

Towards assimilating InSAR data into a model of a highly anisotropic aquifer system

Sona Salehian Ghamsari*, Tonie Van Dam[†], and Jack S. Hale*

* Institute of Computational Engineering, Department of Engineering, Faculty of Science, Technology, and Medicine, University of Luxembourg.

[†] Department of Geology and Geophysics, College of Mines and Earth Sciences, University of Utah.

Abstract—The flow of water in many aquifers is driven by strong anisotropy created by preferential flow features such as cracks and faults. This anisotropy can be modeled by introducing the anisotropic hydraulic conductivity (AHC) tensor into the equations of poroelasticity. Our overall goal is to assimilate Interferometric Synthetic Aperture Radar (InSAR) remote sensing data into a model of an aquifer system in order to infer information about AHC.

In this work we develop a flexible stochastic prior model of the AHC tensor that respects its underlying symmetry and positive definiteness. Our method for calibrating and constructing a random AHC tensor involves three steps: 1) fitting a Bayesian model with circular von Mises distributions to fracture outcrop data, 2) fitting a Bayesian model of two independent log-normal distributions to hydraulic conductivity estimates, and 3) feeding these stochastic models into an extended version of [1] model to construct random symmetric positive definite tensors using spectral decomposition to encode size and orientation separately.

I. INTRODUCTION

The flow of water in many aquifers is driven by strong anisotropy created by preferential flow features such as cracks and faults. Our overall goal is to assimilate Interferometric Synthetic Aperture Radar (InSAR) remote sensing data into a model of an aquifer system within a Bayesian framework to infer information about anisotropic hydraulic conductivity (AHC).

This research presents a framework for modeling the uncertainty of AHC in fractured aquifers with a focus on remote sensing techniques such as InSAR.

To this end, we propose a stochastic model of AHC that leverages site-specific fracture orientation data. Using a mixture of von Mises distributions, we model the multimodal fracture directional data, accounting for complex directional behavior in the subsurface.

Then, we develop a flexible stochastic prior model of the AHC tensor that respects its underlying symmetry and positive definiteness using spectral decomposition. This decomposition enables a separation of magnitude and direction.

Our method for calibrating and constructing a random model for the AHC tensor involves three main steps: 1) We employ a parametric Bayesian stochastic model, which is informed by site-specific knowledge about AHC extracted from [2] to model the direction of AHC. 2) We apply a Bayesian model of two independent log-normals to existing estimates of the hydraulic conductivity magnitude in the principal directions. 3) We extended the unimodal stochastic model in [1] of symmetric positive definite (SPD) matrices to the multimodal case.

By using this stochastic model for the in-plane hydraulic conductivity tensor, we propagate uncertainty through a -based model of an anisotropic aquifer.

Following this, we conduct a statistical analysis on the resulting Line of Sight (LOS) surface displacements to compute key metrics, allowing us to evaluate the influence of AHC variations on the uncertainty in LOS surface displacements. This approach facilitates a comparative analysis across the three AHC tensor configurations.

The findings indicate that the model shows heightened stochastic sensitivity to directional variations in AHC relative to its magnitude, underscoring the critical role of fracture alignment in influencing aquifer responses.

The overall methodology is demonstrated via a stochastic finite element model of the Anderson Junction aquifer developed in our previous study [3] following the improved aquifer pumping test described in [2].

II. METHODOLOGY

Figure 1 presents a schematic diagram of the methodology and offers a comprehensive overview of the entire workflow. The process begins with collecting data on the uncertainties in both the direction and magnitude of the AHC (steps 1 and 2). We then proceed to fit a Bayesian model for these parameters (steps 3 and 4), followed by generating random AHC tensors (step 6) using a stochastic SPD tensor model (step 5). Finally, we compute the LOS surface displacement outputs using a poroelastic finite element model (step 7) and perform a statistical analysis of the results (step 8).

III. CONCLUSION AND FUTURE

Regenerating rotation angles using a mixture of two von Mises models and employing them to model random SPD tensors was addressed in this study. The focus is on modeling uncertainties in such a way as to have a fine control independently over the scaling and directional attributes of the AHC tensor—given that the material symmetry is fixed.

The surface displacement is stochastically sensitive to the variation of hydraulic conductivity. From the numerical results of the poroelastic finite element model, it is clear that the aquifer model is more stochastically sensitive to orientational randomness than to magnitude randomness of AHC.

We will integrate InSAR technology into our aquifer model. This entails collecting field and remote sensing data to comprehensively assess aquifer discharge and recharge dynamics. InSAR will offer valuable insights into surface displacement and evolving aquifer structures. By solving the inverse problem using multidimensional data, we aim to estimate aquifer properties. These investigations promise to significantly advance our understanding of aquifer behavior, particularly anisotropic hydraulic conductivity.

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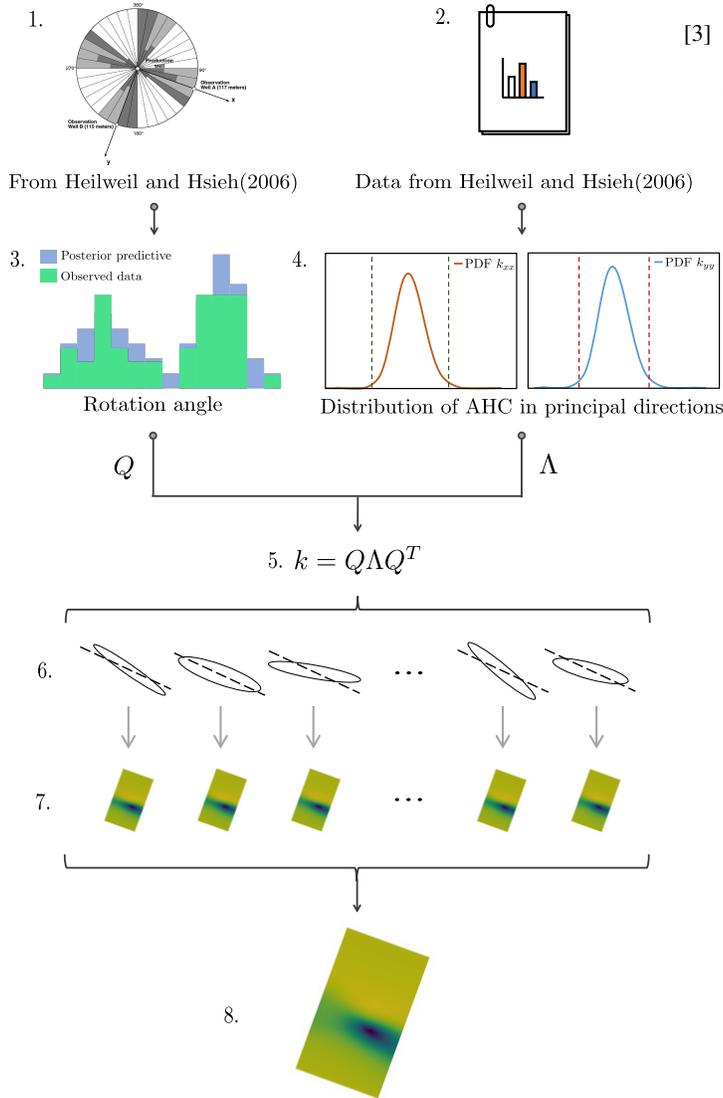


Fig. 1. Schematic diagram of methodology. 1. Extract fracture outcrop data from the rose diagram of the Anderson Junction region. 2. Incorporate reported uncertainties in hydraulic conductivity magnitude in the principal directions. 3. Apply a Bayesian model to determine the rotation angle, accounting for randomness in the AHC direction. 4. Use a Bayesian model to estimate AHC magnitude in the principal directions using a log-normal distribution. 5. Generate a random AHC tensor by incorporating a SPD tensor along with randomness in eigenvalues and eigenvectors. 6. Create thousands of random AHC tensors to serve as inputs for the forward model. 7. Calculate LOS displacement output using a poroelastic finite element model on HPC resources. 8. Conduct statistical analysis of the LOS displacement outputs.