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Numerical modeling and validation for 3D coupled-nonlinear thermo-hydro-mechanical problems in masonry dams

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ABSTRACT

We introduce in this article a fully coupled thermo-hydro-mechanical (THM) model describing the physical phenomenon present in masonry materials. A series of 3D numerical simulations are carried out for the THM analysis of a dam during its impounding process. The results of the coupled THM analyzes are validated with measurements recorded during that process in terms of transient displacement, pore-water pressure and temperature values. An agreement between numerical simulations and measured data proves that the coupled THM model can well reproduce the multi-physical behavior of masonry dams. Furthermore, we introduce herein a solution for a large system of balance equations by combining parallel computation, storage in Compressed Sparse Row format, and iterative pre-conditioned Conjugate Gradient Squared method in order to improve the computational cost.

1. Introduction

Many masonry dams were built at the beginning of the twentieth century e.g. Fürwigge Dam and Ennepe Dam in Germany, and the Theodore Roosevelt Dam in Arizona, USA. After more than one hundred years, the waterproof layers at the upstream side of the dam and the vertical drainage system may be damaged. Additionally, material properties of the dam body were also changed due to ageing, weathering and chemical effects. Consequently, there is a significant amount of water seeping from the upstream side to the downstream side of the dam.

In order to extend the dam operation, rehabilitation processes are carried out. Some common methods are to construct a drainage net of boreholes in the dam body and to repair the waterproof layers. Besides that, measurement devices and sensors are installed in order to monitor the physical behavior of the dam (i.e. deformation, pore-water pressure, effective stress, temperature) [1,2]. Generally, masonry dams have to bear three major loads. The first and most obvious type of load is water pressure and the second load is self-weight load. Thirdly, the temperature load on the dam structure varies according to the water and air temperatures. This causes the stresses within the structure and deformation of the dam. According to the measurement reports [1,3], the effects of temperature on the deformation of the dam and water infiltration are significant.

Therefore, the mutual relations among thermal conduction, water transport in unsaturated media and force-deformation have to be considered simultaneously while performing numerical simulations of the dams. Moreover, the geometry of dams often has an arch form, with complex geometrical boundaries, which minimizes the bending moments in the dam body. In order to analyze precisely the behaviors and processes occurring in the dam body, the numerical simulation as a fully coupled thermo-hydro-mechanical (THM) analysis in three-dimensional models is necessary.

Coupled numerical simulations of water transport with stress-strain relations in saturated porous media applied to dams were introduced in Wang et al. [4] and considering the cracks or damages in the media, e.g. in [5,6] and multi-phase flows in unsaturated porous media, e.g. in [7–9]. However, modeling the water infiltration and deformation for the dams considering the intertwined effects of temperature is still missing. We note that several multi-physical models of coupled THM problems for soils and porous media have been introduced, e.g. in [10–12].

A 3D coupled THM problem requires five degrees of freedom per node (three for displacements, one for pore water pressure and one for temperature). The dam with complex geometry requires a large set of elements. Consequently, if the problem is solved with LU factorization using band storage format, the computational cost will be extremely high. Therefore, we introduce a

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Nomenclature

Ω	domain analysis, first used in Eq. (19)
α_T	coefficient of thermal expansion, first used in Eq. (10)
α_s	coefficient of swelling/shrinkage induced by suction, first used in Eq. (10)
λ_T	thermal conductivity, first used in Eq. (2)
λ_{dry}	thermal conductivity at dried state, first used in Eq. (2)
λ_{sat}	thermal conductivity at saturated state, first used in Eq. (2)
λ	shape parameter for the retention curve, first used in Eq. (12)
λ_w	model parameter in Eq. 1, first used in Eq. (1)
μ_l	dynamic viscosity of the pore liquid, first used in Eq. (11)
μ_o	model parameter for dynamic viscosity, first used in Eq. (14)
μ_T	empirical coefficient of relative viscosity, first used in Eq. (1)
∇^t	partial derivative operator at time t, first used in Eq. (28)
ν	Poisson ratio, first used in Eq. (8)
ω_g^w	vapor density, first used in Eq. (15)
ϕ	porosity, first used in Eq. (3)
$\rho_{(\cdot)}$	density of $(\cdot)$ phase i.e. gas, solid, liquid, first used in Eq. (6)
ρ_v	vapor density, first used in Eq. (15)
$\boldsymbol{\sigma}$	stress tensor, first used in Eq. (5)
τ	tortuosity, first used in Eq. (15)
θ_g^w	volumetric mass of water in the gas phase, first used in Eq. (3)
θ_l^w	volumetric mass of water in the liquid phase, first used in Eq. (3)
$\boldsymbol{\varepsilon}^{T-e}$	elastic strain induced by temperature, first used in Eq. (7)
$\boldsymbol{\varepsilon}^{\sigma-e}$	elastic strain induced by stress, first used in Eq. (7)
$\boldsymbol{\varepsilon}^{s-e}$	elastic strain induced by suction, first used in Eq. (7)
$\boldsymbol{\varepsilon}^{e}$	elastic strain, first used in Eq. (7)
$\boldsymbol{A}$	represents the conductance matrix, first used in Eq. (33)
$\boldsymbol{a}_{(\cdot)}$	flux and conductance of the field $(\cdot)$, first used in Eq. (32)
$\boldsymbol{b}$	vector of body forces, first used in Eq. (5)
$\boldsymbol{B}$	gradients of shape functions, first used in Eq. (19)
$\boldsymbol{b}_{(\cdot)}$	boundary conditions of the field $(\cdot)$, first used in Eq. (32)
b	model parameter for dynamic viscosity, first used in Eq. (14)
$\mathbf{d}_{(\cdot)}$	storage or accumulation of the field $(\cdot)$, first used in Eq. (32)
D_m	diffusion coefficient of vapor, first used in Eq. (15)
$\boldsymbol{D}^e$	elastic material matrix of the solid phase, first used in Eq. (8)
E	elastic elastic modulus, first used in Eq. (8)
e	void ratio, first used in Eq. (1)
f^Q	internal/external energy supply, first used in Eq. (6)
f^w	internal/external water supply, first used in Eq. (6)
$\boldsymbol{g}$	gravity acceleration, first used in Eq. (11)
G_s	soil density, first used in Eq. (1)
$\boldsymbol{i}_c$	energy flux due to conduction, first used in Eq. (6)
$\boldsymbol{j}_{E(\cdot)}$	advective flux of energy caused by mass motions, first used in Eq. (6)
$\boldsymbol{j}_g^w$	mass motion of water in gas phase as the moisture, first used in Eq. (3)
$\boldsymbol{j}_l^w$	mass motion of water in liquid phase, first used in Eq. (3)
$\boldsymbol{k}$	tensor permeability, first used in Eq. (1)
k	time step in finite difference, first used in Eq. (22)
k_{rl}	relative permeability, first used in Eq. (11)
$\boldsymbol{k}_o$	the tensor of reference intrinsic permeability, first used in Eq. (1)
l	iteration step in Newton-Raphson, first used in Eq. (22)
M_ω	molecular mass of water, first used in Eq. (17)
N_i	shape function, first used in Eq. (26)
P_g	gas pressure, first used in Eq. (9)
P_l	liquid pressure, first used in Eq. (9)
P_o	parameter for retention curve, first used in Eq. (13)
$\boldsymbol{q}_l$	vector flux of liquid phase, first used in Eq. (11)
$\boldsymbol{r}_{(\cdot)}$	residual vector of the field $(\cdot)$, first used in Eq. (22)
s	suction/capillary pressure, first used in Eq. (10)
S_e	effective degree of saturation, first used in Eq. (12)
S_g	gas degree of saturation, first used in Eq. (3)
S_l	liquid degree of saturation, first used in Eq. (2)
S_e	maximum liquid degree of saturation, first used in Eq. (13)
S_{rl}	residual liquid degree of saturation, first used in Eq. (13)
T	temperature, first used in Eq. (1)
t	time, first used in Eq. (3)
$\boldsymbol{u}$	vector of displacement, first used in Eq. (21)
w	water content, first used in Eq. (1)
w_0	reference water content, first used in Eq. (1)
$\boldsymbol{X}$	vector of unknowns, first used in Eq. (33)

solution of the system of equations using a combination of parallel computation (openMP), storage in Compressed Sparse Row format [13] and the iterative pre-conditioned Conjugate Gradient Squared method [14]. The results show that the computational cost decreases significantly.

Based on the coupled THM model, we performed numerical simulations for 3D problems applied to the Fürwigge dam. The transient displacement, temperature and water transport are validated with the measured data [2]. The results show that the numerical simulations have a good agreement with the data measured and can be assumed to be validated.

2. Phenomena and mechanisms in masonry dams

2.1. Stress and strain relations

The dam was built using rock blocks and mortar. There are two material patterns, the thin leaf has a regular pattern, whereas the infill has an irregular or random pattern. The elastic modulus of rock is much higher than the elastic modulus of mortar. In meso-scale problem, heterogeneous material can be treated by representative volume elements under the light of first order homogenization theory [15]. However, within the scope of this study, the masonry material is considered as a homogeneous and isotropic material because of the given large scale problem and that major parts of the dam volume follow a random pattern. The stress-strain relations can be influenced by the temperature and wetness state of the masonry materials. The deformation may cause the change in porosity and thus cause the change in permeability, however, the change in porosity can be ignored in cases of the small deformation.

2.2. Effects of temperature

The temperatures inside the dam body and at the boundary are different. Furthermore, the temperature at the surfaces in contact with water are different from the surfaces in contact with air. Water temperature varies significantly with seasons at the water