Journal of Structural Geology 55 (2013) 101–113

Contents lists available at ScienceDirect

Journal of Structural Geology

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

Inverse method applied to a sand wedge: Estimation of friction parameters and uncertainty analysis

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ARTICLE INFO

Article history:
Received 24 January 2013
Received in revised form
15 July 2013
Accepted 18 July 2013
Available online 1 August 2013

Keywords:
Inverse problem
Thrusting sequence
Physical modelling
Numerical simulation
Accretionary wedge

ABSTRACT

We examine the fundamental mechanism of frontal accretion in a sand wedge from the occurrence of a forward thrust ramp evolving into a fault-bend fold to the jump of deformation to a new frontal ramp ahead. We use inverse problem theory to extract quantitative information on friction parameters from the systematic comparison of experimental observations and theoretical predictions. The observables are locations, dips and lifetime of thrust ramps, hinge and associated compression. The experimental values (observed data) are cast into statistical models describing the error bars. The theory of limit analysis provides calculated data, requiring five parameters : material density, friction coefficient of the décollement plane, friction coefficient of the bulk material, and the variation of friction with slip on the ramp as well as the distance for this variation. The misfit between observed data and calculated data is determined for all physically admissible values of the parameters. Values yielding a small misfit are interpreted as highly probable. The mean misfit per observable is within their error bars and therefore application of the theory reproduces the observables. Bulk and décollement friction coefficient values with high probability are compared to independent measurements. The inversion also reveals systematic discrepancies: the frictional weakening on the ramps is overestimated, while the force is underestimated, the calculated thrust sheet is longer than observed and the calculated jump to a second ramp occurs earlier than observed. These conclusions allow us to identify necessary improvements for the experimental set-up and of the theoretical assumptions.

1. Introduction

Frontal accretion is a basic growth mechanism of accretionary wedges and of fold-and-thrust belts. Despite its geometrical simplicity, it involves the spontaneous occurrence of frictional surfaces, the thrusts, and the accumulation of large slip on discontinuities, e.g., the décollements. This spontaneous occurrence is a long recognised challenge for numerical methods based on a continuous description of matter (Leroy and Ortiz, 1989). For geological applications of numerical approaches, substantial progress has occurred in the last twelve years with respect to capturing strain localisation (Strayer et al., 2001; Panian and Wiltschko, 2007; Stockmal et al., 2007), although discrepancies remain between the different implementations and methods (Buiter et al., 2006). Simultaneously, small-scale physical experiments using sand or other granular materials as analogues to frictional sediments have also progressed (impact of physical properties on experimental outcomes (Lohrmann et al., 2003), reproducibility of the results between different laboratories (Schreurs et al., 2006), estimation of error bars (Cubas et al., 2010), and identification of experimental biases (Souloumiac et al., 2012)). Thus, comparison between numerical and physical model experiments is becoming feasible, and they are useful because of the near absence of exact, non-trivial mechanical solutions beyond the critical Coulomb wedge theory (Dahlen, 1984). These comparisons are based on a trial-and-error approach and on qualitative observations of 2D cross-sections (Smart and Couzens-Schultz, 2001; Ellis et al., 2004; Del Castello and Cooke, 2007; Hardy et al., 2009), or on the total width of the accretionary wedge (Cruz et al., 2010), or on thrust dips (Maillot and Koyi, 2006; Egholm et al., 2007). Now one can go beyond trial-and-error to pose the problem of fitting experimental and numerical results using the theory of inverse problems to gain new insights from the comparisons. Maillot et al. (2007), for example, proposed an inversion of experimental data for thrust dips in a stationary geometry to retrieve their friction coefficients. The ambition of the present article is to analyse experimental data about the formation of a

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http://dx.doi.org/10.1016/j.jsg.2013.07.003

thrust sheet from the activation of a décollement and the associated pop-up to the transfer of activity to a new forethrust ramp, using inverse problem theory. In doing so, we will determine the range of friction coefficients for the décollement and the bulk material and of their evolution with deformation that are compatible with the data (i.e., that yield numerical simulations resembling the observations).

2. The experiments

We briefly recall the experiment of Cubas et al. (2010) and the description of the results by statistical laws, which constitute the starting point of the inverse problem considered here.

2.1. Experimental setup

The experiment consists of shortening a sand wedge resting on a flat sand layer (Fig. 1). The experimental box is made of glass treated with a carbon-based product to reduce friction with sand. The shortening force was monitored by strain gages placed at the back wall during shortening. Generally, the first 4–5 mm of shortening are accommodated by diffuse compaction, during which the force increases. The sand then deforms by the formation of two conjugate reverse faults called forethrust 1 and backthrust 1 (Fig. 1b). Continued shortening displaces the wedge over the forethrust creating new relief, until a second forethrust–backthrust system forms (Fig. 1c). The experiment is stopped after a total shortening $S = 30$ mm (Fig. 1d).

2.2. Experimental outcomes : observed data

Eight observables are measured during or after the experiment. Six were measured from photographs of cross-sections in the final stage, using the offset of strain markers in the sand (Fig. 1d): the dips γ_1 and θ_1 of the first forethrust and backthrust; the dips γ_2 and θ_2 of the second forethrust and backthrust; the position of the first

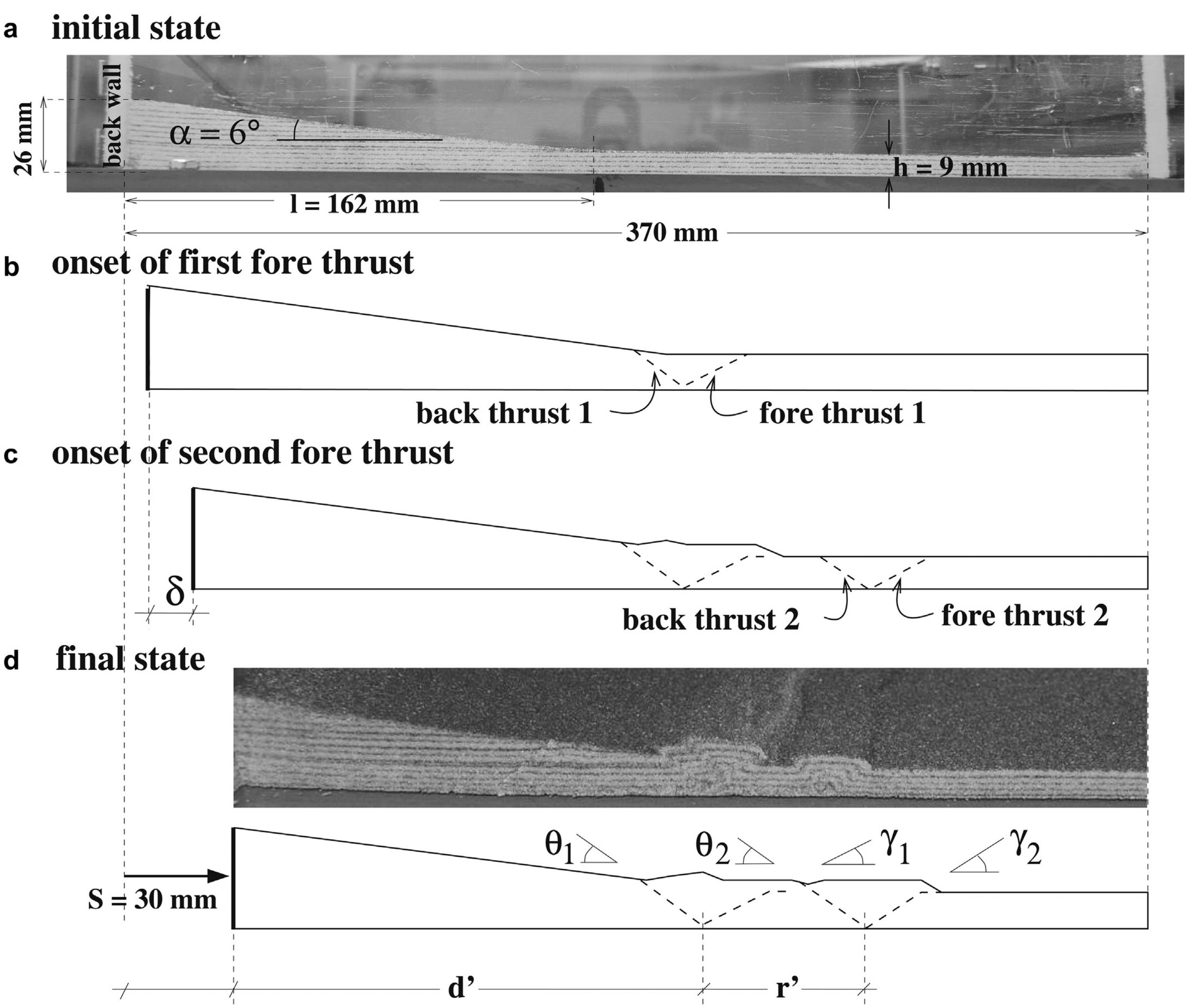

Fig. 1. Experimental setup and observables. a) The initial conditions. b) After about 5 mm of shortening a first forethrust–backthrust pair appears. c) After additional shortening, δ, slip stops on the first forethrust, and a second fore- backthrust pair appears further ahead. d) After total shortening $S = 30$ mm, measured backthrust dips θ_1 and θ_2, and forethrust dips γ_1 and γ_2, and the distances d' and r', using photograph. The seven observables are θ_1,γ_1,θ_2,γ_2,δ,$d = d' - l$, and $r = r' - h/\tan(\gamma_1) - h/\tan(\theta_2)$. The width of the box (perpendicular to the figure) is 280 mm.