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Critical state finite element models of contractional fault-related folding: Part 1. Structural analysis

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ABSTRACT

Fourteen Lagrangian finite element models with a critical state mechanics constitutive model illustrate some of the primary controls on the formation of fault propagation, fault bend, and diffuse folds. The models demonstrate how variable mechanical stratigraphy, initial fault dip and inter-layer detachments affect the way faults propagate and thus exert a significant control on resultant fold layer geometry. For example, models of uniform sandstone properties exhibit efficient strain localization and clear patterns of fault tip propagation. Uniform shale properties tend to inhibit fault propagation due to distributed plastic deformation. Models with mixed inter-layered sandstone and shale deform in a disharmonic manner, resembling lobate–cuspate arrangements that are common to many folds observed in outcrop. Detachments accommodate shortening by bed-parallel slip, resulting in fault-bend fold kinematics and poorly expressed fault propagation across layers. Structural analysis of the numerical model results reveals that contractional deformation is a composite of lateral compaction, pure shear shortening, fault propagation along narrowly localized zones of reverse shear, and flexure of layers. The relative proportions of these shortening components vary in time and with mechanical properties (shale vs. sandstone). Depth-to-detachment calculations performed on selected numerical models suggest that reasonably accurate predictions can be made for detachment fold-thrust belts and toe-of-slope contractional systems. However, our study suggests that applications to mid-crustal level detachments within the basement beneath a sedimentary cover may be inaccurate.

1. Introduction

Through several decades of research, fault-related folds, such as fault-propagation (e.g., Suppe and Medwedeff, 1990) and fault-bend folds (e.g., Suppe, 1983), have proven to be popular subjects of interest in academia and industry. Understanding fault-propagation folds and, for instance, the often associated blind faults, is important for studying seismic hazards (e.g., Allmendinger and Shaw, 2000; Benesh et al., 2007; Shaw and Shearer, 1999). Fault-related folds are also potential and prospective hydrocarbon traps in onshore (e.g., Lingrey, 2000; Mitra, 1990; Mitra and Mount, 1998) and offshore (e.g., Corredor et al., 2005; Hesse et al., 2010; Yan and Liu, 2004) geological settings. The seminal work by Suppe and co-workers established geometric rules for producing internally consistent cross sections of fault-propagation folds (Suppe and Medwedeff, 1990) and fault-bend folds (Suppe, 1983) in fold and thrust belts. Numerical kinematic (e.g., Allmendinger, 1998; Erslev, 1991; Hardy and Ford, 1997; Hardy and McClay, 1999) and mechanical modeling (e.g., Braun and Sambridge, 1994; Erickson and Jamison, 1995; Finch et al., 2003; Finch et al., 2004; Sanz et al., 2007; Stockmal et al., 2007) has provided first-order insight into the relationships between fault displacement and fold development. Typically, geometric/kinematic models do not account for variable layer strength and mechanical models often assume homogeneous material properties. Recent work, however, demonstrates that mechanical stratigraphy has an appreciable control on fault propagation and folding style (Hardy and Finch, 2006). Hence, further understanding of the role of material properties is important.

The objective of this study is to investigate the response of idealized numerical models to systematic variation in material properties. We use a constitutive model that is based on critical state concepts and capable of reproducing large deformation observed in laboratory experiments (Crook et al., 2006a). In addition, the effects of initial fault dip, the type of fault seed (listric versus horizontal), and the presence of inter-layer detachments are examined. The results show a significant dependency of fault propagation dynamics and resulting structural style on material properties. For example, in models with listric fault seeds, sandstone facilitates localizations and thus allows fault tip propagation whereas shale tends to inhibit fault propagation,

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unless it is overconsolidated. Inter-layered sandstones and shales produce strongly disharmonic fold styles reminiscent of pinch-and-swell geometries observed in nature.

In this article, part 1 of a paired investigation, we discuss the structural styles which emerge in our numerical models. The mechanical aspects of our critical state fault-related fold models are discussed in part 2 (Albertz and Sanz, 2012).

2. Numerical method

The computations are based on a quasi-static explicit Lagrangian method. We employ the finite element analysis software Elfen (www.rockfield.co.uk). Elfen includes a sophisticated version of a cam-clay-based critical state constitutive model as well as adaptive remeshing. The latter is particularly useful for models with very large deformation because excessive mesh distortion can result in premature termination of the analysis. The finite element mesh is adaptively refined to achieve the following benefits (Crook et al., 2006b): (1) minimize the local error in the finite element solution; (2) ensure that deformation is appropriately captured, for example in regions of strain localization; and (3) optimize the total number of elements in the model domain by 'coarsening' elements in regions of low activity. Remeshing is triggered when a gradient error or mesh area distortion error exceeds 10%. Element size is varied non-linearly as a function of plastic strain (Table 1). Hence, not only does the model capture progressing plastic deformation, it also refines the mesh in regions of possible failure, whereas the element size increases in inactive zones.

After creating a new mesh, the displacements and history-dependent variables are transferred from the old mesh to the new mesh. For quasi-static solutions the loading rate is sufficiently slow that the solution can be directly mapped to the new mesh without significant loss of accuracy. The updated state is then evaluated using weighted least squares based procedures which map the primary, state, and contact variables (e.g., Crook et al., 2006b; Perić and Crook, 2004).

2.1. Initial and boundary conditions

The initial model configuration (Fig. 1) represents an idealized two-dimensional plane strain cross section with horizontally uniform layer properties. The overburden comprises ten layers with variable properties, each 300 m thick. The overburden is underlain by a mechanically uniform underburden which may be thought of as representing basement or sedimentary units. A fault seed with a listric or horizontal (Fig. 1) geometry is placed at 9 km depth (i.e., 3 times the overburden thickness). The fault seed is defined by a frictionless discrete contact. The tip of the seeded fault propagates by elastic–plastic deformation in a continuum mechanical, critical state fashion. The mesh of the model domain comprises ca. 70,000 (initial mesh) to 100,000 (final mesh after adaptation) triangular finite elements. Element size ranges from 300 (basement) to 35 (smallest adaptive element in overburden) meters. Remeshing parameters are defined in Table 1. In order for the numerical model to capture small-scale localizations as efficiently and early as possible, a ca. 43×3 km rectangular region with 75 m large elements is defined above the seeded fault.

Table 1
Adaptive mesh refinement parameters (values determined by sensitivity analysis).

Plastic strain	Element size (m)
0.0	100
0.1	65
0.3	55
0.5	45
0.7	35
1.0	35

The model base, the thrust fault footwall, and the left side of the model are fixed; horizontal displacement is applied to the right side above the fault seed to produce shortening and deformation. Shallowly dipping fault seeds in the numerical models have a longer fault line than steeply dipping faults seeds. Therefore, we define a slightly wider model for shallower dipping faults and conversely, a narrower model for steeper dipping faults.

2.2. Critical state constitutive model

We use a rate-independent elastic–plastic constitutive model based on critical state soil mechanics (Roscoe et al., 1958; Wood, 2007). A stress state inside the yield surface induces elastic deformation. Upon yielding, deformation proceeds elastic-plastically.

Elastic deformation is computed using a simple non-linear empirical relationship:

$$E = E_{\mathrm{ref}}\left[\frac{\sigma_3 + A}{B}\right]^{n_e} \tag{1}$$

where Young's Modulus, E, increases from a reference value, E_{ref}, as the most tensile principal stress, σ_3, becomes larger. A and B are material constants, and n_e is an exponent used to adjust the shape of the curve.

The yield envelope (Fig. 2) is defined by a smooth three-invariant surface that intersects the hydrostatic axis (i.e., x-axis) in both tension and compression:

$$\Phi(\sigma, \varepsilon_v^p) = g(\theta, p)q - (p - p_t)\tan\beta\left[\frac{p - p_c}{p_t - p_c}\right]^{\frac{1}{n_p}} \tag{2}$$

where effective means stress, $p = (\sigma_1 + \sigma_2 + \sigma_3)/3$, q is the deviatoric stress, θ is the Lode angle, p_t is the tensile intercept of the yield surface with the hydrostatic axis, p_c is the pre-consolidation pressure or compressive intercept of the yield surface with the hydrostatic axis, β (also termed 'friction parameter') and n_p are material constants that define the shape of the yield surface in the p–q plane. $g(\theta, p)$ is a function that defines the shape of the yield surface in the deviatoric plane defined as:

$$g(\theta, p) = \left[\frac{1}{1 - \beta^\pi(p)}\left(1 + \beta^\pi(p)\frac{r^3}{q^3}\right)\right]^{N^\pi} \tag{3}$$

with

$$\beta^\pi(p) = \beta_0^\pi \exp\left(\beta_1^\pi p \frac{p_c^0}{p_c}\right) \tag{4}$$

where β_0^π and β_1^π are material constants and p_c^0 and p_c are the initial and current pre-consolidation pressures, respectively, and

$$r^3 = \frac{9}{2}\mathbf{S}\cdot\mathbf{S} : \mathbf{S} = \frac{27}{2}J'_3 \tag{5}$$

where $\mathbf{S}$ is the deviatoric stress tensor and J'_3 is the third deviatoric stress invariant. The dependence of $\beta^\pi(p)$ on effective mean stress allows for a rounded-triangular shape at low p and a circular shape at high p (Fig. 2B).

The critical state line (csl, Fig. 2A) divides the plastic domain into a dilation and a compaction region. Yielding on the compaction side causes hardening and diffuse plastic deformation, whereas yielding on the dilation side induces softening and shear localizations. In order to achieve faulting (i.e., plastic shear bands) in the numerical models, yielding must occur on the dilation side of the yield surface. A stress state at the intersection of the critical state line and the yield surface induces isovolumetric plastic deformation.