Soil matric suction as an indicator of the mud flow occurrence

Succion matricielle du sol comme indicateur de presence de coulee de boue

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ABSTRACT

The Slano blato landslide is one of the largest landslides in Slovenia with a volume of more than 1 MIO m^3. In dry periods the landslide behaves as a group of several slow moving landslides. In wet periods it moves mainly as a viscous earth flow with occurrences of rapid mudflows. The transformation from the slow moving landslide to the much faster mud flow depends strongly on the combination of the rainfall infiltration at the landslide territory itself as well as the water influx from the bedrock. Instead of monitoring the ground water level and horizontal ground inclination in the short life time inclinometers, a new monitoring system, using soil suction measurements with the Watermark sensors was installed in 2007. The soil suction and the ground temperature data are taken continuously, together with the data from the weather station and the GPS position of sensors. The measured data are available online, together with the TV camera shots observing the landslide surface 24 hours/day. Field monitoring data show clear connection between rainfalls, soil suction and the development of the surface soil instabilities.

RÉSUMÉ

Le glissement de terrain Slano blato est un des plus grands glissements en Slovenie d'un volume de plus d'un million de m3. Pendant les periodes seches le glissement de terrain se comporte comme un groupe de plusieurs glissements lents. Au cours des periodes humides il se deplace principalement comme un glissement de terrain a l'etat visqueux a la mise en mouvements rapides des coulees boueuses. La transformation du glissement de terrain lent en une coulee de boue a un deplacement rapide resulte fortement de la combinaison de l'eau de pluie infiltree au terrain meme du glissement aussi bien que de l'eau provenant de la roche mere. Au lieu de suivi du niveau de l'eau souterraine et de l'inclinaison horizontale du sol de courte duree de vie, des inclinometres, un nouveau systeme de controle, utilisant des mesures de la succion du sol au moyen de Watermark capteurs, ont ete mis en place en 2007. Les donnees de la succion et de la temperature du sol. en compagnie des donnees des stations meteorologiques et des capteurs de position GPS, sont prises continuellement. Les donnees mesurees sont accessible en ligne, ensemble avec des prises de vue de camera tele, sur l'observation de la surface du glissement de terrain 24 heures par jour. Les donnees obtenues lors du controle sur le terrain montrent une correlation claire entre les chutes de l'eau de pluie, succion du sol et development des instabilites aux surfaces de sol.

Keywords: debris flow, earth flow, failure, flysch, landslide, mud flow, shear strength, soil suction, Watermark sensor

1 INTRODUCTION

Rainfall-induced slope instabilities have been reported widely in the literature (Brand et al, 1984; Franks, 1999; Krejči et al, 1997; Logar et al, 2005). Systematic studies of the most important triggering effects in Switzerland confirm that periods of extreme rainfall, combined with a long humid winter and a cool late spring as well as raising groundwater due to infiltration from snowmelt are all highly significant (Latelin et al, 2001). The direct reason for the earth flow that was triggered in November 2000 at Slano blato, Slovenia, was the increased water inflow due to intensive precipitation (Logar et al, 2005).

Traditionally explanations of landslides that occur after large precipitation have been based on the assumption that rainfall infiltrates vertically through the top layers. In turn, water infiltration causes the pore pressure to rise as a result of saturation of the soil layers above the infiltration front. In addition it is assumed that pore water pressure and seepage forces may also increase due to the accumulation of a perched water table above the more stable layers or the less permeable strata of the underlying bedrock (Tarantino and Bosco, 2000).

In comparison with saturated conditions, negative pore water pressures arising from partial saturation increase the available shear strength on a potential slip surface. This additional contribution is lost progressively during infiltration of rainfall, leading to instabilities, sometimes before full saturation is reached (Springman et al, 2003). In such cases, reliable prediction of the safety factor may be achieved by taking the suction history of the soil into account. For rainfall induced shallow landslides, the failure mechanism could be as follows: (i) rainfall infiltration results in a decrease in the soil suction of the slope soil, (ii) the decrease in soil suction reduces the soil shear strength and (iii) the reduction in soil shear strength subsequently causes the slope to become unstable and then fail (Li et al, 2005). Once the soil slope is completely saturated, the soil suction disappears completely and a perched water table with positive pore water pressure develops in the soil slope. The mass movements, the debris and the mud flows can be observed immediately after or during intensive rainfalls, after prolonged periods of rain or with a considerable delay with respect to the rainfall events (Tarantino and Bosco, 2000).

A number of field experiments have been carried out recently to investigate the triggering effect of rainfall on shallow slips in different types of soil (Springman et al, 2003; Li et al, 2005; Zhan et al, 2007). This paper describes the results of the soil suction monitoring at the large landslide Slano blato, Slovenia. Instead of monitoring the ground water level and horizontal ground inclination in the short life time inclinometers and piezometers, a monitoring system using soil matric suction measurements was installed in 2007. The soil suction measurements and the soil temperature data are taken continuously together with the data from the weather station and

Proceedings of the 17th International Conference on Soil Mechanics and Geotechnical Engineering
M. Hamza et al. (Eds.)

doi:10.3233/978-1-60750-031-5-1855

the GPS position of sensors. The measured data are available online together with the two TV camera shots observing the landslide surface 24 hours a day. Periodically the terrestrial laser scanning technology has been used to detect the geomorphic changes due to sliding. Laboratory tests have been performed to define the fundamental properties of the soil, as well as the Soil water characteristic curve (SWCC) and the relationships between the water content, suction and undrained strength of the reconstituted remolded samples.

2 BRIEF HISTORY OF THE SLANO BLATO LANDSLIDE

The Slano blato landslide is one of the largest and the most active landslides in Slovenia with a volume of more than one million m^3 of moving mass. It is situated in the west of Slovenia above the village of Lokavec (Figure 1). Its name "Slano blato" in the Slovene language means salty mud. In dry periods the landslide behaves as a group of several slow moving landslides, while in wet periods it moves mainly as a viscous earth flow with the occurrences of rapid mudflows (Figure 2).

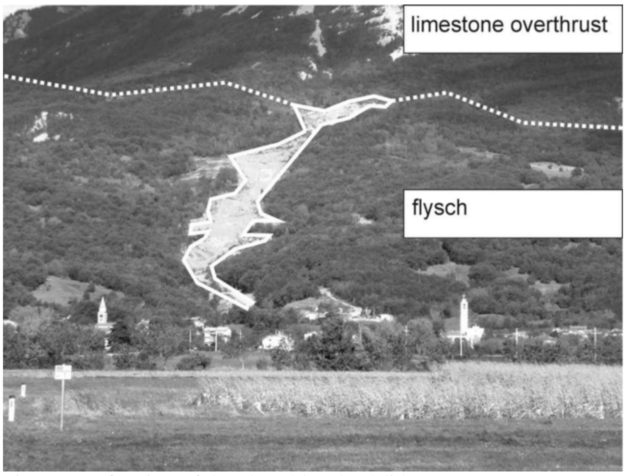

Figure 1. A far view of the Slano blato landslide

Figure 2. The viscous mud flow

The landslide was firstly documented in October 1887, when after the heavy rain, the debris and the mud flow destroyed the main road in the valley. Remediation measures consisted of a series of small retention dams built on the Grajšček streambed to retain the mud and debris and to reduce the energy of stream water. These remediation measures were finished in 1903.

In November, 2000, the landslide was reactivated at the altitude of 570 m a.s.l. Due to the intense rainfall the sliding mass soon became liquid and flowed downwards along a narrow channel with the velocity of 60 – 100 m/day as a mud flow and stopped temporarily at the altitude of 460 m a.s.l in the area called "Mud lake". At the same time, large retrogressive rotational slide occurred above the initial scarp and has progressed slowly until the present day resulting in the widening of the most of the upper part of the landslide area. They are continuously supporting the central part with new volumes of debris presenting the mass which can transform again in new earth and mud flows. The accumulated mud started to move again in March 2001 and in September 2001 when it reached the village.

Mudflow event was repeated again in November 2002 and at the end of 2003. In 2003 the upper part of the landslide progressed significantly into the hinterland. The geodetic measurements indicated ongoing moderate movements of the landslide, while the installed inclinometers failed due to the large displacements. From November 2003 to April 2004 the geodetic observation points moved for 12 – 16 m, although the period was dry. Detailed history of the Slano blato landslide is given in Logar et al (2005).

To protect the area against the progressive widening of the landslide, reinforced concrete shafts (wells), which act simultaneously as dewatering wells and retaining structures, were constructed in 2004 and 2005. The surface dewatering system was built at the upper part of the landslide and the surface was reshaped to reduce the slope inclination angle in the area bellow the shafts. The sanitation measures improved strongly the stability of the whole landslide, although locally limited landslides and mudflows have been observed all the time.

Intensive rainfalls in 2008 triggered again a large number of smaller earth and mud flows of about several thousand m^3 of moving mass, all above the concrete shafts (Figure 3), where the slopes were steeper than 23°, while the central part of the landslide, bellow the shafts, where the slope was reshaped to 12 – 15°, remained in the mode of very slowly moving landslide and no mud flow occurred, although the soil suction was reduced to zero.

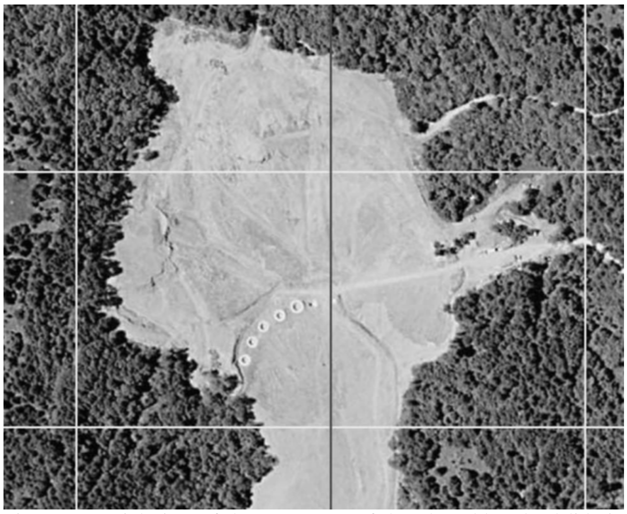

Figure 3. Aerial view of the upper part of the Slano blato landslide in 2005 with the first shafts

3 GEOLOGICAL CONDITIONS

The landslide is located at the contact between Triassic limestone and Eocene flysch formations (Figure 4). Flysch consists of layers of marl and sandstone with the thickness of a few centimetres and up to a few meters. Limestone was overthrusted on the flysch over a very large distance. The consequence is that the flysch and the limestone bedrock are highly tectonized and folded. When denudated, the massive and thick marly layers soften very quickly and rapidly transform into clayey debris and plastic clay. The inclinometers have shown two sliding planes in the upper part of the landslide. The first is at the contact between the clayey debris and the tectonically deformed flysch at a depth of app. 5m, the second sliding plane is inside the flysch bedrock at the contact between the fissured layers of sandstone and marl. The limestone overthrust has been for several decades more permeable than the layered flysch. During the rainy period the saturation of clayey debris increases due to the infiltration of rain from the top as well as due to the water inflows from the bottom, from the faulted bedrock. When the earth mass starts moving, they catch additional quantities of water and turn into fast moving cohesive debris and/or mud flow. Because of large displacement, most of the conventional monitoring points have been destroying several times after only a limited number of measurements, rendering the landslide out of control.

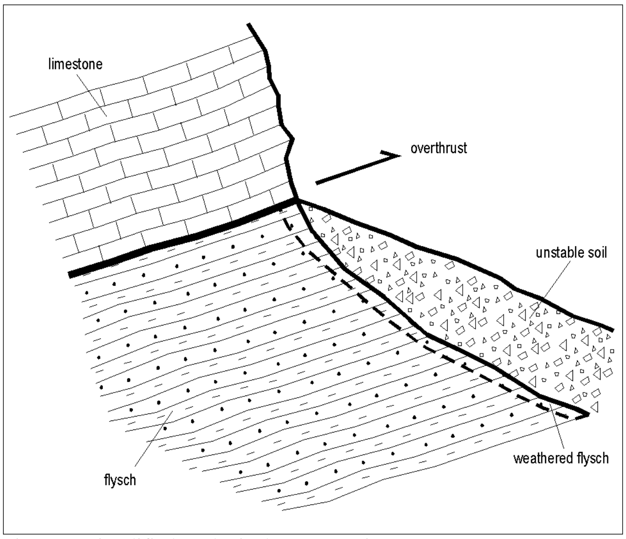

Figure 4. Simplified geological cross- section

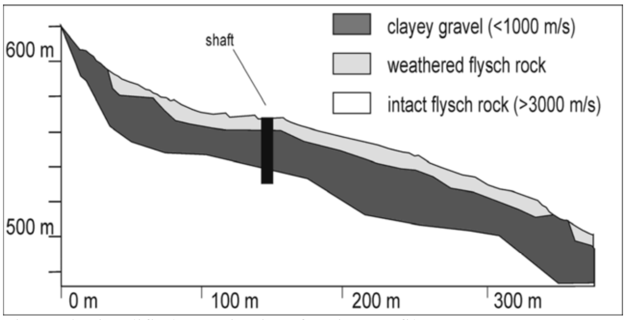

Figure 5. Simplified geoseismic refraction profile

4 INSTRUMENTATION

4.1 *Instrumentation layout*

Knowing the history and the most typical mechanisms of landslide triggering and mass movements, three characteristic locations were selected for the instrumentation: (i) the mud lake, where clayey material from the mud flow has been deposited in nearly horizontal layers, (ii) the central part below the shafts, where the slope inclination was 12° to 15° and the clay with gravel has been deposited from the debris and the mud flow and (iii) the upper part, above the shafts, where strongly tectonized layered flysch was denudated in 2001 and has been progressively deteriorated on the surface. The slope inclination is about 23° or more. Due to the progressive deterioration of the flysch bedrock and ongoing movements of debris, this location has not been in function yet.

On locations (i) and (ii) the characteristic soil profiles were equipped with four Watermark suction sensors and thermometers installed at four different levels under the surface at the depth of 0.2 to 3 m. Each sensor was installed in its own borehole. Before the installation, the sensors were coated on site with the locally excavated plastic soil. After the installation the upper part of the hole was carefully filled with the locally available soil, from which the coarse grains were removed.

The measured data are taken continuously together with the data from the weather station and the GPS position of sensors. The measured data are available online together with the two TV camera shots observing the landslide surface 24 hours/day. The nearby piezometers and inclinometers have already been destroyed and are out of function.

4.2 *Soil profile and soil properties*

Prior to installing the suction and the temperature probes, a borehole investigation was conducted around the monitored area to investigate the ground conditions, the diversities in soil properties and to take soil samples for laboratory tests. The soil properties from the location (ii) are given in Table 1 and the grain size distribution in Figure 7. The instrumentation site (ii) is typical for the central part of the landslide and the samples have been taken several times at the same point. From Figure 8 the influence of the flysch grains deterioration to the increase of fines with time can be observed. Figure 8 shows that the initial water contents above 25 % do not influence the shear strength of the soil.

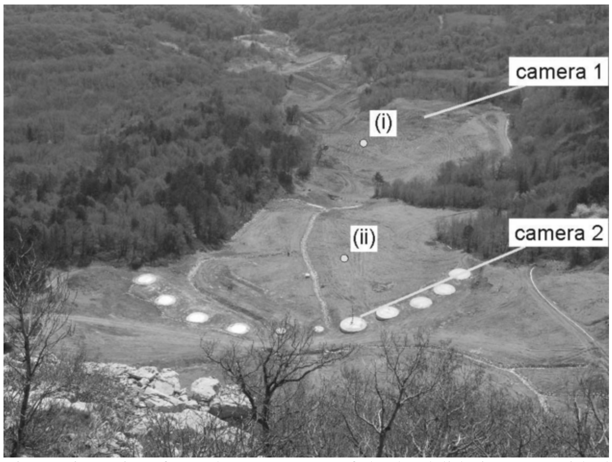

Figure 6. A view from the upper part of the landslide in 2008 with the shafts and the monitoring sites

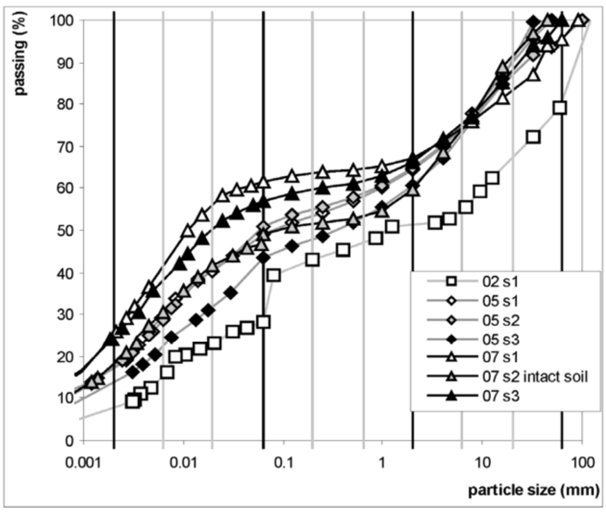

Figure 7. Grain size distribution for samples taken from the monitoring profile (ii)

Table 1. Main material properties of the Slano blato landslide

Year	2002	2005	2007
Natural water content (%)	27.0	14.0-15.7	14.3-21.8
Liquid limit (%)	45-50	45	45-50
Plastic limit (%)	18-20	15	17-19
Fines (<0.06mm) (%)	35-50	43-51	56-62
Angle of internal friction φ (°)	21.5-27.5		21.5-22.5
Cohesion (kPa)	1.4-10		7.0-10

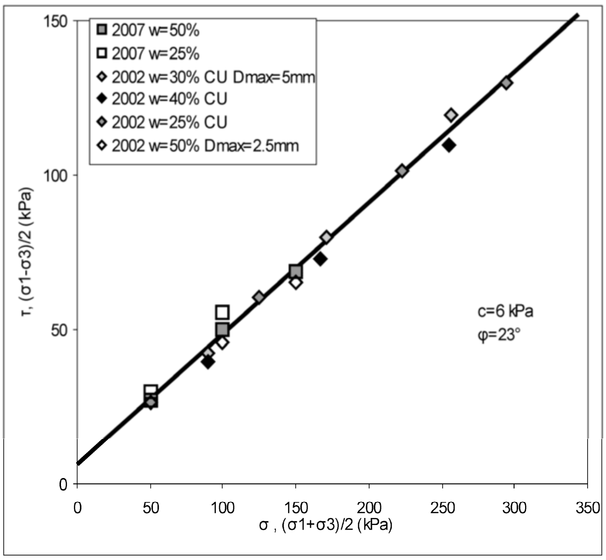

Figure 8. The shear strength of samples from monitoring profile (ii)

4.3 *Calibration of sensors and soil*

Before the installation the sensors were checked in the laboratory for proper functioning. The SWCC curve was determined firstly using the axial translation technique at lower and the Decagon dew point potentiometer at higher suction range. The similar samples were then prepared and the soil suction was measured again with the Watermark sensors, installed into the cylindrical soil samples, prepared in laboratory by wetting. The coarse grains were removed from the soil and only the fractions smaller than 0.5 mm were used.

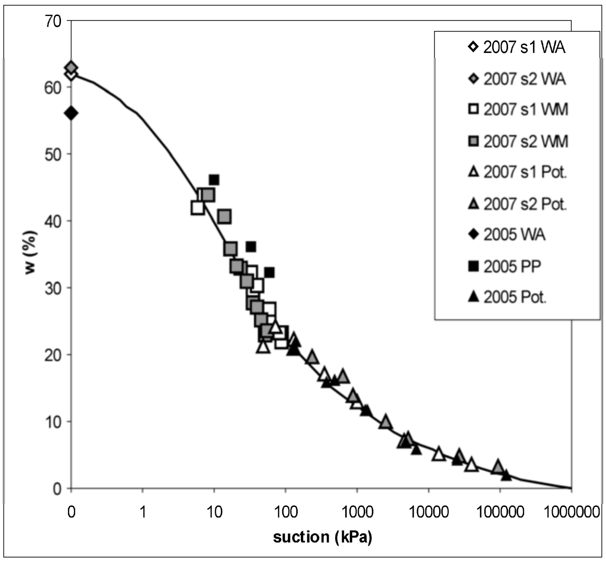

Figure 9. "Virgin" Soil water characteristic curve for soil from the monitoring profile (ii). WA – water adsorption Enslin – Neff test, WM – Watermark sensor, Pot.– dew point potentiometer, PP – axial translation technique

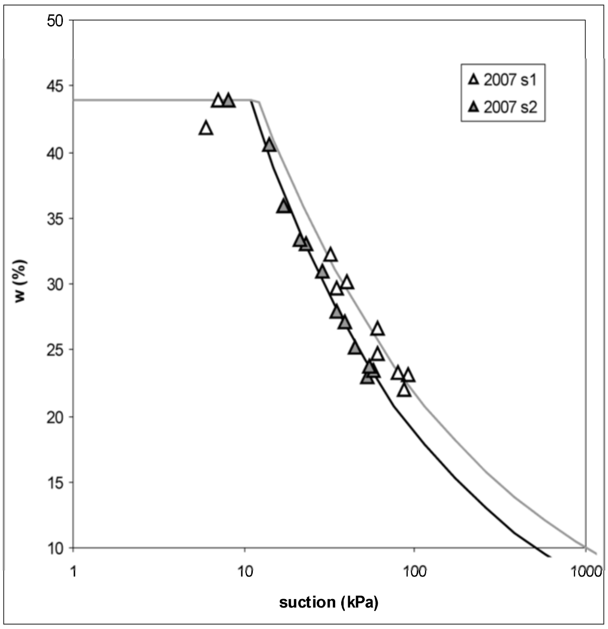

Figure 10. Soil water characteristic curves determined using the Watermark probes

When suction was determined, the Watermark sensors were removed from the cylindrical soil samples and the water content and the undrained shear strength was determined using the laboratory fall cone. The results of the laboratory tests are given in Figure 11 and Figure 12. Results signed as "core sample" in Figure 11 were gathered on undisturbed core samples from the bore holes, using the unconfied compression test. Good correlations were found in soil suction results gathered with different techniques and the relationship between water content and undrained strength as well as the relationship between the soil suction and undrained strength were found in ranges of 10 to 100 kPa. It can be seen that the relationship between the suction and undrained strength can be described by simple power function. The water content at the liquid limit corresponds to the soil suction of app. 10 kPa and the undrained strength of app. 1.5 kPa.

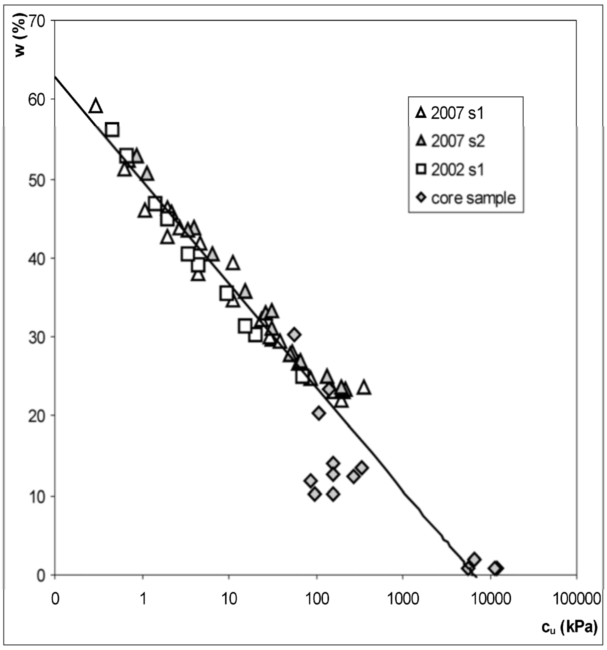

Figure 11. Undrained strength and water content relationships. Remoulded samples from monitoring profile (ii)

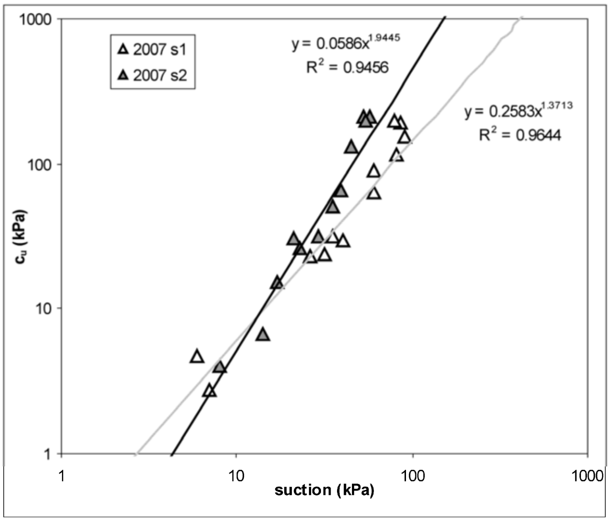

Figure 12. Soil suction and undrained strength relationships. Remoulded samples from monitoring profile (ii)

4.4 *Field monitoring results*

Field monitoring results are given for the period of 1 January 2008 to 31 December 2008. Figure 13 and Figure 14 show the variation of soil suction and temperature at different ground depths during the whole year 2008. The grey zones indicate the periods, when the surface movements were observed on the upper part of the slide, where the slopes were steeper than 23°. At "Mud lake" profile (i) the suction remained almost zero throughout the year. An exception was observed during August and September when the surface drying and the mud shrinkage strongly influenced the suction increase in the upper part at a depth of 0.2m to 1.0m. At the central part (ii) the soil suction decreased to zero during heavy rain period at the end of April. Decrease of suction correlates well with the period of intensive surface earth movements. The surface movements were stopped when the suction in the upper probe increased to 10 kPa, which responds to the undrained strength of 7 kPa or the water content slightly lower then liquid limit. At the end of the year, the upper two probes did not respond to heavy rain in the same way as the probes at position (i). This could be explained by the measuring errors due to intensive temperature changes, earth movements or other unknown reasons which have to be checked in the future. Figure 15 shows the cumulative rainfall from January 2008 to December 2008 along with the daily precipitation and Figure 16 shows the diagram of the air and ground temperature for the same period along with the rate of the evaporation.

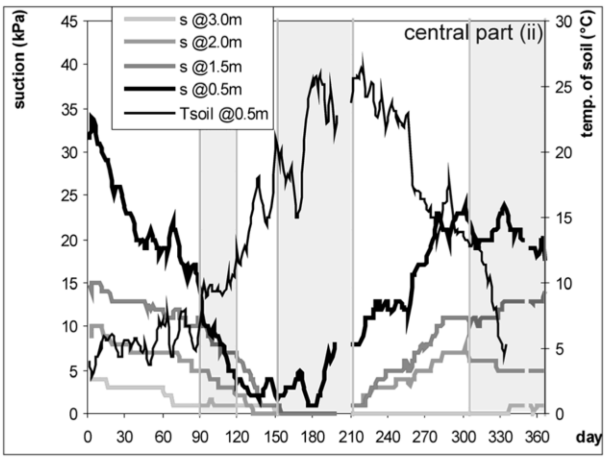

Figure 13. Variations of the soil suction results (point ii) in the period from 1 January to 31 December 2008. Grey lines refer to the periods of intensive mass movements

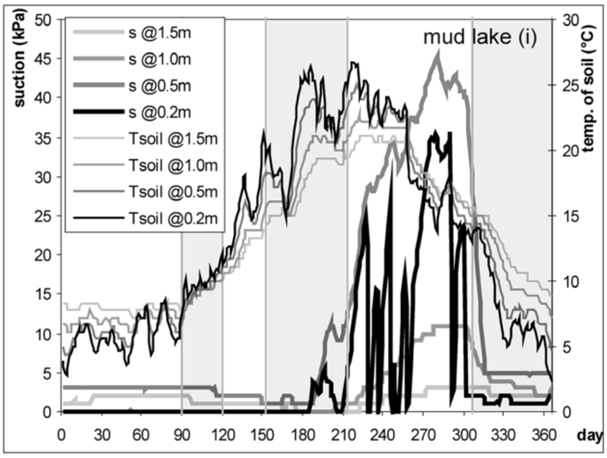

Figure 14. Variations of the soil suction results (point i) in the period from 1 January to 31 December 2008. Grey lines refer to the periods of intensive mass movements

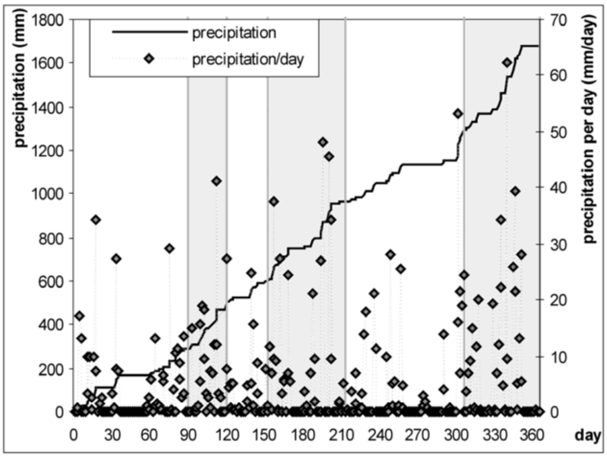

Figure 15. Cumulative precipitation measured in the period from 1 January to 31 December 2008 along with daily precipitations

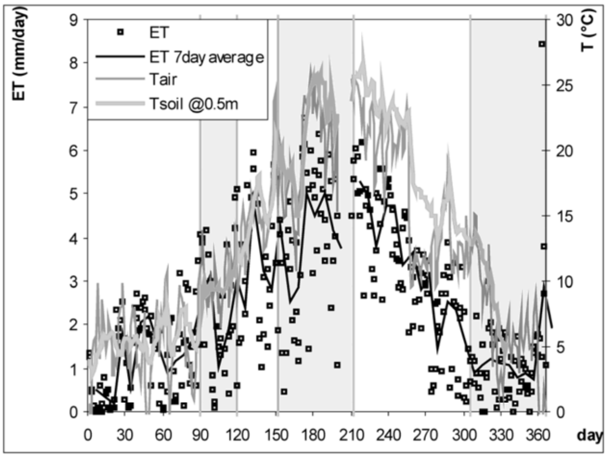

Figure 16. Variations of the air and the ground temperature and the rate of daily evapotranspiration in the period from 1 January to 31 December 2008. Grey lines refer to the periods of intensive mass movements

Figure 17 gives an overview over the period from the first landslide triggering in November 2000 to the end of 2008. It can be seen that the movements were triggered when cumulative rainfall in 28 days reached 200 mm. The suction measurements, included into the graph excellently correlate with other data.

It is also important to note that the cumulative rainfall in 2008 was of the same rate as in 2000, when the Slano blato landslide was reactivated and two other large landslides occurred as fast moving debris flows at a distance of less than 60 km (Majes et al, 2002).

It is important to note that the central part of the landslide bellow the shafts where the monitoring profile (ii) was installed remained more or less stable and no surface earth flows occurred. This can be explained by the relatively mild slope inclination of 12 – 15° and the effect of the dewatering shafts. The earth and the mudflows occurred at the upper part of the landslide, above the shafts, where the slopes are steeper than 23° and the reshaping of the surface was not completed at a proper time.

5 CONCLUSION

Records of different landslides occurring under various topographic, geological and hydrological conditions confirm that most shallow slides, debris flows and mud flows are triggered by precipitation. The basic idea of the instrumentation of the large Slano blato landslide with soil suction probes in 2007 was to investigate the contribution of soil suction to the prevention of the earth flow occurrence as well as to recognize the critical water content in the surface layers at which the surface earth flow may occur. The problem is complicated due to the large territory covered by the deteriorated flysch and heterogeneous soils which remained on the slopes after different stages and types of previous landslide movements and flows.

The monitoring data highlight the importance of the contribution of soil suction of the surface layers to the surface stability of the landslide. The TV cameras and the geological observations of the landslides detected the progressing shallow surface earth flows with delay, after the soil suction had started to decrease. It is important to emphasise that the wetting front and the earth flows occurred only in the upper 2 - 3 m of soil.

From the monitoring results we can conclude that soil suction measurements offer new possibilities in the field of large landslide investigation and monitoring and help to improve the understanding of their behaviour. Analysis and field observation from the Slano blato landslide also show that the earth flows can occur on different sites and under different conditions inside the same landslide under the same general weather conditions. The inclination of the slope seems to be of great importance. From the gathered data we learned that much more experiments and field data have to be collected before a realistic model can be proposed for the comprehensive and coherent understanding of the past events as well as to be able to forecast similar events in the future.

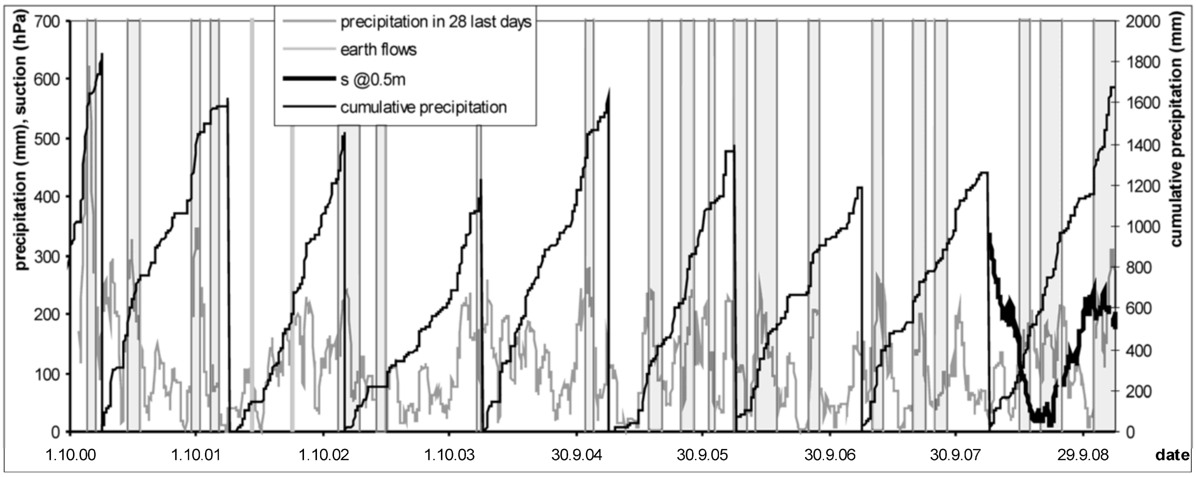

Figure 17. Cumulative annual rainfall and soil suction results. Grey lines refer to the periods of intensive mass movements

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