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Progress on the Development of a Three-Dimensional Capability for Simulating Large-Scale Complex Geologic Processes

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ABSTRACT

Significant progress has been made in developing a three-dimensional capability for predicting the mechanical response of rock over spatial and time scales of geologic interest to the Oil & Gas industry. An Advanced Computational Technology Initiative (ACTI) initiated three years ago to achieve such a computational technology breakthrough has made significant progress towards its goal by adapting and improving the unique advanced quasistatic finite element technology developed by Sandia National Laboratories to the mechanics applications important to exploration and production (E&P). This capability now gives the industry a powerful tool to help reduce risk on prospects, improve pre-project initial reserve estimates, and lower operating costs. Progress to date on this program is reported herein by presenting and discussing the enhancements and adaptations that have been made to the technology, with specific examples to illustrate their use on large E&P geomechanics problems.

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KEYWORDS

Geologic, Computational Mechanics, Finite Elements, Explicit, Cap Plasticity, Analysis, Oil, Gas, Exploration, Production

INTRODUCTION

Three years ago, the "Computational Geomechanics for Geologic Structure and Reservoir Mechanics" program was initiated under the auspices of the U. S. Department of Energy's "Advanced Computational Technology Initiative" (ACTI). Its aim was to achieve a computational technology breakthrough by developing a three-dimensional (3D) capability for predicting the mechanical response of rock over spatial and time scales of geologic interest to the Oil & Gas industry. The need for such a breakthrough arose from the demand for new tools which could contribute to the exploration of petroleum by allowing the simulation of large-scale complex geologic processes in order to better understand them. The program was to achieve its goal by adapting and improving the advanced quasistatic finite element technology developed by Sandia (e.g., Biffle 1993 and Stone 1997) to the mechanics applications important to the exploration and production (E&P) activities within the industry. This finite element technology, which is uniquely based upon iterative (explicit) solvers, was the key element in the program because it had been specifically and extensively developed under defense programs to handle large problems involving large deformations. The use of iterative solvers and the extensive experience with non-linear material response that existed at Sandia would provide a base technology that offered efficient solution of large complex problems, compared to commercially available finite element

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technology that may not efficiently treat the nonlinearities associated with large deformation and fracture and cannot handle the size of problems needed for E&P applications.

Another major element of the program was the close working relationship that was to be established between Sandia and the industry partners. Early in the program, Sandia would transfer its existing 2D and 3D computational technology to the industry, and new capabilities would be added to that existing technology as they were developed. Industry would define the application problems to focus the technology development, and they would also provide continuous input throughout the life of the program on technology issues and implementation. In all phases of this working relationship, active participation by industry was to be ensured through staff dedicated to the project.

Thanks in great part to the two elements of the program described above, significant progress towards its goal has been made over the past three years. In doing so, this program has given the industry a new capability to help reduce risk on prospects, improve pre-project initial reserve estimates, and lower operating costs. It is the intent in this paper to report the progress to date of the program by presenting and discussing the enhancements and adaptations that have been made to the previously existing technology along with specific examples to illustrate their use on large-scale geologic problems of interest to E&P. Additionally, some of the difficulties that were encountered in the 3D modeling process itself will also be discussed, and a summary of future developments that are needed will be provided on the basis of that experience.

TRADITIONAL VERSUS EXPLICIT FINITE ELEMENT APPROACH

Before discussing the various enhancements and modifications made to the previously existing technology over the course of the project, a brief overview of the explicit approach compared to the traditional FEM approach will be presented. Begin by considering the following field equations governing the deformation of a body occupying volume, V ,

$$\partial \sigma_{ij} / \partial x_j + \rho b_i = 0 \text{ on } V. \quad (1)$$

Equations (1) are the quasi-static equations of motion, where σ_{ij} is the Cauchy stress tensor, x_j is the position vector, ρ is the weight per unit volume, and b_i is a specific body force vector. The solutions to Equations (1) are sought subject to the kinematic and traction boundary conditions

$$u_i(x,t) = U_i(x,t) \text{ on } S_U, \text{ and } \sigma_{ij} n_j = s_i(x,t) \text{ on } S_T \quad (2)$$

where S_U represents the portion of the boundary on which kinematic quantities are specified (i.e., displacements, u_i), n_j is a unit normal vector and S_T represents the portion of the boundary on which tractions are specified. The boundary of the body is given by the union of S_U and S_T .

For the displacement-based finite element method, the equations described in the foregoing paragraph can be discretized and rewritten as

$$\left\{ \sum_{N_{ve}} \int \mathbf{B} \sigma dV \right\} = \{\mathbf{F}\}, \text{ or } [\mathbf{K}(\mathbf{u})] \{\mathbf{u}\} = \{\mathbf{F}\} \quad (3)$$

where the term on the left-hand side of each form of the equation is the internal force vector, and $\{\mathbf{F}\}$ is the external force vector. In the first form, $\mathbf{B}$ is the strain-displacement transformation matrix, N is the number of elements in the FEM discretization, σ is an ordered vector of stress components in each element at a Gauss point, and ve is the volume of each element. In the second form of Equation (3), on the right, $[\mathbf{K}(\mathbf{u})]$ represents the global stiffness matrix and $\{\mathbf{u}\}$ represents the global vector of unknown nodal displacements. Both forms of the equation are included to highlight the differences in approach between the traditional FEM approach and the explicit approach used in this work.

The traditional FEM approach involves the direct solution of the second form of Equation (3). Namely, an element stiffness and external force vector is formed for each element comprising the overall structure. The contributions from each of these element stiffness matrices and force vectors are then assembled into a global stiffness matrix and force vector describing the overall system. For the linear-elastic case (stiffness matrix is constant), the unknown vector $\{\mathbf{u}\}$ is found by a direct solution method (i.e., some variant of Gauss elimination, Cholesky decomposition, etc.). For the inelastic and/or geometrically nonlinear case (stiffness matrix varies with the unknowns), the load is typically applied incrementally. The resulting nonlinear equations are then solved at each load increment with a root-finding technique, typically some variant of the Newton-Raphson method to augment the direct solver which is still used within the root-finding scheme. The factorization of this sparse global stiffness matrix can result in extremely large storage requirements and a very large number of arithmetic operations to perform when one ventures into the 3D regime. For example, commercially available software is limited and will typically handle models no larger in size than on the order of tens of thousands of elements. However when attempting to solve large problems of interest to the Oil & Gas industry, models on the order of hundreds of thousands to millions of elements in size may be needed. For problems of this size, the traditional approach becomes prohibitive due to memory and computational time requirements.

The explicit technology that forms the basis of the present work approaches the solution of Equation (3) in a different manner. First of all, in practice, a global stiffness matrix is never formed. Instead, at the element level, the divergence of the stress is found and the contributions to each node in the overall structure are summed (i.e., the vector described by the left side of the first form of the equation). A residual force vector comprised of the internal minus the external forces,

$$\{\mathbf{R}\} = \left\{ \sum_N \int_{ve} \mathbf{B} \sigma dV \right\} - \{\mathbf{F}\}, \quad (4)$$

is computed, and the solution procedure is then one of driving the residual to zero using an iterative technique. Because the quantities being manipulated are vectors, there is no longer a need to store a matrix and factorize it. Consequently the storage requirements are small when compared to the traditional FEM approach. The two iterative techniques that are currently used in the explicit quasistatic nonlinear finite element code, JAS3D (Blanford 1998), which embodies the current 3D technology, are a pre-conditioned Conjugate Gradient (CG) technique (Biffle 1993) and an adaptive Dynamic Relaxation (DR) technique (Stone 1997). Because, in general, most commercially available FEM software uses some variant of the traditional FEM approach, it is currently incapable of the efficiencies afforded by this explicit technology. For example, one of our industrial partners has run a geologic structure problem on the same computer using both a commercially available FEM computer program that uses the traditional approach as well as with the explicit JAS3D code. On the same problem using the same machine, the traditional approach took 30 times the amount of CPU execution time that the explicit technology described herein took.

ENHANCEMENTS AND MODIFICATIONS

As previously mentioned, an explicit finite element technology developed for various defense applications already existed before the start of this project. So the first task of the program was to transfer the existing 2D technology to the industry partners for their immediate use on problems of interest. In this way, they could begin to develop experience with the iterative solution techniques that form the basis of the technology. The 2D technology, as embodied within the explicit quasistatic nonlinear finite element code, SANTOS (Stone 1997), had already been exercised to a limited degree on some Oil & Gas industry problems, as a precursor to this ACTI program (Argüello, Stone, and Lorenz 1996). The JAS3D code, which embodied the base 3D technology described herein, however, was in the infancy of its development at that time. Consequently it had never been used on E&P applications before the start of the program. In fact at the start of the project, JAS3D lacked some of the functionality that was necessary to address this class of Oil & Gas problems. Although some of this functionality was desirable for other potential geomechanics applications and planned for future implementation as programs that needed it arose, it had not been necessary up to that point in time for defense

applications. Consequently, several enhancements and modifications had to be made to JAS3D before its full capability could be brought to bear on problems of interest to the Oil & Gas industry.

Among the first enhancements to the code were the addition of a general initialization capability, a pore pressure coupling capability, and a new cap/plasticity constitutive model. It was felt that these three enhancements would allow the project to address many of the E&P applications of current interest thereby allowing a demonstration of the efficiency of the explicit technology on problems of immediate concern to the partners. The general initialization capability allowed, among other things, for the initial conditions

$$\sigma_{ij}(x, 0) = \sigma_{ij}^0(x) \text{ and } u_i(x, 0) = U_i^0(x) \text{ in } V \quad (5)$$

to be imposed on Equation (1). With this, the in situ state of stress believed to prevail in a field, for example, could then be imposed as an initial condition. Similarly, the pore pressure coupling capability allowed the state of stress that the material in the field sees to be corrected for the presence of any pore fluid pressure, because it is known that the behavior of geomaterials is influenced by the pressures of the fluid present in the pores of the material. This was done by noting that the total stress can be computed as

$$\sigma_{ij}^T = \sigma_{ij} + p\delta_{ij} \quad (6)$$

where σ_{ij}^T is the total stress, p is the pore fluid pressure, δ_{ij} is the Kronecker delta, and σ_{ij} is the “effective” stress that the soil or rock sees. It is this effective stress that is responsible for the deformations of the solid skeleton of the geomaterial. With this, for example, the loading and unloading of material in a reservoir due to depletion and/or injection could now be simulated.

The cap/plasticity model was implemented to allow a more realistic representation of the mechanical behavior of porous soil or rock than the basic Drucker-Prager model that was already in the code (in addition to a suite of other constitutive models used for defense applications). The cap/plasticity model is a multi-surface plasticity model and is a generalization of the Sandler-Rubin constitutive model (Sandler and Rubin 1979) that incorporates Lode-angle dependence of yield in the deviatoric plane and nonassociativity in the meridional plane on the shear failure surface. The yield surfaces for this model are depicted schematically in Figure 1a, where the abscissa is $I_1 = \sigma_{kk}$ and the ordinate is $\sqrt{J_2} = \sqrt{(s_{ij}s_{ij})/2}$, with s_{ij} being the stress

Figure 1: (a) Yield Surfaces For Implemented Cap/Plasticity Model (b) Identification of Various Parameters Used in Cap/Plasticity Model

deviator. As seen in the figure, the loading function is assumed to be isotropic and to consist of two parts: an ultimate shear failure surface which serves to limit the maximum shear stresses attainable by the material and an elliptically shaped strain-hardening surface, or “cap,” that produces plastic volumetric and shear strains as it moves (say from H_1 to H_2 as depicted in Figure 1a). The failure envelope portion of the loading function is denoted by

$$h(I_1, \sqrt{J_2}, \psi) = \Gamma \sqrt{J_2} - [A - C \exp(BI_1)] = 0 \quad (7)$$

where A , B , and C are material constants, and Γ is a function of J_3 , the third invariant of the deviator stress, that incorporates the Lode-angle dependence of yield as follows

$$\Gamma = \{[1 + \sin(3\psi)] + [1 - \sin(3\psi)]/K^*\}/2 \quad (8)$$

where K^* is the ratio of the yield stress in triaxial extension to triaxial compression, and ψ is the Lode angle

$$\psi = \frac{1}{3} \arcsin\left(-\frac{27}{2} \frac{J_3}{(3J_2)^{3/2}}\right); \quad -\frac{\pi}{6} \leq \psi \leq \frac{\pi}{6} \quad (9)$$

where for triaxial extension, $\psi = -\pi/6$, and for triaxial compression, $\psi = \pi/6$. Note that for triaxial compression, $\Gamma = 1$, while for triaxial extension, $\Gamma = 1/K$. The strain-hardening or cap surface is given by

$$H(I_1, \sqrt{J_2}, \psi, \kappa) = \Gamma \sqrt{J_2} - \frac{1}{R} \sqrt{[X(\kappa) - L(\kappa)]^2 - [I_1 - L(\kappa)]^2} \quad (10)$$

where R is a material parameter denoting the ratio of the major to the minor axis of the elliptical cap, as depicted in Figure 1b. Also shown in this figure, $-X(\kappa)$ and $-L(\kappa)$ define the intersections of the elliptic cap with the I_1 axis and the failure envelope, respectively. The cap is chosen so that the tangent at its intersection with the failure envelope is horizontal. The hardening parameter, κ , is a function of plastic volumetric strain

$$\kappa = \varepsilon_{kk}^p = W \{ \exp([D_1(X(\kappa) - X_0) - D_2(X(\kappa) - X_0)] - 1) \} \quad (11)$$

where W , D_1 , and D_2 are material parameters, with W defining the maximum plastic volumetric compaction that the material can experience under hydrostatic loading. X_0 is the initial cap position. Equation (10) and Equation (11) indicate that the cap is not fixed in principal stress space, but that it changes as plastic deformation takes place. In the nonassociative case, the plastic potential takes the form of an ellipse as illustrated in Figure 1b. The functional form of this potential is given by

$$G(I_1, \sqrt{J_2}, \psi, \kappa) = \Gamma \sqrt{J_2} - \frac{[L(\kappa) - X(\kappa)]}{R[X^* - L(\kappa)]} \sqrt{[X^* - L(\kappa)]^2 - [I_1 - L(\kappa)]^2} \quad (12)$$

with $X^* = \ln(A/C)/B$. Parameters for this model can be found using a procedure in Fossum *et al* (1995).

In addition to the enhancements described above, other efforts have been undertaken over the course of the project to adapt and improve the technology to address additional E&P issues. For example, a basic framework within the constitutive model and the code to handle future hardening/softening/localization is being added (e.g., the addition of an Arc-Length solution procedure to handle softening). Efforts to produce a more robust algorithm for three-dimensional contact (Heinstein *et al* 1993 and Heinsteint 1997) have allowed relatively complex contact problems to be addressed, and further improvements specific to geomechanics applications are continuing under this program. A three-dimensional mapped-infinite element for modeling the far-field has been developed (Koterat 1996 and 1997) and is currently under testing and evaluation before its release. This will allow, for example, more meshing resolution in an area of interest by decreasing the number of elements that are needed to model the far-field response. Similarly, the element-free Galerkin (EFG) method is a gridless method that allows propagation of fractures to be tracked computationally. An initial implementation of the EFG method within the 2D explicit technology (Tabbarra and Stone 1998) has been effected as a precursor to its development and implementation in 3D. This development of the EFG method in 3D is currently underway with implementation soon to follow. The result of all this effort has been the advancement of the state-of-the-art for predicting the mechanical response of rock in three dimensions over the spatial and time scales of geologic interest to the Oil & Gas industry.

EXAMPLES

Examples of three geologic processes covering different spatial and time scales of interest are presented and briefly discussed in this section. Each example was chosen not only to demonstrate some modification or enhancement to the explicit technology that has been incorporated during the course of this ACTI project, but also to highlight where additional effort is needed in future development.

Example 1 – A Fault-Bend Fold Problem

The first example addresses a typical geologic structure of interest to the industry, that of a fault-bend fold in which a footwall material is overlain by a different material comprising the hanging wall. This was among the first geologic-structure calculations performed with JAS3D. The motivation behind solving this problem was to demonstrate the applicability of explicit finite element techniques in 3D to this class of problems which involve large amounts of sliding at the interface between the footwall and the hanging wall. Figure 2 illus-

Figure 2: Fault-Bend Fold Example Demonstrating Large Sliding Along Contact Surfaces

trates the ability of the explicit technology to successfully simulate the very large deformations, highly non-linear material response, and finite sliding associated with this fault-bend fold problem. The hanging wall was 1 km thick by 11.9 km wide by 8.5 km long (where it pinches out at the right end). The footwall was 3.5 km thick overall by 16.5 km wide by 16.5 km long (other details are shown in the figure). The hanging wall was assumed to be an elastic/plastic material, and the foot wall block was assumed to be rigid. Because this example was intended to be a “proof-of-concept” with particular emphasis on the finite interface sliding aspects of the problem, the use of a more complicated constitutive model (e.g., Drucker-Prager or cap/plasticity) for the hanging wall was not warranted. Zero friction was specified on the contact surface, the interface between the hanging wall and the footwall. The loads on the structure were gravity loads and an imposed displacement. The left vertical face of the hanging wall was displaced 6 km in the y-direction. An initial lithostatic state of stress was also assumed to exist in the structure. Other boundary conditions were such that no displacement was allowed perpendicular to the other vertical faces of the model. In addition, no displacement was permitted perpendicular to the bottom face of the model. The finite element model contained 15860 nodes (47580 d.o.f.) and 13320 hexahedral elements. The simulation was run on a Cray J-916 super-workstation and took 133 hours of CPU time to complete 3000 load steps using the DR solution technique. The deformed mesh in the figure shows that the hanging wall, whose upper surface was originally at the same vertical level as the upper surface of the footwall, has ridden up along the original interface onto the upper portion of the footwall. This represents a significant amount of finite sliding along the contact surface, demonstrating this capability

of the explicit technology. The 4.8 km displacement of the left vertical face of the hanging wall, in the figure, represents 80% of the final imposed displacement value.

Example 2 – A Coupled-Process Reservoir-Scale Problem

The second example is a reservoir-scale problem in which coupling between fluid flow and geomechanical response was addressed to gain a better understanding of the processes that lead to well casing damage during production from a weak compactible diatomite formation (Fredrich *et al* 1996). This geomechanical analysis was performed in collaboration with a Natural Gas & Oil Technology Partnership (NGOTP) project to serve, from this ACTI project's perspective, as the first truly large-scale demonstration of the explicit technology. Spatially, it included a major portion of Section 33 of the South Belridge Field in California. Temporally, it included 18 years of production and injection from approximately 200 wells. The details of this work are reported in Fredrich *et al* (1996) so only a brief description of the geomechanical model will be included here to demonstrate the computational size and complexity of problems that can be addressed with this explicit technology. The example illustrates the ability of the technology to deal with multiple nonlinear features. The problem included coupling of geomechanical response to fluid flow, non-hydrostatic user-defined initial stresses, the use of a more sophisticated constitutive model, and multiple contact surfaces. Figure 3. shows

Figure 3: Reservoir-Scale Example Used to Demonstrate Geomechanical Response Due To Fluid Flow

the finite element mesh of the overall geomechanical model while the inset of this figure shows the portion of the mesh encompassing the fluid flow (i.e., the volume included in the reservoir simulation with the approximately 200 wells undergoing production/injection). The dimensions for the overall geomechanical model are shown in the figure. It included three layers of overburden; eight layers of diatomite and a layer of porcelanite in the flow portion; and another thick porcelanite layer constituting the underburden, for a total of 13 stratigraphic layers. The three materials of the overburden and the porcelanite layers were modeled using a Drucker-Prager plasticity model. The diatomite layers were modeled using the cap/plasticity model described previously in the third section of this paper. There were three contact surfaces located at the interfaces between (a) the first and second layer of the overburden, (b) the second and third layer of the overburden, and (c) the third layer of the overburden and the top of diatomite "G," identified in the figure. Early calculations assumed that these contact surfaces were all fixed, while later ones permitted sliding with a friction coefficient of $\mu = 0.2$. The loads on the structure were the changes in pore pressure with time, as determined from the reservoir simulation, and gravity. The pressure variation with time from the block-centered finite difference reservoir simulation was mapped onto the geomechanical finite element mesh and used as input to the

geomechanical simulation. An initial stress field was also specified such that the total vertical stress at any point in the configuration was computed from the weight of the overlying material. The other two corresponding principal horizontal components of stress, at this same point, were taken as 0.65 and 1.2 times the vertical value. Boundary conditions were specified such that no displacement was permitted normal to the vertical faces of the configuration. In addition, the bottom of the configuration was fixed. The finite element model contained 437,100 nodes (approximately 1.3 million d.o.f.) and 374,139 hexahedral elements. The simulations were run on a Cray J-916 super-workstation and required approximately 120 megawords of Cray RAM to run. All simulations for this example used the CG solution procedure. To convey the idea of required run-time for these simulations it is noted that an early calculation took 80 CPU hours to complete 30 load steps, while a subsequent one took 425 CPU hours to complete 372 load steps. The only difference between these two simulations was that in the first, all materials were modeled with a simple Drucker-Prager constitutive model, while in the second the more complex cap/plasticity model was used for the diatomaceous material. This illustrates that a significant penalty is paid when going to more sophistication (i.e., going to a more complicated constitutive model, including contact surfaces, etc.). In this example, such sophistication was required because of the need to capture the finite volumetric compaction behavior of the diatomite, which the cap/plasticity model allows.

Example 3 – A Compressional Deformation Problem

This example addresses a regional-scale problem in which lateral motion causes compressional deformation in the structure of interest. This problem involves an interaction of more geometrically complicated 3D layering in which a thinner layer in the middle of the structure is overlain and underlain by softer materials. Figure 4 shows the finite element mesh for the configuration along with pertinent dimensions. Peaks and val-

Figure 4: Regional-Scale Example Demonstrating Large Compressional Deformation

leys appearing on the surface of the upper layer are similarly present, but hidden, in the lower layers. This mesh was generated initially with a tetrahedral mesher to adequately honor the 3D stratigraphy and subsequently each tetrahedral element was further subdivided into hexahedral elements to generate an all-hexahedral element mesh. All three materials in this example were modeled with a Drucker-Prager constitutive model, and as noted above, the middle layer was stiffer than the other two. The loads on the structure were gravity and an imposed y-displacement on the left vertical face of the model, as indicated in the deformed configuration in the figure. That value represents approximately 19% of the original length of the configura-

tion and translates into a significant amount of deformation in the overall structure. An initial lithostatic state of stress was also assumed to exist in the structure. Other boundary conditions imposed on the configuration were such that no displacement was permitted normal to any of the other vertical faces or to the bottom surface. The finite element model contained 181,946 nodes (approximately 550,000 d.o.f.) and 163,492 hexahedral elements and represents a modestly large model capable of being run on a typical workstation. Consequently, this simulation was performed on a SUN ULTRA 2 (200 MHz processor) to determine what sort of performance was to be expected from a more typical workstation environment. This simulation took 10 hours of CPU time to complete 500 load steps using the DR solution procedure.

OTHER CONSIDERATIONS IN MODELING

Other important considerations, dealing with the modeling process itself for this class of problems, became evident during the course of the project. For example, difficulties were encountered in going from the geometric/stratigraphic description to a meaningful and computationally manageable mesh. There are currently no tools available for seamlessly going from geologic structure maps to a final hexahedral finite element mesh for a geologic structure. Generation of a finite element mesh for general 3D stratigraphic layering continues to be a typical major hurdle in the modeling process, requiring a significant portion of the analyst's time. Efforts to develop a general tool of this type are needed. In addition, the issue of how to handle, transfer, and interpolate information between codes using different discretizations (i.e., finite difference coupling to finite element) needs effort devoted to it as well. In the second example, a method for performing such a coupling was devised but needs improvement, generalization, and streamlining. There are also issues associated with post-processing large results databases. Results files of two to four gigabytes in size were generated in the course of the analysis for one of these examples, but future problems will undoubtedly generate even larger ones. The amount of information in these databases easily drives the analyst to the limit of what can be post-processed in a reasonable time, or more importantly what can be absorbed, using traditional post-processing techniques. Visualization software and hardware that can both process and convey information more compactly and quickly are direly needed.

SUMMARY AND CONCLUSIONS,

The progress to date on the development of a three-dimensional capability for simulating large-scale complex geologic processes has been presented in this paper. The enhancements and adaptations that have been made to the previously existing technology have been demonstrated with specific examples to illustrate their use on large-scale geologic problems of interest to E&P. On this basis it can be concluded that the explicit finite element technology described herein provides the Oil & Gas industry with a unique capability for predicting the three-dimensional mechanical response of rock over spatial and time scales of geologic interest. This capability now gives the industry a powerful tool to help reduce risk on prospects, improve pre-project initial reserve estimates, and lower operating costs.

A summary of the current state of the technology, including some of the technical developments that are still ongoing under this ACTI program has also been provided in this paper. In addition, some of difficulties that have been encountered to date in the 3D modeling process itself have also been discussed. From this it can be concluded that additional effort is needed to generalize this new tool to provide additional capability and better functionality. Only by doing so will it become a tool that can be embraced and adopted for everyday use by the industry.

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