Research Article

Sensitivity Study of the Computational Parameters for the Deformation of Homogeneous Earth Dams

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1. Introduction

Dams are large and important engineering facilities that relate to millions of cubic metres of water and, due to the presence of various external and internal loads, are bound to generate corresponding horizontal and vertical motions. These movements, also known as deformations, may lead to catastrophic damage when they reach certain critical limits, for example, leading to the complete collapse of a dam [1]. Therefore, it is necessary to numerically simulate and monitor the dam deformation to see if it is in a safe range. Among many dam types, Earth dams are one of the oldest dam types in the world [2], among which homogeneous Earth dams are again the most economical and practical Earth dams. Many scholars have conducted corresponding studies on the deformation of homogeneous Earth dams [3–6]. Among them, Guo et al. investigated the importance of input variables in stability studies of Earth dams by combining the kriging substitution model, Monte Carlo simulations, the Sobol sensitivity analysis method, and the first-order reliability method [4]. Dong et al. used high Earth and rock dams in China as an example for a static analysis with the Duncan–Chang E-B model and compared it with monitoring data. It was determined that the modified model could better describe the deformation of Earth and rock dams [3]. The study of Earth dams is no longer limited to finite element analyses, with an increasing number of scholars beginning to investigate the stability of Earth dams concerning methods and intrinsic models.

Currently, the commonly used intrinsic models for Earth and rock dam calculations are the nonlinear elastic model and the elastoplastic model [7]. Because the parameters of the elastoplastic model are difficult to obtain and the calculation process is very complicated, the Duncan–Chang model (Duncan–Chang E-B model or Duncan–Chang E-υ model) among the nonlinear elastic models is often used to
analyse the structural properties of dams [8], where not only the Duncan–Chang E-B model reflects the main deformation laws of the soil but also each of its parameters has a clear physical and geometrical meaning. Also, its parameters can be obtained not only by conventional triaxial shear tests simply [9] but also by intelligent algorithms for an inverse analysis. In general, the inverse analysis of model parameters requires us to establish the objective function between the parameters and the deformation results, which in turn transforms the inverse analysis problem of model parameters into an optimization problem [10]. However, parameter inversion requires a large number of finite element simulations to provide sufficient data for the algorithm training set. To improve the computational efficiency, researchers have started using sensitivity analysis methods for the model parameters.

The purpose of the sensitivity analysis is to quantify the effect of input variables on a given outcome. A sensitivity analysis can give a measure of the importance of parameters in a system when considering the extent to which uncertainty in the input parameters affects the model response output [4]. Through a sensitivity analysis, parameters with a low sensitivity can be set to fixed values and only parameters with high impact on the output variables can be studied, thus effectively simplifying the model, improving the model calibration accuracy, and saving time [11]. Earlier parametric sensitivity analyses were more likely to use one-way sensitivity analyses similar to control variables, where the effect of a change in the target parameter on the output parameter was investigated by controlling other parameters to remain constant [12]. Sensitivity analysis methods include local sensitivity analysis methods and global sensitivity analysis methods. The main existing local sensitivity analysis methods are the sensitivity analysis with finite differences, scenario decomposition and generalized tornado diagrams, spiderplots and one-way sensitivity functions, and differential-based differentiation methods [13]. However, these methods have limitations of linearity, normality, and local variability [14]. In contrast to a local sensitivity analysis, a global sensitivity analysis is more concerned with the interaction of all factors on the entire input space and the impact on the target parameters [15]. Global sensitivity analysis methods can be divided into regression-based methods, design of experiments and screening design methods, variance-based methods, and meta-model-based methods [16].

In recent years, sensitivity analysis has been increasingly applied in dam engineering studies. Li et al. used a variance-based global sensitivity analysis method to analyse the static performance of dams at three different levels [17]. Liang et al. then used Latin hypercube sampling (LHS) with an approximate moment estimation to study the parameter sensitivity of the seismic stability performance of high arch dams [18]. Chen et al. then used the modified Morris method to preliminarily analyse the sensitivity of the parameters in the coupled E-v model and the modified Burgers model [19]. Yao et al. used a response surface methodology instead of an artificial neural network to describe the sensitivity relationship between the E-B model parameters and dam deformation [10]. Ren et al. then used the Morris method to study the sensitivity of thermohydraulic coupling model parameters to the temperature field of Earth and rock dams in Shaanxi Province, China [20]. Lakahel and Djemili investigated the sensitivity between E-B model parameters and safety factors using a central combined design test method for homogeneous soil slopes [21], among others. Compared to the above sensitivity analysis methods, orthogonal design is one of the experimental design and screening design methods [22], which can replace a full-scale test with a smaller number of tests and is a scientific method for arranging and solving multifactor tests. Yu and Chen selected three main factors, namely, debris flow accumulation density, drainage ditch slope, and slope of the upstream face of silt dam, in order to establish an orthogonal table to investigate the influence on the debris flow impact presence of influencing factors [23]. Zhong et al. conducted a sensitivity analysis using orthogonal tests for the effect of construction parameters on construction duration during arch dam construction [24]. Sun et al. and Yan et al. performed a sensitivity analysis of the parameters of the Duncan–Chang E-B model for concrete panel rockfill dams in an orthogonal test and analysed the results using the extreme difference analysis method and the analysis of variance method [25, 26].

A traditional single-factor sensitivity analysis mostly takes the specific unit where the maximum displacement of the dam occurs as the object of study; however, the selection of different locations can have an impact on the sensitivity analysis results. In addition, the results of the above orthogonal tests were mostly obtained by applying extreme difference or analysis of variance methods to obtain the corresponding sensitivity conclusions, where mutual validation between the two methods and mutual validation between multifactor and single-factor sensitivity analyses was lacking. At the same time, the current study lacks setting the error columns and does not consider the effect of dam material density on dam deformation. The effect of error and dam material density is therefore prevalent and cannot be ignored. In this paper, a homogeneous loess dam in Gansu Province, China, is used as the research object to investigate the above problem. A static analysis model reflecting the Earth and rock dam is constructed through the finite element method analysis procedure to solve the displacement variation of the dam; a sensitivity analysis of the calculation parameters affecting the deformation of the homogeneous Earth dam is conducted from both single-factor and multifactor aspects in order to provide a reference for the selection of parameters for the simulation of the deformation of the homogeneous loess dam.

2. Duncan–Chang E-B Model Fundamentals

The stress-strain relationship usually used in numerical calculations of homogeneous loess is nonlinear, and the Duncan–Chang E-B model is one of them. The Duncan–Chang E-B model is based on the stress-strain relationship obtained from triaxial compression tests, which can be approximated as a hyperbola.
According to the definition of the deformation modulus, the tangent modulus $E_i$ at any point on the curve is obtained as

$$E_i = \left[1 - R_f S\right]^2 E_i,$$

(1)

where $R_f$ is the damage ratio, whose value is less than 1.0; $S$ is the shear stress ratio, also known as the stress level, that is, the ratio of the difference between the actual principal stress and the difference in principal stress at the time of damage; and $E_i$ is the initial shear modulus.

$$S = \frac{(\sigma_1 - \sigma_3)}{(\sigma_1 - \sigma_3)},$$

(2)

where $\sigma_1$ is the major principal stress and $\sigma_3$ is the minor principal stress.

$$E_i = K_P \left(\frac{\sigma_3}{P_a}\right)^n,$$

(3)

where $P_a$ is the atmospheric pressure, the same unit as $E_i$, which can be approximated by a value of approximately 0.1 MPa, and $K_i$ and $n$ is a parameter determined by the test.

According to the Moore–Coulomb damage criterion,

$$C = \frac{2C\cos \varphi + 2\sigma_3\sin \varphi}{1 - \sin \varphi},$$

(4)

where $C$ is the cohesive force and $\varphi$ is the angle of internal friction.

Substituting equations (2)–(4) into equation (1), the tangential modulus expression is obtained as

$$E_i = K_P \left(\frac{\sigma_3}{P_a}\right)^n \left[1 - R_f (1 - \sin \varphi) (\sigma_1 - \sigma_3)^2\right].$$

(5)

The tangential bulk modulus of the material is

$$K_t = K_b P_a \left(\frac{\sigma_3}{P_a}\right)^m,$$

(6)

where $K_b$ is the initial bulk modulus base and $m$ is the bulk modulus index.

The modulus of elasticity of the material in the case of unloading and reloading is

$$E_{ur} = K_{ur} P_a \left(\frac{\sigma_3}{P_a}\right)^n_{ur},$$

(7)

where $K_{ur}$ is the base modulus of elasticity under load reloading and $n_{ur}$ is the modulus of elasticity index under load reloading.

Since the mean loess is bulk, according to $C = 0$, nonlinear strength parameters are often used in numerical analysis:

$$\varphi = \varphi_0 - \Delta \varphi \log \left(\frac{\sigma_3}{P_a}\right),$$

(8)

where $\varphi_0$ is the initial angle of internal friction and $\Delta \varphi$ is the circumferential pressure increase to 10 times the standard atmospheric pressure.

The main parameters mentioned in the abovementioned formulas are $C, \varphi, \Delta \varphi, R_f, K, K_{ur}, n, m, K_{ur}$, and $n_{ur}$, all of which can be determined through conventional triaxial tests.

### 3. Sensitivity Analysis Method

A single-factor sensitivity analysis method and a multifactor sensitivity analysis method based on the full calculation area of the loess dam shell were used in turn to comprehensively study the sensitivity of the dam material density and the Duncan–Chang $E$-$B$ model parameters to the homogeneous loess dam.

The Duncan–Chang $E$-$B$ model has ten parameters, namely, $C, \varphi, \Delta \varphi, R_f, K, K_{ur}, n, m, K_{ur}$, and $n_{ur}$. In the parameter selection, due to the loess dam construction and filling process, the loess dam shell is in the loading state and the loess particles are bulk materials, so $K_{ur}$, $n_{ur}$, and $C$ are not involved in the discussion, while the dam material density $\rho$ during the construction process is also a factor affecting the loess. Therefore, the eight parameters $\rho, \varphi_0, \Delta \varphi, R_f, K, K_{ur}$, $n$, and $m$ are selected.

#### 3.1. Single-Factor Sensitivity Analysis

Taking a loess homogeneous dam in Gangu County, Gansu Province, China, as an example, a finite element static model is established to analyse the loess dam shell region in the model calculation unit:

1. **Step 1**: determine the test index. The vertical displacement, upstream horizontal displacement, and downstream horizontal displacement of the loess dam shell region were selected as the test indices.

2. **Step 2**: determine the test factors. The eight parameters $\rho, \varphi_0, \Delta \varphi, R_f, K, K_{ur}, n$, and $m$ were selected as factors for the single-factor sensitivity analysis.

3. **Step 3**: determine the levels of the factors. The design parameters are taken as the base test level, and the other test levels are taken as 0.7 times, 0.8 times, 0.9 times, 1.1 times, 1.2 times, and 1.3 times the base level.

4. **Step 4**: calculate finite element. Keep the other parameters unchanged, and substitute different levels of single parameters into the model for the finite element calculation.

5. **Step 5**: Analyse the results. The displacement results of all units in the loess dam shell region obtained from each finite element calculation are counted, and the displacement change amounts and displacement change rates of the vertical displacement, upstream horizontal displacement, and downstream horizontal displacement are calculated.

#### 3.2. Multifactor Sensitivity Analysis

2.2. **Theory of the Orthogonal Experiment Method**. The orthogonal experiment design is referred to as the orthogonal design, which is a method to scientifically arrange and analyse multifactor tests using orthogonal tables. Its main advantages are as follows:
(1) A small number of representative experimental programs are selected evenly among all experimental programs.

(2) Through statistical analysis of the test results of these few test protocols, better solutions can be introduced and the better solutions obtained are often not included in these few test protocols.

(3) Further analysis of the experimental results can lead to more information than the experimental results.

The orthogonal table is a standardized table designed according to the principle of orthogonality and is represented by the symbol $L_n(r^m)$, where $L$ is the orthogonal table code and $n$ is the number of tests that needs to be done. The results that need to be considered for the test are called test indicators, where $m$ is the factor that does the test. That is, $m$ is the variable that is focused on in the test and may have an impact on the test index and is the variable that is in the state that each factor is in may become the level of the factor.

3.2.2. Multifactor Sensitivity Discrimination Method. To obtain the primary and secondary relationships of the influence of the parameters of the homogeneous dam deformation calculation on the deformation index and to analyse the influence law of the change of each parameter on the deformation index, a progressive discrimination method based on the orthogonal test results was established. The steps are as follows:

Step 1: Determine the test indices, selection factors, and levels. Determine each base parameter via engineering analogy as a level of the orthogonal test for each parameter. Then, multiply each base parameter by 1.2 and 0.8, respectively, as the other two levels of orthogonal test for each parameter.

Step 2: Select the orthogonal table to determine the test protocol, conduct the test, and obtain the results.

Step 3: The results of the orthogonal test are analysed by the extreme difference analysis method. The specific principle of the extreme difference analysis method is as follows:

$$K^j_i = \frac{1}{k} \sum_{g=1}^{k} x^j_{ig}, \quad (9)$$

where $K^j_i$ is the mean of the test results corresponding to each trial of factor $i$ at level $j$; $k$ is the total number of trials corresponding to factor $i$ at level $j$; and $x^j_{ig}$ is the result of the $g$-th trial corresponding to factor $i$ at level $j$; $\{x^j_{ig} | i \in (1,m), j \in (1,r), g \in (1,k)\}$.

$$R^i = \max\{K^1_i, K^2_i, \ldots, K^r_i\} - \min\{K^1_i, K^2_i, \ldots, K^r_i\}, \quad (10)$$

The extreme difference analysis method determines the degree of influence of different levels of factors on the test index by calculating the magnitude of $R^i$. A greater $K^j_i$ means a greater influence on the test index, i.e., the factor is more sensitive, and vice versa.

Step 4: the results of the orthogonal test were analysed by the analysis of variance (ANOVA) method. Since the ANOVA method cannot estimate the magnitude of the inevitable error in the test process and in the determination of the experimental results, it is not possible to distinguish whether the difference between the experimental results corresponding to each level of a factor is caused by the different levels of the factor or by the error of the experiment. Therefore, based on the extreme difference analysis method, the analysis of variance method is used to compensate for this shortcoming. It decomposes the sum of the squares of the total deviations of the test data into two parts, the sum of squares of the deviations caused by each factor and the sum of squares of the deviations caused by the errors, to construct the $F$ statistic and makes the $F$ test determine the degree of influence of each factor on the test index.

The specific principles of the analysis of variance (ANOVA) method are as follows:

$$S_T = \sum_{j=1}^{r} \sum_{g=1}^{k} (x^j_{ig})^2, \quad i = 1, 2, \ldots, m, \quad (11)$$

$$S_i = \sum_{j=1}^{r} (\sum_{g=1}^{k} x^j_{ig})^2, \quad S_{ig} = \sum_{j=1}^{r} (\sum_{g=1}^{k} x^j_{ig})^2, \quad i = 1, 2, \ldots, m, \quad \frac{d f_i}{d f_j} = d f_{ij}, \quad d f_{i}, \quad d f_{j}, \quad d f_{e}$$

The mean square of each factor is

$$MS_i = \frac{S_i}{d f_i} \quad (13)$$

The mean square of the error is

$$MS_e = \frac{S_e}{d f_e} \quad (14)$$

The value of the test sensitivity statistic $F$ is
Mathematical Problems in Engineering

\[ F_i = \frac{MS_i}{MS_e} \]  \hspace{1cm} (15)

If \( F_i > F_{0.01} \), the factor is highly significant, denoted as \(* * \); if \( F_{0.01} > F_i > F_{0.05} \), the factor is significant, denoted as \(* \); if \( F_{0.05} \geq F_i \geq F_{0.1} \), the factor has influence, denoted as \( \ominus \); if \( F_{0.1} \geq F_i \geq F_{0.2} \), the factor has some influence, denoted as \( \Delta \); and if \( F_{0.2} \geq F_i \), the factor has no influence.

4. Case Study

4.1. Description of the Site. The reservoir is located near the village of Goutan in the territory of Gangu, the dam region is located in the loess hilly area, the valley is “V” wide, the topography of the reservoir area is broken, and alluvial ditches are developed. The valley floor is covered with 20~40 m of alluvial loess-like soil; both banks are covered with loess, generally 5~30 m in thickness, underlain by Neoproterozoic siltstone and muddy siltstone. There are no major fractures in the reservoir and dam regions. No large-scale collapse, landslide, mudslide, or other adverse geological phenomena are found in the reservoir area. The reservoir mainly has the problem of a loess bank collapse and reservoir siltation brought about by bank collapse, and the reservoir has the conditions for reservoir formation.

Both sides of the dam site area are covered by loess, generally 5~30 m in thickness; the upper part of the dam base is underlain by 20~30 m-thick alluvial deposits of the Fourth Series, and the lower part is underlain by Neoproterozoic mudstone and sandy mudstone. The dam site area mainly has the problems of loess wetting, deep cover leakage, and an uneven deformation, and the dam site area has the conditions for dam construction after treatment.

For the reservoir dam project of the loess homogeneous dam, the maximum dam height is 125.00 m, the top of the dam elevation is 1650.00 m, the width of the top of the dam is 10 m, the upstream slope ratio is 1 : 3.6, the downstream dam slope ratio is 1 : 3.5, the dead water level is 1598.00 m, the dead storage capacity is 0.29 billion m\(^3\), the initial proposed normal storage level is 1650.00 m, the total capacity is 140 million m\(^3\), and the regulating reservoir capacity is 111 million m\(^3\).

The layout of the hub building is shown in Figure 1.

4.2. Model Settings. Through finite element software, a numerical analysis model was constructed to solve the displacement variation of the loess homogeneous dam and to analyse the displacement variation law of the dam during the completion and operation periods.

4.2.1. Geometric Model. Based on the actual situation and characteristics of a loess homogeneous dam, a finite element model of the dam was established and a nonlinear static finite element analysis was performed for the completion and operation periods. According to the construction progress and the water storage process, the dam filling process is simulated in 17 stages and the reservoir water level gradually rises in 5 stages of loading. The stress-strain characteristics of the dam during the completion and operation periods were studied. The finite element model of the dam is shown in Figure 2.

The total number of finite element nodes in the formed finite cell mesh is 11324, and the total number of cells is 10877. The finite element grid is shown in Figure 3, where the orange area is the loess dam shell region.

4.2.2. Model Parameters. The Duncan–Chang E-B model was used for the native model of each material zone, such as the loess dam shell, filter drainage body, loess after dam foundation overfilling, fresh mudstone of dam foundation, and excavation material cover weight. The calculated parameters for each material zone of the dam body are shown in Table 1.

4.2.3. Boundary Conditions and Graded Loading. The computational coordinate system is specified as follows: the X-axis is in the downstream direction, pointing from upstream to downstream, taking the dam axis as the X-axis zero point; the Y-axis is in the direction along the dam axis (horizontal river direction), pointing from the right bank to the left bank, taking the end of the dam axis on the right bank as the Y-axis zero point; and the Z-axis is in the vertical direction, pointing upward, which is consistent with the elevation. The model simulates the geometry of the dam body and its various material partitions.

The boundary ranges of the computational model are as follows:

1. The foundation in the vertical direction is taken to be approximately 200 m below the bedrock building surface in the centre of the riverbed at an elevation of 1304 m
2. The upstream and downstream boundaries extend 150 m upstream and downstream, respectively, from the foot of the upstream and downstream slopes at the maximum cross section of the riverbed
3. The dam and dam foundation material zoning are based on information provided by the design, including cross sections and geological profiles

The dam is constructed using a continuous construction scheme; i.e., the dam is first continuously filled until the top, and then the reservoir is impounded. During the construction period, a total of 22 loading levels were applied to complete the filling and impoundment of the dam, starting from the foundation surface to the top of the dam. During calculation, each level of loading is loaded at once using the midpoint increment method to better simulate the loading process. The graded loading and water storage process is shown in Figure 4.

4.3. Numerical Simulation Results. The calculations were performed by first loading the bedrock and the unremoved overburden and initializing the nodal displacements to zero before loading the dam in a graded manner, retaining only the unit stresses in order to obtain the initial stress field in
the foundation. All displacements described below refer to displacements after the start of the construction fill. The positive and negative displacement numbers are positive in the downstream direction and negative in the reverse direction, i.e., horizontal displacement in the downstream direction (upstream and downstream) is positive, and vertical displacement in the upstream direction is positive in mm. The positive and negative stress numbers are compressive stress and tensile stress in kPa, respectively.
The calculation results are summarized in Table 2, and the displacement distribution of the typical section of the dam during the completion and operation periods is shown in Figure 5.

During the completion period, the maximum vertical displacement (settlement) of the dam body was $-2003.50\ mm$, accounting for approximately 1.61% of the maximum dam height (including the loess cover); the maximum horizontal displacement in the upstream direction was $-980.56\ mm$, and the maximum horizontal displacement in the downstream direction was $1105.48\ mm$. During the operation period, the maximum vertical displacement (settlement) of the dam body was $-2113.00\ mm$, accounting for approximately 1.69% of the maximum height. The maximum horizontal displacement in the upstream direction was $-398.38\ mm$, and the maximum horizontal displacement in the downstream direction was $1226.06\ mm$.

Overall, the deformation distribution of the dam follows the distribution characteristics of a general homogeneous Earth dam. The horizontal displacement of the dam body during the completion period is symmetrically distributed, and the horizontal displacement of the dam body during the operation period is gradually deformed downstream from the symmetrical distribution under the action of water pressure, while the vertical displacement shows a uniformly decreasing trend with the maximum value at 2/3 of the dam body.

5. Sensitivity Analysis

5.1. Single-Factor Sensitivity Analysis. Before conducting the single-factor sensitivity analysis, specific experimental scenarios were designed for the eight parameters to be considered and the seven levels of each parameter, with seven specific scenarios shown in Table 3. Numerical simulations were performed according to the different parameter values taken in the protocols, and the displacement values of 4494 computational units in the loess dam shell region were counted.

After the numerical calculations for the eight parameters $\rho$, $\varphi_0$, $\Delta\varphi$, $R_f$, $K$, $K_b$, $n$, and $m$ in Table 3, the vertical displacement $V$, the upstream horizontal displacement $H_1$, and the downstream horizontal displacement $H_2$ were calculated for the loess dam shell region and the displacement values of all the calculation units in each protocol were fitted using a regression analysis. The values of the parameters in protocol 4 are used as the base level, the calculated vertical displacement, upstream horizontal displacement, and downstream horizontal displacement are used as the horizontal axis, the values of the parameters in the other six protocols are used as the other levels, and the calculated vertical displacement, upstream horizontal displacement, and downstream horizontal displacement are used as the vertical axis.

Figure 6 shows the distribution of the vertical displacement, upstream horizontal displacement, and
downstream horizontal displacement of each parameter at different values in the loess dam shell region. The ratio of the horizontal and vertical coordinates of the calculation results are approximately linear, regardless of the increase or decrease in each parameter. Among the eight parameters, if three parameters, namely, $\rho$, $R_f$, and $\Delta \varphi$, increase in value, then the calculation results of the loess dam shell region increase, while if they decrease in value, then the calculation results of the loess dam shell region decrease. For the five parameters, $\Phi_0$, $K$, $n$, $K_b$, and $m$, if they increase in value, then the calculation results of the loess dam shell region increase, while if they decrease in value, then the calculation results of the loess dam shell region increase.

Since the ratios of the calculated results in both the horizontal and vertical coordinates are approximately linear, the fitted straight line for the calculated results under different values of the parameters taken in Figure 6 is

$$x' = ax - b.$$  

(16)

The amount of vertical displacement, upstream horizontal displacement, and downstream horizontal displacement obtained is

$$\Delta x = ax - b - x.$$  

(17)

The rate of change of its vertical displacement, upstream horizontal displacement, and downstream horizontal displacement is

$$k = \frac{100 \times (ax - b - x)}{x} = 100 (a - 1) - \frac{b}{x}.$$  

(18)

The amount and rate of change of the average vertical displacement, the average horizontal displacement upstream, and the average horizontal displacement downstream in the calculated area of the loess dam shell are used as indicators for the analysis. The amount and rate of change of different cells in the loess dam shell region are different. To obtain relatively accurate conclusions on the single-factor sensitivity of the loess dam shell region, the single-factor sensitivity distribution of each parameter under a vertical displacement, upstream horizontal displacement, and downstream horizontal displacement is given in Figure 7.

As shown in Figure 7, the intensity of the parameter sensitivity is determined by the absolute values of the average value of the displacement change rate and the average value of the displacement amount and different parameters show different sensitivities as the parameter increases and decreases.

It can be determined that the sensitivity of the parameters to displacement is different when the parameters increase and decrease in the single-factor sensitivity analysis.
Figure 6: Continued.
Figure 6: Continued.
When the parameters increase or decrease, $R_f$, $\varphi_0$, and $K_b$ are more sensitive to the vertical displacement, while when the parameters increase, $n$, $K$, and $\Delta \varphi$ are less sensitive to the vertical displacement and when the parameters decrease, $m$, $\rho$, and $\Delta \varphi$ are less sensitive to the vertical displacement. The sensitivity ranking of upstream horizontal displacement and downstream horizontal displacement in the case of increasing parameters is the same, but there are still some differences with the case of decreasing parameters. The specific ranking is shown in Table 4.
In summary, the three parameters $R_f$, $\varphi_0$, and $K_b$ are more sensitive to vertical displacement and the five parameters $R_f$, $\varphi_0$, $K$, $n$, and $K_b$ are more sensitive to upstream horizontal displacement and downstream horizontal displacement.

5.2. Multifactor Sensitivity Analysis. Based on the above analysis, a multifactor sensitivity analysis was conducted based on the calculated parameters of dam deformation for the characteristics of the loess homogeneous dam. First, the results of the orthogonal test were subjected to an extreme

**Table 4: Sensitivity ranking of each parameter by the single-factor analysis method.**

| Method                        | Vertical displacement | Upstream horizontal displacement | Downstream horizontal displacement |
|-------------------------------|-----------------------|----------------------------------|----------------------------------|
| Single-factor (parameter increase) | $R_f > \varphi_0 > K_b > \rho > m > \Delta \varphi$ | $R_f > \varphi_0 > K > n > K_b > \Delta \varphi$ | $R_f > \varphi_0 > K > n > K_b > m > \Delta \varphi$ |
| Single-factor (parameter reduction) | $\varphi_0 > R_f > K > n > m > \Delta \varphi$ | $\varphi_0 > \Delta \varphi > m > \rho$ | $\varphi_0 > \Delta \varphi > n > \rho > m$ |

Figure 7: Sensitivity distribution of each parameter. (a) Vertical displacement change amount and change rate. (b) Upstream horizontal displacement change amount and change rate. (c) Downstream horizontal displacement change amount and change rate.
difference analysis. Then, based on extreme difference analysis, the results were subjected to an analysis of variance (ANOVA) and the results of both analyses were compared. The specific factors and the levels of each factor are shown in Table 5.

The orthogonal test was designed by selecting the appropriate orthogonal table according to the eight factors and three levels due to the addition of an error column, so the orthogonal table of $L_{27}^{9}(3^{9})$ was selected and the different levels of each factor were filled in. It is assumed that there is no interaction between the experimental factors, and the experimental factors are randomly filled into the first eight columns of the orthogonal table to obtain the orthogonal test table. The specific experimental scheme and finite element calculation results are shown in Table 6.

The data in each column of the orthogonal test table and the vertical displacement results were analysed by the extreme difference analysis method and the analysis of variance method, with the results shown in Tables 7 and 8. Among the eight parameters, $R_f$, $\phi_0$, and $\Delta \varphi$ are more sensitive to the vertical displacement with extreme differences of 1.259, 1.152, and 0.851 and variances of 10.350, 9.010, and 5.320, respectively, which are greater than the extreme differences and variances of other parameters, while $m$, $n$, and $K$ are less sensitive to the vertical displacement. The parameters in descending order are $R_f > \phi_0 > \Delta \varphi > K > m > n$.

The data in each column of the orthogonal test table and the vertical displacement results were analysed by the extreme difference analysis method and the analysis of variance method, with the results shown in Tables 9 and 10. Among the eight parameters, $R_f$, $\phi_0$, and $\Delta \varphi$ are more sensitive to the vertical displacement, with extreme differences of 2.480, 1.487, and 0.951 and the variances of 30.820, 10.840, and 5.270, respectively, which are greater than the extreme differences and variances of other parameters, while $m$, $n$, and $K$ are less sensitive to the vertical displacement. The parameters in the descending order are $R_f > \phi_0 > \Delta \varphi > K > m > n$.

The data in each column of the orthogonal test table and the vertical displacement results were analysed by the extreme difference analysis method and the analysis of variance method, with the results shown in Tables 11 and 12. Among the eight parameters, $\Delta \varphi$, $R_f$, and $\rho$ are more

| Number | $\rho$ (g/cm$^3$) | $\phi_0$ ($^\circ$) | $K$ | $n$ | $R_f$ | $K_b$ | $m$ | $\Delta \varphi$ ($^\circ$) | $V$/m | $H_1$/m | $H_2$/m |
|--------|-------------------|-------------------|----|----|------|------|----|-----------------|------|-------|-------|
| 1      | 1 1 1 1 1 1 1 1 1 | 1.216 1.111 1.138 |
| 2      | 1 1 1 2 2 2 2 2 2 | 2.309 1.880 1.927 |
| 3      | 1 1 3 3 3 3 3 3 3 | 3.778 3.731 3.148 |
| 4      | 1 2 2 1 1 1 2 2 2 | 1.895 0.666 0.747 |
| 5      | 1 2 2 2 2 2 2 2 3 | 1.824 0.988 1.086 |
| 6      | 1 2 2 3 3 3 3 3 3 | 1.762 1.686 2.013 |
| 7      | 1 3 3 3 3 3 3 3 3 | 1.728 0.421 0.531 |
| 8      | 1 3 3 2 2 2 2 2 1 | 1.582 0.543 0.658 |
| 9      | 1 3 3 3 3 3 3 3 2 | 1.513 0.800 0.991 |
| 10     | 2 1 2 3 1 2 3 1 2 | 1.728 0.871 0.954 |
| 11     | 2 1 2 3 2 3 1 2 3 | 1.858 0.746 0.871 |
| 12     | 2 1 2 3 3 3 2 3 2 | 1.917 1.157 1.271 |
| 13     | 2 2 3 1 1 2 3 2 3 | 2.632 2.566 2.406 |
| 14     | 2 2 3 1 2 3 1 3 2 | 1.825 0.749 0.871 |
| 15     | 2 2 3 1 3 1 2 1 2 | 2.632 2.566 2.406 |
| 16     | 2 3 1 2 1 2 3 3 1 | 1.825 0.749 0.871 |
| 17     | 2 3 1 2 2 3 1 3 1 | 2.501 0.913 1.044 |
| 18     | 2 3 1 2 3 1 1 2 2 | 2.456 2.517 3.051 |
| 19     | 3 1 3 2 1 3 2 1 3 | 2.019 0.913 1.044 |
| 20     | 3 1 3 2 2 1 3 2 3 | 2.813 1.755 1.795 |
| 21     | 3 1 3 2 3 2 1 3 2 | 5.785 6.621 4.996 |
| 22     | 3 2 1 3 1 3 2 2 1 | 1.991 0.889 1.085 |
| 23     | 3 2 1 3 2 1 3 3 2 | 2.618 1.638 1.670 |
| 24     | 3 2 1 3 3 2 1 3 2 | 2.887 3.329 2.357 |
| 25     | 3 3 2 1 1 3 2 3 2 | 1.967 0.796 0.932 |
| 26     | 3 3 2 1 2 1 3 1 3 | 2.383 1.192 1.369 |
| 27     | 3 3 2 1 3 2 1 2 1 | 2.565 2.615 2.864 |

| Level | $\rho$ (g/cm$^3$) | $\phi_0$ ($^\circ$) | $K$ | $n$ | $R_f$ | $K_b$ | $m$ | $\Delta \varphi$ ($^\circ$) |
|-------|-------------------|-------------------|----|----|------|------|----|-----------------|
| 1     | 13.6 20.8 320 0.44 0.6 200 0.24 4.0 |
| 2     | 17.0 26.0 400 0.55 0.75 250 0.30 5.0 |
| 3     | 20.4 31.2 480 0.66 0.9 300 0.36 6.0 |

Table 5: Parameter values for the factor levels of the orthogonal tests.

Table 6: Orthogonal test design scheme and calculation results.
sensitive to the vertical displacement, with extreme differences of 1.645, 1.635, and 1.468 and variances of 3.070, 2.760, and 2.070, respectively, which are greater than the extreme differences and variances of other parameters, while \( n\), \( \phi_0\), and \( m\) are less sensitive to the vertical displacement. The parameters in descending order are \( \Delta \phi > R_f > K_b > K > n > \phi_0 > m\).

The results of the multifactor orthogonal test are summarized in the order of the results of the extreme difference analysis method and the analysis of variance method, as shown in Table 13.

It can be determined that the results of both are completely consistent and the three parameters \( R_f\), \( \phi_0\), and \( \Delta \phi\) are more sensitive to the vertical displacement and the upstream horizontal displacement, while \( R_f\), \( \Delta \phi\), and \( \rho\) are more sensitive to the downstream horizontal displacement.

Comparing the sensitivity ranking of the parameters of the multifactor analysis method in Table 13 with the
sensitivity ranking of the parameters of the single-factor analysis method in Table 4, the ranking of the two is not completely consistent, but the overall results are relatively consistent.

In summary, the three parameters $R_f$, $\varphi_0$, and $\Delta \varphi$ are more sensitive to dam deformation, while $m$, $n$, and $K$ are less sensitive to dam deformation.

### 6. Conclusion

To more accurately study the effect of the Duncan–Chang E–B model on the deformation of a homogeneous Earth dam, a homogeneous Earth dam in Gangu County, Gansu Province, China, was selected as a case study for this paper and a static analysis model reflecting the Earth and rock dam was constructed through a finite element software program. By constructing the numerical analysis model, we first analysed the displacement variation pattern of the dam during the completion and operation periods. Then, a sensitivity analysis of the calculated parameters affecting the deformation of the homogeneous Earth dam was conducted from both single-factor and multifactor aspects. The following main conclusions were drawn:

1. The deformation distribution of the dam follows the distribution characteristics of general homogeneous Earth dams. The horizontal displacement of the dam body during the completion period is symmetrically distributed, with a maximum horizontal displacement of 200.50 mm, accounting for 1.61% of the maximum dam height (including the loess cover). During the operation period, the maximum vertical displacement (settlement) is 200.35 mm, accounting for 1.61% of the maximum dam height (including the loess cover). During the operation period, the maximum vertical displacement (settlement) is 2113.00 mm, accounting for 1.69% of the maximum dam height (including the aeolian cover).

2. In the single-factor sensitivity analysis, the increase and decrease of the parameters show different sensitivities to the vertical and horizontal displacements of the dam body. The upstream horizontal displacement and the downstream horizontal displacement have the same sensitivity ranking when the parameter increases but still have some differences with the decreasing parameter. In general, the three parameters $R_f$, $\varphi_0$, $K$, $n$, and $K_f$ are more sensitive to vertical displacement, while the five parameters $R_f$, $\varphi_0$, $K$, $n$, and $K_f$ are more sensitive to upstream horizontal displacement and downstream horizontal displacement.

3. In the multifactor sensitivity analysis, the sensitivity rankings obtained by the two methods of the extreme difference analysis and the analysis of variance are the same and the three parameters $R_f$, $\varphi_0$, and $\Delta \varphi$ are more sensitive to the vertical displacement and the upstream horizontal displacement, while $R_f$, $\Delta \varphi$, and $\rho$ are more sensitive to the downstream horizontal displacement.

4. As shown in Table 14, from the results of the single-factor sensitivity analysis and multifactor sensitivity analysis, the three parameters $R_f$, $\varphi_0$, and $\Delta \varphi$ are more sensitive to dam deformation, while $m$, $n$, and $K$ are less sensitive to dam deformation.

| Table 13: Sensitivity ranking of each parameter by the multifactor analysis method. |
|---------------------------------|---------------------------------|---------------------------------|
| Method                          | Vertical displacement           | Upstream horizontal displacement | Downstream horizontal displacement |
| Orthogonal test (extreme difference analysis) | $R_f \varphi_0 K_f > \rho > \Delta \varphi$ | $R_f \varphi_0 K_f > \rho > \Delta \varphi$ | $R_f \varphi_0 K_f > \rho > \Delta \varphi$ |
| Orthogonal test (analysis of variance) | $K_f m > n > K$ | $K_f m > n > K$ | $K_f m > n > K$ |

| Table 14: Sensitivity ranking of each parameter by different methods. |
|---------------------------------|---------------------------------|---------------------------------|
| Method                          | Vertical displacement           | Upstream horizontal displacement | Downstream horizontal displacement |
| Single-factor (parameter increase) | $R_f \varphi_0 K_f > \rho > \Delta \varphi$ | $R_f \varphi_0 K_f > \rho > \Delta \varphi$ | $R_f \varphi_0 K_f > \rho > \Delta \varphi$ |
| Single-factor (parameter reduction) | $\rho f > \varphi_0 K_f > n > m$ | $\rho f > \varphi_0 K_f > n > m$ | $\rho f > \varphi_0 K_f > n > m$ |
| Orthogonal test (extreme difference analysis) | $K_f m > n > K$ | $K_f m > n > K$ | $K_f m > n > K$ |
| Orthogonal test (analysis of variance) | $K_f m > n > K$ | $K_f m > n > K$ | $K_f m > n > K$ |
Data Availability
To support future research studies in this field, the data from this study are available upon request from the corresponding author.

Conflicts of Interest
The authors declare that there are no conflicts of interest regarding the publication of this paper.

Authors’ Contributions
Y. S. designed the framework and wrote the manuscript. Y. S., J. Y., and L. G. collected the data. Y. S., H. Z., and L. X. verified the results of the model. Z. S. provided funding support.

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