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Plastic and viscous shear displacements of a deep and very slow landslide in stiff clay formation

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ABSTRACT

Deep and superficial displacements have been measured since 2005 in a slow active landslide that has occurred in a stiff clay formation of the Italian Southern Apennines. Recently, new inclinometer casings have been installed to achieve further information on the displacement field. In this paper, standard inclinometer profiles and fixed-in-place probe data are analysed over time. New data confirm previous hypotheses on geometry and kinematics and add more information on the viscous component of displacements. The mechanism of movement, in most of the track, essentially corresponds to sliding localized on a shear surface, consistently with stress and strength distribution. However, locally, internal viscous deformations also occur, especially in the weathered and softened zones of the landslide, and contribute to the soil discharge continuity. Viscous displacements can be interpreted by a simplified rheological model based on the Bingham equation. The residual shear strength has been considered as the creep threshold value and the dynamic viscosity has been considered dependent on the stress level, on the basis of long term direct shear tests under controlled shear stresses which were carried out in laboratory.

1. Introduction

Deep and slow landslides are often known to be the cause of severe damage to structures and infrastructures (among others: Picarelli and Russo, 2004; Cascini et al., 2005; Mansour et al., 2011). They represent complex cases in which "land managers oscillate between the decision to live, even though precariously, with landslides, and the one to construct stabilizing work, often expensive and sometimes useless" (Picarelli, 2011). A reliable decision should be based on a deep understanding of the landslide behaviour. However, the displacement rate is often so low that very long term monitoring is required for a satisfactory evaluation of the landslide kinematics. Moreover, the comprehension of the mechanism of movement and of the relative effects of the different influencing factors requires an accurate evaluation of the time trend of movement. A relatively high frequency of data recording is thus necessary.

A long term and frequent monitoring could allow to distinguish movements caused by effective stress variations from those of viscous type. Data reported in the literature actually suggest that creep probably plays a major role in controlling the movement of deep seated landslides (Picarelli and Russo, 2004).

The aim of this paper is to analyse the displacements of a typical clayey deep seated landslide to reconstruct its displacement field and to evaluate the role of creep on its movements.

The *Costa della Gaveta* landslide occurs in a tectonized clay shale formation. Up to 38 m deep, the landslide is from very slow to extremely slow (Cruden and Varnes, 1996), with the average displacement rate increasing in the downslope direction. In correspondence to the landslide head – which is the fastest zone of the landslide – a house has recently been evacuated. In the middle of the track, the displacement rates are in the order of 1 cm/year; only a few houses have been built there in the last twenty years, and they still seem unaffected by the slope movements. The landslide foot is the slowest part (<1 mm/year). It is crossed by a highway and by the national railway and several buildings arise on it.

The displacements of the landslide are being monitored with continuity since 2005 with several types of techniques. The main geometrical and kinematic features were outlined by Di Maio et al. (2010), as summarized in Section 2. In the last two years, the study has gone on with further in situ and laboratory measurements and tests. Recently, new boreholes (I9b, I9c and I12, Figure 1) have been driven and equipped with inclinometers.

The analysis and the comparison of new and previous data reveal further interesting features of the landslide. The results of inclinometer measures carried out periodically by manual probe and "continuously" by some fixed-in-place probes allow to hypothesize the displacement rate field in the landslide body. As typical of active deep-seated slides in stiff clays and clay shales, the kinematics in most of the track essentially corresponds to localized sliding (Leroueil et al., 1996). However,

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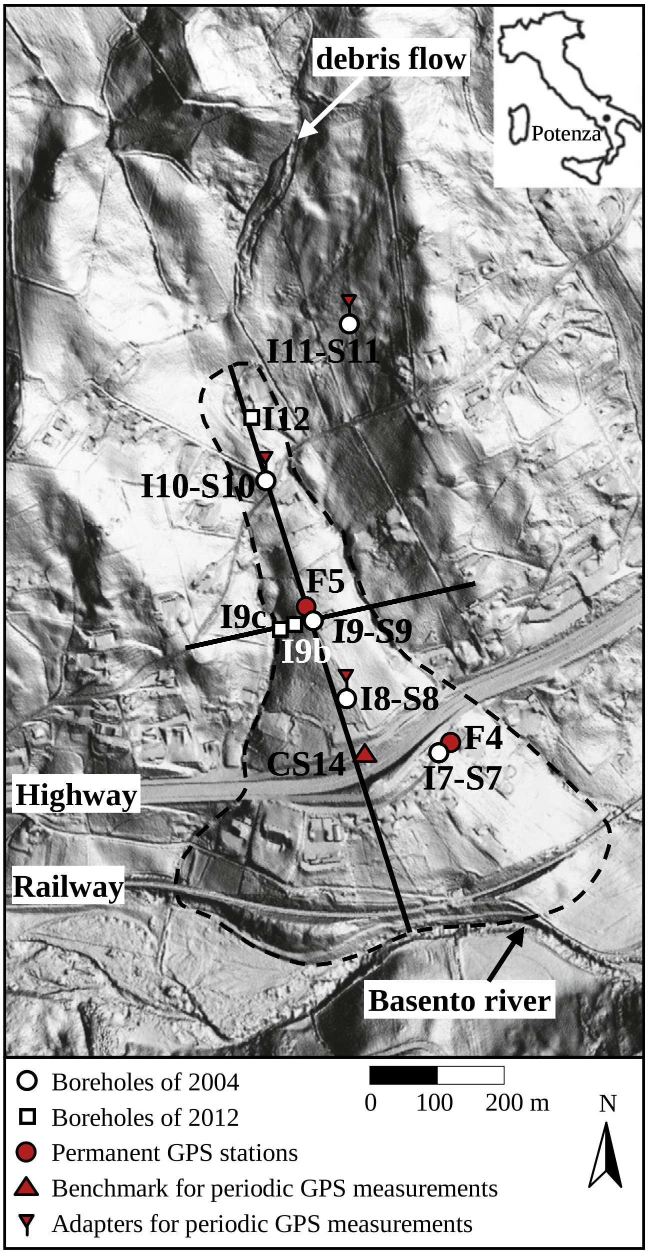

Fig. 1. Costa della Gaveta landslide with the location of inclinometers (I), piezometers (S) and GPS stations.

as years go by, the contribution of internal strains to total displacements can no longer be considered negligible. To evaluate whether the internal strains can be interpreted as secondary viscous shear deformations, a simplified rheological model was used, based on the Bingham fluid, following a procedure proposed by Van Asch and Van Genuchten (1990). In order to investigate the attitude of the material to undergo shear creep, to evaluate the creep threshold values and the flow parameters, long term direct shear tests under controlled shear stresses were carried out both on "intact" specimens and on specimens previously sheared to the residual conditions. The role of strength regain on the creep behaviour of the shear zone is discussed.

2. Main results of previous studies on the landslide geometry and kinematics

The landslide under study occurs in a slope of a hill facing the valley of the Basento river, in the site called *Costa della Gaveta*, east of Potenza, Italy (Figure 1). It is an active landslide, in a tectonized clay formation of marine origin locally known as *Varicoloured Clays*. The landslide is characterized by a large well-defined fan-shaped foot, a track with regular flanks and a wide zone of depletion. This latter is almost empty but upslope, in the head scarp, a shallow rapid debris flow – carrying the material of the overlying *Corleto Perticara* rock formation (Di Maio et al., 2010) – has recently moved some ten metres in a few days, clearly indicating that the hazard level of the area is very high (Fell et al., 2008).

Di Maio et al. (2010) outlined some geological and geomorphological characters of the Costa della Gaveta slope and reported a reconstruction of the 3D geometry of the landslide. The trace of the slip surface in the median longitudinal section was drawn on the basis of inclinometer profiles (Figure 2c). Furthermore, the flanks of the track (Figure 2a) were considered as a part of the original slip surface nowadays outcropping. The flanks were interpolated by families of planes whose extension towards the middle of the track, beneath the landslide body, was considered as the current slip surface. Fig. 2a reports the stereoplot of the families of interpolating planes. Details of this reconstruction are reported in Di Maio et al. (2010). On the basis of such elaboration, some cross sections of the landslide body were drawn (Figure 2b). The section areas were found to increase greatly in the downslope direction.

Inclinometer profiles obtained in the first years were practically uniform from the slip surface to the ground, i.e., sliding along the slip surface could be considered the prevailing mechanism of the landslide displacements. The rate of displacement was found to decrease noticeably from upslope to downslope, i.e. from inclinometer I10 to inclinometer I7 (Figure 2c), as will be discussed in detail in Section 5. Under the hypothesis that the displacements were uniform not only along the inclinometer vertical but also in each entire cross section of the track, the "soil discharge" was found practically of the same value in the different transversal sections (Figure 2d). Following D'Elia (1975), the hypothesis of uniform displacements was advanced on the basis of the soil properties and of the landslide stress state. In fact: *a*) laboratory test results showed that the peak strength of the material of the landslide body is much higher than the residual strength; *b*) the results of stability analysis showed that the available strength on the slip surface is close to the residual strength determined by laboratory tests; *c*) shear stresses within the landslide body calculated by Vassallo et al. (2013) are very close to the residual shear strength. According to Ter Stepanian (1963), Suklje (1969) and Yen (1969), creep can occur for shear stress values between the peak strength and the residual shear strength. For shear stresses close to the residual strength, like those determined in the landslide body, the creep rate is very modest.

However, approximately 7 years after the beginning of monitoring, the contribution of internal deformations to surface displacements no longer appears negligible, although it is lower than that of sliding. Furthermore, recent data (boreholes I9b and I9c) suggest that in some zones of the landslide such contribution can provide a noticeable percentage of total displacements.

Among the possible triggers of movement, erosion at the toe and rain have been considered. Vassallo et al. (2012) reported that, apparently, river erosion at the toe had caused the removal of part of the accumulation which, in turn, had caused a local slide, with a roughly circular scarp (Figure 2a). Consistently, limit equilibrium calculations showed that the hypothesized removal of soil causes a noticeable reduction in the safety factor of the foot. Moreover, a simplified linear elastic–perfectly plastic 2D FEM analysis showed that stress release caused by the removal of part of the foot can explain the mobilisation of both the material in the accumulation and that in the track. Actually, inclinometer data show that in the accumulation, even where the slope is very gentle (close to inclinometer I7) the material has not come to a stop.

Pore pressure distribution was determined by Di Maio et al. (2010) under simplified hypotheses. The authors used piezometer