Structured Method of Dynamic Fully Coupled Rheological Model for Seepage Field and Stress Field in Concrete Dam

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Abstract. The study comprehensively applied mathematics, mechanics theory and method and dam construction knowledge. It’s based on the numerical analysis methods such as the finite element and Fourier transform. It centered on the structured method of dynamic fully coupled rheological model for two fields in concrete dam. The dynamic fully coupled rheological model of seepage field and stress field in concrete dam was built. The finite element equations were given under the dynamic fully coupled actions of seepage field and stress field. The numerical analysis form of finite element under dynamic fully coupling of two fields was proposed. The corresponding calculation program of finite element was developed. The analysis of examples showed that, with the variation of boundary conditions such as dam displacement and water pressure, the model of dynamic fully coupled rheological model could reflect the dynamic change rules of the stress, strain and permeability coefficient in time and space. Thus, it could obtain the distribution of displacement, stress and permeability coefficient in different time within loading process.

1. Introduction
Dam concrete is a heterogeneous and multiphase porous body [1]. It will produce the osmosis phenomenon under the action of high water head. Dam foundation rock mass is generally fractured rock mass. Its permeability directly affects the long-term stability of the project operation [2-4]. The alteration of seepage field will cause that of the internal stress field, while the alteration of stress field will cause that of the internal seepage field [5]. Therefore, when analyzing the deformation of concrete dam, the interactions between seepage field and stress field should be considered. The coupling analysis of seepage field and stress field has always been an important issue of concern in engineering field [6-7]. By study, the relationship between permeability coefficient and normal stress was established, by which hydrostatic pressure was transformed into volume force, and then the coupling of seepage field and stress field was achieved. However, since the concrete dam body and dam foundation were at all times in a broad rheology, besides, the rheology of concrete dam was constantly varying and was often in a state of alternation between rapid rheology and stable (slow) rheology [5]. It could cause the mutual transformation between static and dynamic processes. The transformation and interaction of seepage field and stress field in concrete dam played a significant role on it. In fact, in many engineering practices, due to variations of external environments, the interaction of seepage field and deformation field was an extremely complex problem of dynamic fully coupling [8]. Displacement and water head were variables which could vary over time. In the conventional analysis of static coupling [9-10], it could not fully consider the influence of time-related factors such as deformation and water pressure on research object. Besides, it also could not reflect both laws of
variation over time. Therefore, it needs to do further research on the basis of conventional rheological model, and then establishes dynamic fully coupled rheological model of seepage field and stress field in concrete dam.

Given the above analysis, the direct coupling method is applied to solve the coupling problems of seepage field and stress field. Relying on theories such as the principle of effective stress and deformation compatibility equations, dynamic fully coupled rheological control equations of seepage and stress fields could be obtained. According to the law of conduction and law of fluid mass conservation, it started from the perspective of the rheology, and then studied and put forward the mathematical model of dynamic fully coupling functions for seepage and stress fields, which could reflected the variations of concrete dam boundary conditions. It obtained the corresponding direct coupling overall control equation. Based on Galerkin variation principle, the finite element analysis of concrete dam rheology could be given under dynamic fully coupled function of two fields. On this basis, it verified the validity of the model that constructed in this study through the case analysis.

2. The Building of Dynamic Fully Coupled Rheological Model of Seepage Field and Stress Field

The interaction of seepage field and deformation field was a dynamic fully coupling process. Displacement, water head and permeability coefficient all varied over time. This chapter will depend on the basic principles of effective stress, and then deduce dynamic fully coupling equilibrium equation and continuity equation of stress field and seepage field. Under consideration of all kinds of boundary conditions, this chapter will build dynamic fully coupled rheological model of seepage field and stress field in concrete dam, and then truly present the real working condition of concrete dam.

2.1. The Coupling Rheological Equilibrium Equation of Stress Field and Seepage Field

2.1.1. The Coupling Rheological Constitutive Equation of Two Fields in Dam Body Concrete. The rheological model of the dam body concrete in the study applied Nishihara Masao model.

Its total strain rate tensor $\dot{\varepsilon}_{ij}$ is showed as following.

$$\dot{\varepsilon}_{ij} = \dot{\varepsilon}_{ij}^v + \dot{\varepsilon}_{ij}^{vp}$$  \hspace{1cm} (1)

In equation (1), $\dot{\varepsilon}_{ij}^v$ is viscoelastic strain rate tensor, $\dot{\varepsilon}_{ij}^{vp}$ is sticky plastic strain rate tensor.

According to the principle of effective stress, the coupling rheological constitutive equation of two fields in dam concrete body under stress can be achieved as following.

$$\sigma_{ij} = D_{ijkl} \left[ \dot{\varepsilon}_{ij} - \left( \dot{\varepsilon}_{ij}^v + \dot{\varepsilon}_{ij}^{vp} \right) \right] + \alpha p \delta_{ij} \hspace{1cm} (2)$$

Equation (2) can be transformed as following.

$$\Delta \sigma_{ij} = D_{ijkl} \left[ \Delta \varepsilon_{ij} - \left( \Delta \varepsilon_{ij}^v + \Delta \varepsilon_{ij}^{vp} \right) \right] + \alpha \Delta p \delta_{ij} \hspace{1cm} (3)$$

Equation (3) is the incremental form of the coupling rheological constitutive equation of two fields in dam concrete body under stress. In this, $\Delta \sigma_{ij}$ is general stress increment of dam concrete body, $\Delta \varepsilon_{ij}$ is the total strain increment of dam concrete body, $\Delta \varepsilon_{ij}^v$ is viscoelastic strain increment of dam concrete body, $\Delta \varepsilon_{ij}^{vp}$ is the sticky plastic strain of dam concrete body.

2.1.2. The Coupled Rheological Constitutive Equation of Two Fields in Concrete Dam Foundation. The rheological model of the dam foundation rock mass in the study applied Sunjun model.

Its total strain rate tensor $\dot{\varepsilon}_{ij}$ is showed as following.

$$\dot{\varepsilon}_{ij} = \dot{\varepsilon}_{ij}^v + \dot{\varepsilon}_{ij}^{vp}$$  \hspace{1cm} (4)
In equation (4), $\varepsilon_{ij}^{\text{va}}$ is viscous strain rate tensor of dam foundation, the rest symbols have the same meanings as before.

The coupled rheological constitutive equation of stress field and seepage field in dam foundation rock mass under control of the stress can be obtained as following.

$$
\Delta \sigma_{ij} = D_{ijkl} \left[ \Delta \varepsilon_{ij}^{\text{va}} - \left( \varepsilon_{ij}^{\text{va}} + \varepsilon_{ij}^{\text{ve}} + \varepsilon_{ij}^{\text{vp}} \right) \right] + \alpha \Delta p \delta_{ij}
$$

Equation (5) can be transformed as following.

$$
\Delta \sigma_{ij} = D_{ijkl} \left[ \Delta \varepsilon_{ij}^{\text{va}} - \left( \varepsilon_{ij}^{\text{va}} + \varepsilon_{ij}^{\text{ve}} + \varepsilon_{ij}^{\text{vp}} \right) \right] + \alpha \Delta p \delta_{ij}
$$

Equation (6) is the incremental form of the coupled rheological constitutive equation of stress field and seepage field in dam foundation rock mass under control of stress. In this, $\Delta \varepsilon_{ij}^{\text{va}}$ is elastic strain increment. The rest symbols have the same meanings as before.

Under the coupling condition of stress field and seepage field, systematic rheological analysis for equilibrium differential equations was the same as the expressions of all kinds of problems in elastoplastic theory. Therefore, under the total stress, systematic equilibrium equation can be showed as following.

$$
\partial \sigma_{ij} / \partial x_j - f_{x_i} = 0 \quad i, j = 1, 2, 3
$$

In equation (7), $x_j$ is directions of three axes, $f_{x_i}$ is the volume force of direction $x_i$.

The equilibrium equation expressed with effective stress and pore water pressure can be got as following.

$$
\partial \sigma'_{ij} / \partial x_j + \alpha \Delta p / \partial x_j - f_{x_i} = 0 \quad i, j = 1, 2, 3
$$

Combining geometric equations of media deformation,

$$
\varepsilon_{ij} = (u_{ij} + u_{ij})/2
$$

When geometric equation (9) is put into equilibrium equation (8), the rheological equilibrium equation expressed with displacement can be got as following.

$$
D_{ijkl} (u_{ij} + u_{ij})/2 + \alpha \Delta p / \partial x_j - f_{x_i} = 0
$$

Equation (10) is the same form of the coupled rheological equilibrium equation for concrete dam body and dam foundation in concrete dam.

2.2. The Coupling Analysis Continuity Equation of Stress Field and Seepage Field

The coupling continuity equation of two fields could be inferred through law of mass conservation [11-12], namely, under saturation, the variation of unit body fluid storage capacity in unit time was equal to the difference between the fluid inflow and outflow. For any unit body of pore-containing solid media, in unit time, the quality difference of the fluid into and out of unit body from its left and right sides is showed as following.

$$
\Delta m_i = -\partial \left( \rho v_x \right) / \partial x dxdydz
$$

Similarly, in unit time, the difference of calculation method for the fluid into and out of unit body above and below as well as the front and back is the same as left and right sides.

$$
\Delta m_i = -\partial \left( \rho v_y \right) / \partial y dxdydz \quad \Delta m_i = -\partial \left( \rho v_z \right) / \partial z dxdydx
$$
If the differences between the inflow and outflow quality from left and right, above and below, front and back of unit body in unit time are added together, the fluid quality variation into and out of unit body in unit time can be got, namely the total amount of water is showed as following.

\[
\Delta m = \rho \left[ \frac{\partial}{\partial x} \left( k_x \frac{\partial H}{\partial x} \right) + \frac{\partial}{\partial y} \left( k_y \frac{\partial H}{\partial y} \right) + \frac{\partial}{\partial z} \left( k_z \frac{\partial H}{\partial z} \right) \right] dx dy dz
\]  

(13)

If the porosity of solid phase is \( n \), then, the volume and quality of water in unit body are respectively \( n dx dy dz \) and \( \rho n dx dy dz \), the change rate of water quality over time is as following.

\[
\frac{\partial M}{\partial t} = \frac{\partial (\rho n V)}{\partial t} = \frac{\partial (n \rho V)}{\partial t}
\]  

(14)

In equation (14), \( V \) is the volume of unit body. The rest symbols have the same meanings as before.

By the law of mass conservation, it can be found that, in unit time, the total water inflow of unit body should be equal to the first derivative of time for the unit water quality \( M \) within unit body, then,

\[
\rho \left[ \frac{\partial}{\partial x} \left( k_x \frac{\partial H}{\partial x} \right) + \frac{\partial}{\partial y} \left( k_y \frac{\partial H}{\partial y} \right) + \frac{\partial}{\partial z} \left( k_z \frac{\partial H}{\partial z} \right) \right] dx dy dz = n \rho \frac{\partial V}{\partial t} + n V \frac{\partial \rho}{\partial t} + \rho V \frac{\partial n}{\partial t}
\]  

(15)

In equation (15), If \( V \) is the volume of media skeleton, with respect to the porosity in unit body, it can be considered that the skeleton of unit body is incompressible, namely, \( \partial V / \partial t = 0 \). When the variation of water density is not considered, there is \( \partial \rho / \partial t = 0 \), thus, equation (15) can be transformed as following.

\[
\frac{\partial}{\partial x} \left( k_x \frac{\partial H}{\partial x} \right) + \frac{\partial}{\partial y} \left( k_y \frac{\partial H}{\partial y} \right) + \frac{\partial}{\partial z} \left( k_z \frac{\partial H}{\partial z} \right) = \frac{\partial n}{\partial t}
\]  

(16)

Equation (16) is the basic differential equation of porous media flow.

Since the skeleton of unit body is incompressible, it can be found that the change rate of volumetric strain in unit body is that of soil porosity, namely,

\[
\frac{d e_v}{d t} = \frac{d n}{d t}
\]  

(17)

According to equations (17-18) can be transferred as following.

\[
\frac{\partial}{\partial x} \left( k_x \frac{\partial H}{\partial x} \right) + \frac{\partial}{\partial y} \left( k_y \frac{\partial H}{\partial y} \right) + \frac{\partial}{\partial z} \left( k_z \frac{\partial H}{\partial z} \right) = \frac{\partial u_x}{\partial t} \frac{\partial u_x}{\partial x} + \frac{\partial u_y}{\partial y} \frac{\partial u_y}{\partial y} + \frac{\partial u_z}{\partial z} \frac{\partial u_z}{\partial z}
\]  

(18)

The equation (18) can be written as tensor form. Meanwhile, considering that the initial flow method is used to deal with free surface, the area identification function \( H_x \) [13] can be represented with seepage water pressure.

\[
H_x k_{ij} \left( \frac{p}{\gamma_o} + z \right)_{i,j} = \frac{\partial u_{i,k}}{\partial t} \quad (i,j = 1,2,3)
\]  

(19)

In equation (19), \( k_{ij} \) is permeability tensor, \( u_i \) is displacement component, \( u_{i,k} \) is the first partial derivative of displacement component in direction \( k \). \( t \) is the time. The rest symbols have
3. Finite Element Numerical Form of Dynamic Fully Coupled Rheological Model for Seepage and Stress Fields

3.1. The Discrete Space Domain of Equilibrium Equation

When equation (3) is written as $\Delta t_n$, the incremental matrix form of the coupling rheological equation has,

$$
\{\Delta \sigma\} = [D] \{\{\Delta \varepsilon^c - \{\Delta \varepsilon^{cw}\} - \{\Delta \varepsilon^{wp}\}\} + \alpha \{M\} \Delta P
$$

(20)

From equation (7), according to virtual work principle, the incremental equilibrium equation of analysis system at any moment can be derived as following,

$$
\sum \int_{\Omega} [B]^T \{\Delta \sigma\} d\Omega - \{\Delta f\} = 0
$$

(21)

In equation (21), $[B]$, $[\Delta \sigma]$ and $[\Delta f]$ are respectively the geometric matrix, the stress increment array and the external load increment array.

Equation (21) is written into the form of unit equilibrium equation as following,

$$
\{\Delta \sigma\} = [D][B] \{\Delta u\}^e + \alpha \{M\} [\bar{N}] \{\Delta p\}^e - [D] \{\{\Delta \varepsilon^c\} + \{\Delta \varepsilon^{cw}\} \}
$$

(22)

In equation (22), $\{\Delta u\}^e$ is displacement increment array of element node, $[\bar{N}]$ is shape function, $[\bar{N}] = [N_1, N_2, \ldots, N_n]$. $\{\Delta p\}^e$ is water pressure increment array of element node. The rest symbols have the same meanings as before.

When equation (6) is written as $\Delta t_n$, the incremental matrix forms of the coupled rheological equation have:

$$
\{\Delta \sigma\} = [D] \{\{\Delta \varepsilon^c - \{\Delta \varepsilon^{cw}\} - \{\Delta \varepsilon^{wp}\}\} + \alpha \{M\} \Delta P
$$

(23)

Equation (23) is written into the form of unit equilibrium equation as following,

$$
\{\Delta \sigma\} = [D][B] \{\Delta u\}^e + \alpha \{M\} [\bar{N}] \{\Delta p\}^e - [D] \{\{\Delta \varepsilon^c\} + \{\Delta \varepsilon^{cw}\} + \{\Delta \varepsilon^{wp}\}\}
$$

(24)

When equation (22) is put into the incremental equilibrium equation (21), Galerkin method is applied to discrete its incremental form. Meanwhile, the boundary conditions such as displacement and surface force are utilized to obtain the overall control equation of the rheological finite element numerical analysis under the coupling condition of seepage and stress fields in concrete dam.

$$
[K] \{\Delta u\} + [\bar{K}] \{\Delta p\} = \{\Delta f\} + \{\Delta f^{ew}\} + \{\Delta f^{wp}\} = \{\Delta R_f\}
$$

(25)

In equation (25), $[K]$ is total elastic stiffness matrix, $[\bar{K}]$ is total coupling matrix, $\{\Delta u\}$ is overall node displacement increment array (unknown), $\{\Delta p\}$ is overall node water pressure increment array (unknown), $\{\Delta f\}$ is total external load increment array, $\{\Delta f^{ew}\}$ is additional force caused by viscoelastic strain increment, $\{\Delta f^{wp}\}$ is additional force caused by viscoplastic strain increment, $\{\Delta R_f\}$ is total load increment array.

When equation (24) is put into incremental equilibrium equation (21), it can obtain the overall control equation of the rheological finite element numerical analysis under the coupling condition of the same meanings as before.
seepage and stress fields in dam foundation rock mass.

\[
\begin{bmatrix}
K \\
\bar{K}
\end{bmatrix}
\begin{bmatrix}
\Delta u \\
\Delta p
\end{bmatrix} = \begin{bmatrix}
\Delta f^v \\
\Delta f^w \\
\Delta f^p
\end{bmatrix} + \begin{bmatrix}
\Delta f^u \\
\Delta f^w \\
\Delta f^v
\end{bmatrix} + \begin{bmatrix}
\Delta f^u \\
\Delta f^w \\
\Delta f^v
\end{bmatrix} = \begin{bmatrix}
\Delta R_f \\
\Delta R_v \\
\Delta R_p
\end{bmatrix}
\]

(26)

In equation (26), \( \{\Delta f^u\} \) is additional force caused by viscous strain increment, \( \{\Delta f^w\} \) is additional force caused by viscoelastic strain increment, \( \{\Delta f^v\} \) is additional force caused by viscoplastic strain increment.

3.2. Continuity Equation for Discrete Spatial Domain

For equation (19) and the boundary condition of seepage, they are dispersed by interpolation function of pore water pressure. It can obtain by variation principle of Galerkin that:

\[
\begin{bmatrix}
\bar{K}^T \\
\bar{K}^T \\
\bar{K}^T
\end{bmatrix}
\begin{bmatrix}
\frac{du}{dt} \\
\alpha \frac{du}{dt} \\
\alpha \frac{du}{dt}
\end{bmatrix} - \begin{bmatrix}
\bar{K}^T \\
\bar{K}^T \\
\bar{K}^T
\end{bmatrix}
\begin{bmatrix}
\frac{dp}{dt} \\
\frac{dp}{dt} \\
\frac{dp}{dt}
\end{bmatrix} = Q
\]

(27)

The general form of time integral is applied, the time factor \( \alpha \) is introduced, \( 0 \leq \alpha \leq 1 \). In order to make the iterative processes stable, it often gets \( 0.5 \leq \alpha \leq 1 \). It can get as following.

\[
\begin{bmatrix}
\bar{K}^T \\
\bar{K}^T \\
\bar{K}^T
\end{bmatrix}
\begin{bmatrix}
\Delta u \\
\Delta u \\
\Delta u
\end{bmatrix} - \begin{bmatrix}
\bar{K}^T \\
\bar{K}^T \\
\bar{K}^T
\end{bmatrix}
\begin{bmatrix}
\Delta p \\
\Delta p \\
\Delta p
\end{bmatrix} = \{\Delta R_q\}
\]

(28)

For the un-drained boundary condition, \( q_n = 0 \), then there is \( \{R_q\}^e = 0 \).

3.3. The Finite Element Equation and Iterative Solution of Dynamic Fully Coupling Rheology

Form equations (25-26, 28), it can be seen that the three equations all have coupling terms. They must be united together and then get solved. Meanwhile, since permeability coefficient of seepage and stress fields in coupling process has dynamic variations, the result of its dam stress field and displacement field can be as basis. Its permeability coefficient can be adjusted according to computed ratio or rate of porosity, and then updates and calculates the seepage field. Considering that the dam volume strain is caused mainly by its stress field, as for the variation of dam permeability coefficient, for ease of calculation, the permeability coefficient is set as mathematical function, which presents as exponential distribution with stress state [14].

For confined flow, a unified form of the finite element analysis for dynamic fully coupling flow in two fields as following,

\[
\begin{bmatrix}
K & \bar{K} \\
\bar{K}^T & \alpha \Delta t \bar{K}^T
\end{bmatrix}
\begin{bmatrix}
\Delta u \\
\Delta p
\end{bmatrix}^{k+1} = \begin{bmatrix}
\Delta R_f \\
\Delta R_q
\end{bmatrix}^{k+1}
\]

\[
\begin{bmatrix}
k^{k+1} \\
A^T [k] [A]
\end{bmatrix}
\]

(29)

In equation (29), \( [\Delta R_q]^{k+1} \) is the equivalent flow increment array, its initial flow item is took out from \( [\Delta R_q] \). Since equation (29) considers the coupling relations between permeability tensor and stress, this formula is a non-linear equation. But it still needs iterative solution within each calculation of time step. However, since the formula eliminates the influence of free boundary non-linearity, non-linearity only comes from \( [K'] \) with the variation of stress. The extent of non-linearity weakens to some extent. Thus, the calculated amount of numerical analysis correspondingly is reduced, convergence can also be guaranteed.

Based on the finite element calculation software of MSC.Marc and computing platform of MATLAB, the study developed the finite element analysis program of dynamic fully coupled
rheological model for two fields. The program included pre-processing module, LFEM analysis module and post-processing module. It could realize the calculation of stress and strain, calculation of seepage and dynamic fully coupling calculations of two fields.

4. Examples

4.1. Engineering Overview and Numerical Information
The dam section 4# was selected as the research object, it was non-overflow dam section. When dividing finite element mesh, the dam portion simulated wide slot. Dam foundation part was subdivided according to the distributions of fault strike, weak belt and lithology. And it made the subdivided unit reflect practical situation. When a node was arranged, it should try to make measured points as nodes. The range of the dam finite element model included: the upper stream took 360 m, the downstream took 240 m, under the dam foundation took 200 m, the division of finite element mesh was as following (figure 1). There were 7657 isoparametric elements and 9194 nodes.

The monitoring time series of horizontal displacement in dam crest was taken as basis of calculation. Its time series of horizontal displacement is showed as following (figure 2). The variation curve of reservoir water level is showed as following (figure 3). The value of the main physical and mechanical parameters for dam body and dam foundation is showed as following (table 1).

Figure 1. The finite element model of 4# typical dam section.

Figure 2. The time curve of horizontal displacement for typical measuring point.
Figure 3. The variation curve of reservoir water level.

Table 1. The value table of the main physical and mechanical parameters.

|                    | $E_{MC}$ | $E_{KC}$ | $\eta_{KC}$ | $\eta_{SC}$ | $\mu_c$ | $\gamma_c$ | $k_{0c}$ |
|--------------------|----------|----------|-------------|-------------|---------|------------|----------|
| **Dam Body**       | MPa      | MPa      | GPa×$10^6$  | GPa×$10^7$  | /       | /          | /        |
|                    | 2.61×10^4 | 2.79×10^5 | 8.01        | 2.72        | 0.16    | 24.5       | 3.18×10^-6 |

|                    | $E_{MR}$ | $\eta_{MR}$ | $E_{KR}$ | $\eta_{KR}$ | $\eta_{SR}$ | $\mu_R$ | $c$     |
|--------------------|----------|-------------|----------|-------------|------------|---------|---------|
| **Dam Foundation** | MPa      | GPa×$10^6$  | MPa      | GPa×$10^7$  | /          | /       | N/mm^2  |
|                    | 2.32     | 6.69        | 24.63    | 1.41        | 2.11       | 0.20    | 0.90    |
| $f$                | /        | $\gamma_R$ | $k_{0R}$ | /           | /          |         |
|                    | 0.85     | 26.5        | 2.67×10^-5 |             |            |         |

4.2. The Analysis of Calculation Results

Considering the finite element calculation method of dynamic fully coupled rheological model for two fields, and then not considering the coupling ordinary finite calculation method, in order to compare the two methods, the study selected the horizontal displacement monitoring point in 4# dam crest as study object. It respectively calculated the dam deformation under the above two cases. Besides, the study set that the horizontal displacement of dam toward downstream was positive, the upstream was negative, while the vertical displacement upward was positive, downward was negative. The calculation results are shown as figures 4-5.

Figure 4. The contrast of horizontal displacement along the river.
Figure 5. The contrast of vertical displacement.

From figures 4-5, it can be seen that the horizontal displacement of dam toward downstream direction is enlarged with the increase of time, while the vertical displacement gradually decreases with the increase of time. Since the vertical displacement toward downward is negative, the actual amount of subsidence is gradually increased. The calculated value of horizontal displacement and vertical displacement under two conditions has gradually increasing trend with the increase of the time and has the same variation with measured values. Thus, to some extent, it indicates that the coupling rheological model of two fields established in this chapter is correct. When considering the calculating value of horizontal displacement for dam crest monitoring point under the coupling conditions of two fields, it’s more close to the measured values than without considering the coupling conditions, and the calculation result is smaller. The reason is that, when considering the coupling condition, the seepage water level under dam foundation surface rises, the seepage water level toward downstream face rises more than that toward upstream face in dam foundation rock mass. When the coupling effect is not considered, the water load is only taken as surface force and is exerted on the dam. When considering the coupling condition of two fields, the calculated value of vertical displacement for dam crest monitoring point has similar laws than without considering the coupling condition. When not considering the coupling condition, the calculated value of vertical displacement will gradually deviate more from the measured values with the increase of time. However, when considering the coupling condition, deviation isn’t clear. From the degree of influence on horizontal displacement and vertical displacement under coupled conditions, considering the coupled conditions has relatively larger impact on vertical displacement.

5. Conclusion

Based on the coupling mechanism analysis of two fields, the dynamic fully coupled rheological model of seepage and stress fields in concrete dam was constructed. The finite element numerical analysis of dynamic fully coupling for two fields was presented. The main research content is as following:

(1) On the basis of coupling mechanism analysis for seepage field and stress field in concrete dam body and dam foundation rock mass, according to the basic principles of effective stress and fluid mass conservation law, the basic equilibrium equation and continuity equation of fully dynamic coupling for two fields was deduced. The dynamic fully coupled rheological model of seepage and stress fields in concrete dam was constructed. Besides, the boundary conditions of coupling for two fields were given.

(2) According to the strain increment form of coupling analysis model for seepage field and stress field, the finite element equations are derived under the dynamic fully coupled action of seepage field and stress field. The finite element numerical analysis form is given under dynamic fully coupling of two fields. Besides, the corresponding finite element calculation program is developed.

(3) The dynamic fully coupled rheological model of two fields can reflect changes of boundary conditions such as the dam displacement and water pressure. It also can reflect the dynamic changes of
the stress, strain and permeability coefficient in space and time domain. Thus, the distribution of the displacement, stress and permeability coefficient can be obtained at different times during loading.

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