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Damage identification using inverse analysis for 3D coupled thermo-hydro-mechanical problems

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In this paper, location and degree of damages in massive masonry structures are identified by a multi-field based inverse analysis which relies on a series of measurements such as transient displacements, temperatures and water pressures. As it is typical for the multi-field problems, the existence of damage leads to local changes in parameters of the different physical fields. The degree of the damage is defined by one primary variable, from which other quantities are derived. For fluid-flow problems in deformable porous media under non-isothermal boundary conditions such a quantity is the porosity of the material. The inverse analysis bases on a global search method, in which a dual-level parallel-computation is applied to improve computational cost. The effects of uncertainties in measurements and the size of the damage on the accuracy of the solutions are also discussed in the paper.

1. Introduction

Model-based damage identification in structures relies on a comparison between model responses and those recorded of the structure of interest. If the material properties of the structures change due to aging, cracking, weathering or other reasons, the misfit between model response and structural behavior increases. Minimizing this misfit by means of inverse analysis, the current state of the structure can be mapped into the model. By this, the operators can conclude the structure's integrity and judge on its stability.

The damage in the dams and other massive structures can be detected by means of inverse analysis relying on various dynamic experiments [1–5]. In addition, the damage of the structure has been identified by means of inverse analysis based on a comparison between pseudo-measured displacements in static experiments and finite element (FE) model [6–8]. It will be more economically advantageous, when the damage can be identified based on the measurements from the sensors installed in the dams during the impounding period instead of stopping operation and doing experiments.

Recently, inverse analysis has been employed to identify the damages/cracks in the structures by using coupled models, which allows considering multi-field measurements simultaneously, e.g. hydro-mechanical models [9] or piezoelectric models [10,11]. Using coupled models enables the usage of the multi-field measurements in the inverse problem. Increasing the number and types of measurements may decrease probabilistically the insufficiency and the errors in measurements, thus, an increase in the reliability of the results is expected.

Masonry dams are built of permeable materials, which allow slow water penetration. Furthermore, the recent measurements indicates that the effects of temperature on the deformation of masonry dams are significant [12]. Therefore, thermal field, water pressure field, and displacement field have to be coupled when performing numerical simulations of this type of dams. Moreover, the geometry of dams often has an arch form with complex geometrical boundaries. The arch form helps to minimize bending moments in the dam's body. A 3D modelling is a proper choice to simulate accurately the behavior of the dams. Modelling and validation of three dimension masonry dams have been carried out for undamaged conditions considering effects of temperature and water infiltration in [13].

Correlations of different parameters in non-isothermal fluid-flow problems can be expressed via the porosity. The porosity is considered as the unknown; the permeability, the elastic modulus, and the thermal conductivity are considered as dependent variables. The masonry dams are modeled in three dimensions based on these material models. The inverse analyses are established to localize the damage and to determine the degree of damage, which relies on a series of measurements i.e. transient displacement, temperature, and water pressure. The inverse problem is solved

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NOTATION

$\boldsymbol{\alpha}_T$	tensor of the coefficient of thermal expansion, first used in Eq. (8)
λ_{ref}	reference thermal conductivity, first used in Eq. (13)
λ_T	thermal conductivity, first used in Eq. (13)
μ_l	dynamic viscosity of the pore liquid, first used in Eq. (9)
μ_o	model parameter for dynamic viscosity, first used in Eq. (11)
μ_k	systematic error value, first used in Eq. (30)
ν	Poisson's ratio, first used in Eq. (5)
ϕ	porosity, first used in Eq. (1)
ϕ_o	reference porosity, first used in Eq. (8)
$\rho_{(\cdot)}$	density of $(\cdot)$ phase i.e. gas, solid, liquid, first used in Eq. (3)
$\boldsymbol{\sigma}$	stress tensor, first used in Eq. (2)
$\boldsymbol{\sigma}'$	effective stress tensor, first used in Eq. (6)
θ_w	volumetric mass of water in the liquid phase, first used in Eq. (1)
θ	correlation length, first used in Eq. (30)
$\boldsymbol{\varepsilon}^{T-e}$	elastic strain induced by temperature, first used in Eq. (4)
$\boldsymbol{\varepsilon}^{\sigma-e}$	elastic strain induced by stress, first used in Eq. (4)
ε^e	elastic strain, first used in Eq. (4)
$\boldsymbol{\varepsilon}(t)$	vector of noises, first used in Eq. (15)
ϑ	degree of uncertainty in measurement, first used in Eq. (31)
a	permeability attenuation coefficient, first used in Eq. (10)
$\boldsymbol{A}$	tensor of the radii, first used in Eq. (23)
$\boldsymbol{b}$	vector of body forces, first used in Eq. (2)
b_μ	model parameter for dynamic viscosity, first used in Eq. (11)
$\boldsymbol{c}$	vector define the elliptic center, first used in Eq. (23)
C_k	correlation matrix, first used in Eq. (30)
$\boldsymbol{D}^e$	elastic material matrix of the solid phase, first used in Eq. (5)
E	elastic modulus, first used in Eq. (5)
E_{min}	minimum elastic modulus, first used in Eq. (8)
E_s	Energy in the solid phase, first used in Eq. (3)
E_w	Energy in the water phase, first used in Eq. (3)
f^Q	internal/external energy supply, first used in Eq. (3)
f	objective function, first used in Eq. (17)
f^w	external supply of water, first used in Eq. (1)
$\boldsymbol{g}$	gravity acceleration vector, first used in Eq. (9)
$\boldsymbol{i}_c$	energy flux due to conduction, first used in Eq. (3)
$\boldsymbol{j}_{E(\cdot)}$	advective flux of energy caused by mass motions, first used in Eq. (3)
$\boldsymbol{k}$	intrinsic permeability tensor, first used in Eq. (10)
k	number of measurement device, first used in Eq. (29)
$\boldsymbol{k}_o$	reference intrinsic permeability tensor, first used in Eq. (10)
$\boldsymbol{p}$	vector of model parameters, first used in Eq. (14)
P_l	liquid pressure, first used in Eq. (6)
$\boldsymbol{q}_w$	flux of the water phase, first used in Eq. (1)
R_ϕ	deviation of porosity, first used in Eq. (38)
R_V	deviation of damage volume, first used in Eq. (37)
$\boldsymbol{R}_o$	rotation vector, first used in Eq. (23)
R_t	vector of Gaussian random numbers, first used in Eq. (30)
T	temperature, first used in Eq. (8)
t	time, first used in Eq. (1)
$\boldsymbol{v}_i^l$	velocity vector in PSO, first used in Eq. (26)
$\boldsymbol{y}$	vector of responses, first used in Eq. (14)
Z_k	auto-correlation function, first used in Eq. (30)

iteratively by means of nonlinear optimization, e.g. modified Particle Swarm Optimization (PSO) [14]. 3D non-linear thermo-hydro-mechanical (THM) problems are computationally expensive. For improving computational cost, a dual-level parallel computation is employed on a multi-core computer. The first level is a parallelization of the preconditioned conjugate-gradient solution in the FE systems using the application programming interface (API) [13]. The second level is a parallelization of the PSO algorithm using the paradigms of Distributed Computing.

Furthermore, we model the uncertainties in the synthetically generated data by using time correlated random field models. The errors of the identified damage zones due to the uncertainty of the measurements and the size of the damage are quantified and discussed.

2. The forward model of coupled thermo-hydro-mechanical analysis

The forward model describes the fluid flow through porous deforming materials (masonry) under non-isothermal boundary conditions over the impounding process. Stress-induced cracks or damage are not considered because the stress variable in the gravity dams is merely acting within the elastic zone. However, the existence of damages (weakened zones) is assumed due to erosion, aging (loss of mortar), weathering and other effects. These weakening leads to locally changed material parameters, which are taken into consideration in our model and which need to be identified in the inverse problem, see Section 3. The THM problems for the saturated porous media are formulated by a system of coupled balance equations.

Equations for mass balance are established by following the composition approach [15]. Constitutive equations are used to link between the primary unknowns (i.e. displacements, liquid pressure and temperature) and the dependent variables e.g. stress, energy flux and so on. This constitutive equations are established on the basic of mechanics, which has been validated in [13]. In the sequel, the forward model is described briefly by the basic balance equations and constitutive equations.

2.1. Balance equations

2.1.1. Mass balance of water

The total mass balance of water in the saturated conditions is expressed as follows:

$$\frac{\partial}{\partial t}(\phi\theta_w) + \nabla\cdot\boldsymbol{q}_w = f^w. \tag{1}$$

where ϕ is the porosity; θ_w is the volumetric mass of water; $\boldsymbol{q}_w$ is the advective flux; f^w is the external supply of water, when deformation is negligible, f^w can be considered equal to zero. The assumption of full saturation is justified for situations where the dams are in operation for a long time after the impounding process.

2.1.2. Momentum balance for the medium

If the inertial terms are neglected in the static loading conditions, the momentum balance reduces to the equilibrium of stresses as

$$\nabla\cdot\boldsymbol{\sigma} + \boldsymbol{b} = \boldsymbol{0}, \tag{2}$$