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Predictive modelling of structure evolution in sandbox experiments

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Abstract

In this paper a computational approach is presented that is able to forward model complex structural evolution with multiple intersecting faults that exhibit large relative movement. The approach adopts the Lagrangian method, complemented by robust and efficient automated adaptive meshing techniques, a constitutive model based on critical state concepts and global energy dissipation regularized by inclusion of fracture energy in the equations governing state variable evolution. The efficacy of the approach is benchmarked by forward simulation of two extensional analogue experiments that exhibit the development of a roll-over anticline with a series of superimposed crestal collapse graben systems. These sandbox experiments are excellent benchmarks for computational models, as both intersecting localisations with different rates of slip and large relative movement on localisations must be represented, while other complex phenomena associated with structural evolution over geological timeframes are not present.

Keywords: Fault prediction; Numerical modelling; Analogue modelling; Sand; extension

1. Introduction

Accurate reconstruction of current day geological structure has the potential to provide additional insight into the effect of the depositional history on the current geomechanical and hydrogeologic state of potential target reservoir formations and overburden. The aim is to computationally model the burial and deformational history of the sediment from initial deposition to the current day state, whilst also accounting for the reaction and transport processes occurring in the basin. This has a large potential benefit when interpreting the current-day structure, especially where the seismic imaging is poor, e.g. due to seismic interference caused by overlaying salt bodies or gas accumulations. Gaining a better appreciation of the timing of reservoir trap evolution relative to source-rock maturation and hydrocarbon migration will also impact views as to whether potential targets are oil- or gas-bearing.

Considering geomechanical modelling aspects only (the main thrust of this paper), the aim is to determine the style and distribution of the fault geometry from predictions of shear band formation and fault localization. Furthermore, fine scale gridding, below the level of seismic resolution, has the potential to allow prediction of the sub-seismic fault density, or at least identify regions with high levels of damage. Within these regions, porosity and permeability may be reduced as a consequence of grain-crushing, for example, so reducing hydrocarbon prospectivity (Fisher et al., 1999). In the context of hydrocarbon extraction from deep reservoirs mapping of these smaller faults could greatly aid decision-making of required well numbers and their placement. Interpretations of the extent of faulting also provide scenarios for determining cost-effective recoverable hydrocarbon volumes from fault-block size estimations.

The geomechanical information arising from computational modelling of the evolution of geological structure is currently qualitative rather than quantitative, due to a variety of physical and computational considerations. Physical considerations include: sizeable scale effect between laboratory tests and field scale models, the temporal variation in material constitution (lithification, creep), transient pore pressure and temperature fields, the non-uniqueness of the interpretation of the kinematic history. While computational considerations include: the effectiveness of the model in describing the onset and evolution of the localisations, the compatibility of the assumptions used to restore the geometry with the assumptions used in the forward reconstruction analysis. Resolution of these

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issues requires an integrated modelling framework that properly accounts for the coupling between the reaction, transport and mechanical dynamic evolution. This necessitates computation of the simultaneous evolution of the state variables that describe the internal state of the rock formation, i.e. the material state boundary surface, rock permeability, fluid properties, the evolving rock texture and mineralogy, thermal conductivity and fault and fracture characteristics.

From the geomechanical perspective, a key computational prerequisite to developing such a framework is the accurate representation of strain localisation and the subsequent relative displacement on faults. In many cases, quantitative prediction of fault geometry necessitates accurate representation of the evolution of the material state from initial deposition to the current day conditions. Mechanical compaction, chemical compaction and long-term deviatoric creep may all play an important role during the growth of a structure. For example, porosity reduction induced by mechanical and chemical compaction, and strengthening due to cementation, may alter the position of the stress state relative to the state boundary surface, thereby either increasing or decreasing the likelihood of fault formation. In this case, the evolution of the complete state boundary surface must be represented, e.g. by extending critical state concepts, with specific models for clays and sands calibrated to enable representation of the evolution from uncemented sediment to cemented rock (Crook et al., in preparation).

The onset of localization, i.e. the formation of shear and compaction bands, arises naturally from rigorously formulated continuum constitutive models in a finite strain setting. Consequently, the inception of shear banding may be simulated in a relatively straightforward fashion. At the point of localisation initiation, however, there is a well-documented breakdown of the governing equations induced by load shedding on the discontinuity. This leads to a number of unwelcome characteristics; in particular energy dissipation in both mode-I or mode-II deformation on the localisation bands that is sensitive to the fineness and the direction of the discretisation. Consequently, strategies that either preclude, or at least mitigate, these deficiencies are essential. An overview of the commonly adopted approaches is provided in Section 2.

While procedures for prediction of the onset of localisation and the resolution of the high displacement gradients immediately following localisation are well developed, strategies suitable for resolution of large-relative-sliding that allow for gross geometric changes and topology evolution due to sedimentation and erosion have received less attention. Lagrangian, Eulerian and Arbitrary Lagrangian Eulerian (ALE) computational frameworks have all been applied in an attempt to capture the structural evolution with gross geometric changes.

The Eulerian fluid approach, for example, supplemented with appropriate techniques for fluid interface tracking, has been used in the simplified representation of the Rayleigh–Taylor instability phenomena associated with salt diapirism (Woidt, 1978; Zaleski and Julien, 1992). In this case the salt is often represented as a Newtonian or non-Newtonian fluid, which is at best a very crude approximation of complex materials that typically exhibit large deformations at finite strains dominated by viscous, plastic behaviour. Additionally, the standard Eulerian approach does not allow for accurate modelling of faulting, which is a common feature in the overburden layers.

The ALE method has also been employed for structural geology applications (Fullsack, 1995; Wissing et al., 2003; Ellis et al., 2004). However, depending on the precise formulation, ALE techniques inherit some difficulties apparent in both Eulerian and Lagrangian methodologies, e.g. for large deformation problems the ALE reduces but does not completely remove the need for remeshing. The explicit treatment of discontinuous displacement fields is also not straightforward.

The Lagrangian methodology, which is based on the reference configuration that is attached to the particles, has the advantage that: (i) free surfaces and interfaces between different phases of the system are intrinsically represented; and (ii) material state evolution is modelled directly. The complex constitutive response of rock and the initiation of structural complexity that derives from the constitutive response, e.g. fault development, are, therefore, easily incorporated. Consequently the Lagrangian methodology is most frequently employed for structural geology applications (e.g. Erickson and Jamison, 1995; Strayer and Hudleston, 1997; Nino et al., 1998; Vanbrabant et al., 1999; Erickson et al., 2001; Schultz-Ela and Walsh, 2002; Exadaktylos et al., 2003). A major disadvantage, however, is that large shear strain, e.g. diffuse straining during basin subsidence (Luo et al., 1998) or localized straining near evolving fault systems, causes excessive mesh distortion, which destroys the solution unless remedial action is undertaken, i.e. frequent rezoning or remeshing during the simulation.

The computational approach described in this work is based on the Lagrangian method, which is complemented by robust and efficient automated adaptive meshing techniques. Such methodology has been successfully employed in computational modelling of inelastic solids (Peric and Owen, 1998; Peric et al., 1999; Peric and Crook, 2004; Crook et al., in press). It is emphasized that, in addition to overcoming the difficulties caused by excessive mesh distortions, the adaptive Lagrangian formulation: (i) allows accurate tracking of the evolving localisations, as the mesh is refined in regions with high strain gradients; and (ii) provides a natural framework for computational modelling of complex interface phenomena, which may also incorporate frictional contact phenomena.

The constitutive model adopted is a single-surface, rate independent, non-associated plasticity model, based on critical state concepts. This is the simplest form of a hierarchical constitutive model specifically formulated for simulation of material evolution over geological timeframes (Crook et al., in preparation). The primary yield function is a smooth three-invariant surface that intersects the hydrostatic axis in both tension and compression. Global energy dissipation is regularized by including fracture energy in the equations governing state variable evolution (Pietruszczak and Mróz,