Inversion of fine-scale aquifer permeability structure using distributed strain sensing data

Yi Zhang

1. Geological Carbon Dioxide Storage Technology Research Association, Kyoto, Japan
2. Research Institute of Innovative Technology for the Earth, Kyoto, Japan

１. Introduction

This manuscript is for the introduction of the research results related to a project partially supported by Initiative on Promotion of Supercomputing for Young or Women Researchers, Supercomputing Division, Information Technology Center, The University of Tokyo. For more details, refer to the recent paper published in Journal of Geophysical Research: Solid Earth (Zhang et al., 2021).

2. Research background

Permeability and compressibility are two of the most critical hydraulic parameters in understanding and modeling fluid behavior in subsurface reservoirs. They are often used in the modeling and managing of groundwater or oil/gas resources, optimizing the exploitation or utilization of pore space for water, oil, or gas storages (for example, CO2 sequestration in saline aquifer), and modeling pressure or contaminant migration.

Numerous attempts have been conducted to obtain the in-situ permeability or compressibility of aquifers. One primary difficulty in obtaining hydraulic parameters is the measurement of in situ formation pressure or hydraulic head for multilayer formation. It is impossible to measure the hydraulic head at each depth location of each layer in a well (and not practical in many wells). The measurement of in situ formation pressure also has an intrinsic problem—it is not engineering-easy to embed many pressure sensors in the formation (along the wellbore).

Recently, the technology of fiber-optic distributed strain sensing (DSS) has been rapidly developed and utilized in geotechnical and geophysical studies. Unlike pressure sensors, an optical fiber cable can be placed between the well casing and the sedimentary formation by cement grouting with fewer challenges (though still with some engineering difficulties). The DSS technology can utilize the entire fiber cable as many sensors in a distributed fashion for the measurement of local formation strain. Regarding the purpose of reservoir formation evaluation, one problem is that the measured physical property is strain instead of pore pressure. Physically, the pore pressure induced strain is strongly associated to the change in the pore pressure according to the Biot’s poroelastic theory. Importantly, the strain change can bring the information of permeability and compressibility. However, the mechanical effect may be also included in the recorded strain.

To clearly evaluate effects from pore pressure induced and mechanical deformations, **a coupled geomchanical deformation model** should be considered for inversely estimating permeability and compressibility. Here we present an introduction of **the method that using the DSS data to inversely estimate the fine-scale hydraulic parameters** through a coupled model. The DSS data were acquired in a field aquifer pumping test. In the study, we used **Oakbridge-CX Supercomputer System** to accelerate the computation in parallel.

3. The poroelastic coupled forward model

Poroelastic theory describes the ubiquitous mechanical interactions of porous media (for example, geological sediments) and fluid within it on each other under stress. The interactions are also called hydromechanical coupling. There are two important works in the history of development of poroelastic theory. Terzaghi first developed the notion of effective stress, describing the portion of the stress tending to compress the porous matrix is equal to the applied stress subtract the pore fluid pressure, in attempting to explain time dependence of soil and sediment consolidation after loading. In other words, the pore fluid pressure bears part of the load. Terzaghi also connected the concept to explain the dissipation of consolidation induced excess fluid pressure into pressure diffusion equation, where both effects of permeability and compressibility of rock are considered.

Later, Biot put the deformation of porous media under the more rigorous framework of elastic theory and formulated the governing equations of poroelasticity considering full coupled three-dimensional fluid flow and deformation. Since then, poroelastic theory has been widely used in many subjects of research in earth science. The main equations of the theory needed in this study are outlined below.

Equations of deformation. By analogy with linear elastic theory, the poroelastic constitutive equations can be expressed as

$$\sigma_{ij} = 2G\varepsilon_{ij} + 2G\frac{\upsilon}{1-2\upsilon}\varepsilon_{kk}\delta_{ij} + \alpha p\delta_{ij} \quad (1)$$

where G is shear modulus, υ is Poisson’s ratio, σ is stress, ε is the strain, p is pressure, α is Biot’s coefficient, ij are the indexes of direction, δ_{ij} is the Kronecker delta (is zero when $i \neq j$ and one when $i = j$), $\varepsilon_{\mathrm{kk}}$ is volume strain. The coupling between pore fluid pressure and matrix deformation is from the last term, describing the contribution of pore pressure to stress.

Equations of fluid flow. The fluid flow equation is based on mass conservation, which is stated as

$$\frac{\partial(\rho\phi)}{\partial t} + \nabla\cdot(\rho q) = Q \quad (2)$$

where ρ is fluid density, ϕ is porosity, t is time, Q is the source or sink and q

is the Darcy flux, can be denoted as

$$q = -\frac{k}{\mu}(\nabla P + \rho g \nabla z) \quad (3)$$

where k is rock permeability, μ is fluid dynamic viscosity, g is gravitational acceleration, and z is the elevation. For that the matrix deformation involves the fluid content change due to the change in porosity, which is associated with the compressibility of rock matrix and fluid, the storage coefficient S is introduced into the fluid flow equation as

$$\rho S \frac{\partial p}{\partial t} + \nabla \cdot (\rho q) = Q - \rho \alpha \frac{\varepsilon_{kk}}{\partial t} \quad (4)$$

where $S = \phi C_f + C_\alpha$, with C_f is the fluid compressibility and C_α is the formation compressibility.

In hydrogeological study, permeability k is often represented by hydraulic conductivity $K = k\rho g/\mu$ and pressure P is represented by hydraulic head $H = P/\rho g$. The equations used for aquifer well testing can be viewed as the simplified form of poroelastic theory, i.e., with less consideration in the tensorial elastic deformation but only the consolidation due to pressure change is considered.

As shown by above equations, by the hydromechanical coupling, permeability and compressibility together control the evolution of pore pressure and strain. Inversely, by monitoring strain changes of an aquifer, the hydromechanical coupling provides an opportunity to characterize the two hydraulic parameters.

The open-source code MOOSE is used to solve the forward poroelastic or geomechanical model. MOOSE is a multiphysics FEM framework with the PETSc non-linear solver package and libmesh to provide the finite element discretization. We use the mumps SMP preconditioner and Newton solver with automatic scaling.

The forward model is set for a field aquifer pumping test. We construct an axisymmetric cylinder 2D (RZ2D) model for the modeling (Figure 1). To avoid the boundary effect, we set a much larger modeling domain (500 m×500 m). We use dense Cartesian mesh gridding (10 m×1 m) within the ROI and near-by regions and sparse gridding at other regions. The water extraction interval is between 161~240 m (80 m thick). A water extraction condition is set at the left boundary with time-dependent flux. We assume that the background stress-strain field has reached the equilibrium state and only consider the changes caused by water pumping.

In the model, Young's modulus E= 0.29, porosity ϕ = 0.43, Biot's coefficient α = 1, and water compressibility C_f = 4.5×10^{-10} 1/Pa are set everywhere. Permeability and compressibility are assigned at each grid with length interval of 1 m within the ROI along vertical direction. An observation well is located at 175.1 m away from the pumping well. All components of the stress and strain under the coordinate can be obtained by forward modeling. Here we only consider the vertical strain component, which is related to the DSS measurement.

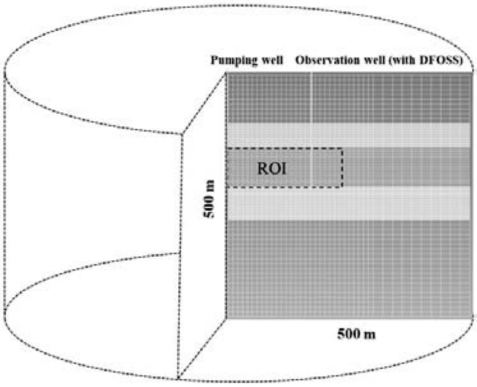

Figure 1. Schematic geometry of the forward model(Zhang et al., 2021).

4. The inverse model

We formulate the inverse problem is by minimizing the difference between the true and inferred fields of the two hydraulic parameters. There are totally 80×2 unknown parameters (permeability and compressibility) within the 80 m thickness formation. We deploy a nonlinear least-squares method to iterate and search the best solution for the unknowns. The least-squares method with Trust Region Reflective minimization algorithm is realized using the optimization module in Scipy library. For the forward modeling is relatively slow (~2 minute/cpu), the computation of Jacobian matrix is quite time consuming for this high-dimensional problem. We use Oakbridge-CX Supercomputer System to perform the computation in parallel. Because the two types of unknowns are significant different in the numerical ranges, we scale them to a similar range to reduce the inversion difficulty. We do not use any statistical methods with priors in our inverse modelling as commonly utilized in inverse studies.

5. Results

The numerical synthetic studies without and with noise are first conducted to investigate the feasibility of the proposed method for inversely estimating hydraulic parameters using DSS data. In the synthetic model, assumed permeability and compressibility values are used. The synthetic transient strain records are obtained by running the forward modeling once. To consider noise effect, we add Gaussian random noise with a standard deviation of 0.5, 2 and 5 με. We then set permeability and compressibility were as unknowns. The assumed permeability and compressibility are arbitrarily generated using a Gaussian correlation distribution model with a correlation length of 1 m. The spikes (e.g. 1 m) in the distribution are used to understand the spatial resolution of the inverse model. In the inversion, we find that an optimal solution for simultaneously estimating both permeability and compressibility can be obtained through inverse modeling when strain data are free from noise. Figure

2 show that most parts of the permeability structure can be recovered except some local parts with small values, and the estimated compressibility profile almost overlaps the assumed distribution. For the spatially dense coverage of strain records, even the values for very narrow spikes can be correctly estimated. Most of the permeability and compressibility structures can be inversely estimated with errors <2%. The errors in low-permeability parts can be understood from the low sensitivity of the permeability values to the objective function, which makes it difficult for the gradient-based optimization algorithm to find the global minimum.

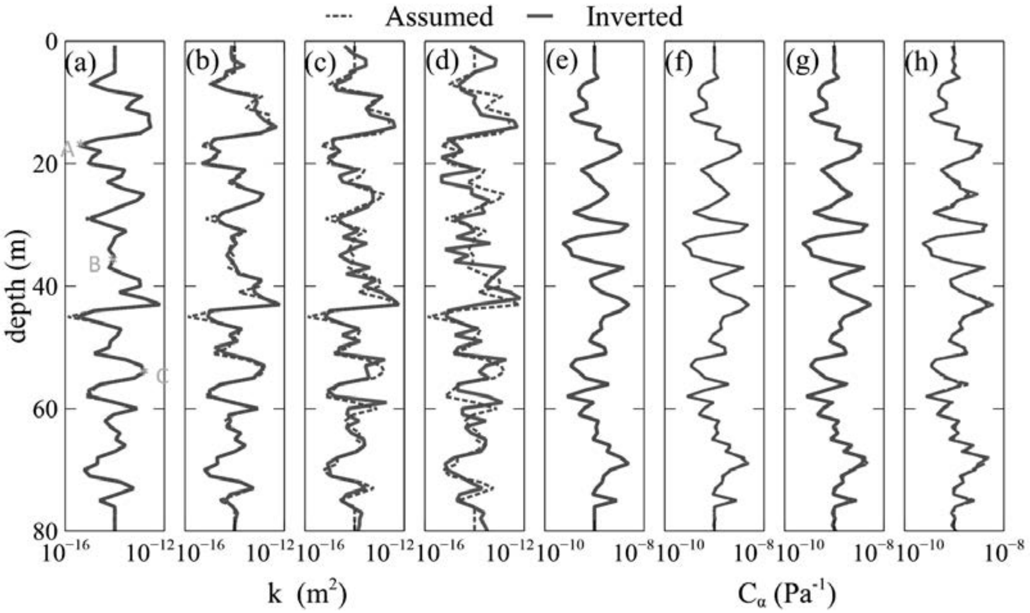

Figure 2. (a-d) Inversely calculated permeability and (e-h) compressibility compared with the assumed input values in the synthetic model. (Zhang et al., 2021).

If the strain data contain noise (e.g. $\sigma = 0.5\ \mu\varepsilon$), it turns difficult to obtain the global optimal solution at some locations using the gradient-based algorithm (Figure 2c and d). Perhaps due to the integrated effect of parameter crosstalk and noise, the solution may represent local minimums near the global minimum and cannot further reach the global one. The influence becomes even significant with higher noise level (e.g. 2 and 5 $\mu\varepsilon$ in Figure 2e and f). Regardless, overall, the magnitude and main structure of hydraulic parameters can be estimated. This demonstrates the feasibility of the proposed inversion method.

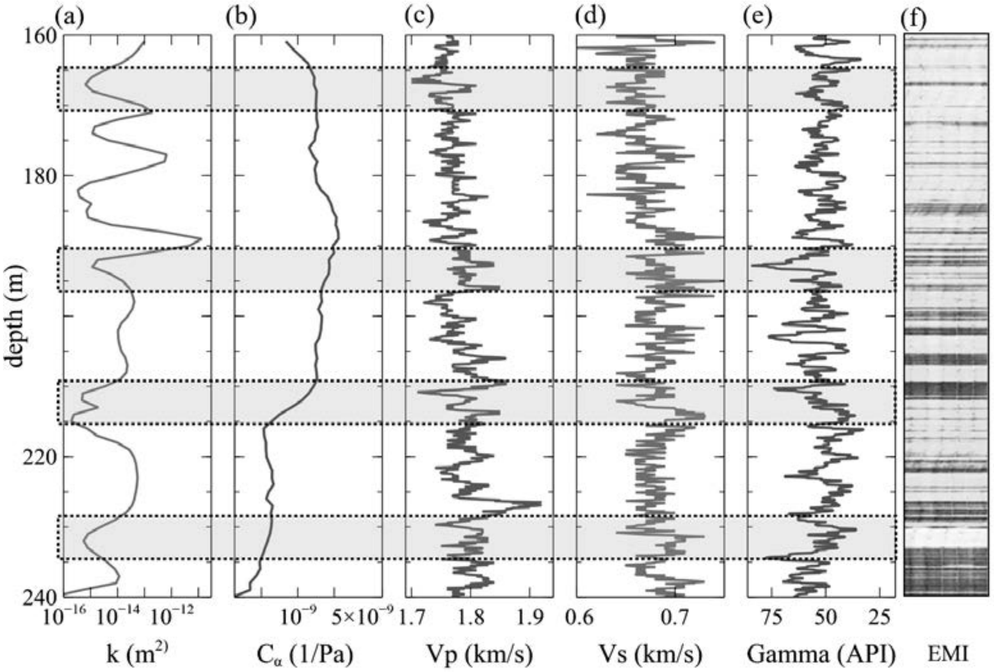

Figure 3. Inversely calculated (a) permeability and (b) compressibility, with well logs of (c) the compressive wave velocity, (d) the shear wave velocity, (e) the gamma ray and (f) the EMI of the well showing the sandstone-mudstone lithological alternation structure. (Zhang et al., 2021).

The same method is used for the field study. We use field monitoring records of strain acquired by DSS. Figure 3a and b show the inversely estimated permeability and compressibility profiles. The estimated permeability ranges from approximately 0.1 mD to 1 D in different parts of the profile. There are several units with higher permeability (>20 mD). The intervals with high and low permeability (near 190 and 215 m, respectively) are consistent with the strain peak and trough. Although there are some inconsistent parts, the depth intervals with higher permeability values generally point to layers that mainly consist of sandstones, as shown by the Electrical Micro Imaging (EMI). It seems that some of the low permeability intervals can be also matched to some featured spikes in the well logs (Vp, Vs and gamma ray). Some inconsistent parts between the estimated permeability structure and EMI can be attributed to the fact that the lithological changes may only partially reflect the permeability structure.

The estimated compressibility generally shows a pattern like the spatial strain distribution; however, the changes are smaller. As strain changes, two parts (from 160 to 215 m and from 215 to 240 m) in the compressibility profile can be distinguished. It seems that the corresponding changes are also distinguishable from the Vp and Vs well logs.

Overall, the permeability and compressibility determine the strain pattern. Some local strain fluctuations (e.g. peaks or troughs) are predominated by the permeability structure. For a multi-layer formation, the overall changes in the aquifer pressure and deformation are partitioned to the sub-layers. Layers with high permeability and compressibility can easily develop greater deformation and thus dominate the deformation pattern. Hydromechanically, the lithological layers may be grouped into several units. The inversely estimated hydraulic parameters can be generally and reasonably interpreted from the geological information.

6. Conclusions

We show that parameter estimation using DSS data can provide detailed information of formation properties in the vertical direction. This gives a new method for formation characterization in which previously developed methods focus the usage of pressure. The information is thought to be useful for understanding formation pressure communication, numerical reservoir modeling, as well as for designing proper fluid injection or extraction strategy in underground fluid storage projects. In the inversion method, the usage of Oakbridge-CX Supercomputer System was extremely helpful in the acceleration of the Jacobian matrix computation, making the inversion feasible and faster.

Acknowledgements

This paper is based on results obtained from a project (JPNP18006) commissioned by the New Energy and Industrial Technology Development Organization (NEDO) and the Ministry of Economy, Trade and Industry (METI) of Japan. This research is partially supported by Initiative on Promotion of Supercomputing for Young or Women Researchers, Supercomputing Division, Information Technology Center, The University of Tokyo (for the usage of supercomputer system).

References

Zhang, Y., Lei, X., Hashimoto, T., & Xue, Z. (2021). Towards retrieving distributed aquifer hydraulic parameters from distributed strain sensing. Journal of Geophysical Research: Solid Earth, e2020JB020056. https://doi.org/10.1029/2020JB020056