Engineering Geology 177 (2014) 54–65

Contents lists available at ScienceDirect

Engineering Geology

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

Progressive shear-surface development in cohesive materials; implications for landslide behaviour

J.M. Carey [a,*], D.N. Petley [b]

[a] GNS Science, 1 Fairway Drive, Avalon, Lower Hutt 5010, PO Box 30368, New Zealand
[b] Department of Geography, Durham University, Durham DH1 3LE, UK

ARTICLE INFO

Article history:
Received 13 February 2014
Received in revised form 14 May 2014
Accepted 19 May 2014
Available online 29 May 2014

Keywords:
Landslides
Strain localisation
Microcracks
Failure
Deformation

ABSTRACT

The aim of this study was to investigate mechanisms of progressive shear surface development using a series of specialised triaxial cell tests. Intact and remoulded samples of Gault Clay from the Ventnor Undercliff on the Isle of Wight in southern England were subjected to pore pressure reinflation (PPR) testing in a triaxial cell, in which failure is generated by increasing pore pressure under a constant total stress state. In addition, a novel very long term (>500 days) creep test was undertaken, in which the sample eventually failed at a constant stress state below the failure envelope.

The experiments showed that undisturbed samples of the Gault Clay failed in a brittle manner, generating a linear trend when plotted using the Saito technique. On the other hand, remoulded samples showed ductile behaviour, as indicated by a non-linear Saito trend. A number of otherwise identical PPR tests were conducted in which the rate of increase in pore water pressure was varied. These tests showed that strain rate generated at any point in the PPR tests depended on both the effective stress and the rate of change of effective stress. The latter is important because a change in stress generates a change in strain. Thus, whilst tests at different rates of change of effective stress are similar when plotted in q–p′ space and in strain–p′ space, they are markedly different in strain rate–p′ space.

The long term creep test failed when the stress state had been constant for over 80 days. This mechanism was reminiscent of creep rupture, occurring below the failure envelope defined in the conventional experiments.

We conclude that first time failure in the Gault Clay is a progressive mechanism dominated by the development of micro-cracking, which leads to strain localisation and the development of one or more shear surfaces at failure. Whilst this mechanism may usually occur in response to a change in stress, the study indicates that failure can develop progressively. In the remoulded Gault Clay shear strains cannot localise along a singular shear surface.

The results provide new insight into the mechanisms of landslide movement operating within the Ventnor landslide complex and indicate that present movements are likely to be occurring on a pre-existing shear surface. The lab tests suggest that this material is unlikely to undergo catastrophic failure.

1. Introduction

Progressive failure in landslides has been long identified (Terzaghi, 1950), and was conceptualised over 40 years ago (Bjerrum, 1967). The essence of the process for a simple translational landslide is that progressive failure requires time-dependent deformation of material forming the landslide shear surface (Federico et al., 2004). Laboratory and field based studies undertaken by Varnes (1983) and others have shown that brittle landslide materials progress through three distinct phases of creep to failure, in common with separate observations within the damage-mechanics literature (Main, 2000 for example). In the latter case three-phase creep behaviour is conceptualised as being the result of contrasting strain hardening and strain weakening processes, in which strain hardening initially dominates but is subsequently superceded by strain weakening. In both the models and the laboratory observations a gradual decrease of the factor of safety (FoS) is observed as damage accumulates through time.

Despite these observations progress in understanding the relationships between material deformation and the resultant movement of a slope have been surprisingly limited, although some progress has been made in recent years (e.g. Voight, 1988; Iverson, 2005; Petley et al., 2005a,b,c; Liu, 2009; Ng and Petley, 2009; Ostric et al., 2011). The renewed interest in this topic has been driven at least in part by the need for better models to underpin strategies to reduce the losses from, and to manage the risk posed by large, brittle landslides. In many cases, failure cannot be prevented due to the size of the unstable slope, the difficulty of accessing it and/or the potential cost of large-scale engineered interventions. Thus, recent research has focused on the development of an understanding of the mechanisms and processes of progressively failing landslides in order to allow predictions to be made for likely patterns of behaviour. In principle, such methods could provide powerful tools to underpin landslide warning systems.

* Corresponding author.

http://dx.doi.org/10.1016/j.enggeo.2014.05.009
0013-7952/

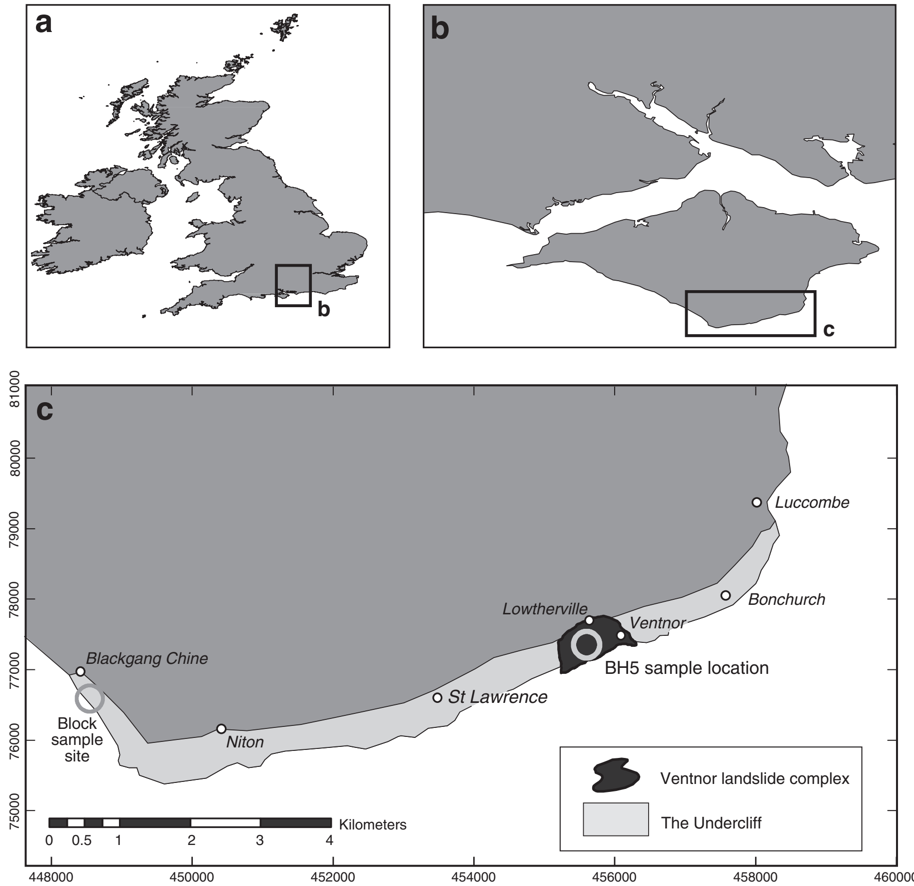

Fig. 1. The location of the Ventnor Undercliff, Isle of Wight, UK.

The so-called 'Saito approach' (Saito, 1965), and its subsequent developments (Fukuzono, 1990 for example), has been the key technique for analysing progressive failure. The approach is based on the concept that the time to failure can be estimated by identifying a linear trend in inverse velocity (1/v, where v is velocity)–time space as the landslide approaches failure. Using this method, time to failure can be estimated from the extrapolation of the inverse velocity trend to zero (i.e. the point at which the velocity of the slope is theoretically infinite). Petley et al. (2002) and Kilburn and Petley (2003) linked the linear trend to micro-crack development and shear-surface development. This crack-propagation model provides a theoretical explanation of why the development of strain rate with time in a brittle material is a hyperbolic function (i.e. why it yields a linear trend in 1/v–t space, as the inverse rate of displacement changes linearly with time). An alternative model lies in the rate- and state-dependent friction (e.g. Helmsetter et al., 2003), but the observation that non-brittle materials show a non-linear trend in 1/v–t space favours the crack-propagation model, and is also consistent with the model of Bjerrum (1967).

Whilst such methods have been successful as predictors for some slope failures (e.g. Voight, 1988; Fukuzono, 1990; Petley et al., 2002), in general approximating the time to failure of landslides remains uncertain. This, in part, is because the physics controlling the deformation to failure has yet to be fully elucidated (Hutchinson, 2001a). The observations of Petley et al. (2002) and Petley and Petley (2006) suggest that the Saito technique is only applicable in brittle materials, which can yield a linear trend in 1/v, t space.

To determine the safety and future potential of landslide initiation and reactivation, a detailed understanding of the physical, hydrological and geotechnical properties of materials is essential (e.g. Hutchinson, 1967; Varnes, 1978; Hutchinson, 1984, 2001b). However, generating laboratory-based geotechnical data that can be compared with field-based landslide monitoring records has remained complex. One significant limitation is that conventional geotechnical tests generate failure by increasing deviator stress at a constant displacement rate. Most rainfall-induced landslides occur as a result of increasing pore pressure acting within the slope, which reduces mean effective stress at approximately constant deviator stress. Thus, standard geotechnical tests are not well-suited to defining the true failure envelope in such conditions (Zhu and Anderson, 1998; Orense et al., 2004) although they are optimised for providing conservative strength parameters for design purposes.

A range of novel testing procedures has been developed to simulate failure conditions resulting from elevated pore pressures (Brand, 1981; Anderson and Sitar, 1995; Zhu and Anderson, 1998; Dai et al., 1999; Orense et al., 2004 for example). The key feature of these studies has often been the concept of increasing pore pressure within a sample at constant total normal stress and shear stress – the so-called "field" stress path, but termed by Petley et al. (2005a) and subsequent papers the pore pressure reinflation (PPR) test (e.g. Petley et al., 2005b; Carey et al., 2007; Ng and Petley, 2009). Whilst these tests have yielded useful results, their applicability to understanding landslide behaviour has been limited. Often the rationale behind rates of pore pressure reinflation has not been considered in detail and the system capabilities for controlling pore pressures and deviator stress acting on the sample have been inadequate. Interpretation of the results has often focussed on the form of the Mohr–Coulomb failure envelope. In addition, testing has focused largely on tropical and subtropical soils, which mainly comprise weathered soils subject to shallow failure (<5 m) in intense rainfall conditions. As a consequence testing has been skewed toward understanding residual-strength materials at low effective stresses and high rates of pore-pressure reinflation.

Further research is required to link movement patterns in both first-time landslides and reactivation failures to the patterns and