IDENTIFICATION OF SOME CHEMOPOROELASTIC PARAMETERS OF A REACTIVE SHALE FROM EXPERIMENTAL DATA

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Summary This paper is concerned with the experimental identification of some chemoporoelastic parameters of a chemically reactive shale from data obtained in pore pressure transmission-chemical potential tests. The parameter identification is carried out by matching the observed pressure response with a theoretical solution of the experiment. This solution is obtained within the framework of Biot theory of poroelasticity, extended to include physico-chemical interactions.

EXPERIMENTAL ISSUES

The so-called pore pressure transmission-chemical potential test is used in the petroleum industry to evaluate the osmotic membrane efficiency of a shale in contact with a drilling fluid [10, 8]. It is motivated by the need to assess the capacity of improving the stability of a borehole in a chemically active shale by increasing the salt concentration of the drilling fluid [4, 5, 9]. In this test, a saturated cylindrical sample of shale is subjected sequentially to a hydraulic and a chemical loading at the upstream end of the sample ($z = 0$), with the downstream end ($z = L$) connected to a closed reservoir. The hydraulic loading consists of applying a pressure p_m at $z = 0$ with the solution used during the saturation phase. In the chemical loading the upstream end is placed in contact with a solution of a different salt concentration but at the same hydraulic pressure p_m.
This experimental program was conducted with a two-fold objective: (i) check the relevance of the theory by its ability to be consistent with the observations; (ii) provide data to allow identification of the parameters of the model.

Experimental Setup

A series of experiments on Pierre II shale (a shale from the Rocky Mountains in Colorado) has been carried out with the Membrane Efficiency Screening Equipment (MESE) in the laboratory of CSIRO Petroleum, Australia [11]. This apparatus consists of six test cells with a confining pressure and pore pressure capacity of 35 MPa and 20 MPa, respectively. There is a fluid cylinder for each test cell. Up to six different solutions can be tested at any one time and the test on each cell may be started and terminated independently from the others. Six different samples of 25.4 mm diameter and length up to 25 mm can be tested at the same time in this device. For each cell, both upstream and downstream pressures are recorded with the help of a computerized data acquisition system using a dedicated program built in the Labview environment. This program also controls the loading and confining pumps.

Specific Test Conditions

Six samples of Pierre II shale were tested in the six cells of the MESE; four of them were 13 mm long and two were 25 mm long samples. The applied confining pressure was $p_c = 20$ MPa. The saturation stage was conducted under a pressure $p_s = 10$ MPa applied at the bottom end (upstream) of the sample using a simulated Pierre II shale pore fluid [6]. The pressure transmission stage (hydraulic loading) was conducted under a pressure $p_m = 15$ MPa applied at the bottom end of the sample using the same solution as previously. Eventually, the chemical potential stage (chemical loading) was conducted under the same pressure p_m but with a highly concentrated solution of either potassium or sodium chloride.

PARAMETERS IDENTIFICATION

The aim is now to identify the unknown chemoporoelastic parameters, characterizing a shale-drilling fluid system, involved in the theoretical solution of the problem. In other words, we want to identify the parameters $\mathbf{c}$ of the model from experimental measurements $\mathbf{y}$ for given loadings $\mathbf{F}$. This process may be performed by using only a few characteristics of the system response curves such as extrema and position of these extrema, or by applying an iterative minimization procedure, using the whole set of experimental data [3].

Minimization Procedure

The identification of parameters from experimental data is a typical inverse problem. Generally, the direct problem is solved under the form

$$\mathcal{L}\left(\mathbf{u}\left(\mathbf{c}\right),\mathbf{c}\right)=\mathbf{F} \tag{1}$$

where $\mathcal{L}$ is a partial differential operator and $\mathbf{u}$ is the solution of the direct problem, the experimental measurements $\mathbf{y}$ being, in a sense, a discrete sampling of $\mathbf{u}$. Note that the parameters in (1) appear implicitly in the formulation of the direct problem. There is an explicit way to link the parameters of the direct problem $\mathbf{c}$ to the experimental measurements

$\mathbf{y}$ through a matrix operator $\mathbf{A}$ as follows

$$\begin{aligned} \mathbf{A} \quad : \quad & \mathcal{C}_{ad} \rightarrow \mathcal{Y} \\ & \mathbf{c} \rightarrow \mathbf{y} = \mathbf{A}(\mathbf{c}) \end{aligned} \tag{2}$$

where $\mathcal{C}_{ad}$ is the space of admissible parameters (corresponding to the unknowns of the inverse problem); $\mathcal{Y}$ denotes the space of measurements. The inverse problem may then be formulated as

$$\text{knowing } \; y \in \mathcal{Y}, \; \text{find } \mathbf{c} \in \mathcal{C}_{ad} \; \text{ such that } \; \mathbf{A}(\mathbf{c}) = \mathbf{y} \tag{3}$$

In this problem, $\mathbf{A}$ is known explicitly and is non-linear with respect to the parameters $\mathbf{c}$. Typically, when $\mathbf{A}$ is non-linear, the problem of identification becomes a problem of iterative minimization of a cost functional $\mathcal{J}(\mathbf{c})$ quantifying the distance between the measurements $\mathbf{y}$ and the predictions $\mathbf{A}(\mathbf{c})$ [1, 2]

$$\begin{aligned} & \min_{\mathbf{c} \in \mathcal{C}_{ad}} \mathcal{J}(\mathbf{c}) \\ \mathcal{J}(\mathbf{c}) \quad = \quad & \|\mathbf{A}(\mathbf{c}) - \mathbf{y}\| \end{aligned} \tag{4}$$

The form of the functional is a matter of choice; however, most of the time a least square procedure is used, i.e.,

$$\mathcal{J}(\mathbf{c}) = \|\mathbf{A}(\mathbf{c}) - \mathbf{y}\|^2 \tag{5}$$

Moreover, the functional form chosen may not be convex with respect to the parameters $\mathbf{c}$. Actually, the convexity and the geometry of the functional is partly related to the unicity of the inverse problem solution (ill-posedness. of the inverse problem).

Sensitivity Analysis

An analysis of the sensitivity of the theoretical solution to the parameters is carried out along with this iterative minimization procedure. A mathematical way to quantify the sensitivity of a solution $\mathbf{u}$ to a given parameter c_i is

$$\delta_{c_i} \mathbf{u} = c_i \frac{\mathrm{d}\mathbf{u}}{\mathrm{d}c_i} \tag{6}$$

The critical parameters are then brought out among all the parameters of the solution, i.e., the transport parameters which are the hydraulic diffusivity D_h, the apparent chemical diffusivity D_c and, above all, the chemical reflection coefficient $\mathcal{R}$ (membrane efficiency) [7]. The robustness of the algorithm is also estimated through several numerical tests on simulated data.

Eventually, a more pragmatic approach is deduced from this analysis, e.g., the chemical reflection coefficient is directly correlated with the pressure drop during the chemical loading. Coherence of the results obtained with both methods is shown.

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