LAND SURFACE SUBSIDENCE ASSOCIATED WITH GEOTHERMAL ENERGY PRODUCTION

S. K. Garg
Systems, Science and Software
P.O. Box 1620
La Jolla, California 92038

Land subsidence, sometimes observed during oil field production, is potentially a serious problem in geothermal energy production, particularly of liquid-dominated hydrothermal and geopressured fields. In the Imperial Valley--one of the most promising liquid-dominated geothermal regions in the United States--extensive subsidence could damage irrigation canals and other surface structures. Even if the subsidence is confined to the production area, special measures may be necessary to protect the geothermal extraction and electrical generating equipment. Subsidence is, in general, caused by the compaction of the semi-consolidated and unconsolidated strata of the reservoir as the effective overburden stress is increased due to fluid withdrawal. In some oilfields (e.g., the Wilmington oil field in the Los Angeles basin), injection of water into the formation has been successfully employed to reduce subsidence. Subsidence is potentially a more serious threat in geothermal production due to the much larger volume of fluid required to produce a given amount of energy. Fluid reinjection, while undoubtedly useful, is not a universal remedy to subsidence, for several reasons. First, while some of the compaction is elastic and may be recovered, it is well known that irreversible pore collapse (permanent deformation) also accompanies fluid withdrawal. Second, due to the nature of the electrical generating process, only a fraction of the produced fluids will be available for reinjection; the reinjection fluid may, of course, be augmented by surface water to make up the volume deficit. Third, reinjection (especially of concentrated brines which are characteristic of some Imperial Valley geothermal anomalies) may not always be practical at (or near) the same horizontal and vertical location as production. Reinjection at a sufficient lateral distance from the producing well may result in uneven surface displacement. Furthermore, subsurface fluid injection may, by increasing pore pressures, tend to increase levels of seismic activity. Many geothermal reservoirs (including those in the Imperial Valley and the geopressured systems in the Gulf Coast) lie in regions of extensive faulting--thus, the danger of earthquake triggering cannot be discounted.

MATHEMATICAL MODEL

All of the geohydrological effects described above involve mechanical interactions between the rock and fluid components. The theoretical model, developed within the framework of the Theory of Interacting Continua, describes the thermomechanical response of the rock and fluid (water and/or steam) composite material in terms of the isolated components. The stress-strain equations for the rock matrix are coupled with the diffusion equations for the fluid. The microscale details of the pore/fracture network in the rock are ignored, but the fluid pressures and the stress field in the rock matrix are permitted to assume distinct values within each computational region for the composite. The fluid flow equations and their solution is discussed elsewhere (Pritchett, ~~et al.~~, 1975). In this paper, we shall confine our attention to rock response under a given fluid pressure history.

Assuming that (1) the rock matrix undergoes only small deformations and (2) the reservoir behaves in a quasi-static manner during production/injection, the equation expressing momentum balance for the rock matrix can be written as follows:

$$-\nabla[(1-\phi)P_s + \phi P] + \text{div}\, \underset{\sim}{S} + [(1-\phi)\rho_s + \phi(1-S)\rho_\ell + \phi S\rho_v]\, \underline{g} = 0 \qquad (1)$$

where

$\underline{g}$ = Acceleration due to gravity

p = Fluid pressure

P_s = Solid pressure

S = Relative vapor volume $[=V_v/(V_v + V_\ell)]$.

$\underset{\sim}{S}$ = Deviatoric stress tensor for porous rock.

$V_v(V_\ell)$ = Vapor (liquid) volume.

ρ_i = Density (i=s, solid; i=ℓ, liquid; i=v, vapor)

ϕ = Porosity

It is necessary to complement Eq. (1) with suitable constitutive relations for the rock matrix.

The bulk strain-rate tensor for rock $\dot{\underset{\sim}{\varepsilon}}$ is given by:

$$\dot{\underset{\sim}{\varepsilon}} = \frac{1}{2}[\nabla \underline{v}_s + (\nabla \underline{v}_s)^t] = \frac{\dot{\varepsilon}}{3}\underset{\sim}{I} + \dot{\underset{\sim}{e}} \qquad (2)$$

where $\dot{\underset{\sim}{e}}$ denotes the deviatoric part of the strain-rate tensor. Bulk volumetric strain ε is related to the rock grain (or effective) volumetric strain ε^e through the relation:

$$\varepsilon^e = \frac{\rho_{os}}{\rho_s} - 1 = \left(\frac{1-\phi}{1-\phi_o}\right)(1+\varepsilon) - 1 \qquad (3)$$

The rock grain may be assumed to be a linear thermoelastic material over the range of temperatures and pressures encountered in geothermal reservoirs.

$$P_s = -K_s \ (\epsilon^e - 3\ \eta_s\ T_s) \qquad (4)$$

where K_s (η_s) denotes the bulk modulus (coefficient of linear thermal expansion) for the rock grain. Additionally, we will postulate that the shear stresses $\underset{\sim}{S}$ are linearly related to shear strains $\underset{\sim}{e}$ through Hooke's law:

$$\underset{\sim}{S} = 2\ \mu_p\ \underset{\sim}{e} \qquad (5)$$

where μ_p is the shear modulus of the porous rock.

Posority ϕ depends in a complex manner on the current state of stress ($\underset{\sim}{\sigma}^s$, P), stress history, temperature and the rock type. Consolidated rocks generally exhibit greater compaction at elevated temperatures than they do at lower temperatures; the effect of temperature is not, however, so significant in loose or unconsolidated sands. Shear stresses $\underset{\sim}{S}$, depending upon the rock type, may contribute to compaction, may lead to dilatancy, or may have no significant effect upon ϕ. Let us consider the case when ϕ does not appreciably depend on $\underset{\sim}{S}$; in this case porosity ϕ depends on a close approximation only upon P_c - P (Garg and Nur, 1973):

$$\phi = \phi_o\ [1 + \alpha(P_c - P)] \qquad (6)$$

where

$$\alpha \ 3\ \alpha\ (P_c - P) = \frac{1}{\phi_o}\left[\frac{1}{K_S} - \frac{1-\phi_o}{K}\right] \qquad (7)$$

Here $K(P_c - P)$ is the bulk modulus of the porous rock and has different values during loading (increase in effective pressure P_c - P) and unloading (decrease in effective pressure P_c - P).

The theoretical model discussed above requires K, μ_P K_s and η_s as empirically determined input functions. Although most of these properties can be obtained from standard laboratory tests on cores, it should be noted that the reservoir behavior is frequently governed by fractures, formation inhomogeneities, and other large scale features such as faults. It, therefore, becomes important to supplement the laboratory measurements by suitable field data. In particular, the bulk and shear moduli (K, μ_P) of reservoir rocks should be obtained from seismic measurements.

COMP TER CODE AND APPLICATIONS

To solve the rock response equations (1-7), a finite element solid equi ibrium code, **STAGR** (STatic Analysis of Geothermal Reservoirs) has been deve oped. Like any such finite element code, it is basically a program for solv ng the problem of a loaded linear elastic continuum; however, materially nonl near prbblems may be solved by iteration, using effective elastic modu i ("tangent" or "secant" moduli) in the elements. Due to the very sma 1 matr x displacements expected in geothermal reservoir calculat ons, only material nonlinearity, and not geometric nonlinearity, has been included. In addition to the usual features found in finite element continuum codes, STAGR can solve problems involving nonsymmetric stress-strain relations (necessary for problems involving incremental loading of materials which undergo plastic deformation). This requires the use of a nonsymmetric stiffness matrix. Further details of the finite element code are given elsewhere (Pritchett, et al., 1975).

The STAGR equilibrium code has been used to perform 2-D calculations of the rock response to production of a hypothetical geothermal reservoir. Details of the reservoir geometry and elastic properties, and the assumed production strategy are given in Pritchett, et al. (1975). We will here merely summarize the significant results.

For the present reservoir, the principal stress directions at $t = 0$ (i.e., prior to fluid production) were almost coincident with the x (horizontal) and y (vertical) directions. Changes induced in σ_x, σ_y and σ_{xy} by the production of reservoir fluids were monitored as a function of time. It was found that both MAX $|\Delta\sigma_y|$ and MAX $|\Delta\sigma_{xy}|$ are much smaller than MAX $|\Delta\sigma_x|$. Thus, as a result of fluid production, σ_x becomes much less compressive whereas σ_y is essentially unaltered. This has interesting implications for reservoir stability. Large reductions in the magnitude of σ_x without corresponding reductions in σ can lead to rock failure and growth of normal faults. Surface manifestation of these phenomena may be localized reservoir slumping, and increased seismic activity.

Surface displacement contours show that the central portion of the reservoir subsides almost uniformly. Elsewhere, the vertical motion is accompanied by significant horizontal movement. Experience from oilfiellds (e.g., Wilmington oil field in Los Angeles basin) indicates that horizontal motion may cause even more severe damage to surface installations (e.g., roads, bridges, and buildings) than that caused by vertical subsidence. Thus, in order to assess the possible environmental impact of fluid production from geothermal reservoirs, it is necessary to take into account both horizontal and vertical motions of the ground surface.

REFERENCES

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