Temporal variability of a slow-moving landslide: the Heumöser Hang case study in Vorarlberg, Austria

J. Wienhöfer, F. Lindenmaier & E. Zehe
Institute of Water and Environment, Technische Universität München, München, Germany

ABSTRACT: Movement rates of a slow moving landslide in cohesive sediments were observed at the study area *Heumöser Hang* (Ebnit, Austria) with geotechnical and geodetic methods. Measurements using GPS (Global Positioning System) indicated surface displacements between 0 and 25 cm a^{-1} distributed over the central slope area. Borehole inclinometer measurements revealed that most of the movement is along a slip surface in 7-12 m depth. Hourly data from continuous monitoring of an inclinometer and pore pressures at different depth are available since March 2008. This high-resolution time series gives detailed insight into the temporal variability of slope movement and considerably enhances the database for future modelling attempts to relate deformation rates and possible influencing factors.

1 INTRODUCTION

Mass movements at natural slopes can be of various forms, depending on the geological, topographical and climatical situation (e.g. Dikau et al. 1996). Their impact on the natural and human environment ranges from local damages in infra-structure to life-threatening catastrophes. Comparably slow, long-lasting movements along a relatively deep slip surface may be the precursors of sudden catastrophic slope failures. The development of such slow moving landslides is favoured by thick (> 10 m), fine-grained soils on moderately steep slopes (Iverson 2000).

The triggering of mass movements is strongly connected to the prevailing climatical and hydrological conditions that contribute to a very different measure and on a wide range of space and time scales to the different slope deformations; for example, debris flows and shallow landslides (1-2 m depth) are often triggered directly by heavy precipitation, whereas deeper landslides (5-20 m) are commonly triggered by positive pore pressures on the slip plane (van Asch et al. 1999). In the latter case, the link between rainfall and landslide activity is commonly less direct and not necessarily constrained to exceptional meteorological conditions, such that complex interactions of different factors have to be considered (Terlien 1998; Flageollet et al. 1999). Furthermore, the relationships of pore pressures and landslide mobility may be non-linear and hysteretic (van Asch et al. 2007). Therefore, comprehensive field data on both slope movement and slope hydrology are required to improve the understanding of such landslides. This is essential for any attempts to satisfactorily model these natural dynamic systems that are complex in time and space, and thus may require complex 3-D landslide models and consideration of hydrological processes of an entire catchment (Terlien 1998; Brunsden 1999).

The study area *Heumöser Hang* (~ 1 km²) is an example of a slow-moving landslide in cohesive sediments and with a pronounced humid hydrological setting. It is located near Bregenz, Austria. In a former project, geotechnical and geodetic methods indicated a variation of movement rates between 0 to over 10 cm a^{-1} in the central slope area (Schneider 1999; Lindenmaier et al. 2005). However, a relation to hydrological signals was difficult to establish, foremost due to the coarse temporal resolution of the data.

The objectives of this study are to elucidate the characteristics and temporal variability of slope movements at the *Heumöser Hang* site, preliminarily explore possible relations to hydro-meteorological forcing and enhance the database for future modelling attempts. Towards this goal, the geotechnical and hydro-meteorological monitoring network at the study site has recently been expanded. The measurements include multi-level pore water pressures at different locations and continuous, high-temporal resolution deformation monitoring at different depths in one borehole.

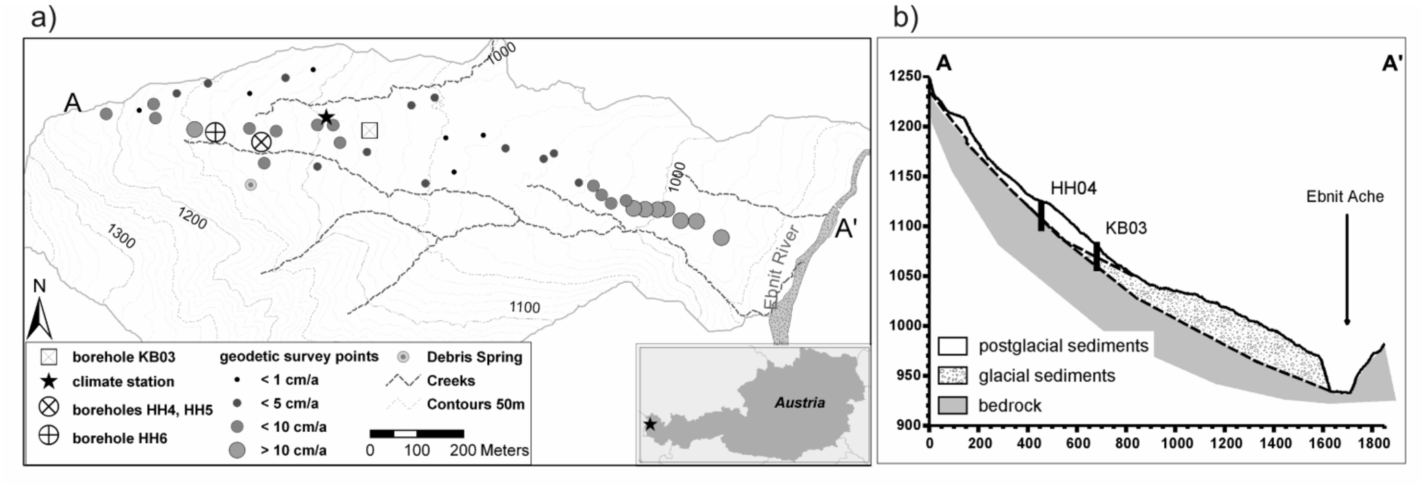

Figure 1. a) Map of the study area *Heumöser Hang* with locations of measurement network. The inlet shows the location of the area in Austria. b) Schematic geological cross-section (W-E).

2 MATERIALS AND METHODS

2.1 *Study area*

The study area *Heumöser Hang* (Fig. 1a) is located in the Vorarlberg Alps (Austria), 0.5 km south of the village of Ebnit (47°21'0.2" N, 9°44'46.62" E). The extension of the slope is 1800 m in east-west and about 500 m in north-south direction, the elevation ranges from 940 m to 1360 m. The study area belongs to the head of a steep mountainous catchment which is drained by the Ebnit River. Average annual precipitation is about 2100 mm. Storm events with short-term rainfall intensities up to 140 mm h^{-1} frequently occur during the summer months (April to September).

The bedrock is formed by upper cretaceous sediments, mainly marls and limy marls; the hillslope body reaches thicknesses of 40 m and consists of subglacial till and scree from weathered marls (Fig. 1b).

Infiltration rates are low in the central slope area, which features saturated patches and fine-textured soils (Wienhöfer et al. 2009). Instead, fast preferential infiltration and flow processes in the steeper sideslopes were proposed to drive rapid increases in groundwater pressures which were observed at KB03 in the central slope body, and thus deemed to also be triggering slope deformations (Lindenmaier et al. 2005; Lindenmaier 2008).

2.2 *Monitoring network*

Inclinometer measurements in borehole KB03 were conducted in intervals of several months during 1997-98 (Schneider, 1999). A geodetic survey network with a total of 40 points monitored surface movement with GPS (Global Positioning System) and terrestrial measurements in each May, August and November during the years 1998–2001 (Depenthal & Schmitt 2003).

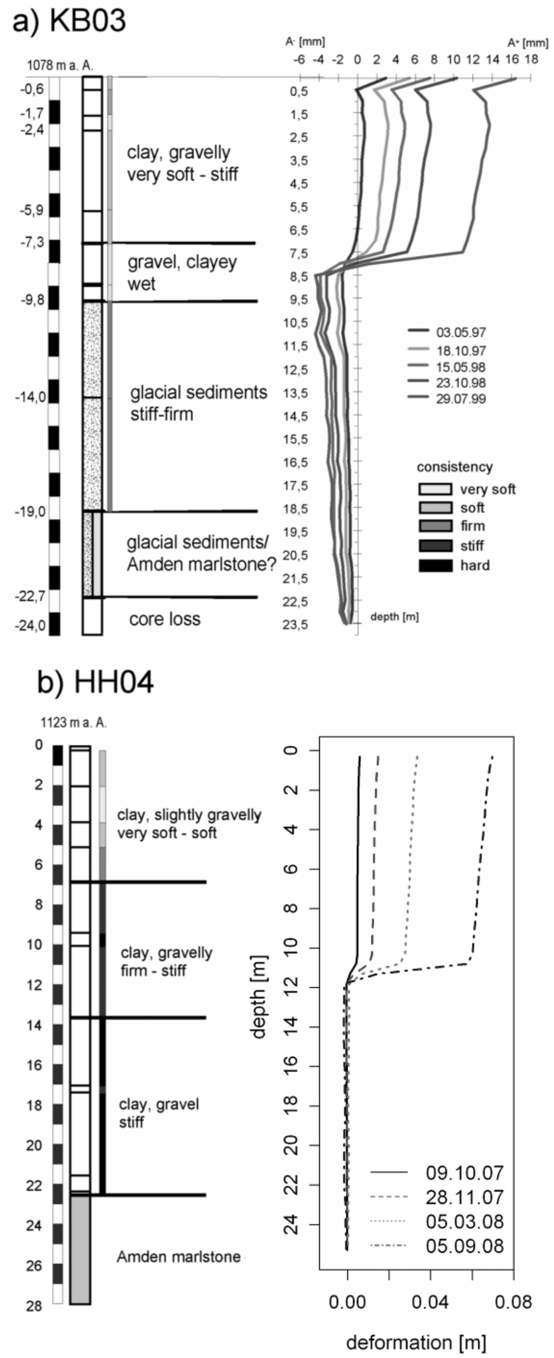

Figure 2. Borehole logs and slope deformation from inclinometer measurements at KB03 (a) and HH4 (b).

In 2007, three boreholes (HH4-6) were drilled in the western part of the slope. Borehole HH4 (28 m depth) was equipped with inclinometer casing, and HH5 and HH6 (20 and 15 m) were equipped with multilevel pore pressure sensors. The inclinometer was measured manually four times during the first six month after installation with a digital inclinometer sensor of 0.5 m length. Then, a stationary inclinometer chain with sensor elements of 1–2 m in length was installed at depths from 0.5–1.5, 10–11, 11–12 and 20–22 m for continuous monitoring of borehole inclination at one hour intervals.

3 RESULTS AND DISCUSSION

Movement rates of the hillslope body of 1.2 cm in 1.5 years and a deformation zone in 7.5-8.5 m depth (Fig. 2) were observed using manual inclinometer measurements at KB03 (Schneider, 1999). Geodetic survey revealed three zones of different movement velocities. The upper western part of the slope body exhibited surface movements up to 10 cm a^{-1}, while the central part was slower with up to 5 cm a^{-1} and the lower eastern part moved faster with up to 25 cm a^{-1} (Depenthal and Schmitt, 2003). The data suggest a seasonality of the movement with maxima in fall and minima in winter (Fig. 3). However, temporal resolution is coarse, with time intervals of 2 months or longer. This restricts more detailed inferences on temporal variability of the movement and detailed discrimination of influencing factors.

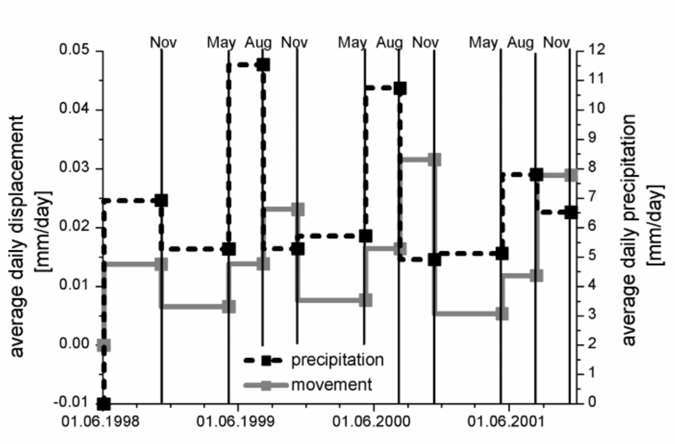

Figure 3. Average daily slope deformation rates from GPS measurements and average daily precipitation during the measurement intervals. Survey times are indicated by vertical lines.

Manual inclinometer readings gave deformation rates of 8 cm a^{-1} at HH4, of which 85 % occurred along a shear zone between 10.5–11.5 m depth, while 15 % of the deformation was distributed linearly between the shear zone and the surface (Fig. 2). The effects of slope movement were observable at most at three depth intervals between 10.5–12 m depth; hence the apparent thickness of the shear zone is between 1.0 and 1.5 m. The actual shear zone may in fact be narrower; however, the accuracy with which the shear zone can be localized with inclinometer measurements is restricted by probe length (vertical resolution 0.5 m) and the deformation properties of the inclinometer casing.

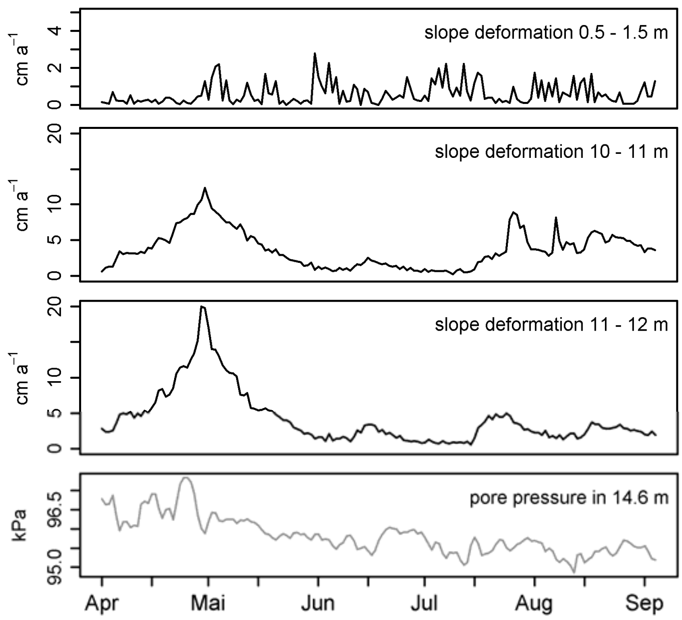

Figure 4. Maximum daily slope deformation rates at three depths at HH4 and median daily pore water pressure at 14.6 m at HH5 (hourly data from continuous monitoring in 2008).

The different deformation rates from inclinometer measurements at KB03 and HH4 are in good accordance with the displacements of surface points obtained with GPS. From the data at HH4 it becomes obvious that most of the movement takes place as a translational sliding along a slip surface located between 10.5 and 11.5 m depth; above this depth additional mass creeping contributes to a minor extent. Thus, the surface movement rates appear to be a good approximation for a distributed assessment of the slope deformation. However, the measurement intervals of several months, which are necessary for detecting displacements due to accuracy limitations of GPS measurements, make the assessment of the temporal dynamics in relation to hydrological signals difficult.

This may be achieved with continuous monitoring techniques. The first six months of hourly data from the stationary inclinometer chain revealed a temporal variation of slope deformation rates and pore water pressures on the timescales of days (Fig. 4). The largest movements occurred between 11 and 12 m and varied between 0.6 and 20.0 cm a^{-1}. At the other levels the deformation rates ranged from 0.2 to 12.4 cm a^{-1} (10–11 m) and 0.0 to 2.8 cm a^{-1} (0.5–1.5 m); virtually no movement was recorded in bedrock between 20–22 m (0.0–0.2 cm a^{-1}). Pore water pressures in this period ranged from 37.7–45.6 kPa (8.10 m), 94.9–97.4 kPa (14.60 m) and 126.6–129.3 kPa (19.10 m). While at lower depths the pore pressures showed a dynamic variation (cf. Fig. 4), the data at 8.10 m showed a continuous decline in pore pressures from September to December 2007, and a quick rise in January 2008, followed by a steady increase until September 2008.

The variations in slope movement at the slip surface are positively correlated to pore pressure variations at lower depths. For example, the deformation rates at 11–12 m are correlated to pore water pressures at 14.60 m with a maximum correlation coefficient $r = 0.72$ at a time lag of 6 d. In contrast, pore water pressures above the slip surface seem to be negatively correlated to the movement; e.g. movement at 11–12 m and pore pressures at 8.10 m ($r = -0.64$, time lag 12 d), although it should be noted that the representativity of the pore pressures at this depth has to be validated with future data. Nevertheless, these results corroborate the common finding that positive pore pressures below the slip surface have a destabilizing effect due to a reduction of retaining forces (van Asch 1997; Iverson 2000). In contrast, saturation of the layers above the shear zone may exhibit a stabilizing effect, if additional loading results in an increase in normal stress acting on the slip surface. This demonstrates the complex nature of the relationship of slope deformation and the groundwater system in the case of deeper landslides, where simple correlations between mobility and rainfall are rare (Terlien 1998).

These preliminary results are based on the first six month of high-resolution data on slope deformation. Nevertheless, it is evident that this kind of data allows a significantly enhanced analysis with respect to the dynamics of slope deformation, which had not been possible with manual inclinometer data or GPS measurements based on field campaigns with intervals of several months. GPS surveys, on the other hand, allow a spatially distributed observation of slope movement for single points at the surface, and manual inclinometer measurements are needed to assess the complete vertical deformation profile.

With the growing time series from the ongoing deformation monitoring it will be possible to address the coherences of slope movements and possible forcing variables during the course of several seasons. This is necessary to detect possible non-linear dynamics of the landslide, e.g. threshold effects or hysteretic behaviour (Terlien 1998; van Asch et al. 2007), and check the role of other possible triggering factors like local seismicity.

The data will also be valuable as target variables for modelling attempts within the group of researchers working at *Heumöser Hang*. Hydrological, hydraulic and mechanical modelling as well as additional field explorations on materials, structures and processes will be carried out to enhance our perception of the complex slope dynamics and to further investigate influencing factors quantitatively in the future.

4 SUMMARY AND OUTLOOK

Movement rates of a relatively slow landslide have been measured with geotechnical and geodetic methods. The slope movement in the study area *Heumöser Hang* (Austria) spatially varied between 0 and 25 cm a^{-1} over the extent of the slope (~ 1 km²), most of the displacement occurred as a sliding movement along a single slip surface. Continuous monitoring of slope deformations in a borehole delivers a data set of high temporal resolution. The data show a temporal variation of movement rates on a timescale of days during the first six months of measurement. The movement rates already varied between 0 and 20 cm a^{-1} during this first observation period and were positively correlated to pore pressure dynamics below the failure plane, while the correlation to the saturation of the overlying layers appears to be negative. The findings imply that the movement of a relatively slow-moving, deeper landslide in fine-textured soils responds to short-term dynamics of driving factors.

The spatial and temporal dynamics of such a landslide can only be resolved with a combination of geotechnical and geodetic methods like those presented in this paper. Hence, the ongoing measurements at *Heumöser Hang* provide a valuable dataset which in future will also be analysed with hydrological, hydraulic and mechanical modelling tools. However, the simulation tools to be developed will need to be verified based upon controlled experiments in the laboratory (cf. Germer & Braun, Stadler et al., this issue) and at the field site (cf. Lindenmaier et al., this issue). Furthermore, detailed field data on geological structures and material properties will be required for distributed modelling of the *Heumöser Hang* adequately, for which a number of geophysical and hydrological investigations are planned in the future.

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