Optimal Monitoring of Gravity Dams by Multifield Considerations

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ABSTRACT: The safe operation of gravity dams requires continuous monitoring in order to detect any changes concerning the statical structure. Damages which may result from cyclic loadings, variations in temperature, aging, chemical reactions and so on, need to be identified as fast and as reliable as possible. Generally, existing dams are well monitored by different type of measurement devices, which log different physical quantities, such as deformation, pore water pressure, seepage or temperature. The aim of this research is to perform an optimal experimental design for the reliable estimation of damages for dams. The basis for these investigations is a thermo-hydro-mechanically coupled model with heterogeneous material distributions in which damages are described by a smeared crack model. In the case of damages, the changes of the main parameters in a multifield model are strongly correlated. This correlation is particularly considered during the inverse analysis, which is the detection of the damages from combined hydro-mechanical observations at a discrete set of observation points. The identification of damages is in mathematical terms not only an inverse but also an ill-posed problem which requires regularizing methods to solve it in a stable manner. For an efficient monitoring, an optimal experimental design framework for nonlinear inverse and ill-posed problems is applied.

1 INTRODUCTION:

Operators of dams are often in predicament, that they should act after the following three aspects, namely

- to use dams as long as possible with high filling (maximal efficiency),
- to guarantee highest safety, and
- to operate with minimal costs.

Since these three demands contradict each other it is a demanding task to determine how a monitoring of a dam should be designed in order to

- obtain most reliable and robust predictions about the current state of the structure, and
- to use most efficiently all information which can be retrieved from the sensors installed.

Construction, maintenance and the operation of dams are generally prescribed by appropriate guidelines in different countries, e.g. [13, 1]. Therein, one finds building regulations how to monitor the dams accordingly to their type. It is not always clear how the engineer in duty may accomplish the monitoring for a certain dam. Usually, the engineer acts by his own personal knowledge and experience. Sometimes, he follows the monitoring practice of similar existing dams. Generally, the numbers and types of sensors installed allow for a reliable monitoring of the complete structure and proofs of stability according to the guidelines can be performed. However, the data may not be sufficient for the identification of local damages, their location, shape and size. The mentioned local damages usually result from cracking or ageing of the materials from which the dam is built. Whether these local damages are severe for the dams reliability can only be judged if one knows precisely their location.

It is the aim of this work to develop tools based on mathematical inversion methods which allow detecting damages from combined hydro-thermal-mechanical observations, e.g. measurements of the pore water pressure, mechanical deformations in horizontal and vertical direction or temperature measurements inside the construction. By an evaluation of the data with a subsequent inversion, one can test, if a monitoring design (i.e. number, type and location of a set of sensors) provides sufficient data to identify possibly existing damages. Since these tests can be performed with the help of numerical models combined with inversion schemes, the monitoring design can be performed even before the dam is built.

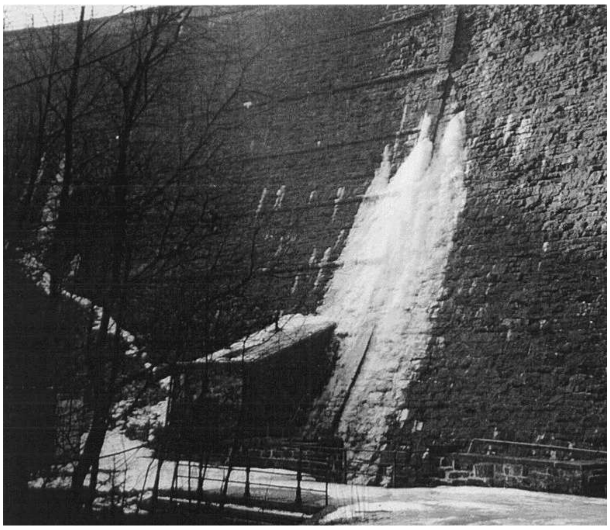

Figure 1. Frozen seepage water along the downstream side of a dam (Source: Ruhrverband, Essen, Germany). Undesired percolation is a common indicator for local damages.

2 THERMO-HYDRO-MECHANICAL FINITE ELEMENT MODEL:

The basis for this research is the development of a multifield Finite Element model which allows to describe all dominant physical effects within a dam with enough precision. It is upon the engineers preferences, if he investigates only stress-strain relationships in the structure or if he accounts additionally for hydrologic and thermal loadings. Our approach proposes to consider all three fields to capture all loadings in the analysis. In particular during the inversion more information are provided by a multifield treatment compared to single field analyses. This gain in information results mainly due to the inherent correlation in the changes of the most dominating material properties in case of damages.
If one assumes a local damage, the following is observable

- an increase of mechanical displacements due to a lowered stiffness,
- an increase in pore water pressure flow due to locally increased hydraulic conductivity,
- a change of temperature within the dam due to a higher amount of seepage, which depending on the temperature of the reservoir's water, affects the temperature distribution of the structure.

Consequently, the model to use must be able to describe thermal-hydro-mechanical effects and their interactions. Additionally, in order to model localized damages, the dominating material parameters, like hydraulic conductivity and Young's modulus, are modelled as space dependent variables, which results in a heterogeneous description of non-isothermal flow through deforming porous media. The corresponding theory and the Finite Element formulation are e.g. well described in [12] (Chapter 10) and are the basis for this analysis. Figure 2 plots the simulation results of a three-field plane strain Finite Element Analysis of the Fürwigge dam.

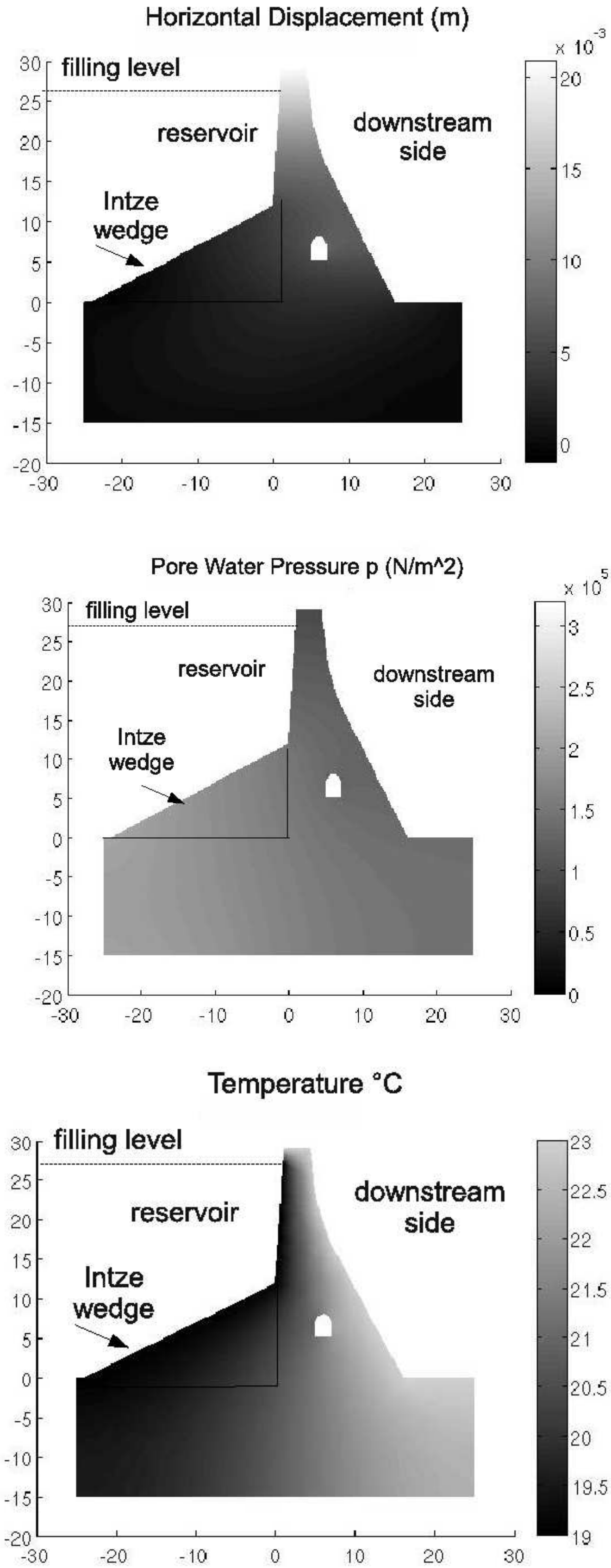

Figure 2. Simulation results: A) Deformation in horizontal direction due to hydraulic and thermal loads. B) Pore water pressure distribution in the structure. C) Thermal field for temperatures assumed to hold in September (Germany).

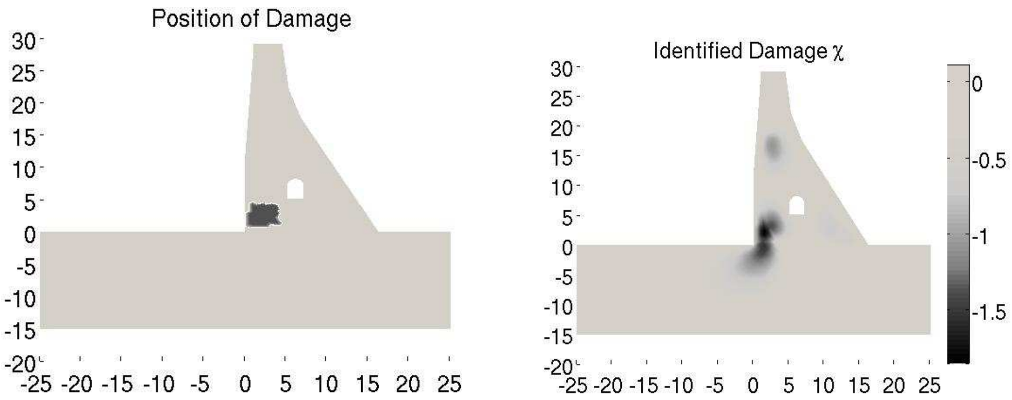

Figure 3. Left: Position of an arbitrary damage zone, Right: Reconstruction of the damage by a multifield inverse analysis. The locations of the sensors are as giben in Figure 4. The Intze Wedge is not considered in the inverse analyses, since we do not expect damages there.

3 DAMAGE AND CRACK DETECTION BY INVERSE ANALYSIS:

Generally, in any inverse analysis a set of measurements is given and the modeler is interested in the causes which describe the observed effect. In the example discussed subsequently, the data is assumed to be measurements at different times and locations in the dam of

- mechanical displacement,
- pore-water-pressure,
- temperature (devoted to future research).

Figure 3 shows the reconstruction of a damage at the bottom of the dam from combined hydro- and mechanical quantities. These quantities have been generated in a synthetic way, i.e. by running a multifield finite element simulation which includes a damage at the location indicated in the left profile in Figure 3. Additionally, normally distributed noise is added to the data in order to capture effects resulting from measurement errors.
Inversions are nonlinear problems which tend to be ill-posed, that is that existence and uniqueness of the solution are not guaranteed. Further, and this is the most critical point, a stable dependency of the solution given data is most often violated [4]. Therefore, appropriate iterative regularizing methods need to be applied in order to solve the inverse problems in a stable manner [8]. Applications of such methods to crack detection in dams are reported in [9, 11].

4 DESIGN OF MONITORING - OPTIMAL EXPERIMENTAL DESIGN:

The coupled finite element model together with the inversion schemes can subsequently be used to design optimal monitoring systems, or in mathematical terms, to find an optimal experimental design.
Several approaches are suitable to determine an optimal design, i.e. to determine the number, the types and the locations of all sensors. Among these approaches the authors propose the following strategies which seem to be promissing for the application at hand (sorted according to their complexity):

1. testing of existing designs,
2. minimization of variances,
3. minimization of averaged reconstruction errors.

1) Testing of existing designs
In this case one runs a forward simulation with an artificially included damage (e.g. in regions where one expects the highest mechanical stresses). Afterwards, one examinates if by an inversion as described in Section 3 (using a fixed experimental design) it is possible to recover the position of the damage with sufficient accuracy. This strategy is mainly suitable to test existing monitoring systems.

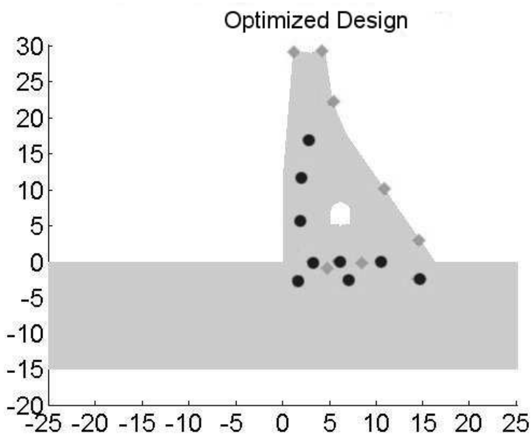

Figure 4. Optimized positions for both the pore water transducers (black points) and object points for geodetic measurements and position of extensometers (gray rhombi along downstream side and inside structure). The results have been obtained by a two field (hydro-mechanical) analysis.

2) Minimization of variances
In this case, parameter variances are minimized by increasing the parameter sensitivies. This can be done by differentiating the forward problem with respect to small changes in the description of the damages. Systematically, the positions of the sensors are shifted, such that they are most sensitive to changes of the damage decription. This automatically leads to small parameter variances, i.e. high confidence in the identification results. Those approaches are mainly suitable for linear and nonlinear well-posed problems. For designs of experiments based on parameter sensitivies, see[3, 2, 7].

3) Minimization of averaged reconstruction errors
As location and shape of damages are generally not known beforehand, our approach intends to minimize reconstruction errors on average. For this purpose one samples the damage, following a uniform distribution over the structure, and runs a series of inverse analyses. It is necessary to store the reconstruction results from which in the quality of each reconstruction can be derived. Now, by a subsequent optimization process one adapts positions of sensors in order that, on average, one can recover the damages as robustly and reliably as possible, see e.g. [5, 6]. These types of designs guarantee both small variances of the parameters and also small biases which are inevitably introduced by the reguarization of the inverse problems.

This third strategy has successfully been applied to a model describing the Fürwigge dam run by the Ruhrverband in Essen. Results of the optimal monitoring design are given in Figure 4 and are already reported in [10]. For all three approaches the design with the highest number of sensors provides naturally the best identification results. This, however, shall be avoided in order to keep the operation costs as low as possible. By including constraints in the different optimization procedures one can penalize a high number of sensors. By this, the trade-off between precise and cost-efficient monitoring is guaranteed. Analysing at the design as proposed in Figure 4 based on minimizing the average reconstruction error reveals, that almost all pore water sensors are located in regions where one expects comparatively high water pressures in the structure. In these regions, a damage would have most severe influences on the fluid field.

5 SUMMARY AND OUTLOOK:

Finite Element models together with powerful inversion schemes allow forward and inverse analyses of dams. It can be shown [9] that in particular by a multifield treatment it is possible to identify damages more reliably due to the correlations of the dominating material parameters in the area of damages than compared to single-field investigations. Optimal designs for a reliable safety monitoring of existing structures can be performed model-based. Such designs support the engineer in his descission how to configure the monitoring setup of a dam. Future work will be devoted to include thermal measurements into the design process, too, and to validate the proposed designs for existing dams and examine for their feasability.

Acknowledgment

The author, Tom Lahmer, gratefully acknowledges his support of the German Research Foundation (DFG) through the Research Training Group 1462.

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