Geomechanical numerical simulations of complex geologic structures

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ABSTRACT: The ability to predict the mechanical response of rock in three dimensions over the spatial and time scales of geologic interest would give the oil and gas industry the ability to reduce risk on prospects, improve pre-project initial reserve estimates, and lower operating costs. A program has recently been initiated, under the auspices the Advanced Computational Technology Initiative (ACTI), to achieve such a computational technology breakthrough by adapting the unique advanced quasistatic finite element technology developed by Sandia to the mechanics applications important to exploration and production activities within the oil and gas industry. As a pre-cursor to that program, in an effort to evaluate the feasibility of the approach, several complex geologic structures of interest were analyzed with the existing two-dimensional quasistatic finite element code, SANTOS, developed at Sandia. Some examples will be presented and discussed in this paper.

1 INTRODUCTION

The ability to predict the mechanical response of rock in three dimensions over the spatial and time scales of geologic interest would give the oil and gas industry the ability to reduce risk on prospects, improve pre-project initial reserve estimates, and lower operating costs. A program has recently been initiated, under the auspices the Advanced Computational Technology Initiative (ACTI), to achieve such a computational technology breakthrough by adapting the unique advanced quasistatic finite element technology developed by Sandia to the mechanics applications important to exploration and production (E&P) activities within the oil and gas industry. The need for such a program arose because of the demand for new tools which can contribute to the exploration of petroleum reservoirs by the better understanding of geological processes.

The interpretation of seismic data, on which exploration is mainly based, allows the industry to identify potential traps that can enable the accumulation of hydrocarbons. This is possible because seismic data can provide a picture of geologic structures as they are encountered in the present. However, for the proper evaluation of such potential traps, not only the present structure, but also the time history of the geologic processes that led to that trap are important. The sequencing in time of such events as sedimentation, erosion, faulting, thrusting, etc. needs to be known. Current techniques used in the industry for getting this information are based on two dimensional (2D) or pseudo-three dimensional (3D) kinematic reconstructions and some limited 2D finite element geomechanics models.

The kinematic reconstructions try to trace back encountered cross sections by relying solely on conservation of mass. As Plischke, et.al (1991) have noted, although some of these methods may also incorporate compaction laws and have gained a professional degree of functionality, they do not account for equilibrium as required in mechanics: they simply try to trace back the encountered cross-sections more or less by purely geometrical operations.

Although a limited amount of work has been done using continuum mechanics to improve the understanding of geologic structures through the use of the finite element method in 2D, currently available commercial finite element technology does not efficiently treat the non-linearities associated with large deformation and fracture and cannot handle the size of problems needed for E&P applications. Furthermore, 2D analysis does not accurately describe complex 3D geometries in oil fields. Consequently, techniques that can handle hundreds of thousands of elements are needed to solve typical geomechanics problems encountered by industry. However, because of the nature of the techniques used in commercial finite element technology, practical limits of 2D analyses exist, and the use of 3D techniques for more complex problems is more common.
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Because of its long history of nonlinear large strain finite element code research and development and its application of these codes to geomechanics problems in waste management programs, in particular, the key technical element for this project is Sandia's core quasistatic finite element technology. This technology is uniquely based on iterative solvers and has been extensively developed for large problems involving nonlinear large deformations. The use of iterative solvers and experience with nonlinear material response provides a base technology that offers efficient solution of very large complex geomechanics problems. It is the intent of the ACTI project to adapt this iterative (or "explicit") technology to the mechanics applications in the oil and gas industry.

As a pre-cursor to the ACTI program, in an effort to evaluate the feasibility of the approach, several complex geologic structure problems of interest were analyzed with the existing two-dimensional quasistatic finite element code, SANTOS (Stone 1995), developed at Sandia for other applications. Some of these example problems will be presented and discussed in this paper. These include an example rollover fold problem, an example of the re-activation of an old fault, and finally, an example of an actual larger-scale structure, the Green River Basin, subjected to thrusts of the Uinta and Wind River mountains at the edges of the basin.

In all of the problems addressed herein, two-dimensional plane-strain geomechanical models are used in the idealization of the problem. The term "geomechanical model" as used in this paper will be understood to encompass the idealization of the geometry; the boundary and initial conditions, as well as loads, applied to the idealized geometry; a description of the constitutive behavior of the materials involved; and the discretization of the resulting initial/boundary value problem into a finite element formulation that permits a computational solution of the problem.

2 ROLLOVER FOLD

The first example deals with an extensional geologic structure, a rollover fold. This was among the first geologic structure calculations performed to demonstrate the applicability of explicit finite element techniques to this class of problems. In this example there is a footwall material upon which has been overlain a material comprising what is known as the hanging wall. Relative movement between the footwall and the hanging wall occurs with time because the interface between them can permit slippage to occur as a result of some extensional mechanism.

2.1 Geomechanical model of the rollover fold

Most of the features of the geomechanical model for the rollover fold are depicted in Figure 1. As far as the geometric idealization is concerned, the left and lower boundaries on the footwall are assumed to be far-field boundaries, as is also the right boundary on the hanging wall. The overall length of the footwall along its lower boundary is 33,750 m (although only a portion is shown in the figure) and the depth along its left boundary is 4,000 m. The length of the footwall along its upper boundary is 2,550 m. Similarly, the overall length of the hanging wall along its upper boundary is 13,950 m and the depth along its right boundary is 3,000 m.

The figure shows that the boundary conditions applied to the idealized geometry are as follows. There is no horizontal movement permitted along the right boundary on the hanging wall. Similarly, there is no vertical movement permitted along the lower boundary of the footwall. Along the left and lower boundaries of the footwall, there is a prescribed horizontal displacement of 17,250 m to the left.

There are initial stresses applied to the configuration. These are assumed to be lithostatic, varying linearly with depth and equivalent in all directions. A gravity load is also present and is constant throughout the analysis.

The finite element discretization of the rollover fold problem contains 4,789 nodal points and 4,444 four-node quadrilateral uniform-strain elements.

Two separate analyses were performed for the rollover fold problem. In both analyses the response for the footwall material was considered to be elastic with a Young's modulus, \( E \), of 68.95 GPa and a Poisson's ratio, \( v \), of 0.3.

However, the hanging wall material was assumed to be elastic/plastic, in one case, with a yield stress, \( \sigma_y \), of 25.0 MPa and a hardening modulus, \( H \), of 1.0 MPa. The Young's modulus was an order of
magnitude smaller than for the footwall and Poisson’s ratio was the same as for the footwall.

In the other case, the hanging wall material was treated as a Drucker-Prager material and allowed to strain soften. The Drucker-Prager criterion can be written as:

\[ f = \sqrt{3J_{2D}} - \alpha J_1 - \kappa = 0, \]

where \( \alpha \) and \( \kappa \) are positive material parameters; \( J_1 = \sigma_{ij} \) is the first invariant of the stress tensor, \( \sigma_{ij} \); and \( J_{2D} = (S_{ij}S_{ji})/2 \) is the second invariant of the deviatoric stress tensor, \( S_{ij} \). The deviatoric stress is further defined by, \( S_{ij} = \sigma_{ij} - (\sigma_{kk} \delta_{ij})/3 \). The \( \kappa \) parameter is in fact the yield stress at zero confining pressure: a value of 50.0 MPa at \( J_1 = 0 \) was used in this case. A value of \( \alpha = 0.4 \) was also used.

For purposes of these demonstration calculations, a somewhat empirical model for strain softening was incorporated in the overall constitutive behavior, as depicted in Figure 2. Namely, upon reaching the yield stress at the corresponding value of confining pressure, strain softening was allowed to occur over a finite value of strain. For this particular problem, at 20% strain the stress reached a minimum value, and plastic flow could continue without further decrease in stress.

2.2 Results of the rollover fold analysis

Although a great deal of information is available from the analyses, herein we will concentrate on the deformations that the structure undergoes. The rock mass comprising the footwall is slowly pulled to the left (over a period of about 2 million years in an actual structure). As this happens the material in the hanging wall begins to bend and roll over, as depicted schematically in Figure 3. A complex strain field sets up in the hanging wall as a result. Figure 4 shows the computed equivalent plastic strain field in the hanging wall for both the elastic/plastic and Drucker-Prager with strain softening cases. In the figure shown for the elastic/plastic case, the footwall has been displaced about a tenth of its maximum value, and the equivalent plastic strain fringe values range from zero in the darker regions to six percent in the lighter regions. Similarly, in the figure shown for the Drucker-Prager case, the displacement of the footwall is about a sixth of the maximum, and the equivalent plastic strain ranges from zero in the darker regions to forty percent in the lighter regions. Although there are differences in the level of footwall movement, more significant difference is that the strain field is much more diffuse for the elastic/plastic case than for the case of Drucker-Prager with...
strain softening. Note, for example, the smooth upper surface of the hanging wall for the elastic/plastic case: it remains smooth throughout the complete simulation. For the Drucker-Prager case, however, ripples and depressions at the surface are evident early, as localized features develop in the strain field and lead to the deformation of the surface. These “graben-like” features, similar to those found in the field for structures of this type, were seen to develop only when a constitutive model that allowed for “strain-softening” was used for the hanging wall material. This indicates that the constitutive idealization of the materials used for such problems must contain the appropriate physical characteristics to be able to successfully capture the behavior of the geologic structure. For this reason, research into the development and implementation of such strain localization constitutive models, within the overall computational scheme, will need to be addressed under the ACT1 project.

3 RE-ACTIVATION OF OLD FAULT

This demonstration calculation has both extensional and shearing characteristics. It is assumed that an old existing fault has been overlain by a layer of salt, on top of which is then deposited a layer of overburden rock. The old fault is then reactivated, resulting in extension and shearing of the salt and overburden layers above it.

3.1 Geomechanical model of fault reactivation

Most of the features of the geomechanical model for the fault reactivation demonstration problem are depicted in Figure 5. As far as the geometric idealization is concerned, the left and right boundaries are assumed to be far-field boundaries. The fault is not explicitly modeled, instead one portion of the configuration is moved relative to the remainder of the configuration to simulate the fault displacement implicitly. The overall length of the model is 20,000 m, and the thickness of the salt and overburden layers are 1,000 m and 1,000 m, respectively.

The boundary conditions applied to the idealized geometry are shown in the figure. There is no horizontal movement permitted along the right boundary. Similarly, there is no vertical or horizontal movement permitted along right half of the lower boundary. It is only along the left boundary and the left half of the lower boundary that there is a prescribed horizontal displacement to the left of 500 m and a prescribed vertical displacement down of 1,000 m. The resultant of the horizontal and vertical components of this displacement simulates the old fault reactivation. The displacement is prescribed over 25,000 years.

There are initial stresses applied to the configuration. These are assumed to be lithostatic, varying linearly with depth and equivalent in all directions. A gravity load is also present and is constant throughout the analysis.

The finite element discretization of the fault reactivation problem contains 1,616 nodal points and 1,500 four-node quadrilateral elements.

The material response for the overburden material was assumed to behave as a Drucker-Prager material and allowed to strain soften as described previously for the rollover fold problem. For this case the material properties used were a Young’s modulus, \( E \), of 10.0 GPa; a Poisson’s ratio, \( v \), of 0.15; a yield stress, at zero confining pressure, \( K \), of 50.0 MPa; and an \( \alpha \) of 0.4. The material response of the salt was considered to be elastic/secondary-creep. Table 1 lists the constants that were used with the model. In the table, \( G \) is the shear modulus; \( K \) is the bulk modulus; \( A \) and \( n \) are constants determined from data analysis; \( Q / RT \) is the effective activation energy in calories per mole, \( R \) is the universal gas constant (1.987 calories per calorie per degree Kelvin), and \( 2G \left( \frac{n+1}{n} \right) A \exp(Q/RT) \left( \frac{\alpha (n+1)}{\alpha (n+1) - 1} \right) s_{ij}^2 \).
mole-Kelvin); and T is the temperature in degrees Kelvin. The first equation in the table describes the deviatoric behavior of the material, and the second describes its volumetric behavior. The $s_{ij}$ are the components of the deviatoric stress tensor; $e_{ij}$ are the components of the deviatoric strain tensor; $\sigma_{kk}$ is three times the mean stress; and $e_{kk}$ is the volume strain. The dot in the equations denotes rates.

3.2 Results of the fault reactivation analysis

Once again, we concentrate on the deformations that the structure undergoes. The left half of the structure moves left and drops as the old bedrock fault is reactivated. Figure 6 shows the development of the equivalent plastic strain field in the overburden material as this happens, at three distinct times. The fringes again denote magnitude of inelastic strain, from zero at the darkest regions to a maximum at the locations of the asterisks (for example, the asterisk in 6c denotes a maximum strain for that case of about 65%). Early in the process (6a), strains begin to concentrate in two small areas. One is immediately to the right above the fault at the interface between the salt and the overburden. A second, slightly larger, zone is located at the surface along with a corresponding small dimple. As movement continues, these two zones of strain concentration grow and coalesce (6b), and the magnitude of the strains increases, as does also the depression at the surface. At later time (6c), both the size of the coalesced zone and the magnitude of the strains within the zone continues to increase, along with the depression. This behavior, including the development of the “graben-like” depression, is consistent with the behavior observed in laboratory experiments of a similar configuration, as well as with that seen in the field.

It should be noted that the analysis was only carried out to a certain level of deformation and then stopped because the mesh was beginning to deform to such an extent that continuation of the analysis may not have been possible. This will be a typical difficulty encountered in this class of problems because of the extremely large deformations that these structures undergo. To solve the problem, automatic or semi-automatic techniques of stopping the solution before the distortion of elements becomes extreme will be needed. A new mesh with appropriate refinement in the areas of high distortion will need to be substituted in place of the distorted one to continue the solution. This is an area of research which the ACTI project intends to address.

4 GREEN RIVER BASIN

While the first and second examples above have dealt with a more-or-less generic sort of geologic structure and were simply calculations used to demonstrate the applicability of explicit methods to this class of problems, it was desirable to attempt to solve a larger, actual field example that was more realistic in terms of the size of problem that would need to be solved by industry. This third example deals with a specific geologic structure, namely the Green River Basin.

In this case, a model was developed to predict in situ stresses along a cross-section through the basin, within the context of the basin’s geologic/tectonic history. Of special interest was one of the layers in the basin known as the Frontier Formation. A North-South stratigraphic section across the basin was used in the idealization, and a preliminary analysis was performed with the model. The analysis incorporated indenter movement at the ends of the section, simulating the effects of the Laramide, thick-skinned thrusts of the Uinta and Wind River mountains at the edges of the basin, and plausible mechanical proper-
ties for 14 different stratigraphic units from Precambrian basement rocks to Tertiary strata. The information that was of particular interest from the analysis was the state of stress that developed in the Frontier Formation as a result of the large indenter movements at the edges of the basin. This information would be useful for evaluating the propensity of fracturing in the formation.

4.1 Geomechanical model of Green River Basin

Figure 7 is a plan-view conceptual drawing of the emptied Green River Basin showing the thrust movement of the Wind River mountains from the North and the Uinta mountains from the South. A fold and

![Figure 7. Conceptual Drawing of Emptied Green River Basin](image)

The boundary conditions include displacement constraints along the lower boundary that allow displacements parallel, but not perpendicular, to this boundary. In addition, the left boundary is constrained to displace horizontally to the right a distance of 16.85 km, and the right boundary is constrained to move horizontally to the left a distance of 6 km. The latter displacement boundary conditions are imposed to simulate the Wind River and Uinta thrusts from the north and south, respectively. The loading includes gravitational body forces throughout the configuration that are constant throughout the analysis.

 Twelve distinct layers above the basement rock were identified in the stratigraphy for the configuration. However, one layer was subsequently divided by the authors into two layers to allow the geometric model to capture the details of the response in the Frontier Formation because this is the producing layer in the basin which was of principal interest. There are, in general, four materials that appear in the layers either alone or combined. These are sandstone, limestone, dolomite, and shale. A fifth material comprising the basement rock is assumed to be granite. The five materials were modeled with a Drucker-Prager constitutive relation, as described previously. However, no strain softening was allowed in this case.

Because no site-specific material properties for the rock were available, generic properties were obtained from the literature (Touloukian, et.al 1981, Serdengecti and Boozer 1961, Handin and Hager 1957, Costin and Stone 1987) to arrive at what is considered to be a plausible set of mechanical properties for use in the constitutive relation. Specifically,
mechanical material properties for Sandstone, Shale, Dolomite, Limestone, and Granite were used. Table 2 lists the mechanical properties used in the model for the five materials. These basic properties were apportioned accordingly to arrive at material properties for the 14 different layers of the geomechanical model. Additional details related to the development of this geomechanical model and the analysis can be found in Argüello and Stone (1994).

The finite element mesh that was used in the study will not be shown because the aspect ratio of the geometry and the level of refinement used are such that the mesh would simply show up as a solid and not provide much useful information. Suffice it to say that the overall mesh contained 59,169 nodal points and 58,624 elements. This level of refinement was necessary because of the multiple thin layers, in general, and also to capture the response of the very thin Frontier Formation, in particular. It should be noted that a great deal of effort was expended in developing this mesh because of the multiple long thin layers. Once again, this will be a typical difficulty encountered in this class of problems. The problems related to meshing will be further exacerbated when one goes to 3D. Consequently, the procedure of taking a general geometry definition for a geomechanics problem of this type to convert it into a finite element mesh needs to be automated and streamlined in order to reduce the time required to generate the mesh. This is another area of research which will be addressed under the ACTI project.

### 4.2 Results of the Green River Basin analysis

In general, the results from this preliminary analysis indicate that the \((x,y,z)\)-components of normal stress correspond closely to the principal stresses, with the least compressive in the vertical direction and the most compressive occurring in-plane horizontally. One must keep in mind, however, that this is a 2D plane strain idealization, which implies that out-of-plane strains are zero. In situ, the out-of-plane constraint (in the third direction) does not exist and, as a result, deformation in that third direction, with attendant straining, will occur. This will undoubtedly lead to complex stress fields in which the least compressive stress may occur at some arbitrary orientation not coincident with the \((x,y,z)\)-directions.

Specific results of interest from this analysis were the state of stress in the Frontier formation, the producing zone. The three components of normal stress in this layer, along its length, are shown in Figure 9.

The vertical component, \(\sigma_y\), is seen to vary by about 50 MPa from one end of the basin to the other. The out-of-plane horizontal component, \(\sigma_z\), varies by about 100 MPa, and the in-plane horizontal component, \(\sigma_x\), varies by about 150 MPa from the north end to the south end of the basin. The three principal stresses in the Frontier along its length are shown in Figure 10. Comparing this figure to the previous one, it becomes apparent that the \((x,y,z)\)-components of normal stress correspond very closely to the principal stresses. Figure 11 shows the shear stress, \(\tau_{xy}\), and it is small relative to the normal stresses. The value is close to zero along most of the basin length, except near the north end: this explains why the \((x,y,z)\)-components of normal stress correspond so closely to the principal stresses. The maximum shearing stress in the Frontier formation is also shown in Figure 11. It occurs in-plane and is significantly larger than \(\tau_{xy}\), varying from about 200 MPa to 240 MPa from one end of the basin to the other, increasing from the
north to the south end.

In summary, results from this preliminary analysis of the Green River Basin indicate that the \((x,y,z)\)-components of normal stress correspond closely to the principal stresses, that the normal stresses in the Frontier Formation become more compressive from the north end of the basin toward the south, and that the maximum shear stress in this formation increases from the north to the south end of the basin.

5 SUMMARY AND CONCLUSIONS

Several complex geologic structures of interest have been analyzed with the existing two-dimensional quasistatic finite element code, SANTOS. Three examples have been presented and discussed in this paper. In carrying out this work, it was found that the constitutive idealization of the materials used for this class of problems must contain the appropriate physical characteristics (strain softening) to successfully capture the behavior of the geologic structure. In addition, automatic and/or adaptive remeshing of the idealization will be required for this class of problems as elements begin to distort, because of the extremely large deformations that these structures undergo. Finally, it was also found that the procedure of taking a general geometric/stratigraphic description for a problem of this type to a meaningful and computationally manageable finite element mesh needs to be automated and streamlined.

The work reported herein was done, as a precursor to an ACTI program, in an effort to evaluate the feasibility of using explicit finite element techniques to solve this class of problems. The successful solution of the problems described herein, using this technology, indicates that iterative techniques can indeed be extremely powerful tools for the analysis complex geologic structures as encountered by the oil and gas industry. In fact, they may be the only tools capable of allowing industry to solve the size problems that will naturally arise as it ventures into the 3D arena.

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