

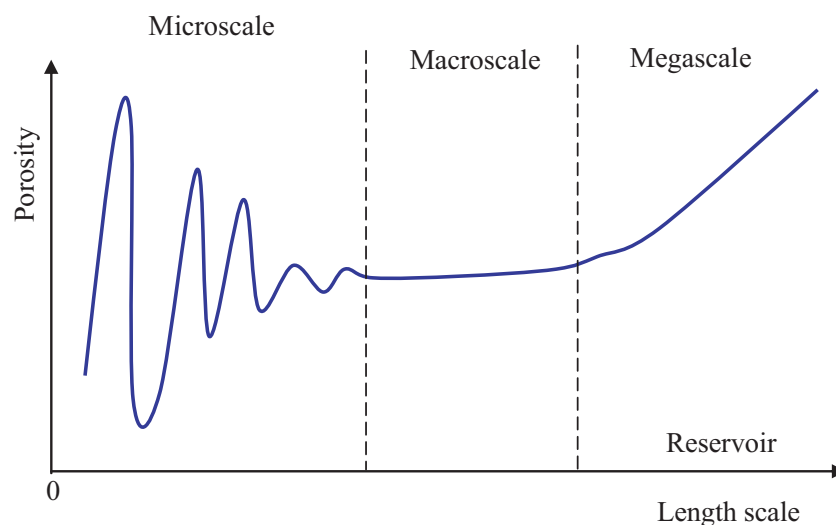
## Iterative Coupling Between Geomechanical Deformation and Reservoir Flow

With the help of geomechanics, many physical phenomena can be explained (e.g., reservoir compaction and subsidence, casing failure, or pore collapse). Several methods for coupling geomechanics to fluid flow in the reservoir have been proposed. The iterative-coupled method has proved effective.

### Introduction

The coupling of a reservoir simulator to a geomechanics module has wide application in petroleum production. With the aid of geomechanics, many phenomena can be explained, such as compaction, subsidence, wellbore stability, and pore collapse, as well as loss and gain in production. In a traditional reservoir simulator, subsidence can be estimated by a simple formula without knowing the geomechanical response. In some problems, such as primary production and linear materials, the subsidence computed by a reservoir simulator alone may give results that are comparable to the coupled solutions. Yet, when nonlinear materials are used, the results obtained with a conventional simulator will be much different from those obtained with a flow/geomechanics-coupled simulator. The main reason is that in a coupled simulator, the flow is affected strongly by the stress and strain through the porosity. However, in a conventional simulator, this stress dependence is

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**Fig. 1—Variation of porosity in length scales.**

ignored. Therefore, if a stress-sensitive reservoir is considered, the solution obtained from a conventional simulator cannot deliver expected results. In addition, for thermal problems, a conventional thermal simulator does not properly account for thermal stresses, the effects of which can be significant. The coupling between reservoir flow and geomechanical deformation can appear in various forms.

- The fully coupled approach is the tightest coupling because deformation and reservoir pressure and temperature are solved simultaneously.

- The iterative-coupled approach is less tight than the full-coupling method because the geomechanics calculations are performed one step after the reservoir-flow calculations.

- The explicit-coupled approach is considered a special case of the iterative-coupled approach. The information from a reservoir simulator is sent to a geomechanics module, but the calculations in the geomechanics module

are not fed back to the reservoir simulator. Reservoir flow is not affected by the geomechanics responses calculated by the geomechanics module.

The full-length paper details basic equations for reservoir flow and solid deformation to show how variables in those equations are coupled. Only the iterative-coupled approach and explicit-coupled approach are discussed. Examples related to different constitutive models such as an elastoplastic model, a plastic-cap model, and a pseudodilation/recompaction model are used to demonstrate the effects of such coupling.

### Basic Flow Equations

The basic equations for fluid flow in a porous medium consist of the equation of mass conservation, the equation of energy conservation, Darcy's law, and equations of state depicting the fluid characteristics. A continuum approach was used to develop these equations.

*For a limited time, the full-length paper is available free to SPE members at [www.spe.org/jpt](http://www.spe.org/jpt). The paper has not been peer reviewed.*

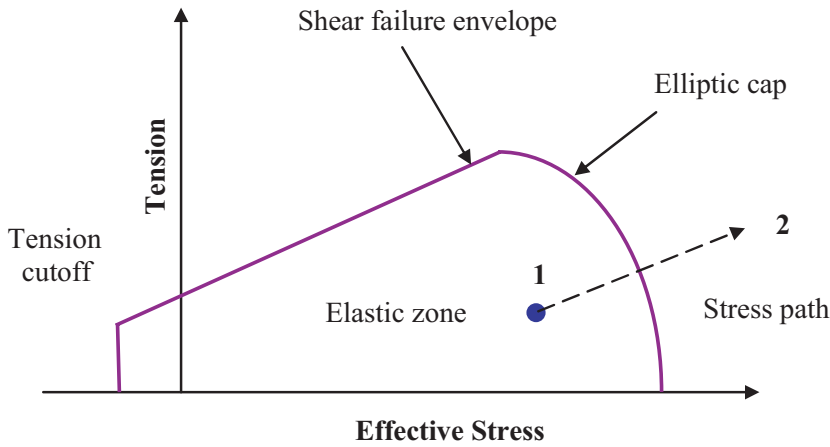


Fig. 2—Example-2 plastic-cap model.

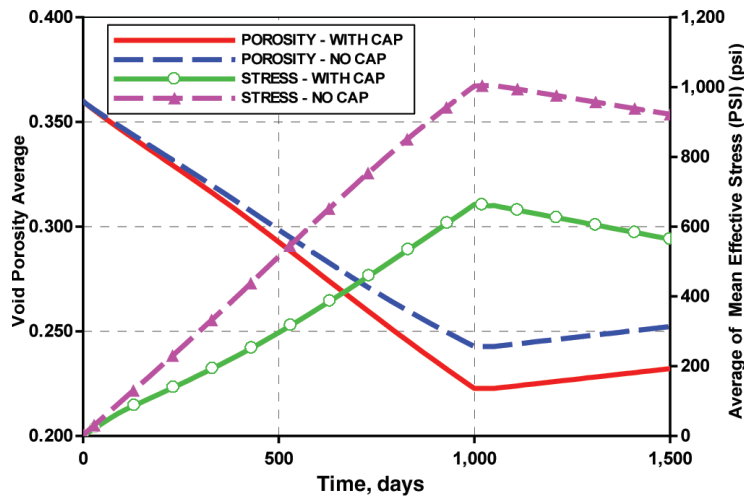


Fig. 3—Example-2 average porosity and mean effective stress.

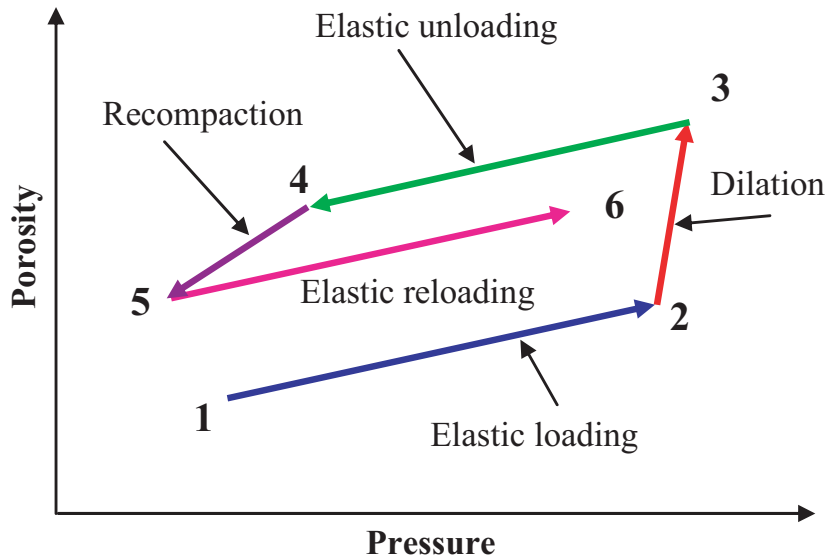


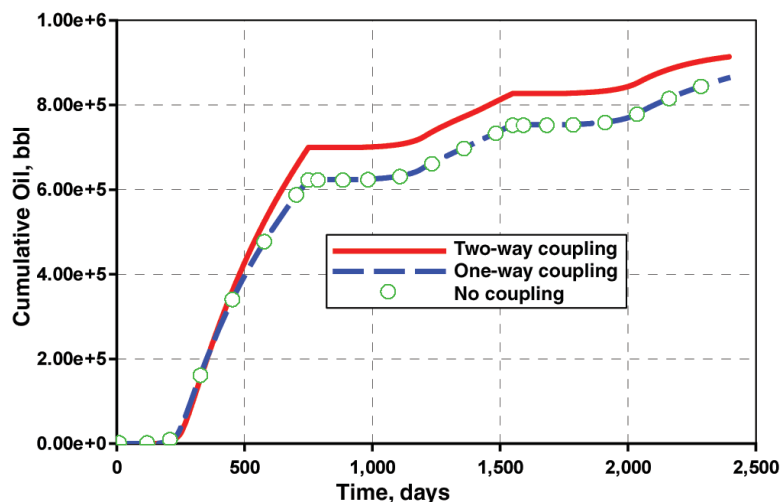
Fig. 4—Example-3 empirical dilation/recompaction model.

The microscopic scale is defined as the length scale at which the molecular structure of matter is disregarded such that it may be conceptualized as having no gaps or empty space. Functions describing the system at this scale are continuous and have continuous derivatives. The megascopic scale is the largest and has a length scale on the order of the system (reservoir) dimensions. At the middle (macroscopic) scale, different phases in a porous medium are described as overlapping continua, and each phase occupies a fraction of space at a point. Consider the porosity averaged over these different scales as shown in Fig. 1. In the macroscale region, the average porosity remains constant, whereas in the microscale region, the average porosity fluctuates because of pore structure, and in the megascale region, the average porosity varies because of heterogeneities in the porous medium. Among these three scales, both reservoir simulation and continuum mechanics commonly use the macroscopic scale to describe the continuous distribution of constituents in the control space being investigated. At this scale, a quantity is defined as the average of its microscopic quantity over an integration volume, which is also called the representative-element volume. This volume corresponds closely, if not exactly, to the reservoir-simulation concept of grid cells that results from the spatial discretization of fluid-flow equations. For example, the porosity for a grid cell is single value that is assumed to apply to the entire cell.

For simplicity, the basic equations in this paper are developed for a single-component, single-phase flow system. However, extending the flow system to multiple components and phases is straightforward and does not change the discussions.

#### Applications

**Example 1: Elastoplastic Drucker-Prager Model.** In this test case, a 3D 13×18×5 radial grid was used for simulating a single-well cycling process of a reservoir. The prescribed boundary was constrained at the bottom and around its horizontal outer radius. The injection/production well was at the center of the reservoir. Saturated steam at 450°F was injected at 1,000 B/D cold-water equivalent for the first 100 days. Then, the injector was closed to allow the reservoir to soak for 20 days. At



**Fig. 5—Example 3 cumulative oil production.**

120 days, the producer was opened at the rate of 1,000 BOPD for 500 days. The problem is divided into linear and nonlinear cases.

In the linear case, the porous medium was assumed to be linear thermoelastic. The Young's modulus and Poisson's ratio were 39,400 psi and 0.3, respectively. The linear thermal expansion for solid rock was  $18.28 \text{ E}-6/^{\circ}\text{F}$ .

In the nonlinear case, the constitutive model was the thermoelastoplastic Drucker-Prager model. In addition to the geomechanical properties given in the linear case, the cohesion and friction angle had values of zero and  $30^{\circ}$ , respectively.

The iterative-coupled approach (two-way coupling) was used in the calculations. The pressure in the reservoir increased with steam injection for the first 100 days. This pressure increase led to a decrease of the mean effective stress in the solid rock. When the stress path intercepted the shear-failure envelope in the thermoelastic model, plastic deformation occurred. Therefore, in this case, the total strain was the sum of elastic strain and plastic strain, which caused the volume of a plastic gridblock to dilate more than the volume of a gridblock without plastic deformation. Consequently, the heave for the plastic gridblock was larger than the heave for a gridblock without plastic deformation.

#### Example 2: Elastoplastic-Cap Model.

A Cartesian grid was used for a primary-production process in an isothermal reservoir. The well was at the center of the reservoir modeled with

an  $11 \times 11 \times 5$  grid. The material was assumed to obey the associated elastoplastic-cap model. The purpose of this test case was to illustrate how the plastic-cap model affects the porosity. Without the plastic cap, the material might behave elastically under compression (increasing the effective-stress tensor) if the stress path did not intercept the shear-failure envelope. The plastic cap put a boundary on the elastic zone that the stress path could not cross. In Fig. 2, if the stress path (Line 1–2) intercepted the cap, plastic behavior would occur even if the stress was in the compressive zone. As shown in Fig. 3, the average mean effective stress in the case without the plastic cap was higher than in the case with the plastic cap. However, the porosity in the latter case was smaller than the porosity in the former case. Therefore, the porosity in the case with the plastic cap was squeezed more when plastic behavior occurred.

#### Example 3: Pseudodilation/Recompaction Model.

The purpose of this test case was to compare a pseudodilation/recompaction model and an empirical dilation/recompaction model in a reservoir simulator. The reservoir was covered with an  $11 \times 11 \times 5$  Cartesian grid. In the pseudodilation/recompaction model, Young's modulus changed at a threshold pressure, which was defined by the user. Depending on the material state of a gridblock, its Young's modulus was modified to suit the material behavior. In this example, no-coupling, one-way-coupling, and two-way-coupling approaches were

compared. The term of no coupling was used to indicate that the reservoir simulator runs without a geomechanics module. For one-way coupling and two-way coupling, the Young's modulus used for each zone was 50,000 psia for the elastic zone, 10,000 psia for the dilation zone when pressure was greater than 1,536 psia, and 20,000 psia for the recompaction zone when pressure was less than 500 psia.

In a dilation/recompaction model, a full process normally was divided into several stages as shown in Fig. 4.

- Elastic-loading path (Line 1–2): The pressure increased when fluid was injected into a reservoir. The path was limited from a starting point in an elastic state to a point where plastic behavior begins.

- Dilation path (Line 2–3): If the pressure continued to rise in the reservoir, the material behaved in a plastic manner.

- Elastic-unloading path (Line 3–4): The pressure was reduced when the injector was shut in and the producer was opened. The material behaved elastically.

- Recompaction path (Line 4–5): If the pressure continued to decrease because of production, the material would behave plastically.

- Elastic-reloading path (Line 5–6): When the producer was shut in and the injector was opened, the pressure began to increase. The material behaved elastically. If the pressure continued increasing, the material would go along the dilation path (Line 2–3).

As Fig. 5 shows, the cumulative oil production in the case of one-way coupling and no-coupling was the same; however, it was higher in the case of two-way coupling. The main difference between these cumulative oil productions was a result of the feedback of geomechanics information in the two-way-coupling run.

#### Conclusions

The one-way coupling shows displacement calculation that is comparable to the one obtained with two-way coupling, while with the no-coupling approach, the displacement prediction is quite different. This example also illustrates that rigorous geomechanics calculations of subsidence are performed without the constraint of feeding back the information to the reservoir simulator. JPT