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HYDROMECHANICAL FACTORS CONTROLLING THE CREEPING CAMPO VALLEMAGGIA LANDSLIDE

Luca Bonzanigo, Geological Consultant USIC EURING, geolog.ch,
Bellinzona, Switzerland
Erik Eberhardt, Engineering Geology, ETH Zurich, Switzerland
Simon Loew, Engineering Geology, ETH Zurich, Switzerland

ABSTRACT

Mass movements at Campo Vallemaggia in the south-central Swiss Alps have been reported for over 200 years. Surface and borehole investigations of the unstable mass have revealed a 300 m deep, complex structure incorporating strongly weathered and broken metamorphic rocks divided into blocks along primary fault zones. Boreholes also revealed the presence of artesian water pressures. This paper presents the comparative findings between the *in situ* monitoring program and numerical modelling, performed with respect to the hydromechanical factors controlling the unstable mass and the successful mitigative measures taken.

INTRODUCTION

The Campo Vallemaggia landslide is located in the crystalline penninic nappes of the Canton Ticino, in southern Switzerland. Two small villages, Campo Vallemaggia and Cimalmotto, are located on the toe of the slide mass where surface displacements have been geodetically measured for over 100 years. Recorded observations in the villages go back 200 years.

The geology of the slide mass consists of a metamorphic series of amphibolite and micaceous schists, and several types of gneiss. Geological structures are characterized by isoclinal folding, dipping 30° SSE. A brittle fault system crosses the region in a NNW-SSE direction and divides the landslide body into distinct blocks, the Campo Vallemaggia block and the Cimalmotto block (Fig. 1). These longitudinal blocks are generally intact higher up near the head of the slope and pass gradually to a highly weathered and disturbed state towards the toe.

Inclinometer measurements show signs of multiple slip surfaces along the borehole profile and zones of creep deformation down to depths of approximately 300 m. When combined with surface seismic and displacement measurements, the slide volume appears to incorporate approximately 800,000,000 m^3 of weathered and intact rock. Slide masses of this scale are considered rare (1) and, as in the case of Campo Vallemaggia, are almost always restricted to crystalline rock masses.

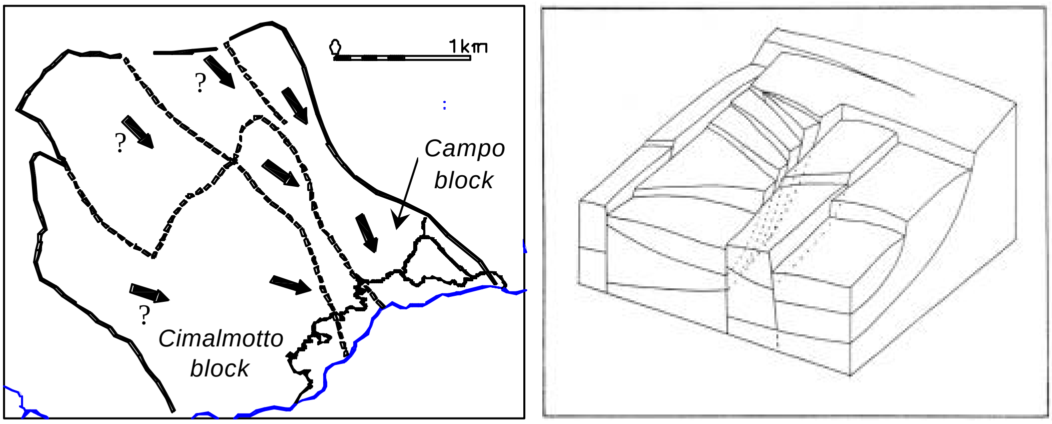

Figure 1. Plan view (LEFT) and block model (RIGHT) of the Campo Vallemaggia slide mass.

HYDROGEOLOGY

The regional hydrogeology is typical of that seen in most crystalline metamorphic environments. Jointing and faulting primarily control the hydraulic conductivity, with schistosity playing a less significant role. The glacial till overburden constitutes a relatively isotropic aquifer of higher porosity and conductivity than that of the deeper anisotropic rock mass.

Similarly, the hydrogeological characteristics of the Campo Vallemaggia slide are dominated by strongly anisotropic flow occurring within the discontinuous rock mass. Flow paths are largely controlled by discontinuities, especially those associated with high conductivity fault zones. In crystalline rock masses, these fault zones are generally associated as having:

- an enhanced permeability along fracture zones neighbouring a central fault gouge;
- a central fault gouge zone forming a relatively impervious aquiclude which prevents flow perpendicular to the fault.

Thus, the subvertical discontinuities associated with faulting in the undisturbed rock below the slide mass produce a strong vertical flow component (i.e. $K_V > K_H$).

These conditions, combined with regional topographical effects, produce a reversed equipotential gradient and upward acting seepage forces, which in turn contribute to the overall destabilization of the slide mass. Hydrogeochemical and isotopic analysis of spring water and water collected at depth help to support these observations and show that the fault zones play a major role in controlling the pore pressure distribution (Fig. 2).

Within the slide body, multiple zones of large deformation and deep weathering result in a predominantly horizontal flow anisotropy (i.e. $K_H > K_V$). Hydrogeological data collected from piezometers and borehole pore pressure transducers were used to develop a conceptual model of the pore pressure distribution and groundwater flow patterns within the unstable slope mass (Fig. 3).

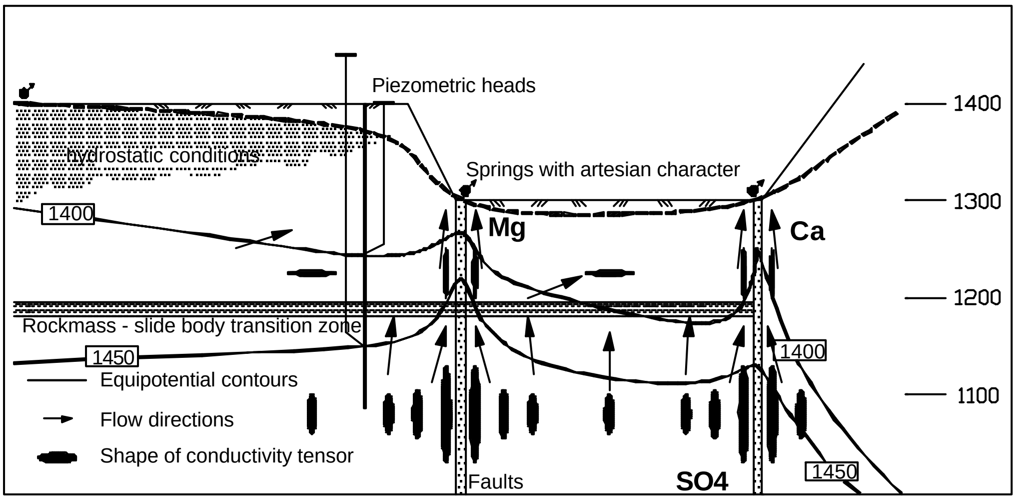

Figure 2. Schematic model of hydraulic conductivity anisotropy formed by fault zone systems as shown through hydrogeochemical analysis of spring waters.

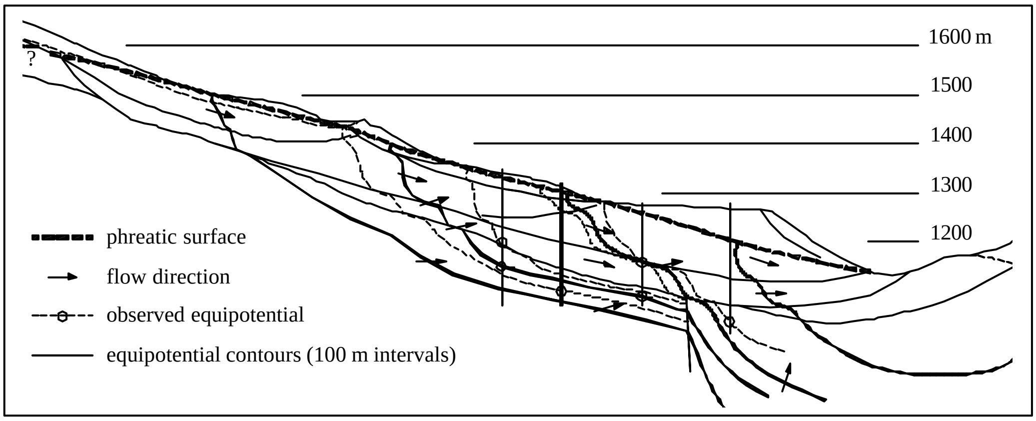

Figure 3. Cross-section of the slide mass showing groundwater flow vectors and equipotential contours.

COUPLED HYDROMECHANICAL BEHAVIOUR

Instability Mechanisms

Before mitigative measures were taken, surface displacements showed an average rate of 5 cm/year. These displacements were not constant, but presented a background rate of 1 cm/year with peaks in the order of several mm/day. Although these rates could be described as creep deformations, other mechanisms relating to multiple slip surfaces are viewed as being equally critical. However, the slow but consistent displacements, 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 (2).

In deep sliding masses, high pore water pressures are often a significant contributor to instability. One of the more notable characteristics of the Campo Vallemaggia slide is the presence of deep artesian water pressures. As previously described, 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.

Inclinometer measurements reveal that displacements are distributed unevenly along the slide profile and concentrate along zones of several meters in thickness (Fig. 4). Further analysis of pore pressure measurements made in these boreholes show that this behaviour is more sensitive to accumulated pore pressures than to precipitation. Figure 5 demonstrates that pore pressures exceeding an apparent threshold coincide with sudden accelerations of the slide mass. Velocities then return to background levels as pore pressures dissipate and drop below the threshold value.

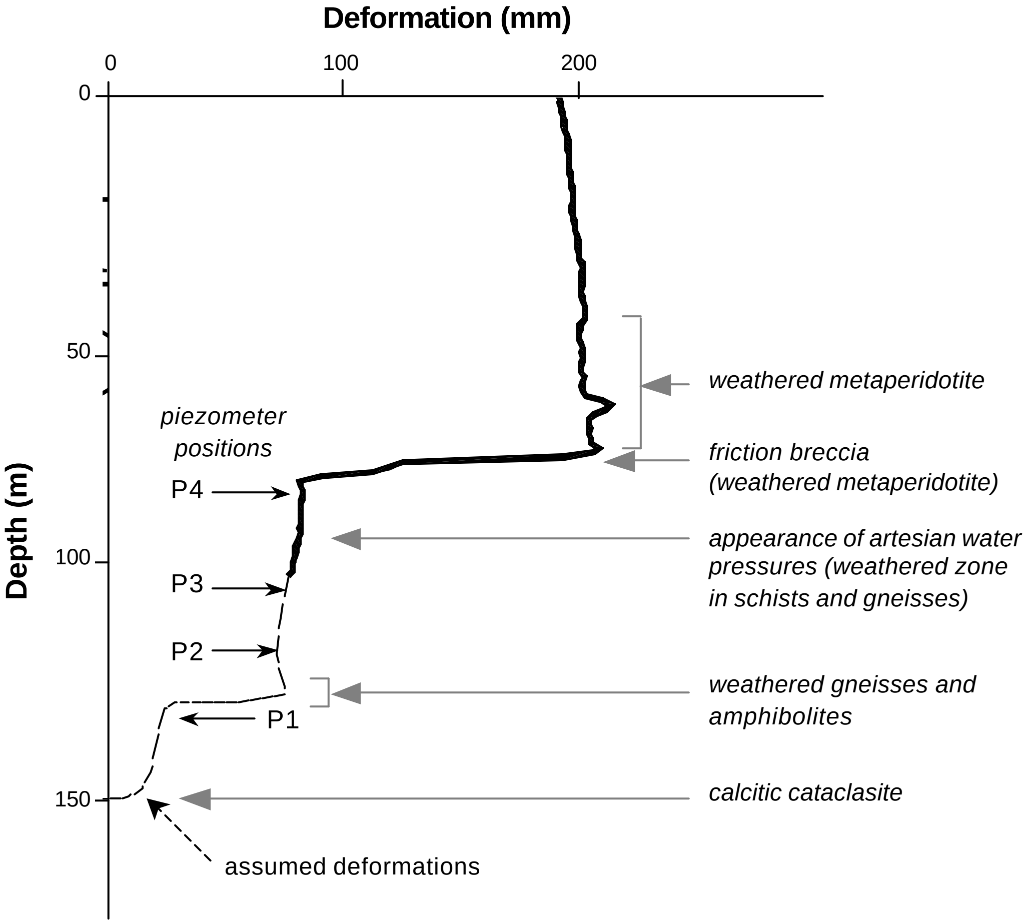

Figure 4. Inclinometer measurements made in borehole CVM6.

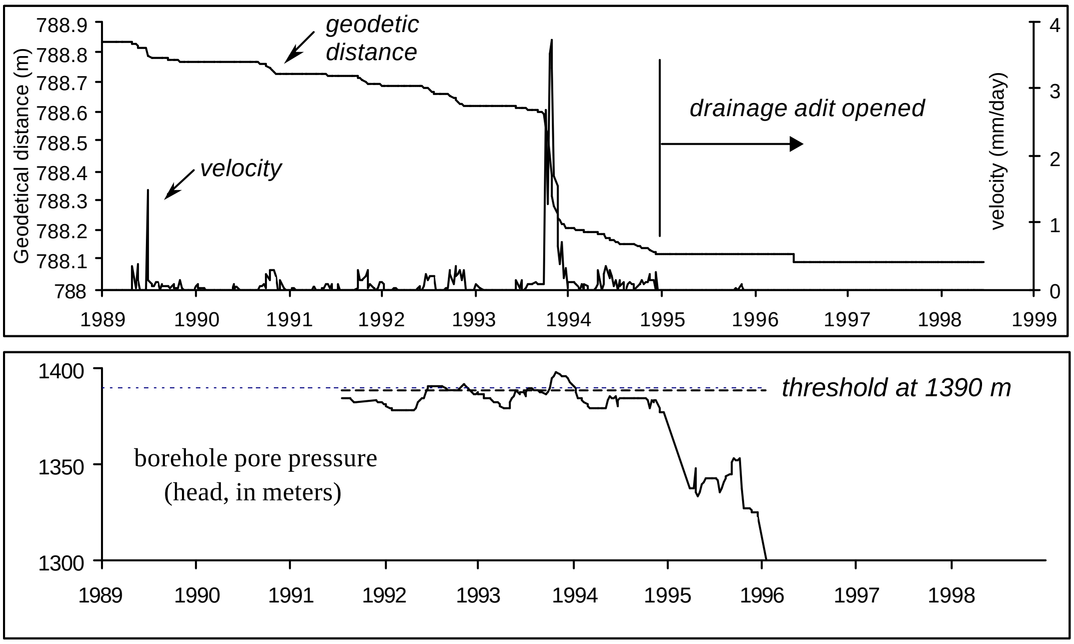

Figure 5. Plots of slide block movement and velocity versus time (as measured using an automated geodetic station - UPPER), and borehole pore pressure versus time (LOWER).

Mitigative Measures

Given the potential threat to the two local communities positioned on the unstable mass and to those located downstream of the valley, mitigative measures were subsequently taken. These efforts are described by Lombardi (3) and Bonzanigo *et al*. (4). The measures taken primarily involved the construction of an 1800 m long drainage adit in the undisturbed rock below the creeping slide mass. From this adit, 30 boreholes varying in length between 25 and 70 m were drilled into the transition zone forming the slide's 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. This produced an immediate drop in water head in addition to surface settlements of up to 40 cm (Fig. 6). 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 measured pore pressure distributions is also shown in Fig. 5. It was thus concluded that slope stabilization occurred through a subsequent increase in effective stress and resisting forces, as well as a decrease in the acting seepage forces.

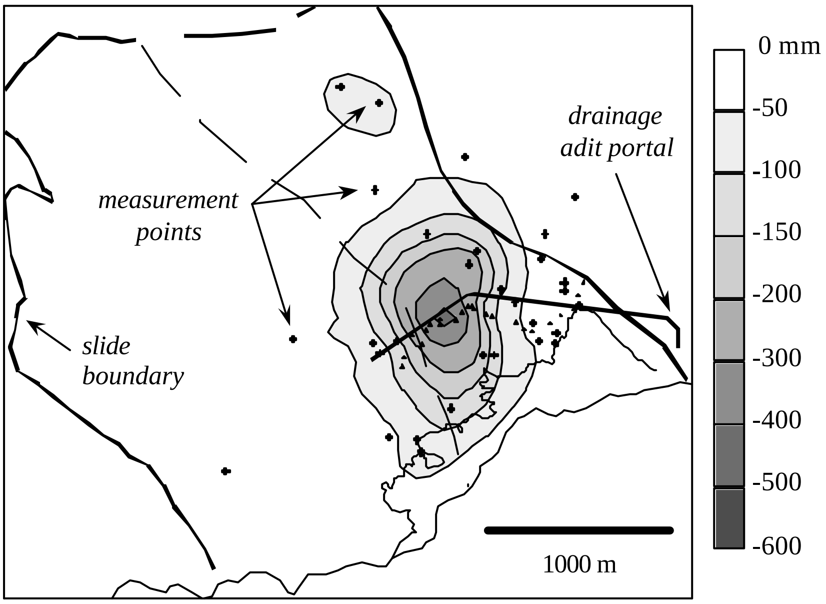

Figure 6. Total surface settlements above drainage adit between 1995 and 1998.

Numerical Modelling

Numerical modelling was performed to explore the mechanisms and effects that drainage may have had on the stabilization of the slope. A coupled hydro-mechanical approach was adopted using the distinct-element program UDEC (5). Models were created using a representative 2-D section through the slide body (Fig. 7). Joint set geometries and characteristics were generated to portray the strong horizontal anisotropy within the slide body and the vertical anisotropy below it.

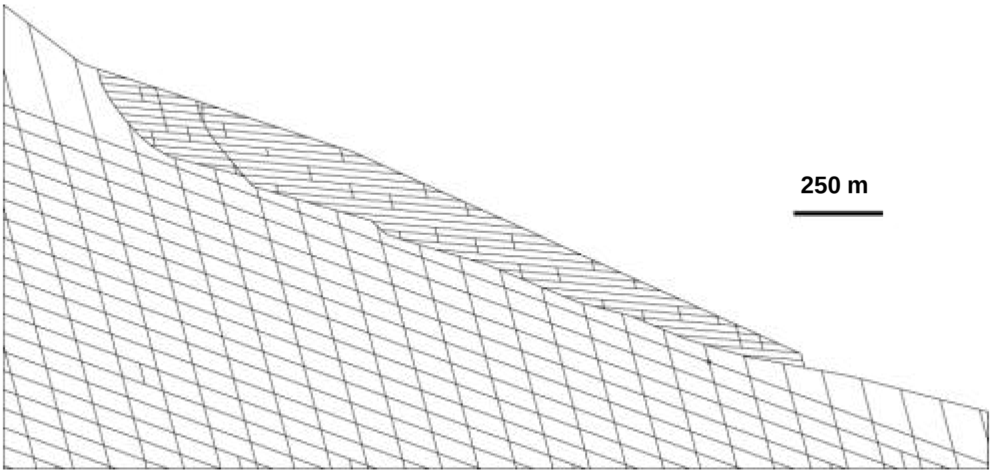

Figure 7. UDEC model geometry of the Campo Vallemaggia slide.

Table 1 shows the properties used for model for which the intact material forming the base of the slope is modelled as elastic, and the weaker slide body material is modelled as elasto-plastic. Material properties were based on field observations and back calculations (6) and *in situ* stresses were set assuming gravity loading. Results show that under these conditions, i.e. before pore pressures are introduced, the model converges to an equilibrium state with downslope displacements reaching peak values of 2 - 3 cm before stopping. These small displacements suggest that the slope, if dry, could be stable and/or possibly near limit equilibrium conditions.

Table 1. Material properties used in UDEC simulations.

Material Parameter	Slide Base	Slide Body
Density, ρ	2700 kg/m^3	2400 kg/m^3
Young's modulus, E	30 GPa	8 GPa
Poisson's ratio, ν	0.25	0.2
Cohesion, c	n/a	5 MPa
Internal friction angle, ϕ_i	n/a	35°
Joint friction angle, ϕ_j	30°	20°
Joint aperture, a_j	1 mm	0.1 mm

Pore pressures were then introduced to the model using a water table that correlated to surface observations and *in situ* piezometer measurements. Figure 8 shows the pore pressure histories for several monitoring points at and above the drainage adit as the model was time-stepped to steady state. Note that the pore pressures at the tunnel level are approximately 1.4 MPa as was measured by piezometer transducers during construction of the drainage adit (Fig. 5).

With the addition of pore pressures, slope instability is initiated and mass movements ensue (Fig. 9). Model results show that although displacements occur along the entire profile of the slope, velocities are greatest over the lower 500 m of the slope (Fig. 10). This area overlies the location where the drainage adit was eventually constructed.

The final modelling step involved the opening of the adit to allow drainage. This step resulted in the abrupt termination of downslope displacements and velocities, and the stabilization of the slope model (Figs. 9 and 10). The effect of drainage on reducing pore pressures diminishes moving away from the tunnel, but still results in a 33% decrease near the base of the slide 40 m directly above the drainage adit (note that the displacements shown in Fig. 9 also correspond to the same point). In terms of tunnel inflows, the model shows that very little drainage is required for this stabilization effect to occur. For the examples shown, modelled tunnel inflows were 5 l/s or 0.005 m^3/s. This correlates closely with *in situ* observations following the implementation of mitigative measures, which suggested that pore pressures were significantly reduced even though only a relatively small volume of water flow was captured through the drainage system.

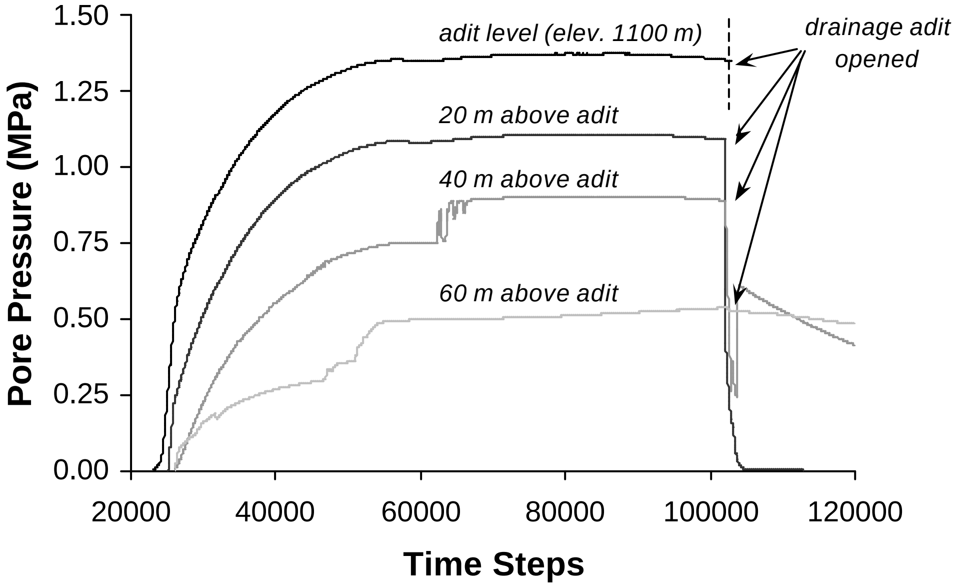

Figure 8. Modelled pore pressures at and above the drainage adit. Note that near steady state conditions are reached after approximately 75,000 time steps, and tunnel drainage is introduced after 100,000 time steps.

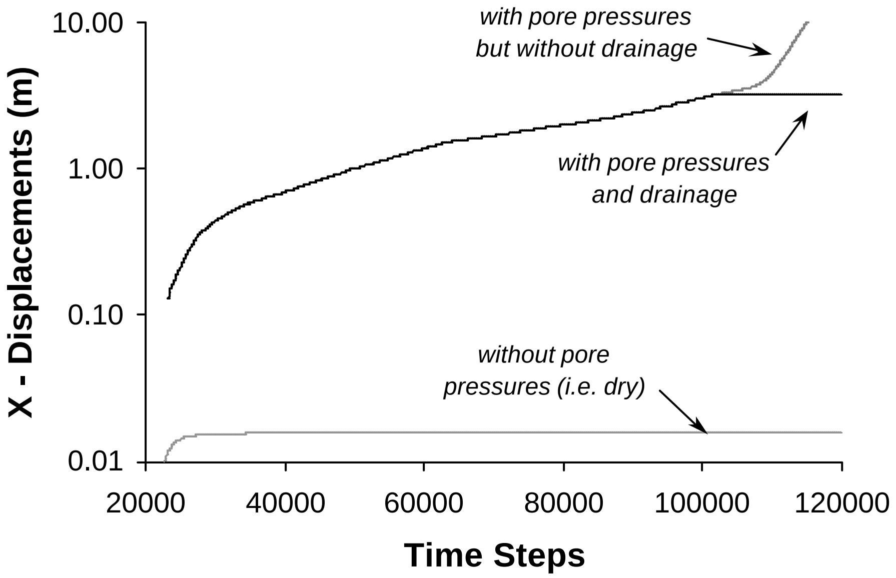

Figure 9. Modelled horizontal displacements (i.e. x-direction) for a point at the base of the unstable zone, 40 m directly above the drainage adit. Displacements are included for three model cases: dry slope conditions; slope with pore pressures; and slope with pore pressures followed by drainage.

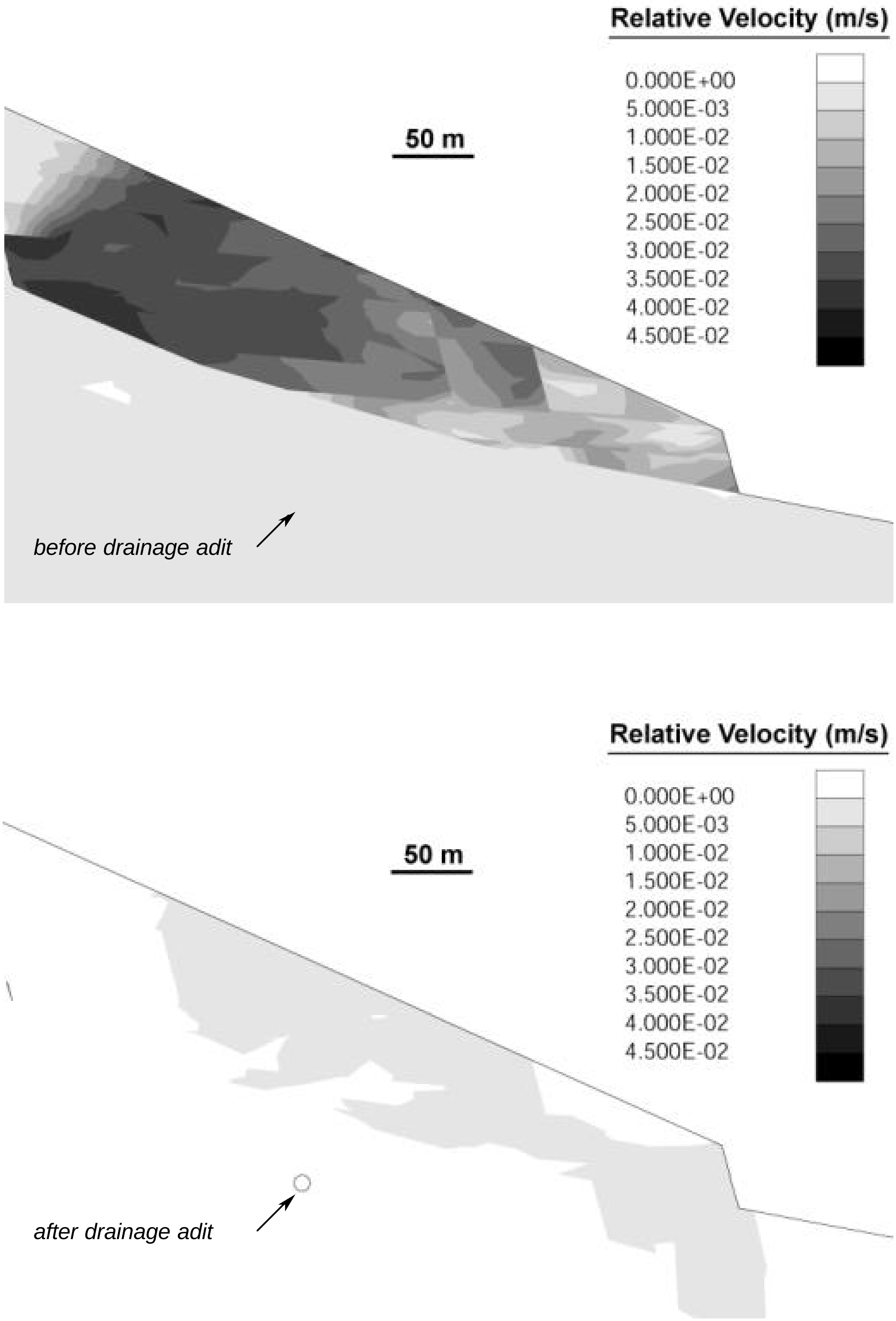

Figure 10. Modelled horizontal velocities *before* (UPPER) and *after* (LOWER) introduction of drainage adit.

CONCLUSIONS

The Campo Vallemaggia landslide represents a creeping slide mass 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 and seepage forces, for which an 1800 m long drainage adit was constructed to reduce pore pressures and decelerate slope movements.

The measured response of the slope to the drainage adit system shows that pore water pressures were greatly reduced. These results are reflected in geodesy measurements which indicate that downslope movements have generally ceased confirming the effectiveness of the mitigation strategy.

Numerical models, generated using a coupled hydromechanical distinct-element approach, show that under dry conditions the slope is relatively stable. After pore pressures are introduced to replicate those measured *in situ*, instability occurs in the form of increasing displacements and downslope velocities. These velocities stabilize once drainage through the simulated tunnel adit is permitted. Similar to *in situ* observations following the construction of the drainage adit, very little drainage was required (approximately 5 l/s) to reduce modelled pore pressures and to stabilize the slope.

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