Journal of Structural Geology 33 (2011) 731–742

Contents lists available at ScienceDirect

Journal of Structural Geology

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

Influence of combined incision and fluid overpressure on slope stability: Experimental modelling and natural applications

Aurélien Lacoste [a,*], Bruno C. Vendeville [a], Lies Loncke [b]

[a] UMR 8157 Géosystèmes, Université de Lille 1, Bâtiment SN5, 59655 Villeneuve d'Ascq Cedex, France
[b] Université de Perpignan, Via Domitia, Laboratoire IMAGES, Bat U, 2e étage, 52 avenue Paul Alduy, 66800 Perpignan, France

ARTICLE INFO

Article history:
Received 11 September 2009
Received in revised form
14 January 2011
Accepted 29 January 2011
Available online 1 March 2011

Keywords:
Landslides
Fluid overpressure
River incision
Analogue modelling

ABSTRACT

Onshore slides are driven by gravitational forces that are either related to a basal or a surface slope. Resisting these driving forces are the friction at the base of the slide, and the strength to compressional failure at the downslope edge of the slide. Two distinct processes can reduce these resisting forces and thereby promote slides. On one hand, fluid overpressure at the base of low-permeability layers decreases the effective stress, shifting the Mohr circle closer to the failure envelope. On the other hand, river incision removes the downslope buttresses. We undertook analogue experiments to investigate the combined influence of both processes on promoting landsliding. We applied air pressure at the base of horizontal or tilted models made of high and low-permeability layers to induce basal overpressure, combined with local incision similar to river incision in nature. We also tested the differences in deformation as a function of whether the incision was continuous throughout the models' evolution.

No deformation occurred in the regions not subjected to overpressure. In models subjected to continuous incision, normal faults formed first along the valley flanks, then propagated upslope retrogressively. Where incision was not continuous through time, a downslope buttress progressively formed with the sliding mass comprised of an extensional domain upslope, a long, translated but non-deformed slab at mid-slope, and a shortened domain downslope. In our models, the size of the deformed area increased with incision depth and/or increasing basal slope. These results show that river incision, combined with fluid overpressure is a potential landslide-triggering factor, as suggested by field data gathered at the Waitawhiti landslide complex, North Island, New Zealand.

1. Introduction

A slope instability requires that the driving force (the slope-parallel component of the weight along the sliding section) must exceed the two forces resisting deformation: the frictional force along the slope-parallel sliding plane, and the force resisting shortening at the base of the slope (Terzaghi, 1959). The first resisting force can be reduced by the presence of overpressured fluids. Fluids accumulating at the base of low-permeability layers induce a critical decrease in effective stress (Terzaghi, 1923; Hubbert and Rubey, 1959; Mourgues and Cobbold, 2003, 2006), and therefore can generate gravitational slides (Amazon deep-sea fan, Cobbold et al., 2004; Niger delta, Weber and Daukoru, 1975; Hooper et al., 2002; "Storegga slide", Kvalstad et al., 2005).

Rising fluids, such as water, methane or hydrogen, can easily be detected in marine environments when they reach the surface, forming pockmarks or gas chimneys. The development of high-resolution tools, such as seismic reflection, well logging and bathymetric imagery, has revealed frequent associations between fluids originating at depth and the onset of submarine mass movements (Hovland et al., 2002; Gay et al., 2004; Lastras et al., 2004; Loncke et al., 2004; Sultan et al., 2004; Trincardi et al., 2004; Bayon et al., 2009).

By contrast, when dealing with instabilities located onshore, the traditional approaches consider only meteoric fluids. Intense rainfall and subsequent subsurface water flows lead to increased pore-fluid pressure, reducing the effective stress along hillslopes (Binet et al., 2007) and causing landsliding (e.g., Taïwan, Chen et al., 2006). Rainfall-induced landsliding may be enhanced by the presence of clay-rich layers (e.g., swelling clay, such as smectite) that can act as very efficient décollement layers (Shuzui, 2001). On one hand, swelling of the clay-rich layers induces a pervasive decrease in the mechanical strength, and sliding takes place *on* or *near the top* of these layers. On the other hand, overpressured fluids originating at depth and migrating upward can cause a drastic reduction in the effective stress *along the base* of low-permeability layers, which

* Corresponding author. Tel.: +33 3 20434692; fax: +33 3 20434910.
E-mail address: aurelacoste@gmail.com (A. Lacoste).

0191-8141/$ – see front matter © 2011 Elsevier Ltd. All rights reserved.
doi:10.1016/j.jsg.2011.01.016

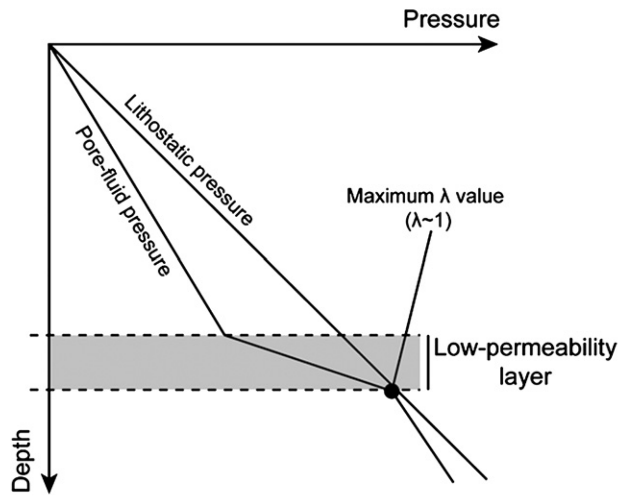

Fig. 1. Theoretical diagram showing change with depth in the lithostatic and pore-fluid pressures. Note that the coefficient of fluid pressure (λ) reaches maximum values at the base of low-permeability layers, where the two pressures are equal (Mourgues and Cobbold, 2003).

then can act as a very sharp detachment (Osborne and Swarbrick, 1997; Mourgues and Cobbold, 2003, 2006).

Recent work by Lacoste et al. (2009) documented the presence of onshore landslides associated with gas seeps and river incisions. They proposed that overpressured fluids originating at depth could be one of the main instability factors controlling this area. However, onshore study of fluids originating at depth and rising to the surface is more complicated than in submarine environments. The observation of the fluid seeps is only possible with the sparse occurrence of mud volcanoes, or in water-filled ponds and streams. Furthermore, monitoring fluid overpressures and their links with landsliding would require time, as ongoing activity of sliding was not clearly attested in the field (Lacoste et al., 2009), and additional logistics, such as piezometers and fluid sensors, whose maintenance would be costly, due to their location in remote streams subjected to seasonal flooding and livestock damage. One approach is to complete detailed field analyses and to determine the potential role of such fluids on landslides by coupling field observations with numerical and/or physical modelling.

The second type of force resisting deformation is the resistance to shortening in the downslope part of the slided mass. Schultz-Ela and Walsh (2002) and Azañon et al. (2005) showed that the removal of distal buttresses by river incision decreases the resisting force downslope and can be an important predisposing factor for gravitational slides. These authors showed that gravitational motion initiated where the river has incised down to potential *décollement* layers (evaporites or shale).

In the Coastal Ranges of the North Island of New Zealand, in the Waitawhiti area, Lacoste et al. (2009) suggested that a strong link exists between landslides, fluvial incision and fluid overpressure. However, on the sole basis of field data, it remains difficult to prove unequivocally that such a link exists. We therefore tested this hypothesis using a series of analogue experiments to delineate the respective roles of combined incision and fluid overpressure on the triggering, structure pattern and evolution of landslides. We then compared the models to natural onshore and marine prototypes, and discussed the influence of combined incision and fluid overpressure on these slides.

2. Scaling

Small-scale models require scaling of the different parameters controlling deformation. The dimension and time ratios between the natural prototype and the experimental model must be constant (Hubbert, 1937; Ramberg, 1981). In this work, we constructed models made of porous, near cohesionless granular materials (quartz sands and glass microbeads) that all obey a Mohr-Coulomb deformation criterion, a frictional-plastic rheological behaviour independent of time and strain rate.

For a brittle model to be properly scaled, it suffices that the density and angle of internal friction be similar in nature and model, and that the value of the cohesion be negligible compared with the other stresses, including gravity, in both models and nature. The mechanical effect of pore-fluid pressure was modelled by injecting a constant flux of compressed air at a precalculated pressure at the model's base. An increase in fluid pressure leads to an increase in the coefficient of fluid pressure (λ) (or Ru). The coefficient of fluid pressure is defined, for any given depth, as the ratio between the fluid pressure and lithostatic pressure, $\lambda = 0$ meaning that fluid overpressure is absent (Fig. 1):

$$\lambda = \left(P_f(z) - P_f(0)\right) / \rho g z$$

A model is properly scaled for fluid pressure if the value of the coefficient of fluid pressure is similar in nature and model at proportionally equivalent depths. Prior to constructing the models, we calculated the layer thickness required to reach a coefficient of fluid

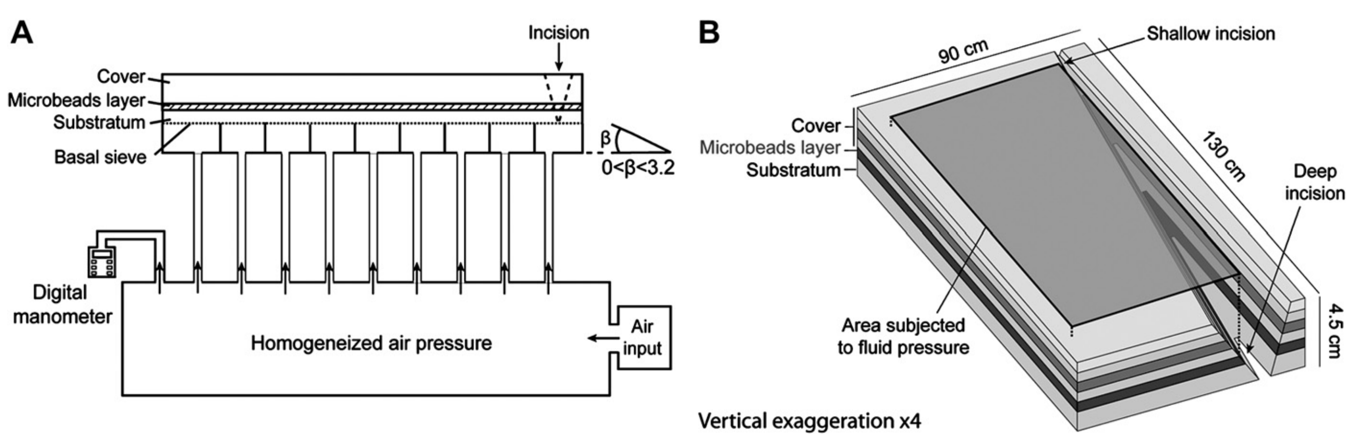

Fig. 2. Experimental set-up. (A) Schematic cross section view of the experimental set-up. (B) 3D view of the models showing differential incisions and the area subjected to fluid pressure.