Journal of Structural Geology 39 (2012) 199–209

Contents lists available at SciVerse ScienceDirect

Journal of Structural Geology

journal homepage: www.elsevier.com/locate/jsg

Localization patterns in sandbox-scale numerical experiments above a normal fault in basement

Sofie Nollet [a,c,*], Gisa J. Kleine Vennekate [b], Steffen Giese [b], Peter Vrolijk [c], Janos L. Urai [a], Martin Ziegler [b]

[a] RWTH Aachen, Structural Geology, Tectonics and Geomechanics, Lochnerstr. 4-20, 52056 Aachen, Germany
[b] RWTH Aachen, Chair of Geotechnical Engineering, Mies-van-der-Rohe-Str. 1, 52074 Aachen, Germany
[c] ExxonMobil Upstream Research Company, P.O. Box 2189, Houston, TX 77252-218, USA

ARTICLE INFO

Article history:
Received 23 June 2011
Received in revised form
7 February 2012
Accepted 22 February 2012
Available online 3 March 2012

Keywords:
Numerical modeling
Finite element
Localization
Faulting
Sandbox

ABSTRACT

The finite element program ELFEN is used to study the effect of basement fault dip on the evolution of shear band patterns in unconsolidated sand. The material properties and boundary conditions of the model were chosen to correspond to generic sandbox experiments.

Model results reproduce the range of structural styles found in corresponding sandbox experiments. With a basement fault dip of 60° and lower, a graben structure is formed, composed of a synthetic shear band followed by one or more antithetic shear bands. With a basement fault dip of 70° and steeper, a reverse (precursor) shear band forms first, followed by a synthetic, normal shear band that accommodates all further displacement. The dip of the synthetic shear band is close to the basement fault dip. For basement fault dips between 60° and 70°, we observe a transition in localization patterns. An analysis of the stress fields and velocity vectors in the model explains the first-order aspects of the relationships observed.

We consider the observed 'precursor-dominated' and 'graben-dominated' *structural domains* to be important components of normal fault systems in which the first order structural style and deformation patterns are only weakly dependent on the details of the rheology of the model materials and explore the interesting problem of the change in structural style from 'precursor-dominated' to 'graben-dominated' *structural domains* above a normal fault in basement. We find similar *structural domains* in sandbox experiments for the same set of boundary conditions but with slightly different material properties, suggesting that the modeled patterns are robust within these two *structural domains*, (i.e. will occur over a range of similar material properties and boundary conditions).

The results of this study contribute to our ability to validate numerical models against experiments in order to finally better simulate natural systems.

1. Introduction

In many sedimentary basins, sediments cover a faulted basement. In contrast to co-seismic faults, where stress changes cyclically (e.g. Nuechter and Ellis, 2010), the faults resulting in these sediments are more slowly moving and stress conditions approximate steady-state conditions. The location and the geometry of deformation in the overlying sediments is strongly dependent on these major basement faults and lineaments (e.g. Richard, 1991; Higgins and Harris, 1997; Bailey et al., 2005; Hardy, 2011; Taniyama, 2011). More specifically, sandbox experiments that model deformation in sand above a basement fault have demonstrated that the basement fault dip has an important impact on the resulting shear band pattern (Sanford, 1959; Horsfield, 1977; Tsuneishi, 1978; Withjack et al., 1990; Patton, 2005; Schöpfer et al., 2007a, b). Two classes of structural evolution have been observed in these studies, with "precursor-dominated" and "graben-dominated" shear band patterns. It is unclear which parameters control the change between these patterns and whether the experiments can be scaled to predict fault structures in nature (Mandl, 2000).

A method to explore this parameter space efficiently is through the use of numerical simulations (Kenis et al., 2005; Abe et al., 2011; Abe and Urai, 2012). However, it is an unsolved challenge to assign the appropriate constitutive relations with a complete set of accurately and independently measured material parameters in an attempt to achieve an exact correspondence between sandbox and numerical experiments.

---

* Corresponding author. RWTH Aachen, Reservoir-Petrology, Wüllnerstraße 2, 52056 Aachen, Germany. Tel.: +49 241 80 98273.
E-mail addresses: sofie.nollet@emr.rwth-aachen.de, sofie.nollet@gmail.com (S. Nollet).

0191-8141/$ – see front matter © 2012 Elsevier Ltd. All rights reserved.
doi:10.1016/j.jsg.2012.02.011

Here, we present a series of numerical models of the effect of basement fault dip on the evolution of shear bands in sandbox experiments. In this study we make the implicit assumption which is made in all similar modeling studies (e.g. modeling results in the BENCHMARK project, Buiter et al., 2006) that the first-order structural style and shear band patterns are only weakly dependent on the details of the rheology of the model materials within the corresponding fields of material properties. Therefore, within these fields, both sandbox experiments and numerical models tend to produce similar, i.e. robust patterns of shear bands that compare to faults in natural prototypes.

We define a *structural domain* as a set of faults or shear bands that develop with similar geometric and temporal characteristics. In our study of the effects of changing fault dip, we relate shear band geometry to the orientation of basement fault, to identify different *structural domains*, and we infer that corresponding *domains* are present in other deformation systems.

Geomechanical models also complement sandbox models by serving as the foundation upon which a deeper physical understanding of fault processes is built. For example, in previous work by Adam et al. (2005) , Holland et al. (2006), van der Zee et al. (2008), Schmatz et al. (2010), van Gent et al. (2010a,b) and Holland et al. (2011), it was shown that experiments which included the formation of precursors in layered models produced significant complexity in the evolving fault zone, such as relays, lenses and lateral variations in thickness of clay smear.

To the extent that the evolution of localization patterns dictates fault zone internal structure, it becomes imperative to understand the primary controls on different *structural domains*.

2. Methods

Traditional continuum modeling methods have limited capabilities for modeling spontaneous localization and large displacements on faults because of distortion of the numerical grid (e.g. Schultz-Ela and Walsh, 2002; van der Zee et al., 2003). Recent advances in numerical methods (both finite element and discrete particle modeling) now allow strains and displacements similar to those produced in sandbox experiments (e.g. Ellis et al., 2004; Panien et al., 2006; Crook et al., 2006, Gudehus and Karcher, 2006; Schöpfer et al., 2007a, b, Schöpfer et al., 2009a, b; Welch et al., 2009).

The finite element modeling approach in ELFEN is based on a quasi-static, explicit Lagrangian method with automated remeshing (Crook et al., 2006). The constitutive law for sand provides a hardening/softening model for the evolution toward a critical state surface where constant-volume plastic flow occurs at constant effective stress. This constitutive law is able to reproduce the experimentally observed response of sands in confined triaxial tests at large strains for a wide range of initial stress conditions, in contrast to the more commonly used Mohr-Coulomb constitutive models (e.g. van der Zee and Urai, 2005). This allows localization of deformation in the continuum, however the energy dissipation in the deformation bands is sensitive to the scale of the discretization. In other words, solutions depend on the element length scale rather than a physical material length scale. To avoid this, a fracture energy approach is included in the constitutive law that limits the global energy dissipation by setting a characteristic length. An adaptive mesh refinement process is incorporated to allow large shear strains. Remeshing is triggered by a combination of error estimators and mesh distortion indicators. For a more detailed description of the numerical approach of ELFEN, we refer to Crook et al. (2006), who have shown that by an appropriate choice of a constitutive law with generic (i.e. not measured precisely) properties for the model material, a good correspondence with the evolving first-order structures in sandbox experiments is obtained. The method used by Crook et al. (2006) is justified by the fact that the required set of material properties of model materials under the appropriate (i.e. stress) conditions has never been accurately and completely measured up to now, and doing this in the future requires significant development of instrumentation.

The geometry and boundary conditions of the numerical model in this study are chosen to represent typical conditions in corresponding sandbox experiments (e.g., Adam et al., 2005; Schmatz et al., 2010; Horsfield, 1977), with the additional assumption of plane strain (Fig. 1). The sand is 400 mm wide and 140 mm high and overlies a faulted stiff basement with variable normal fault dip. A Coulomb friction interface model is defined to represent the contact between sand and the basement. The top of the model is a free surface.

The finite element mesh is composed of unstructured quadrangles with an initial element size of 4 mm (Fig. 2a). Adaptive remeshing is allowed in two regions to create a finer mesh when a threshold strain is reached. The first region includes the complete overburden and the basement, and the second region contains only the area where localization with large shear strain and high strain gradients is expected to occur (Fig. 2b). In the second region we assigned a minimum element size of approximately 2.0 mm to obtain a shear band width corresponding to that in sandbox experiments (Fig. 2b).

The model runs in two stages: (1) a settling stage and (2) a fault displacement stage. In the settling stage, the equilibrium stress state under a gravitational body force is reached (Fig. 1a). In the displacement stage, the shear process is simulated using the boundary conditions shown in Fig. 1. The maximum displacement on the basement fault is set to 58 mm. (Fig. 3).

A material grid is defined for the overburden part of the model to allow visualization of the deformation independent of remeshing. A set of points, attached to the material grid, is defined to monitor the displacements and velocities in selected points and fault blocks of the model. This significantly increases the calculation time and therefore, only these two properties are monitored in this study.

Material properties (Table 1) are chosen to represent generic sand that is estimated to be typical of existing sandbox experiments. Because at present there is no technique available to completely and accurately measure the properties of materials used in sandbox experiments at the appropriate stress conditions, we do not aim to use precisely and independently measured parameters to accurately match all measurables in our simulations. The parameters used correspond to an “usual” drained sand modeled using an elasto-plastic constitutive law with non-linear elasticity and an initial yield surface (Fig. 4) which is plastic-strain-dependent defined. The basement is modeled as elastic with a Young’s modulus of 2.1×10^8 kPa and a density of 7860 kg/m^3. We realize that such a sharp material contrast may be unrealistic in nature and future numerical models could help in understanding its impact on deformation in the overlying sediments.

We varied the basement fault dip between 0° (horizontal block motion) and 90° (trapdoor), in steps of 10° to analyze its impact on the deformation patterns in the overlying sand package. Based on the results of these analyses we subsequently ran a series of additional experiments, varying basement fault dip in 1° increments, between 60° and 70°.

3. Results

3.1. Localization patterns and orientations

A constant basement fault displacement value of 29 mm was selected to compare deformed material grids (Fig. 4). In addition,