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Measured response to a drainage adit in a deep creeping slide mass

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ABSTRACT
Down slope deformations of the Campo Vallemaggia landslide in the southern Swiss Alps have been reported for well over 200 years. The average rate of deformation has been measured as being approximately 30 cm/year, with a minimum of 1 cm/year and a peak of 5 cm/day (reported in 1940). Although these rates could be described as creep deformations, other mechanisms relating to multiple slip surfaces are viewed as being equally critical. Following an in-depth study between 1984 and 1991, a decision to stabilize the slope through the construction of a drainage adit was undertaken. This paper reports the findings and the interpretation of an extensive *in situ* monitoring program with respect to the measured response of the slope before and after implementation of the drainage adit system.

INTRODUCTION

The Campo Vallemaggia landslide is located in the crystalline penninic nappes of Ticino, in southern Switzerland, 50 km NW of Lugano. Two small villages, Campo Vallemaggia and Cimalmotto, are located on the toe of the slide mass from which surface displacements have been geodetically measured for over 100 years. Surface and borehole investigations of the Campo Vallemaggia landslide have shown that the unstable mass incorporates approximately 800,000,000 m^3 of weathered and intact rock.

The geology of the slide mass can be described as a metamorphic series consisting of amphibolite and micaceous schists, several types of gneiss, ultramafic metaperidotites and metacarbonates. The geological structure is characterized by isoclinal folding, dipping 30° SSE, with amphibolitic formations positioned at the core of the fold. A brittle fault system crosses the region in a NNW-SSE direction and divides the landslide body into distinct blocks (Figure 1). These longitudinal blocks can be described as displaced clusters of rock which are primarily intact higher up near the head of the slope and pass gradually to a highly weathered material towards the toe.

The unstable mass reaches depths of approximately 300 m, as delineated through seismic surveys and inclinometer measurements of slip and creep. Slide masses of this scale are considered rare (Petley, 1996) and, as in the case of Campo Vallemaggia, are almost always restricted to crystalline rock masses. Examples of deep rock slides analogous to the Campo Vallemaggia slide include 'La Clapière' in southeast France (Julian and Anthony, 1996), the Rosone slide in northern Italy (Forlati *et al*., 1991), and multiple slides at the Clyde Dam in New Zeland (e.g. Beetham *et al*., 1992).

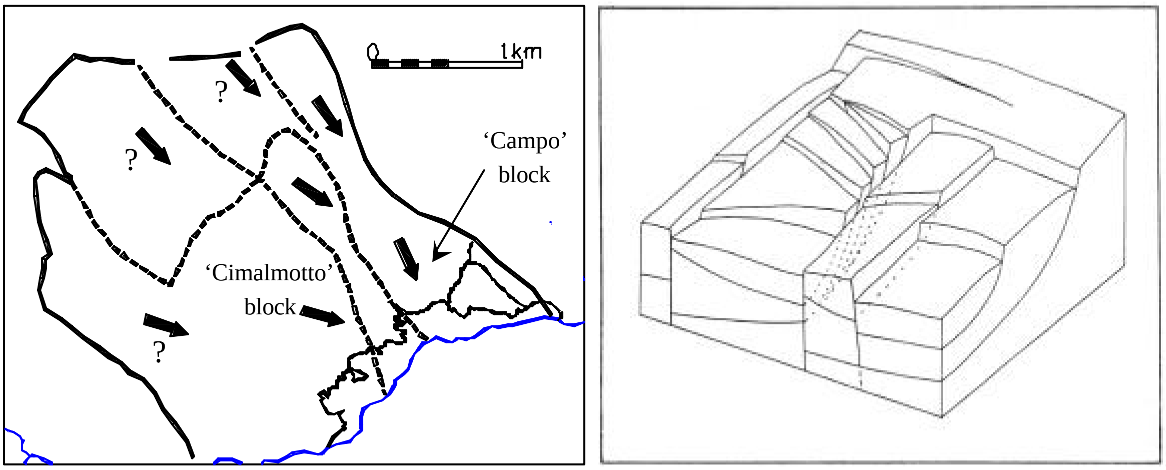

Figure 1. Plan view (left) and three-dimensional block model (right) showing the moving elements and complex subdivision of the Campo Vallemaggia creeping slide mass.

In deep sliding masses, high pore water pressures are a significant contributor to instability. One of the more notable characteristics of the Campo Vallemaggia slide is the presence of deep artesian water pressures. Hydraulic conductivity within the slide mass is highly anisotropic owing to the fractured and weathered state of the rock mass. The distribution of potential heads, as measured in several boreholes, indicate a high vertical component likely relating to the presence of a subvertical fracture system below the sliding mass. These upward moving seepage forces, together with the strong reduction in effective stress, were viewed as the instigating factors for the deep mass movements and instability. Given the potential threat to local communities, mitigative measures were subsequently taken. In the following sections, this paper will describe the acting slide mechanisms based on surface and borehole observations, the actions taken to decrease slope movements (i.e. construction of a drainage adit), and the monitored effect of these mitigative measures.

SLIDE MASS MECHANISMS

Several key factors have been examined in an attempt to better understand the acting mechanisms responsible for the slope movements/instability observed. These include:

- the presence of deep artesian overpressures;
- slope movements which do not directly correspond to precipitation;
- the pulsing behavior of the slide mass;
- the massive but unbalanced erosion at the slope's toe; and
- several hydrogeological anomalies which are still not completely understood (e.g. eruptive source behaviour and the presence of hydrogen).

The slow but consistent displacement rate of 30 cm/year, the depth of disturbed material and the low slope dip angle (approximately 30°), suggest that the Campo Vallemaggia slide can be classified as a 'deep-seated creeping landslide' as defined by Hutchinson (1988).

Inclinometer measurements reveal that displacements are distributed unevenly along the slide profile and concentrate along zones of several meters in thickness. Displacements in these zones indicate visco-plastic type deformations as described by Desai *et al.* (1995). Further analysis shows that this behaviour is highly sensitive to precipitation and accumulated pore pressures. Figure 2 demonstrates that pore pressure values exceeding an apparent threshold value coincide with sudden accelerations of the slide mass. Velocities then return to background levels as pore pressures dissipate and drop below the threshold.

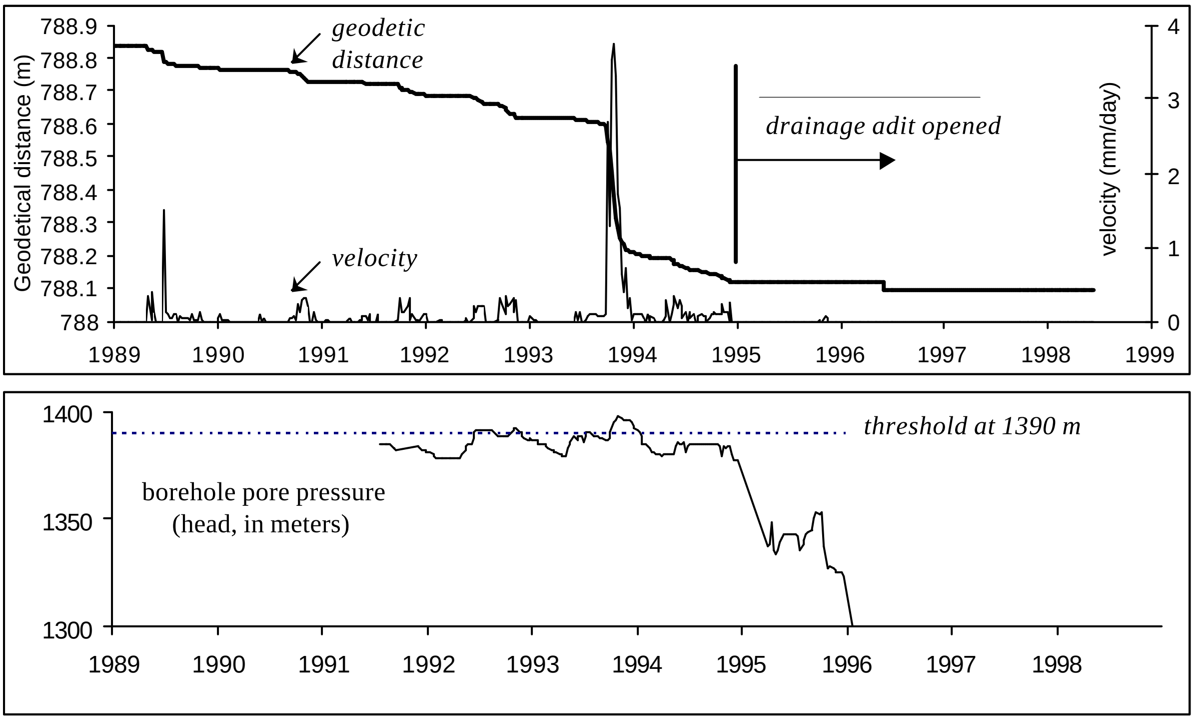

Figure 2. Plots of slide block movement and velocity versus time (top), as measured using an automated geodetic station, and borehole pore pressure versus time (bottom).

Hydrogeology

The hydrogeology of the region is characteristic of crystalline environments, with strongly anisotropic flow occurring within discontinuous and fractured aquifer systems. Flow paths are largely controlled by jointing in the undisturbed rock mass with higher hydraulic conductivities being found along fault zones. Discontinuities associated with these fault zones produce a strong subvertical flow component (i.e. hydraulic conductivity much greater vertically). These conditions are similar to those found below the slide mass and combine with regional topographical effects to produce a reversed equipotential gradient and upward acting seepage forces, which in turn contribute to the overall destabilization of the slide mass.

Within the slide body, multiple zones of large deformation and deep weathering result in a predominantly horizontal anisotropy. Hydrogeological data collected at the site (i.e. piezometers, borehole pressure transducers, etc.) was subsequently used to develop models of the pore pressure distributions and groundwater flow patterns within the unstable slope mass (Figure 3).

IMPLEMENTATION OF DRAINAGE ADIT SYSTEM

The successful use of drainage tunnels/adits to lower pore waters pressures and stabilize hazardous slopes has been widely documented in a number of case studies. For example, Moore and Imrie (1995) report mitigative measures at Dutchman' s Ridge where the piezometric head was lowered more than 150 m through one drainage gallery. Other examples include the Taren slide, UK (Martin and Warren, 1992) and the Pacific Palisades area, USA (Krohn, 1992).

Similarly, the decision was made to construct an 1800 m long drainage adit in the undisturbed rock below the creeping Campo Vallemaggia slide mass. The design, shown in Figure 4, included 30 drainage boreholes drilled from the adit into the transition zone forming the slides base. The total discharge upon completion of the drainage adit system (at the end of 1995) was approximately 50 l/s, decreasing to 30 l/s by 1998. It should be noted that drainage into the adit alone (i.e. before the auxillary boreholes were drilled) was 9 l/s.

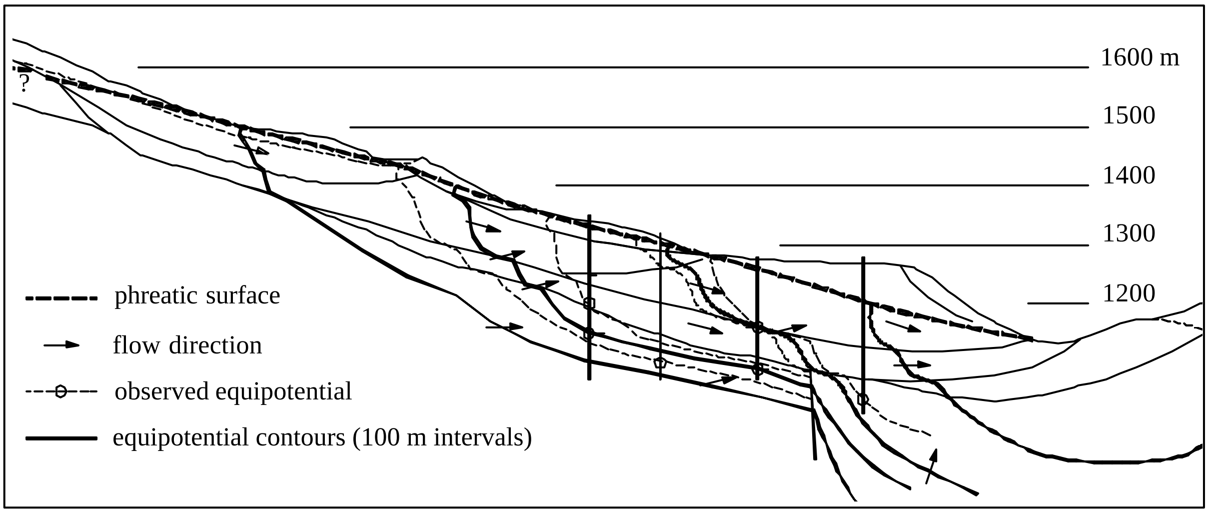

Figure 3. Cross-section of the slide mass showing groundwater flow vectors and equipotential contours *before* drainage adit construction.

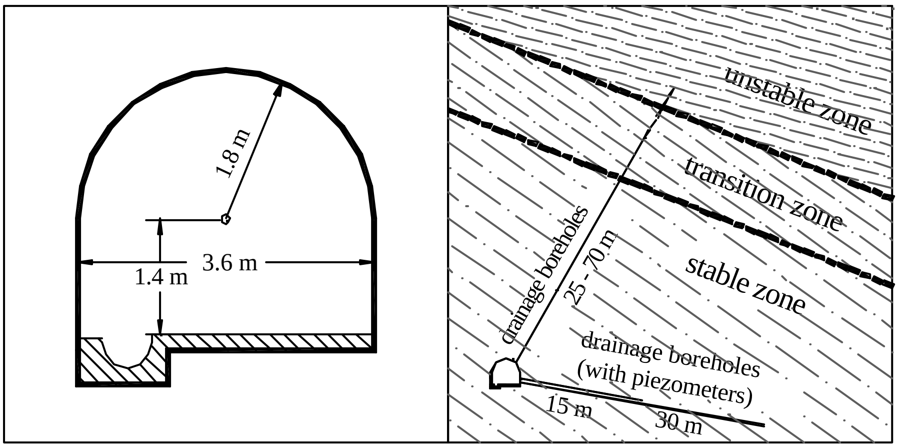

Figure 4. Drainage adit profile (left) and adit with perforated drainage boreholes (right).

Drainage, Ground Settlements and Post-Adit Behaviour of the Slide Mass

Following the completion of the drainage adit system, an immediate drop in water head was detected and surface settlements of up to 40 cm were measured (Figure 5). Slope movements decreased significantly and in some cases, upslope displacements were recorded (relating to the development of a subsidence cone).

The effect of drainage on pore pressure distributions, as verified through borehole pressure transducer measurements, is shown in Figure 6. From this figure, it can be seen that the upward moving seepage forces within the unstable transition zone (as shown in Figure 3) are inverted, thus suggesting slope stabilization through a subsequent increase in effective stress and resisting forces. Steady state conditions have yet to be reached but are expected in the next few years. Meanwhile, monitoring of the drainage adit performance continues.

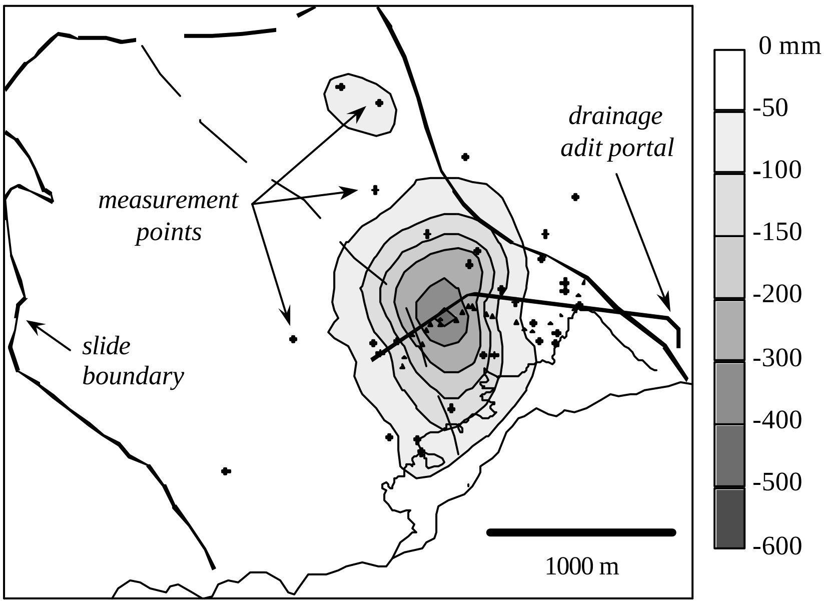

Figure 5. Total surface settlements above drainage adit between 1995 and 1998 (settlement contours in mm).

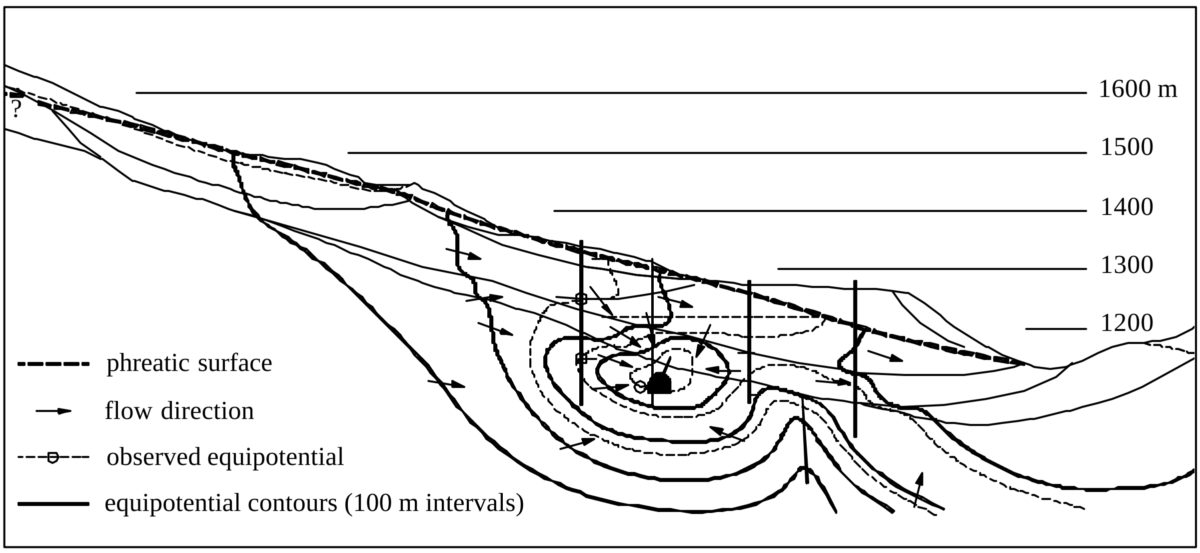

Figure 6. Cross-section of the slide mass showing groundwater flow vectors and equipotential contours *after* drainage adit construction.

CONCLUSIONS

The Campo Vallemaggia landslide represents a creeping mass movement of 800,000,000 m^3 of metamorphic rocks broken into a complex assemblage of blocks divided by tectonic elements. The unstable mass reaches depths of approximately 300 m, within which viscous rock deformations and artesian water pressures have been measured.

Slope movements were attributed to these high pore water pressures, for which an 1800 m long drainage adit was constructed to reduce pore pressures and to stop or decelerate slope movements. In addition, a series of boreholes were driven from the adit through the artesian aquifers to increase drainage and to speed up the mitigative effort.

The measured response of the slope to the drainage adit system shows that pore water pressures have been greatly reduced. These results are reflected in geodesy measurements which indicate that downslope movements have nearly ceased and in some cases have begun to move back upslope due to settlement and consolidation effects.

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