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Geomechanical Analysis of Pressure Limits For Gas Storage Reservoirs

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ABSTRACT

One of the most cost-effective ways to increase deliverability and working gas capacity in gas storage reservoirs is to operate at higher pressure (increased delta pressure). Reservoir discovery pressures do not always represent the maximum short-term pressure capacity for the formation. Maximum safe operating pressures for a reservoir depend on several geomechanical factors, including in-situ stresses, stresses induced by local and global pressure changes in the reservoir, and the mechanical properties of the reservoir and overburden material. In many instances the pressure can be safely increased if the geomechanical behavior of the reservoir and overburden is well characterized. This paper presents, and illustrates with examples, a step-by-step process to evaluate maximum pressure limits for gas storage reservoirs.

KEYWORDS

gas storage, delta pressure, fracture, faulting, poroelasticity, numerical analysis, stress

INTRODUCTION

Maximum safe operating pressures for a reservoir depend on several geomechanical factors, including in-situ stresses, stresses induced by local and global pressure changes in the reservoir, and the mechanical properties of the reservoir and overburden material. The typical practice in North America has been to operate gas storage reservoirs at levels at or below original reservoir pressure due to concerns about caprock integrity, fracturing, faulting, and gas loss. However, current approaches for choosing maximum operating pressure limits with respect to initial discovery pressure are often overly conservative. This leads to under-utilization of existing storage resources and consequent competitive restrictions on particular projects. In many instances the pressure in a gas storage reservoir can be safely increased if the geomechanical behavior of the reservoir and overburden is well characterized.

Two basic geomechanical processes limit maximum operating pressures in gas storage reservoirs. They are: the tensile fracture pressure for the reservoir; and the stresses at which faulting or mechanical damage may be induced in the reservoir or caprock and overburden formations.

Tensile fracturing can occur when the pore pressure within a formation is increased above the minimum *in situ* stress. At this point a hydraulic (or pneumatic) fracture is generated and propagated. The hydraulic fracture pressure provides an absolute limit to maximum storage reservoir operating pressure, as it is necessary to avoid fracturing through the caprock and allowing gas leakage into overlying permeable formations. Minimum stresses are best determined from hydraulic fracture tests in a formation. When this information is unavailable, then regional stress data can often be reviewed to provide estimates of stresses.

Another constraint on gas storage operations is the pressure at which faulting or substantial bedding plane slip may be induced in the reservoir or overburden. Such overburden damage can be induced by two mechanisms. In the first type of process, pore pressure changes within an existing fault plane may modify the effective normal stress sufficiently to activate the fault. In the second type of faulting process, reservoir compaction and dilation can induce shear stresses in the overburden, resulting in rock failure or slip of weak zones, along existing faults, or along bedding planes.

In this paper we present a step-by-step methodology to assess maximum operating pressures for gas storage reservoirs. We briefly review methods to obtain initial estimates of mechanical properties and in-situ stress. Next we present some analytical and numerical techniques available to estimate stresses in the reservoir and caprock induced by gas pressure cycling. Finally, we present field examples that illustrate the analysis process.

MAXIMUM PRESSURE ANALYSIS PROCESS

A systematic evaluation process should be followed, as outlined in Figure 1. The basic process involves estimating the current rock strength and reservoir stress values with the best available data, calculating induced stresses due to pressure cycling, and then comparing the induced stresses to the estimated limiting strength and stress values. The specific steps taken for a field will depend on the available data and the desired solution accuracy. These design steps may be summarized as follows:

1. Determine the mechanical properties of the reservoir and caprock;
2. Determine the *in situ* stresses and reservoir fracture pressures;
3. Evaluate fracture pressure variations with position and with reservoir pressure;
4. Evaluate caprock stresses induced by pressure cycling with geomechanical modeling;
5. Compare stresses induced by pressure cycling with estimated strength properties and with estimated *in situ* stresses and reservoir fracture pressure; and,
6. If they are the same order of magnitude, then more detailed analyses and field verification are recommended.

The first stage in such an assessment is to characterize the geomechanical properties of the reservoir and overburden based on the best available data. The second stage in assessing delta pressure potential is to analyze stresses induced by gas storage operations in the caprock and overburden with geomechanical models.

ASSESSMENT OF MATERIAL PROPERTIES

The most accurate estimation techniques for mechanical properties and stress are those encountered first in the process diagram (towards the left) shown in Figure 1. Rock stiffness and strength properties should ideally be measured in the laboratory on core samples and reservoir stresses should ideally be measured at several locations in the field with hydraulic fracture tests. However, because in many cases there is little core data or direct stress measurement data available, initial assessments often tend to rely on estimates of mechanical properties and reservoir stresses derived from correlations from other fields of similar lithology and depth and regional stress estimates.

When core measurements are not available for reservoir formation material, stiffness and strength properties must be estimated from available geophysical log data and lithology correlations from the literature. Rock stiffness properties are primarily determined from acoustic logs; and it is best when both compressional velocity and shear velocity data is recorded and they can be calibrated against core data. Empirical correlations are then used to relate rock strength properties to the stiffness properties or velocities, often with additional clay content and/or porosity dependencies. A few empirical correlations are available in the literature to estimate compressive or shear strength from rock stiffness values (see for example, Tixier et al, 1973; Coates and Denoo, 1981; Gatens et al, 1990; Schlumberger, 1987; Vernick et. al, 1993), but it is important to use correlations for materials of similar lithology. Because of the inherent large uncertainty in these properties, the analysis results (which scale with stiffness properties) are only qualitative in nature, and should be recognized as order of magnitude type estimates.

ASSESSMENT OF IN-SITU STRESS

As summarized in Figure 1, the preferred technique to determine *in situ* stresses is through hydraulic fracture stress measurements (see for example, Haimson, 1993). If hydraulic fracture measurements are not available, then the analyst should review any available leak-off and borehole breakout data. Extended leak-off test data, if carefully measured, can often be used to provide reasonable estimates of minimum stress values (Kunze and Steiger, 1992). Another useful stress estimation technique is measurement and analysis of borehole breakouts from vertical wells to provide stress directions (Plumb and Hickman, 1985; Zoback et al, 1985), and from deviated wellbores to constrain stress magnitudes (Aadnoy, 1990; Peska and Zoback, 1995).

The final option is to review regional stress data and lithology/depth correlations for the area. Extensive work has been done in measuring and tabulating stress fields worldwide (Zoback et al, 1989; Bell, 1979, 1996). To a great extent, the global orientation of stress patterns and their relative magnitudes are consistent with the directions of tectonic forces that are acting at present. Although map consulting is a necessary step in the process, reliance on regional stress maps should be restricted to reservoirs in areas that are not heavily folded or faulted, or where local impacts such as local hydrothermalism, salt domes, local vulcanism, and so on, have not acted.

ANALYSES OF STRESSES INDUCED BY GAS PRESSURE CYCLING

Pressure cycling in a gas storage reservoir modifies the reservoir volume both vertically and laterally, and this causes flexure in the overburden, expansion of the reservoir rock relative to the rock around it, and other effects. Normal and shear stresses are altered, and this affects the stress conditions along natural discontinuities or planes of weakness, such as bedding planes and joints. During pressurization, lateral stresses increase adjacent to the reservoir formation, but decrease above and below, giving rise to shear stresses at the interface. During pressure depletion the opposite occurs.

To evaluate stresses in the reservoir and caprock induced by gas pressure cycling, a geomechanical model needs to be assembled for the field. This model is then used to investigate reservoir caprock interface shear and horizontal stresses arising from lateral expansion and contraction of the gas storage zone. Isopach and structure data is used to define the geometry of the model. Input data for the model can be collected from a hydraulic fracture report, stress constraint studies based on borehole breakout of the region, and estimates of elastic modulus and strength properties from the literature.

The geomechanical review and simulation results should then be examined for the following:

- Do local pressure values exceed the current fracture gradient in the area, based on measurements or stress estimates?
- Of what magnitude are the induced shear stresses due to pressure cycling?
- Are the induced shear stresses small relative to the estimated matrix rock strength and the field shear stresses?

- Are the shear stresses induced in the overburden enough to cause potential faulting and bedding plane slip?
- Can lowering the minimum pressure in the field also induce shear stresses which may be of concern.

Analytical Techniques

Stresses induced by pressure cycling in gas storage reservoirs may be estimated by applying the nucleus of strain concept from continuum mechanics, described by B. Sen (1950) and Geertsma (1973). The volumetric strain at a point, caused by a local change in pore pressure, is treated as a center of dilation in an elastic half space. The volumetric strain of a reservoir element, $\Delta V/V$, is assumed to depend on the change in pore pressure times the reservoir material compressibility, C_b:

$$\Delta V/V = C_b \Delta P \qquad (1).$$

Analytical solutions are then available to determine stresses throughout an elastic half-space due to any combination of reservoir element volume changes. The assumptions are that the overburden material behaves in a linear elastic, isotropic, and homogeneous manner. For example, the total induced shear stresses caused by a varying pressure within an arbitrarily shaped reservoir can be obtained by integrating the contribution of all these expansion points over the reservoir volume, V as follows:

$$\tau_{yz}(x_0, y_0, z_0) = \frac{C_b E_0}{12\pi(1-\nu)} \int_V \Delta P(x,y,z) \left[\frac{\partial^2 V_1}{\partial y \partial z} + 2z \frac{\partial^3 V_2}{\partial y \partial z^2} + \frac{\partial^2 V_2}{\partial y \partial z} \right] dV \qquad (2)$$

$$\tau_{xz}(x_0, y_0, z_0) = \frac{C_b E_0}{12\pi(1-\nu)} \int_V \Delta P(x,y,z) \left[\frac{\partial^2 V_1}{\partial x \partial z} + 2z \frac{\partial^3 V_2}{\partial x \partial z^2} + \frac{\partial^2 V_2}{\partial x \partial z} \right] dV \qquad (3).$$

In the expression above τ_{xz} and τ_{yz} are the horizontal shear stresses at position (x_0,y_0,z_0). E_o is the Young;s Modulus for the overburden material and ν is the Poisson's ratio for the reservoir and overburden. V_1 and V_2 are distance functions given by:

$$V_1 = \frac{1}{\sqrt{(x-x_0)^2 + (y-y_0)^2 + (z-z_0)^2}} \qquad (4).$$

$$V_2 = \frac{1}{\sqrt{(x-x_0)^2 + (y-y_0)^2 + (z+z_0)^2}} \qquad (5).$$

The change in pressure, $\Delta P(x,y,z)$ is measured from some reference state (usually the normal reservoir pressure) from which induced stresses are to be determined. Equations (2) and (3) above may be integrated analytically if the pressure distribution is a simple function, or numerically if pressures are obtained from a simulation model.

To illustrate a typical distribution of shear stresses within the caprock at the top of a reservoir, we present parametric results from numerical integration of equations (2) and (3). In Figure 2, shear stresses normalized with respect to reservoir radius, height, and material properties are presented for an assumed reservoir pressure change which varies linearly with radius, from r=0 to r=R, in an axisymmetric reservoir of outer radius R. Shear stress magnitude increase with larger radius to depth ratio. However, once a reservoir is deeper than about the distance of its radius, shear stress magnitude are relatively unaffected by depth, and are controlled primarily by the ratio of reservoir thickness to reservoir radius.

Numerical Techniques

Stresses induced in the reservoir and caprock by gas pressure cycling can also be analyzed with several numerical modeling techniques currently available for geological materials. These include finite element methods, finite difference methods, and boundary and discrete element methods. The use of numerical models is justified when heterogeneous material property data is available for the overburden, or when the analysis is to be carried out beyond the elastic regime to evaluate slip and material failure.

Although full three-dimensional models with coupled fluid pore pressure rock matrix interaction are now available (see for example, Fredrich et al, 1996), they are computationally expensive and generally unwarranted for a semi-quantitative assessment. The accuracy of any geomechanical model depends to a large extent on the accuracy and availability of material properties and boundary conditions. Inherent uncertainty in these parameters, combined with geometrical complexity, tends to limit the efficacy of elaborate three-dimensional models.

Two-dimensional finite element and finite difference models using symmetry properties of various fields have been employed in this investigation to illustrate the geomechanical effects of gas pressure cycling in parametric examples and in actual field examples. If the field has complex geometry, then more than one sectional analysis is used to get a qualitative understanding of the magnitude and local variations.

Figure 3 presents a comparison of analytical and numerical model results for a simple axisymmetric reservoir. Numerical results were calculated using the FLAC finite difference code (Flac3.3, Itasca 1996). The shear stress distribution at the top of the reservoir is presented for two pressure scenarios: one in which pressure change varies linearly from the center of the reservoir to its outer radius; and one in which the pressure change is uniform over the entire reservoir. In the examples presented, the maximum pressure change is 8.2 MPa, the reservoir radius is 325 m, the thickness is 50 m, and the reservoir depth is 475 m. The Young's Modulus for the reservoir and caprock is assumed equal to 1GPa. Note that for a linearly varying pressure distribution, the shear stresses are relatively uniformly distributed over the top of the reservoir. However, for the constant pressure distribution shear stresses are asymptotic at the outer radius where there is severe discontinuity in reservoir pressure and volumetric strain.

FIELD EXAMPLE

Next we describe the steps taken to evaluate delta pressure options for an actual storage field. Gas is to be injected into an aquifer reservoir on a structural anticline located in California. A structure and isopach map for the gas zone is presented in Figure 4. The depth to the structural crest is about 3100 ft and the average reservoir net thickness is about 60 ft. The permeability of the water sand is about 200 mD and the porosity is about 30%.

For this field example we evaluate pressure changes during cycling equal to about 1500 psi (10.3 MPa), over a range from about 750 psi to 2250 psi. Regional and local hydraulic fracture data in the area indicate that the fracture gradient is about 0.9 psi/ft in the field. Therefore, the concern for hydraulic fracturing due to pressure increase is secondary, and the primary analysis emphasis was on the induced shear stresses and potential for faulting and bedding plane slip.

No core data or hydraulic fracture data was available from the field. Data from available sonic logs from two wells were used to estimate the stiffness parameters. Both wells showed relatively consistent values for Young's Modulus in the range of 1.0 to 3.0 E6 psi. Given these estimates for stiffness properties, the next step is to estimate a range of shear strength values for the reservoir and caprock. Applying the empirical correlations for shear strength from elastic moduli provided by Coates and Denoo (1981), and the correlations for shear strength from porosity provided by Vernik et al (1992), shear strength estimates range from about 200 psi to 4000 psi. Therefore, for our order-of-magnitude preliminary assessment, we take the 200 psi value. Note that this is very conservative, and shear strength will in general increase with confining pressure, dependent on the friction angle of the material.

A numerical finite difference model was assembled to estimate shear stresses in the caprock above this reservoir. Shear stress patterns above the gas reservoir vary with respect to position. In general, stresses are largest towards the flanks of reservoirs and at the locations with greater pressure contrast. Figure 5 presents two vertical trajectories along which stresses are plotted, from locations A and B shown in Figure 4. Maximum induced shear stresses are on the order of 200 psi at the reservoir flanks, and about 50 psi in the caprock along the length of the reservoir. Closer the to the center of the field, induced shear stresses in the overburden are generally low (on the order of a few psi), except right at the caprock-reservoir boundary. Here the stresses are on the order of 50 psi. Closer to the edge of the reservoir, stresses on the order of 20 psi are generated within the overburden, while the caprock-reservoir boundary stresses are also about 50 psi at this location.

The induced shear stress values of 200 psi for this field example are on the same order as the estimated shear strength values. Because the induced stresses are on the same order as the estimated strength values, there is potential for bedding plane slip and induced shear damage and fault movement at this field if it is operated at the desired delta-pressure conditions. The preliminary geomechanical assessment therefore indicated that before increased pressures could be justified at this field, actual measurements of caprock material properties would be recommended.

SUMMARY AND DISCUSSION

Maximum safe operating pressures for a gas storage reservoir depend on three primary geomechanical factors. These are:

1. The mechanical properties of the reservoir and overburden;
2. The natural state of stress in the reservoir and overburden;
3. The stress changes induced in the reservoir and overburden by gas pressure cycling.

The objectives of this investigation has been to investigate and summarize the geomechanical processes associated with gas storage operations and to provide some practical guidelines and tools for increasing maximum pressure limits in order to improve short-term deliverability and working gas storage capacity in existing reservoirs. A step-by-step protocol is presented for evaluating delta pressure options at gas storage reservoirs, and its application has been illustrated with examples.

In addition to geomechanical limits on gas storage operations, there may also be geologic and hydrodynamic limits to increasing pressure, due to potential gas diffusion or loss through the caprock or bounding materials. A complete delta pressure investigation for a field would therefor include both a geomechanical assessment and a reservoir characterization assessment, combined with economic evaluation of the necessary surface facilities and the enhanced value for increased deliverability and working gas capacity in particular area of operation for the field.

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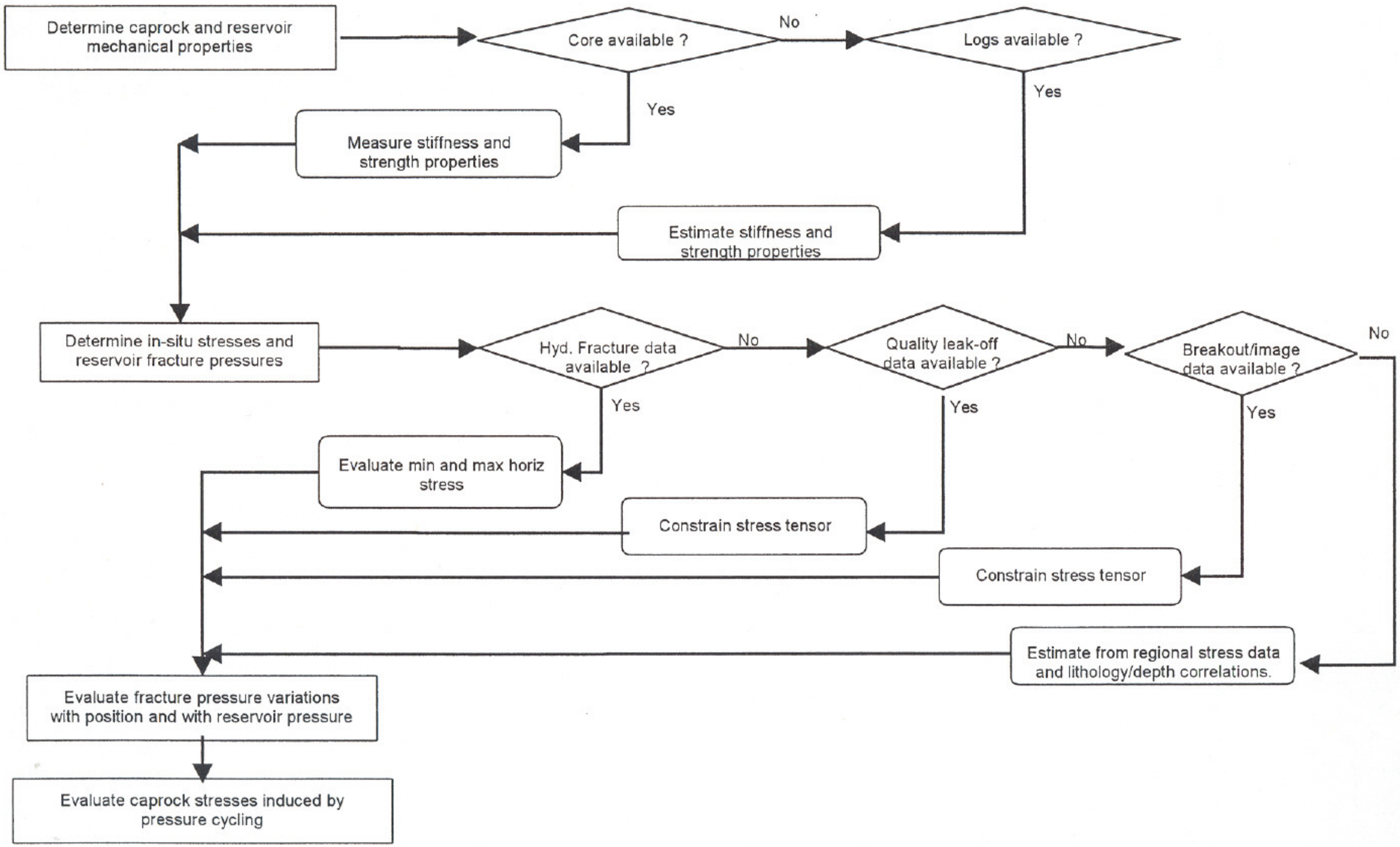

Figure 1: Step-by-step procedure to evaluate maximum operating pressures for gas storage reservoirs

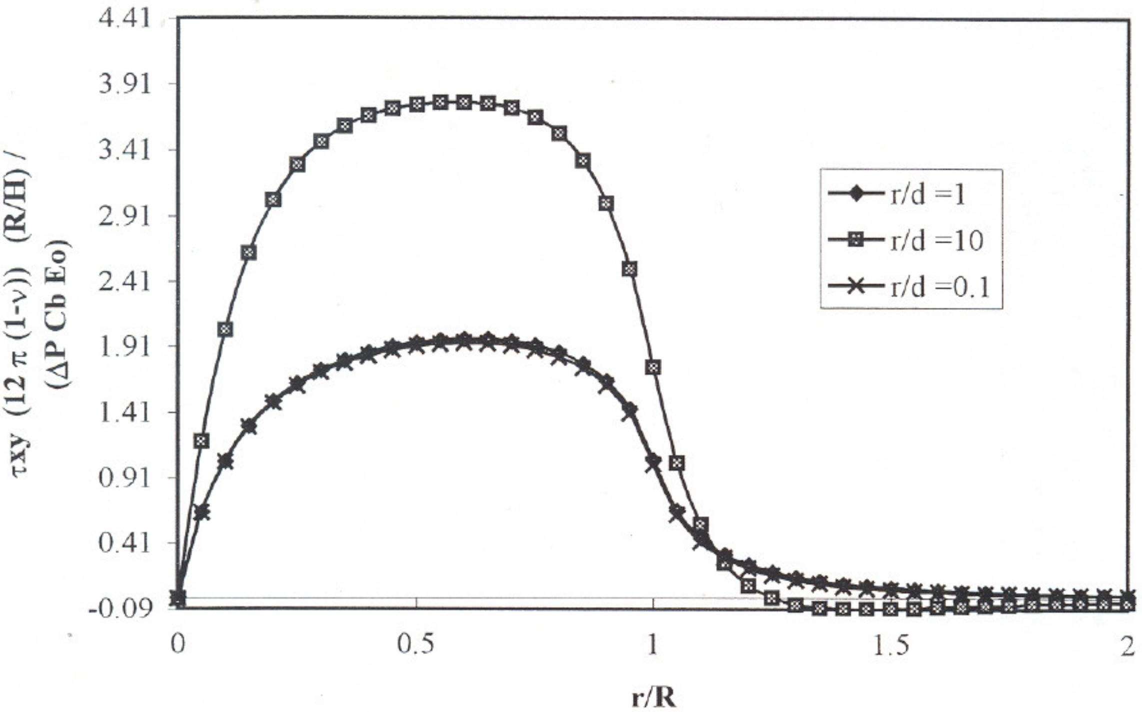

Figure 2. Normalized shear stresses at the top of an axisymmetric reservoir with linear pressure gradient.

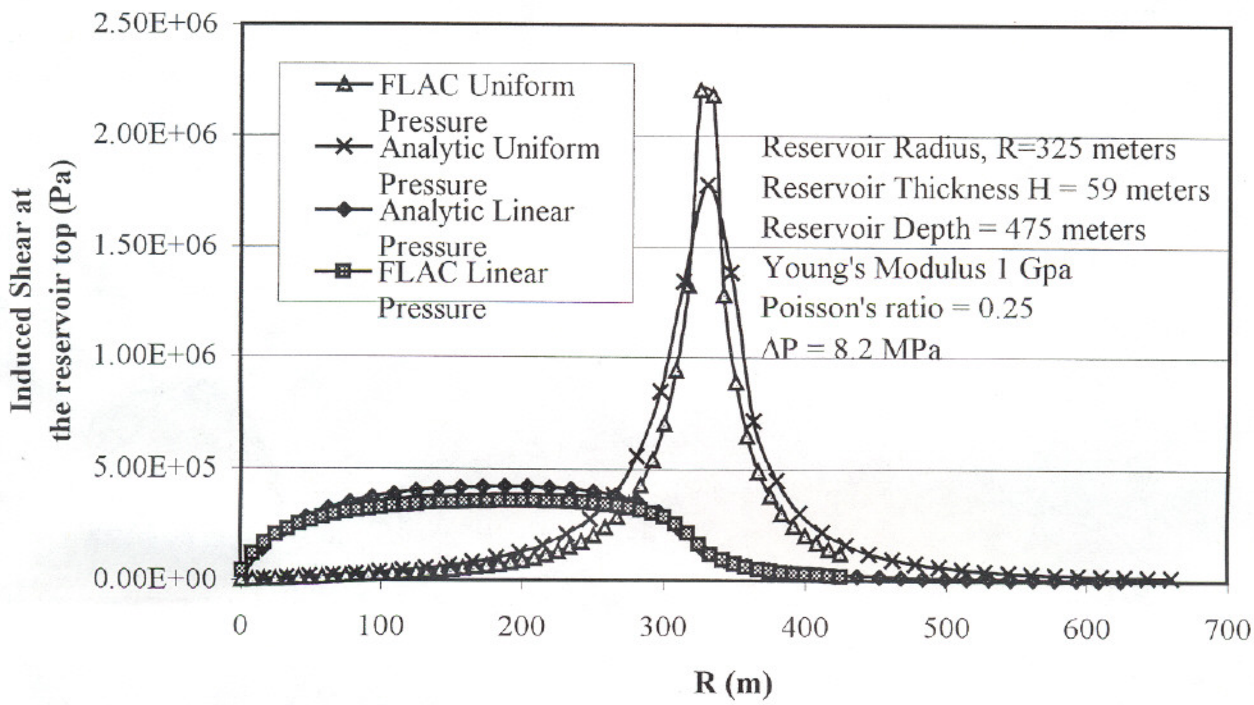

Figure 3. Comparison of induced shear stresses for cases with linear and uniform pressure gradients.

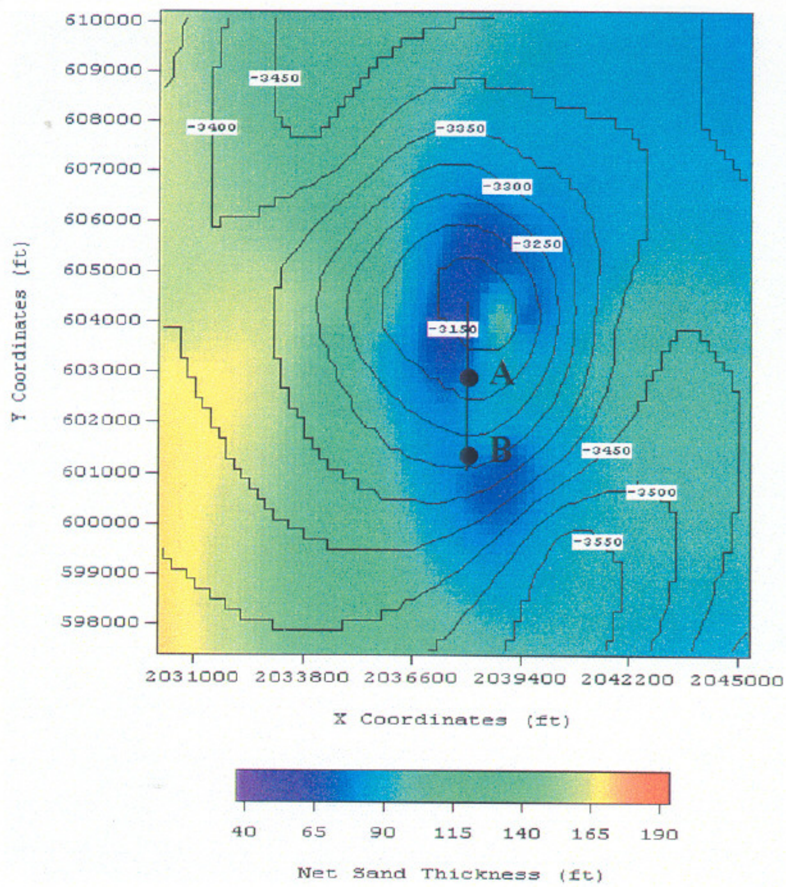

Figure 4: Field A Isopach model with overlay of structure contours.

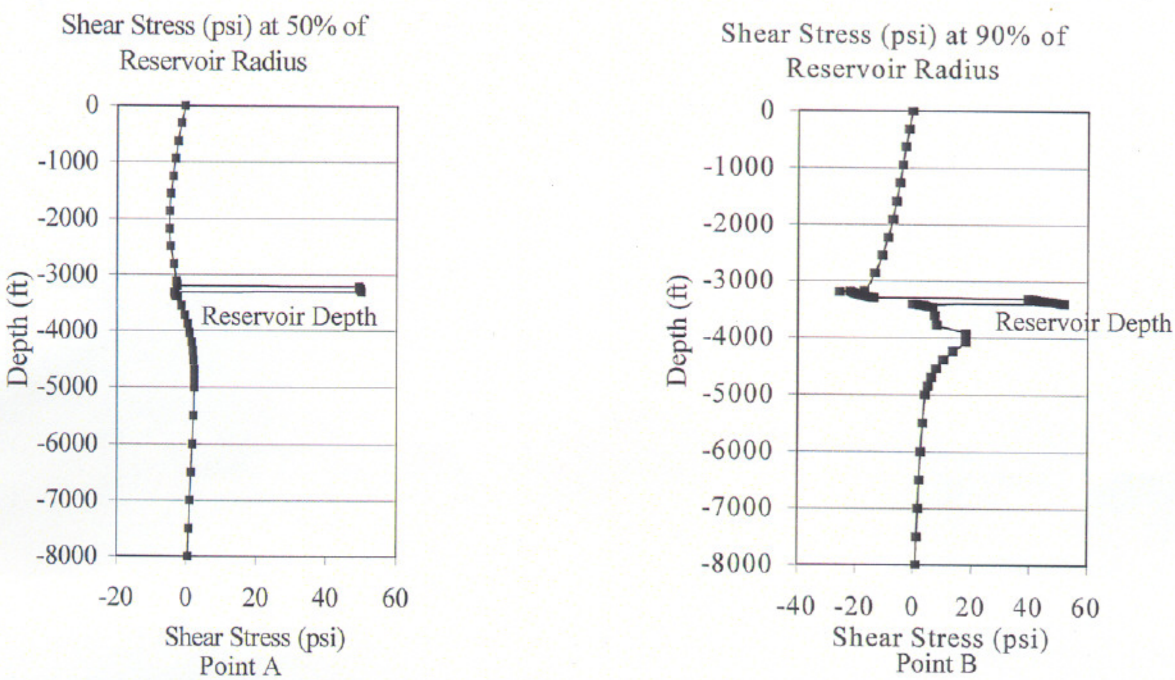

Figure 5: Induced shear stress at vertical cross sections at points A and B.