

Simulation of flow in fractured rocks using effective stress-dependent parameters and aquifer consolidation

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Abstract Effective stress plays an important role in aquifer dynamics, especially in those affected by high variations of water pressures. Increasing/decreasing effective stresses affect hydrogeological parameters, even in media of high stiffness, such as fractured rocks. This study presents a modelling approach of groundwater flow in fractured rocks and aquifer deformation taking into account the dependency of hydrogeological parameters on effective stress. This approach has been illustrated by modelling a fractured aquifer dynamic, the Zeuzier arch dam settlement. The calibrated model showed agreement with measured data. This simulation method could be used to study the sensitivity of aquifers to variations in effective stress due to water pressure.

Key words numerical modelling; effective stress; fracture permeability; fractured aquifers consolidation; Zeuzier

INTRODUCTION

This paper proposes an approach to simulate groundwater flow in fractured rocks, taking into account the effect of effective stress (i.e. geological stress and water pressure) on hydrogeological parameters (i.e. permeability, porosity and specific storage coefficient) and the possible consolidation of the aquifer.

The dynamic of aquifers is related to effective stresses. In deep aquifers, the reduction of water pressures leads to increasing effective stresses and decreasing porosities/permeabilities, with possible consolidation. Assuming that aquifers have an elastic behaviour, the process described above is reversible. In granular porous aquifer (i.e. unconsolidated sediments) the dependency of hydrogeological parameters on effective stress has received much attention in the last decades on account of land subsidence produced by excessive pumping of water (e.g. Mexico City, Po Delta, San Joaquin Valley) (Rivera *et al.*, 1991; Gambolati *et al.*, 2000; Teatini *et al.*, 2005). In fractured aquifers (i.e. fractured crystalline and non karstic sedimentary rocks) this relationship was not investigated as much by the hydrogeologists, because of the smaller magnitude of the phenomenon and the low permeability of such media. However, the sensitivity of fractured aquifers to effective stress was seriously considered after several cases of instabilities in fractured and saturated rock masses, especially after the construction of tunnels or dams (Londe, 1987; Lombardi, 1988; Zangerl *et al.*, 2003). This topic is an important issue that must be taken into account in problems such as geologic radioactive waste repositories or CO₂ sequestration fields (Rutqvist *et al.*, 2002; Ferronato *et al.*, 2010).

Bear & Cheng (2010) suggest that two main methods are used to answer this hydromechanical coupled process: (1) the Biot theory of poroelasticity (Biot, 1941), which includes stress, strain and water flow in a single equation able to solve for water pressure and aquifer deformation; and (2) the non-simultaneous coupling of fluid flow and solid deformation. The distribution of water pressures, and effective stresses, calculated by a first simulation, is used in a second detailed simulation of solid deformation. Those techniques apply well to relatively small scale problems, but are computationally demanding and could become impractical at hydrogeological scales. Moreover, equations involved do not directly consider hydrogeological parameters as a function of effective stress. The aim of this work is to illustrate a modelling approach solving for water flow and aquifer deformation using stress-dependent parameters at a regional scale. The approach consists of three phases: a first one computing the distribution of lithostatic stresses in the aquifer; a second nonlinear simulation of water flow in which the equivalent hydraulic conductivity tensor of the rock mass and the specific storage coefficient depend on effective stresses; and a third

simulation computing the aquifer consolidation/expansion. This method has been applied to the case study of the Zeuzier arch dam settlement (Valais, Switzerland), which occurred at the beginning of 1979. The drilling of an exploratory adit next to the dam, the Rawyl tunnel, drained a surrounding confined aquifer. The decreasing water pressure caused the aquifer consolidation, and the dam settlement (Schneider, 1982; Lombardi, 1988).

MODELLING APPROACH

Computation of the lithostatic stress field

The lithostatic stress $\sigma(z)$ which corresponds to the weight of overlying rocks above elevation z , is defined as:

$$\sigma(z) = g \int_z^{z_{surface}} \rho_r(u) du \quad (1)$$

where g is the gravitational acceleration and ρ_r is the density of the rock at a given elevation z . In a vertical 2D or 3D domain Ω , the following boundary-value problem can be used to solve equation (1):

$$\nabla \cdot \frac{1}{\rho_r(z)} \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 1 \end{bmatrix} \nabla \sigma = 0 \quad \text{in } \Omega \quad (2)$$

$$\sigma(z_{surface}) = 0 \quad \text{on } \Gamma_+$$

$$\frac{d\sigma}{dz} = -g \rho_{r_{bottom}} \quad \text{on } \Gamma_-$$

where the Dirichlet boundary condition is prescribed on the upper boundary Γ_+ of the simulation domain Ω , and the Neumann condition is used on the bottom boundary Γ_- . Equation (2) is of the Laplace type, with anisotropic and heterogeneous parameters, which allows an easy computation of the lithostatic stress field over the model domain. This stress will be used in groundwater flow and aquifer consolidation simulations.

Simulation of flow

Preisig *et al.* (2012) developed stress dependent equations for fracture porosity, specific storage coefficient and hydraulic conductivity derived from Hooke's law.

Assuming the equivalent porous medium approach, and inserting the stress-dependent hydraulic conductivity in the respective tensor of a fractured aquifer composed by m fracture families' yields:

$$\mathbf{K}(\sigma') = \sum_{i=1}^m K_{0_i} \left[1 - \left(\frac{\sigma'_i}{\sigma'_{0_i}} \right)^{\frac{1}{n_i}} \right]^3 (\mathbf{I} - \mathbf{n}_i \otimes \mathbf{n}_i) \quad (3)$$

where for each fracture family i , K_{0_i} is the parallel hydraulic conductivity at no stress, σ'_i is the normal effective stress, σ'_{0_i} is the fracture closure stress, n_i is the coefficient describing the distribution of asperity lengths, \mathbf{I} is the identity matrix, \mathbf{n}_i is the unit vector normal to the fracture family i , and \otimes denotes a tensor product. $\mathbf{K}(\sigma')$ is the hydraulic conductivity tensor of a fractured aquifer as a function of effective stress σ' . In the case of saturated conditions, i.e. fractures are completely filled by water exerting the pressure p , the normal effective stress acting

on a fracture plane is:

$$\sigma' = \mathbf{b} \cdot \mathbf{n} - \alpha p, \quad \mathbf{b} = \begin{bmatrix} \sigma_z \lambda & 0 & 0 \\ 0 & \sigma_z \lambda & 0 \\ 0 & 0 & \sigma_z \end{bmatrix} = \rho_r g Z (\lambda n_x^2 + \lambda n_y^2 + n_z^2) - \alpha \rho_w g h \quad (4)$$

where n_x, n_y, n_z stand for the components of the unit vector \mathbf{n} normal to the fracture plane, ρ_w is the water density, h is the pressure head, α is the Biot-Willis coefficient, and λ is the ratio of horizontal to vertical stress. σ_z is the lithostatic stress as defined in equation (1).

The stress dependent specific storage coefficient proposed by Preisig *et al.* (2012) is:

$$S_s(\sigma') = \sum_{i=1}^m S_{s0_i} \left[1 - \left(\frac{\sigma'_i}{\sigma'_{0_i}} \right)^{\frac{1}{n_i}} \right]; S_{s0_i} = \frac{\rho_w g \phi_{0_i}}{E_w} \quad (5)$$

where S_{s0} and ϕ_0 are the specific storage coefficient and the fracture porosity at no stress, respectively. E_w is the elasticity of water. Introducing equations (3) and (5) in the transient groundwater flow equation, yields:

$$S_s(\sigma') \frac{\partial H}{\partial t} = \nabla \cdot (\mathbf{K}(\sigma') \nabla H); \quad H = h + z \quad (6)$$

where the symbols stand for hydraulic head H , and time t . The nonlinear equation (6) considers stress-dependent parameters. This equation implemented in a boundary value problem, is able to solve for the distribution of hydraulic head, pressure head, and for the recharge and discharge rates of the hydrogeological model.

Simulation of the aquifer consolidation

In hydrogeology, consolidation is the subsidence resulting from the release of water contained in the aquifer porosity, such as fractures or connected pore spaces. The decrease in water pressure leads to increasing effective stress, and to the closure of porosity. The summation of these porosity changes results in the aquifer consolidation, and causes ground settlement on surface. Preisig *et al.* (2012) proposes the following model relating fracture porosity to effective stress:

$$\phi = \sum_{i=1}^m \phi_{0_i} \left[1 - \left(\frac{\sigma'_i}{\sigma'_{0_i}} \right)^{\frac{1}{n_i}} \right] \quad (7)$$

where ϕ and ϕ_0 are the fracture porosity and the fracture porosity at no stress, respectively. For each fracture family i , constituting the fractured rock mass, the vertical change in fracture porosity, $\Delta\phi$, that follows the release of the water pressure, is:

$$\Delta\phi = \sum_{i=1}^m (\phi_{h_i} - \phi_{h_{s_i}}) n_{z_i} = \sum_{i=1}^m \phi_{0_i} \left[\left(\frac{\sigma'_{h_{s_i}}}{\sigma'_{0_i}} \right)^{\frac{1}{n_i}} - \left(\frac{\sigma'_{h_i}}{\sigma'_{0_i}} \right)^{\frac{1}{n_i}} \right] n_{z_i} \quad (8)$$

where ϕ_h and ϕ_{h_s} are the fracture porosity at an initial and at a successive pressure head state. The vertical change in fracture porosity results from the multiplication with the component n_z of the unit normal vector \mathbf{n} . Integrating all porosity changes in the vertical direction, from the aquifer bottom, z_b , to the top, z_t , gives the aquifer consolidation:

$$T(x,y) = \int_{z_b}^{z_t} \Delta\phi(z) dz \quad (9)$$

Equation (9) can be easily computed by the solution of the following boundary-value problem:

$$\begin{aligned} \nabla \cdot \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 1 \end{bmatrix} \nabla T &= \frac{d\Delta\phi}{dz} \quad \text{in } \Omega \\ T_{bottom} &= 0 \quad \text{on } \Gamma_- \\ \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 1 \end{bmatrix} \nabla T \cdot \mathbf{n} &= 0 \quad \text{on } \Gamma_+ \end{aligned} \quad (10)$$

In equation (10), the Dirichlet boundary condition, applied on the bottom of the model domain, indicates that there is no consolidation at the base of the aquifer. The implicit Neumann condition, used on the upper boundary, specifies that there is no porosity change at the domain surface (stress is zero). The solution provides the aquifer consolidation, and the ground settlement. When solved for increasing water pressures and decreasing effective stresses, the solution leads to aquifer expansion.

Finally, the three main assumptions of the modelling approach are: (1) aquifer consolidation only results from fracture porosity closure (no rock matrix compression), (2) the aquifer deformation is elastic, and (3) the stress fields remain constant during the water depletion. These assumptions are acceptable in stiff fractured rock masses.

CASE STUDY: THE RAWYL TUNNEL AND THE ZEUZIER ARCH DAM

The Rawyl tunnel and the Zeuzier arch dam are located in the Canton Valais, Switzerland, close to the city of Sion (Fig. 1(a)). From a geological point of view, the dam and the tunnel are situated in the Helvetic nappe system of the Swiss Alps, more precisely in the Wildhorn nappe. At the end of 1978, the Zeuzier arch dam showed an abnormal deformation. The board of experts proposed the following conceptual model to explain the dam deformation:

- An exploratory adit under construction, the Rawyl tunnel, drained, through vertical and subvertical faults, an underlying confined aquifer in the fractured Dogger sedimentary rocks. Extremely high flow rates (maximum of 1000 L/s) were drained by the tunnel at the crossing of subvertical fault zones. The discharge rate dropped rapidly to a steady state (~40 L/s), corresponding to the aquifer recharge (Fig. 2(b)).
- The release of the water pressures in the fractures leads to an increasing effective stress distribution in the rock mass, resulting in the closure of fracture porosity, and in the consolidation of the confined aquifer. This consolidation resulted in the regional settlement, which affected also the overlying massive Malm limestones that constitute the foundation of the Zeuzier arch dam. The settlement at the valley bottom reached finally about 13 cm.

More details on this case study can be found in: Schneider (1982) and Lombardi (1988).

The equations presented before were implemented in the multi-purpose Groundwater finite element software (Cornaton, 2007), and used to model the present case study.

The first step consists in the calculation of the lithostatic stress field. The simulation domain is composed of two material classes: the non aquifer sedimentary rocks (mainly composed of Malm limestones) and the aquifer, both having a density of 2200 kg/m^3 (Fig. 1(b)). At the top of the domain a Dirichlet boundary condition is specified, that matches a zero stress state (except for the nodes forming the bottom of the dam lakes, whose stress corresponds to the weight of the above water column). At the bottom of the aquifer the implicit Neumann condition $-g\rho_{r_{bottom}}$ is indicated.

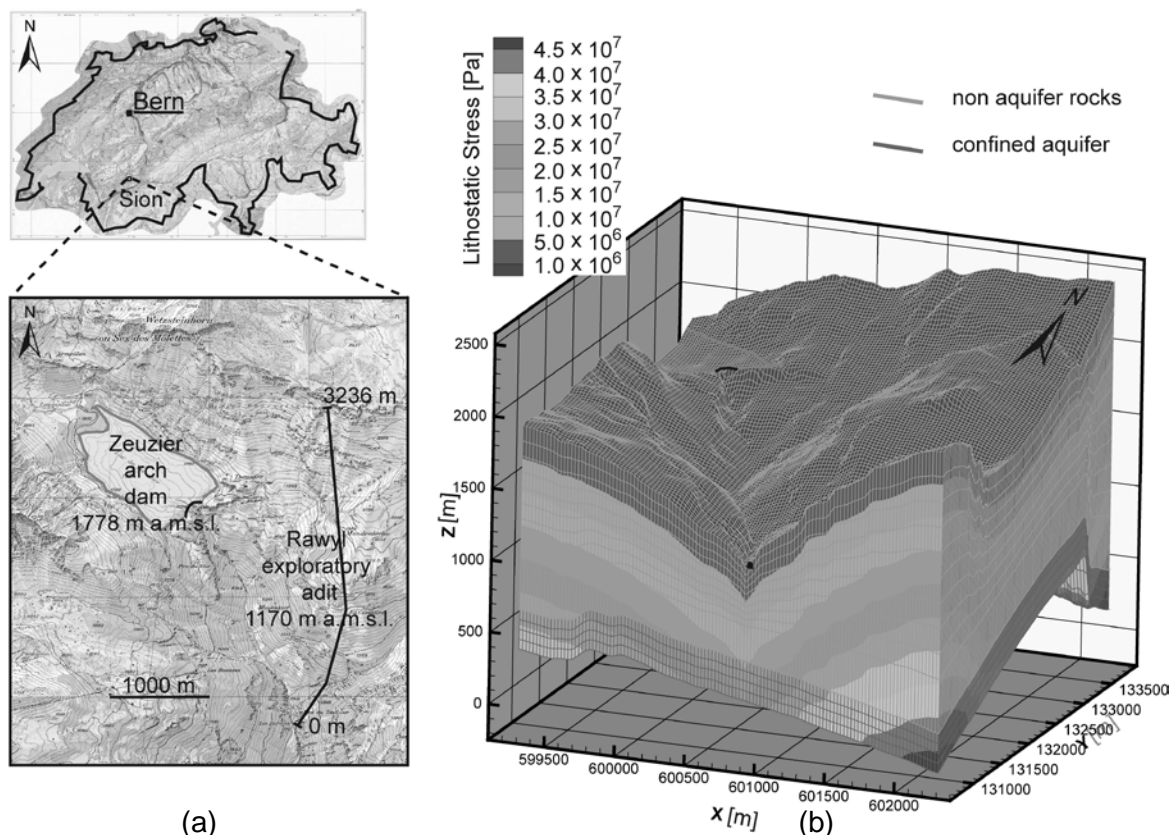


Fig. 1 (a) Location and information about the Zeuzier arch dam and the Rawyl tunnel site. (b) Simulated lithostatic stress field, and material classes forming the domain.

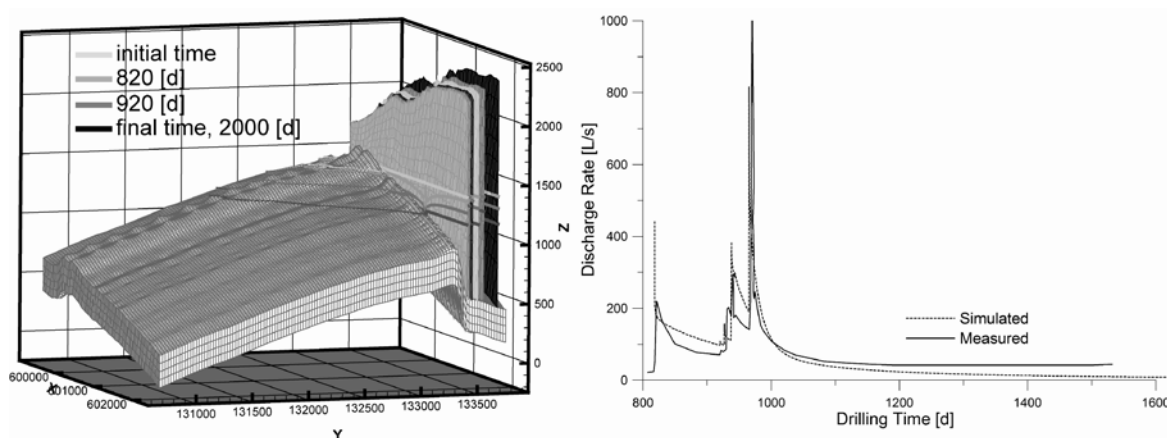


Fig. 2 (a) Evolution of the water table level with drilling progression, and groundwater flow domain. (b) Discharge rate drained by the exploratory tunnel as a function of drilling progression time (measured data, solid line; modelled data, dashed line).

The resulting stresses are then used in the groundwater transient flow model. The domain presented in Fig. 1(b) is reduced to the aquifer and to six vertical faults, introduced in the 3D domain as 2D discrete structures. Note that, rock masses form a local fold near the dam, which extends to the aquifer. The geometry of this fold has been simplified to allow the finite element discretization (Fig. 2(a)). The tunnel is discretized as a square of 4 m edge, representing a hole in the mesh, which crosses the faults. Constant atmospheric pressures are specified at the tunnel nodes, this Dirichlet boundary condition is activated according to a time function of drilling progression. The initial heads

present in the model matches 1400 m a.m.s.l. The aquifer recharge has been neglected, because of its low value compared to the discharge rate drained by the tunnel. The model is calibrated using the measured discharge rate drained by the Rawyl exploratory adit, by varying the hydraulic conductivity and the specific storage coefficient of faults and aquifer (Fig. 2(b)).

Using equations (8) and (9) and the final pressure head distribution as input, consolidation and settlement are computed. The change in porosity only takes place in the aquifer, where the pressure head varied; no deformation occurs in the non aquifer sedimentary rocks. The computed settlement near the dam at the valley bottom is 8 cm. Maximum simulated subsidence reaches about 20 cm, and is located at the valley bottom between coordinates 131'500–132'300°N and 600'100–600'250°E. Here, the change in porosity and the consolidation are important because: (1) the confined aquifer is nearly cropping out (low lithostatic stress), and consequently the fracture porosity was high; (2) after the drilling of the Rawyl tunnel there is a wide drop in water pressure leading to significant closure of fracture porosity (Fig. 3).

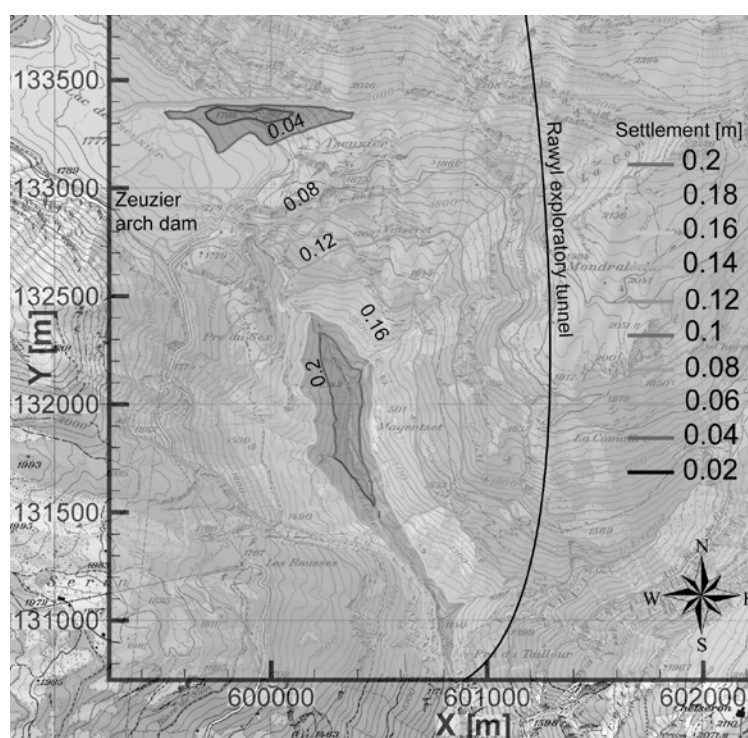


Fig. 3 Simulated settlement map resulting from the final distribution of water pressures. The tunnel drainage empties the system; this depressurization causes aquifer consolidation.

CONCLUSION

Effective stress plays an important part in groundwater flow, especially for deep confined aquifers. These effects must also be considered in fractured rocks.

A modelling method of hydromechanical coupling in fractured aquifers has been described. Stress-dependent parameters are used to solve the governing equations of groundwater flow and aquifer deformation. First the lithostatic stress field is computed, solving an original and very practical boundary value problem. A nonlinear form of the groundwater flow equation is then solved, followed by the solution of a second original boundary value problem providing aquifer consolidation/expansion.

The present approach is limited to elastic deformations, because it is developed from Hooke's law and therefore neglects shear stresses and brittle deformations. However, in most cases the

variation of water pressures only affects the elastic part of a deformation. In such a case, this approach can be used to study the sensitivity of aquifers on decreasing/increasing water pressures. Especially in the presence of civil engineering works, such as dams or tunnels; and in projects of geologic radioactive waste repositories or CO₂ sequestration fields.

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