic rules:

| Measuring point | Expansion coefficient variance VIF |
|-----------------|-----------------------------------|
| TA1-1           | 46.20                             |
| TA1-2           | 35.93                             |
| TA1-3           | 30.28                             |
| TA1-4           | 30.89                             |
| TA1-5           | 30.70                             |
| TA1-6           | 33.06                             |
| TA1-7           | 33.21                             |
1. The CFRD usually stores water after the completion of rockfill filling. The influences of the upstream and downstream water levels on the settlement of a CFRD are very small during the construction period. Therefore, they are not taken into account in the statistical model.

2. The impact of temperature change on internal settlement is very small. Generally, the internal subsidence caused by temperature changes is less than 5% of the total sedimentation.\(^{[14]}\)

3. Rockfill flow deformation mainly occurs during the construction and impoundment periods of a new reservoir.\(^{[23]}\) The internal settlement caused by rockfill flow deformation during construction is difficult to distinguish from the rockfill compression caused by increasing filling height.

4. After rockfill filling is completed, the filling height can be regarded as final. Therefore, internal CFRD settlement during the construction period is mainly caused by the increase in the rockfill filling height and the rheological factors of the rockfill filling material. Notably, settlement caused by filling height changes is the main factor. Thus, eliminating or reducing the multicollinearity between the filling height and time factors in the traditional statistical model is the basic approach toward improving the model.

Therefore, this study proposes the following concepts for improvement:

1. Choose the settlement monitoring data during the construction period and use the filling height factor separately. The statistical model of the filling height component \( \hat{y}_h(t) \) is introduced according to Equation 2. The regression coefficient \( a_i \) in Equation 2 can be obtained as follows:

\[
\hat{y}_h(t) = \sum_{i=1}^{r} a_i h^{(i)}.
\]

2. Because the internal settlement during the construction period is not entirely caused by the change in the filling height, the settlement during construction, according to Equation 11, will result in error. At this point, an adjustment coefficient \( \Phi \) is introduced to adjust \( \hat{y}_h(t) \):

\[
\hat{y}_h(t) = \Phi \hat{y}_h(t) = \Phi \sum_{i=1}^{r} a_i h^{(i)}.
\]

3. Equations 3, 4, 6, and 8 are based on the upper and lower water level factors, the temperature factor, and the aging factor. The structure of the improved statistical model is as follows:

\[
\hat{y}(t) = a_0 + \Phi \hat{y}_h(t) + \hat{y}_{H_u}(t) + \hat{y}_{H_d}(t) + \hat{y}_T(t) + \hat{y}_\theta(t) = a_0 + \Phi \sum_{i=1}^{r} a_i h^{(i)} + \sum_{i=1}^{n} b_i H_u^{(i)}(t) + \sum_{i=1}^{m} c_i H_d^{(i)}(t) + \sum_{i=1}^{p} d_i T_i(t) + \sum_{i=1}^{s} e_i I_i(t),
\]

where \( a_i \) is obtained using Equation 11 and \( a_0, \Phi, b_i, c_i, d_i, \) and \( e_i \) are the solution coefficients. Utilizing the entire sequence of monitoring data, including the construction period and operation periods and using multiple and stepwise regression analyses, the above coefficients can be determined on the basis of Equation 13. As a result, the improved statistical model is obtained.

### 4.2 Validating the improved statistical model

To verify the feasibility and rationality of the proposed improved statistical model, the internal settlement point at TA1-5 at an elevation of 410 m in the Longbeiwan CFRD is used, and the dam axis is used as a representative measuring point. The measured settlement data from December 9, 2012–December 24, 2015, are selected. The traditional statistical model is arranged according to Equation 9. Finally, the improved statistical model is established according to Equation 13. On the basis of the analysis in Section 3.1 for model construction, the preset factor sets are selected as follows.

- Filling height subset: \( h^{0.25}, h^{0.5}, h^{0.75}, \) and \( h^{1.0}; \)
- Upstream water pressure subset: \( H, H^2, \) and \( H^3; \)
Temperature subset: $T_{0-1}, T_{1-2}, T_{3-7}, T_{8-15},$ and $T_{16-30}$.

Aging subset: On the basis of the qualitative analysis of the process line of measured internal settlement at TA1-5, the variation is consistent with the characteristics of the combination of linear change and logarithmic change. Therefore, $t_1$ and $\ln(t_1 + 1)$ are selected as the preset aging factors from the six types of factors in Equation 7.

Downstream water pressure subset: Because the Longbeiwan hydropower station is a diversion type dam, there is no water at the downstream dam foot. Therefore, the influence of the downstream water level is not considered.

The result of the internal settlement modeling at TA1-5 using the traditional statistical model is as follows:

$$y = -7213.4383 - 1991.1627t_1 + 13227.2097 \ln(t_2 + 1) - 22.0613 + 0.0240H^2 + 1.1426H - 0.7259T_{1-2}. \tag{14}$$

According to the above analysis of the preset factor set, the traditional statistical model and the improved statistical model of TA1-5 are established by stepwise regression analysis. Stepwise regression analysis introduces the preset factors into the model individually. After the $F$ test is used to remove the factors that influence the model less significantly, we ultimately obtain the optimal statistical model, which consists of the factors that significantly impact the model.

The result of internal settlement modeling at TA1-5 using the improved statistical model is as follows:

$$y = -1244.4471 - 250.9550t_1 + 2100.0191 \ln(t_2 + 1) - 4.2423H + 0.0050H^2 + 0.8040(-6449.983 + 3079.01xh^{0.25} - 18.379xh^{0.75}) + 0.6401T_{16-30}. \tag{15}$$

Figure 5 shows the fitting results of the traditional and improved statistical models of internal settlement at TA1-5 (positive values reflect sinking and negative values reflect lifting in Figure 5 and subsequent figures). The multiple correlation coefficient of the traditional statistical model is $R = 0.995$, whereas the multiple correlation coefficient of the improved statistical model is $R = 0.998$. Figure 5 shows that the complex correlation coefficients $R$ of both the traditional statistical model and the improved statistical model are high, and the increase in the complex correlation coefficient of the improved statistical model is not large. However, the fitting effect of the traditional statistical model is not ideal in the construction period of the CFRD, whereas the fitting effect of the improved statistical model is better in the construction and operation periods of the dam. This result indicates that although the traditional statistical model is likely to yield a high complex correlation coefficient, the modeling results do not truly reflect the actual deformation scenario.

Figure 6 shows the various factors of influence that alter the process line of internal settlement at TA1-5 using the traditional statistical model, whereas Figure 7 shows the same for the improved statistical model. Table 2 presents the proportions of the various factors of influence that affect the internal settlement at TA1-5 using the traditional and improved statistical models.

Figures 6 and 7 and Table 2 express the following results:

1. In the traditional statistical model, the proportion of the filling height is 10.5%. Additionally, the proportion of aging is 77.2%, which is significantly larger than the proportion associated with the filling height. TA1-5 is located at an elevation of 410 m above the dam axis position, and the total rock body height is higher than 410 m. Theoretically, the internal settlement at TA1-5 should be the result of the compression of the filling materials caused by the
continuous increase in the rockfill height. Thus, internal settlement should be a function of the filling height. In addition, the various components of the internal settlement at TA1-5 determined using the traditional statistical models are unreasonable and unrealistic. The traditional statistical model cannot make exact estimates with regard to the causes and rules of internal settlement at TA1-5.

2. The proportion of the filling height determined using the improved statistical model is 71.2% whereas that of aging is 25.8%. Among the components, the proportion of the filling height is the largest and significantly greater than the proportion of aging. This result is consistent with the basic characteristics of internal settlement theory at TA1-5. Overall, the improved statistical model can be used to accurately analyze the causes and rules of internal settlement at TA1-5.

3. The traditional statistical model cannot reasonably determine the proportions of the various factors that influence internal settlement at TA1-5 because of the associated multicollinearity between the filling height and time factors. As shown in the traditional statistical model in Equation 14, the filling height only uses the \( h^{1.0} \) factor and not the \( h^{0.25} \), \( h^{0.5} \), and \( h^{0.75} \) factors. This selection is due to the strong similarity in the curves of the filling height factors \( h^{0.25} \), \( h^{0.5} \), and \( h^{0.75} \) and the aging factor \( \ln(t_1 + 1) \). The filling factor \( h \) after filling to the maximum rockfill elevation remains unchanged, and \( t_1 \) in the aging factor increases over time. Therefore, according to the traditional statistical model, aging should contribute more to internal settlement at TA1-5, as shown in the long-term monitoring data. However, this phenomenon is not a true reflection of the actual causes and variations at in internal settlement at

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**TABLE 2** The proportion of influence of each component at TA1-5 using the improved and traditional statistical models

| Model category          | Filling height proportion (%) | Aging component proportion (%) | Upstream water level component proportion (%) | Temperature component proportion (%) |
|-------------------------|-------------------------------|--------------------------------|-----------------------------------------------|--------------------------------------|
| Traditional statistical model | 10.5                          | 77.2                           | 10.9                                          | 1.4                                  |
| Improved statistical model   | 71.2                          | 25.8                           | 1.7                                           | 1.2                                  |

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**FIGURE 6** The various factors that influence the process line of internal settlement at TA1-5 using the traditional statistical model

**FIGURE 7** The various factors that influence the process line of internal settlement at TA1-5 using the improved statistical model
TA1-5. As shown in the improved statistical model in Equation 15, the multicollinearity between the filling height and time is reduced to a certain extent during construction because of the use of monitoring data to simulate the influence of the filling elevation change. Thus, the modeling result is more reasonable and more consistent with the actual situation.

To illustrate the universality of the proposed improved statistical model, the traditional and improved statistical models of the seven internal settlement points (TA1-1 to TA1-7) on the Longbeiwan CFRD at 410-m elevation are presented. The proportions of the various factors that influence internal settlement using the traditional and improved statistical models at each measuring point are shown in Table 3.

Table 3 shows that similar to TA1-5, the traditional statistical modeling results are unreasonable at other internal settlement points at 410 m of elevation. However, the results of the improved statistical model can accurately consider the causes and regularities of internal settlement at each measuring point. These results show that the proposed improved statistical model has good universality.

| Measurement point number | Filling height proportion (%) | Aging component proportion (%) | Upstream water level component proportion (%) | Temperature component proportion (%) |
|--------------------------|------------------------------|--------------------------------|-----------------------------------------------|-------------------------------------|
| Traditional statistical model | TA1-1 | 19.9 | 62.2 | 17.9 | 0 |
|                           | TA1-2 | 20.7 | 67.5 | 9.9  | 1.9 |
|                           | TA1-3 | 23.6 | 66.1 | 8.5  | 1.8 |
|                           | TA1-4 | 15.7 | 73.9 | 10.4 | 0   |
|                           | TA1-5 | 10.5 | 77.2 | 10.9 | 1.4 |
|                           | TA1-6 | 35.2 | 53.0 | 7.9  | 3.9 |
|                           | TA1-7 | 26.7 | 56.2 | 10.0 | 7.1 |
| Improved statistical model | TA1-1 | 54.9 | 25.8 | 16.6 | 2.7 |
|                           | TA1-2 | 61.8 | 23.3 | 11.7 | 3.2 |
|                           | TA1-3 | 68.8 | 22.1 | 4.4  | 4.7 |
|                           | TA1-4 | 76.4 | 16.9 | 3.4  | 3.3 |
|                           | TA1-5 | 71.2 | 20.8 | 6.7  | 1.3 |
|                           | TA1-6 | 66.4 | 19.4 | 10.0 | 4.2 |
|                           | TA1-7 | 54.4 | 30.1 | 9.4  | 6.1 |

5 | CONCLUSIONS

1. The internal settlement of a CFRD during construction is mainly caused by filling height changes. When the deformation data series are modeled during the construction phase, high multicollinearity exists among datasets because of the similarity between the filling height and time in traditional monitoring and statistical models. The multicollinearity increases the negative impact of the modeling effect and leads to difficulty in describing the actual causes, trends, and characteristics of internal settlement using the traditional model.

2. To overcome the multicollinearity issues of the traditional statistical model of CFRD deformation, this paper proposes an improved statistical model of CFRD deformation. First, the internal settlement monitoring data from the construction period are selected for analysis, and the filling height factor is one of several factors studied. The filling height component of the statistical model is presented, and an adjustment coefficient \( \Phi \) is introduced to correct the error associated with the filling height of the statistical model. The entire sequence of monitoring data containing the construction and operation periods is used in the model. Multiple and stepwise regression analyses are used to solve for the corresponding regression coefficient, and the improved statistical model of deformation is introduced. The main purpose of this paper was to construct an improved statistical model to eliminate or reduce the adverse effects of multiple collinearity between the filling height factor and the aging factor using a statistical deformation model. In this novel method, the improved statistical model can accurately describe the causes and characteristics of deformation, and it provides a new and more reasonable modeling method to quantitatively analyze the deformation monitoring data of a CFRD in the construction period.
3. The concept of the improved statistical model proposed in this paper has been applied to the Shuibuya CFRD and Dongjin CFRD in China with good results. Thus, this improved model is suitable for deformation monitoring during the construction period. Moreover, the improved model considers not only the statistical models of CFRD deformation during construction but also other types of statistical models of dam deformation. The proposed model can serve as a reference for future studies.

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