Analysis of the effect of dam impoundment at the Baihetan site using coupled fluid-mechanical elasto-plastic simulations

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Abstract. Contractional valley deformation is a phenomenon quite specific to high dams in the southwest of China. Numerical simulations with coupling of stress and seepage were performed to study the mechanisms of valley deformation after impoundment and to determine whether and when valley contraction could develop at the Baihetan site. The initial generic study highlighted two competing mechanisms, a “Mattress Effect” and a “Swelling Effect”, associated with dam impoundment. The comprehensive FLAC3D model incorporates detailed rock mass property values, a grout curtain, an impounding plan, and the drainage volumes. The large-scale coupled seepage-mechanical simulations show that the convergence mechanism is activated by fluid diffusion in the valley. At sites upstream and up to about 400 m downstream of the dam, the valley deformation occurs shortly after the impoundment water level is raised; this behaviour reflects the impact of the mattress effect caused by the weight change of the standing impoundment water. However, deformation also occurs during periods when the impoundment level remains the same; this behaviour is caused by the large-scale water seepage associated with pore-pressure changes under and around the dam in the valley banks. The maximum convergence along the monitoring lines does not exceed 5 cm in the simulations, where affected by the presence of faults and bedding planes.

1. Introduction

Many arch dams with height greater than 200 m have been designed and successfully constructed within the last 20 years in the southwest part of China. These dams are part of hydro-power plan projects; they are associated with high steep slopes, large underground caverns at great depth, and associated tunnels. Valley width measurements at the site of some of those projects have indicated that valleys experience contraction during filling of the dams. Contractional valley deformation is a phenomenon quite specific to high dams, and several hypotheses [1-4] have been advanced to explain its root cause, including rock mass fluid-induced creep, coupled thermal-seepage effect, and large-scale subsidence caused by changes in hydrogeological conditions.

This paper presents whether valley contraction could possibly be caused by large-scale seepage after dam impoundment and whether and when a similar mechanism could develop at the Baihetan site. Numerical simulations with coupling of stress and large-scale seepage were performed to achieve the objectives: 1) a generic study of the mechanisms at play in coupled seepage-mechanical impoundment problems; and 2) numerical predictions of valley deformation following dam impoundment obtained using a detailed model with suggested material and fluid properties [5,6].

2. Basic mechanisms with dam impoundment
The initial generic study was carried out in 2D; it highlighted two competing mechanisms associated with dam impoundment. The first is a “Mattress effect” caused by the hydrostatic water pressure applied on the valley surface upstream of the dam. The second is a “Swelling effect” caused by the large-scale seepage associated with pore-pressure changes in the valley after dam impoundment.[7]

2.1. Poro-elastic Study of Mechanisms

The 2D model is represented in Figure 1. The approximate dimensions are 620 m for the valley width, 414 m for the bank heights, 226 m for the maximum impoundment height (valley center), 3 km for the model width, and 1.650 km for its height (the y-coordinate is -500 m at the base of the model and 1150 m at the top). The x-reference axis is horizontal and oriented to the right.

The results of undrained and drained impoundment analyses are shown for a generic example in Figure 1 and Figure 2. Incremental x-displacement contours and displacement vectors due to the impoundment water load only (case 1), and due to just pore pressure dissipation (case 2) are shown to the left in Figure 1 and 2, respectively. Contours of excess pore pressure are plotted to the right for the two cases.

The 2D analyses show that two basic poro-elastic mechanisms develop after dam impoundment: a short-term “mattress” effect caused by the added water load (noting that pushing on a mattress causes nearby points to move downward and inward); and a time-dependent “swelling” effect associated with seepage (the development of a fluid pressure bulb under the valley causes upward and outward movement).

These opposing behaviours (corresponding to undrained and drained response) are illustrated in Figure 1 and Figure 2.

It is important to note that the load applied by the standing water has both vertical and horizontal components. Indeed, the river bottom is usually not flat, and, in addition, the impoundment water exerts pressure on the riverbanks. As a result, the Mattress effect manifests itself in different ways: a
valley convergence mechanism at high elevations (as pointed out earlier), together with valley expansion at low depth, below the impoundment water level. Both mechanisms are represented in Figure 1 and 2.

Also, the swelling effect (caused by seepage) generates displacements that are opposite to those of the mattress effect (caused by mechanical loading of the standing water) in the simulations. For the case considered above, the magnitude of displacements induced by seepage are significantly smaller than those generated by the pressure from the standing water in the valley. The 2D poro-elastic simulations showed that with the model and properties used for the runs, valley convergence was larger at a higher height and larger in the short term after impoundment.

The swelling and contraction of the rock in the model reflects the elastic material behaviour assigned in the model. This displacement reversal would be resisted by cohesive and frictional forces if a more realistic elasto-plastic behaviour was assigned to the rock.

2.2. Poro-elastic Constitutive Laws

Simple relationships often help in the interpretation of numerical simulation results. As an example of that practice, we note that the Mattress effect is characterized in poro-elasticity by the following volumetric constitutive law\[^8,9\] (the sign convention is negative for compression):

\[\Delta P = K_u \Delta \varepsilon \]

where \(\Delta\) stands for increment, \(P\) is mean (total) stress, \(\varepsilon\) is volumetric strain, and \(K_u\) is the undrained bulk modulus of the material:

\[K_u = K + \alpha^2 M\]

with \(K\) being the material (dry) bulk modulus, \(\alpha\) the Biot coefficient, and \(M\) the Biot modulus. \((K = E/(3(1-2v)))\) and \(v\) is Poisson’s ratio.\(^\dagger\)

The Biot modulus is related to the poro-mechanical properties of material bulk modulus, water bulk modulus, \(K_w\), porosity, \(n\), and Biot coefficient as follows:

\[M = \frac{K_w}{n+(\alpha-n)(1-\alpha)K_w/K}\]

It is expected, intuitively and from Eq. (1), that, for the same load increment, the mattress effect (or punching effect that induces convergence of the valley banks) will be stronger if the material is ‘softer’, that is, if the undrained bulk modulus is smaller. The prediction is thus of a stronger mattress effect for a smaller Biot coefficient and/or smaller Young’s modulus, and the trend is consistent with the numerical simulation results.

On the other hand, the Swelling effect is described in poro-elasticity by the familiar constitutive law:

\[\Delta P + \alpha \Delta P = K \Delta \varepsilon \]

This law can be expressed as:

\[\Delta \varepsilon = \frac{\Delta P}{K} + \Delta \varepsilon^f\]

where

\[\Delta \varepsilon^f = \frac{\alpha \Delta P}{K}\]

Eq. (6) describes the volumetric expansion, caused by a pore pressure increase, that can induce valley expansion in the 2D model. This equation indicates that the Swelling effect is stronger for a larger Biot coefficient, \(\alpha\), and/or smaller Young’s modulus, or \(K\), a trend that is consistent with the numerical simulation results.

2.3. Sensitivity analyses

Additional 2D poro-elastic analyses were conducted, using the \textit{FLAC} model represented in Figure 1, to study the impact on mattress and swelling effects of the following parameters: 1) Young’s modulus; 2)
Biot coefficient; 3) slope angle; 4) water table elevation at the model far boundaries; 5) lateral extent of the model; and 6) permeable versus impermeable boundary conditions. The parameter values considered in the analyses are listed in Table 1.

Table 1. 2D Parametric Analysis.

| Parameters                        | Reference value | Exercised values                  | Additional parameters |
|-----------------------------------|-----------------|-----------------------------------|-----------------------|
| Young’s modulus [GPa]             | 15.0            | 10,5,4,3,2,1                      | Young modulus = 10GPa |
| Biot coefficient                  | 1               | 0 to 1 in 0.1 increments          | Biot coef. = 0.5, 0.0 |
| Slope angle [degree]              | 90              | 75,60,45,30                       |                       |
| Water table height [m]            | 1150            | 1042,933,825                     |                       |
| Additional model extent [m]       | 0               | [50 - 10,000]                     |                       |
| Far boundary condition            | Fixed pressure  | Impermeable                       | Biot coef. = 0.5, 0.0 |

With the quantities used in the parametric study, the simulation results indicate that:

Mattress Effect – the Mattress effect is more intense (it induces more valley convergence) for a smaller Young’s modulus, larger slope angle, and to a lesser extent, smaller Biot coefficient. However, the sampled change in water table elevation, lateral model extension, and type of far-field fluid boundary conditions have little influence on model results.

Swelling Effect – On the other hand, the swelling effect is more pronounced (it reduces valley convergence more) for a larger Biot coefficient, smaller Young’s modulus, larger slope angle, and for fixed pressure (compared to no flow) far-field boundary condition. The effect of extending the lateral length of the model is non-monotonic: the swelling effect increases up to a boundary distance of about 6 times the valley span and it decreases thereafter.

These findings only hold for elastic, plane strain, and planar flow conditions such as those prevailing upstream of a dam in a valley undisturbed by discontinuities and material inhomogeneities. They may not apply to most of real-life cases but may still serve as a starting point to explore more complex situations.

3. Comprehensive FLAC3D model of Baihetan Dam site

The initial generic study highlighted two competing mechanisms associated with dam impoundment. The first is a “mattress effect” caused by the hydrostatic water pressure applied on the upstream valley surface of the dam. The second is a “swelling effect” caused by the large-scale seepage associated with pore-pressure changes in the valley after dam impoundment.

3.1. FLAC3D Model Components

The FLAC3D model is 4 km long by 3 km wide. The model stratigraphy, bedding faults, C (in green) and vertical faults, F (in magenta) are plotted in Figure 3. A simplified geometry is considered for the dam body in this task. However, both dam self-weight and grout curtain are included in the simulations.

Figure 3. FLAC3D model for the analysis with stratigraphy, structure, and curtain.
The origin of the model reference axes is located at the base of the dam (center), the z-axis is up, and positive y-values denote downstream distance.

3.2. FLAC3D Model Properties
The continuum Mohr-Coulomb representation of the rock mass includes Basalt, Columnar Basalt, Sandstone, and Weathering layers. The properties for the simulations are listed in Table 2 and Table 3. Instead of impermeable, the permeability of the curtain is set to $1 \text{Lu}$ (or $10^{-5} \text{ cm/s}$). The Biot coefficients of basalt, sandstone and tuff are 0.5, 0.75 and 1.

### Table 2. Mechanical and Hydraulic Properties of Rock Mass.

| Rock stratum | Density ($\text{kN/m}^3$) | Deformation Modulus (GPa) | Poisson ratio | $f'$ | $c'(\text{MPa})$ | Permeability Coefficient (cm/s) |
|--------------|---------------------------|---------------------------|---------------|------|----------------|-------------------------------|
| Basalt       |                           |                           |               |      |                |                               |
| strong unloading zone | 25 | 3.5 | 0.31 | 0.75 | 0.55 | $3 \times 10^{-3}$ |
| weakly weathering zone | 26 | 8  | 0.27 | 0.95 | 0.95 | $8 \times 10^{-4}$ |
| Fresh zone   | 27 | 15 | 0.24 | 1.20 | 1.30 | $5 \times 10^{-5}$ |
| Tuff         |                           |                           |               |      |                |                               |
| strong unloading zone | 22 | 1.5 | 0.35 | 0.40 | 0.10 | $5 \times 10^{-3}$ |
| weakly weathering zone | 24 | 3  | 0.32 | 0.60 | 0.50 | $8 \times 10^{-4}$ |
| Fresh zone   | 25 | 7  | 0.30 | 0.75 | 0.70 | $1 \times 10^{-4}$ |
| Sandstone    |                           |                           |               |      |                |                               |
| strong unloading zone | 22 | 1  | 0.34 | 0.45 | 0.25 | $1 \times 10^{-3}$ |
| weakly weathering zone | 24 | 3  | 0.31 | 0.65 | 0.55 | $2 \times 10^{-4}$ |
| Fresh zone   | 26 | 6  | 0.28 | 0.75 | 0.70 | $5 \times 10^{-5}$ |

### Table 3. Mechanical and Hydraulic Properties of Discontinuities.

| Rock stratum | Thickness (cm) | Deformation Modulus (GPa) | Poisson's ratio | $f'$ | $c'(\text{MPa})$ | Permeability Coefficient (cm/s) |
|--------------|----------------|---------------------------|-----------------|------|----------------|-------------------------------|
| Bedding planes | 10-40 | 0.04-0.25 | 0.25-0.32 | 0.25-0.45 | 0.04-0.15 | $5.0 \times 10^{-3}$ |
| Faults       | 15-60 | 0.1-0.25 | 0.25-0.28 | 0.35-0.40 | 0.04-0.1 | $1.0 \times 10^{-3}$ |

3.3. Simulated impoundment process
The planned staged impoundment schedule used in the simulations is plotted in Figure 4. It includes increasing, constant and decreasing changes of impoundment level in time. When shown together with a contour plot, the red dot corresponds to the time of the plot.
The flow pattern in the model is strongly influenced by the in-situ flow conditions. These conditions, which are assumed to have reached a steady state, are characterized by overall flow from the lateral boundaries towards the river valley. Also, the maximum change of water pressure due to impoundment is less than 2 MPa, a rather small quantity compared to the mean in-situ pressure level. To evaluate the impact of impoundment on the distribution of water pressure in the model, it is more informative to present the results in terms of excess water pressure (i.e., total current water pressure minus initial water pressure).

Excess water pressure contours on the cut plane at x = 0 (approximate valley axis) are plotted at various impoundment times in Figure 4. The excess pore pressure ‘bulb’ is progressing downstream as seepage takes place; also, the ‘size’ of the bulb increases when impoundment increases and vice-versa. A steady state of pore pressure is reached at the end of the 1,800 days simulation.

4. Coupled seepage-mechanical analyses of Baihetan Dam site

4.1. Seepage domain

The in-situ water table in the model (transition surface between one and zero saturation contours) is compared to the measured field value (yellow trace) on the model front cut-plane located at y = 500m in Figure 5. Saturation contours at the end of the maximum impoundment level stage are also represented for comparison (to the right in the figure). The dam is represented for reference only to the left in the figure (it is not present at the in-situ state in the model).

As seen in the figures, the match on the cut plane at y = 500 m between simulated and measured water table level in-situ is good. A good match is also obtained on additional cut planes along the y-axis; however the results are not represented here for the sake of concision. The impoundment impact on water table level is apparent upstream of the dam, and it is more subtle downstream, as expected.
4.2. Predicted valley convergence behavior

Contours of x-displacements 1,800 days after the start of impoundment are shown in the whole model in Figure 6. The model predicts valley convergence downstream of the dam and valley expansion upstream at approximate locations below the dam crest. Downstream of the dam, a sliding mechanism is observed towards the valley on the left bank, and superficial toppling is noticed at high elevations on the right bank. A map view with iso-surface of x-displacement five years after the start of impoundment is plotted in Figure 7. The red arrows on Figure 7 indicate regions of x-displacements away from the river valley, and the blue arrows indicate domains where valley convergence is predicted. The 3D simulation results showed that seepage can be held responsible for valley convergence in the valley. The displacement field in the FLAC3D model was dominated by the presence of ‘discontinuities’, including bedding planes and faults. Two mechanisms were identified (see Figure 7): preferential block displacement along bedding plane C02 and fault F14 on the left bank, and superficial displacement along steep slopes on the right bank.

Figure 5. Saturation contours and trace of measured insitu water table.

Figure 6. Map view of x-displacement contours and iso-surface of zero x-displacement shown in red at 5 years.
Figure 7. Close-up view of x-displacement contours and displacement vectors 5 years after the start of impoundment.

The predicted valley convergence on the plots reaches a maximum of about 5 cm at a y-distance of about 400 m downstream from the dam. The elevation of measuring lines located within 700 m of the dam is at or below the dam crest. In general, valley divergence is predicted by the model at measuring lines upstream from the dam, while the estimate is for valley convergence at the downstream measuring lines. Also, valley convergence is generally predicted to increase with measuring line elevation. Upstream and up to a distance of about 400 m downstream of the dam, the valley deformation occurs mainly during the changes of impoundment; this behaviour reflects the impact of the mattress effect caused by the change in dead weight of standing impoundment water. However, deformation also occurs during the period at a constant impoundment level; this behaviour is caused by water seepage under and around the dam in the valley banks.

We note that the influence of the mattress effect decreases with distance downstream of the dam; seepage-induced convergence clearly dominates at y-coordinates larger than about 700 m. At that location, valley convergence along the measuring lines reaches a maximum value of about 4 cm, then the maximum value decreases to about 1 cm at y = 1300 m, and the discrepancy between values at different elevations is also seen to decrease downstream with increasing distance from the dam.

5. Conclusion
Coupled fluid-mechanical elasto-plastic simulations were carried out to simulate the effect of dam impoundment at the Baihetan site. The model is used in a forward analysis to predict the type of deformation mechanisms that could potentially develop at the site. The simulation results reported in this paper showed that seepage can potentially be held responsible for valley convergence of the order of a few centimeters in the valley. Upstream of the dam, the model predicts valley divergence below the dam crest elevation and valley convergence at high elevations up the banks. Downstream of the dam, the overall prediction is of valley convergence. The displacement field in the FLAC3D model was dominated locally by the presence of ‘discontinuities’ including bedding planes and faults. Two mechanisms were identified: preferential block displacement along bedding plane and fault on the left bank, and superficial displacement along steep slopes on the right bank. The development of two different deformation mechanisms on the right and left banks was attributed to the fact that the bedding planes are sloping toward the valley on the left bank and into the slope on the right bank. The maximum amount of convergence along the monitoring lines does not exceed 5 cm in the simulations. The model
Predictions could be validated, or a back analysis with model recalibration could be conducted, provided measured field displacement data is made available in a further analysis. Nonetheless, at this stage it can be said that the drop in fluid pressure associated with the presence of large drainage domains in the model (not accounted for in this study) is expected to reduce the predicted valley convergence in the dam vicinity. The effect of drainage domains on model results will be included in further analyses.

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