Confined aquifer characteristics and stability of a hillslope in the Vorarlberg Alps, Austria

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ABSTRACT: Many mass movements are driven hydrologically through precipitation and infiltration in unsaturated soils and successional groundwater fluctuations. For understanding flow paths and flow dynamics of infiltrating water in the subsurface, hydrological active structures are considered responsible for fast preferential flow and transport. In mountainous regions, high relief gradients are an additional factor driving fast hydrological and hydrogeological processes. It is also of great importance to understand dominating hydrological thresholds to appropriately account for critical trigger situations; e.g. certain climatic conditions. How the interaction of hydrological and hydrogeological processes influences hillslope stability is yet subject of scientific research. We present the results of recently drilled boreholes, including the observation of new piezometers installed on our study site, the Heumös Slope in the state of Vorarlberg, Austria. In addition, two possible approaches are discussed which can be used to better understand the confined aquifer characteristics in relation to stability considerations and process interaction: 1) the characteristics of pressure propagation in the aquifer in relation to processes at its boundaries and 2) the relationship of the specific storage to the elasticity of the aquifer.

1 INTRODUCTION TO THE HEUMÖS LANDSLIDE AREA

The investigation is conducted at an Alpine slope system which is part of the Dornbirn Ache catchment (~50 km²); located near Bregenz, Austria. The so called Heumös Slope comprises catchments of several small creeks with a total size of 1 km² and up to 400 m of relief gradient. The slope shows translational movement in 8-12 m depth as well as surface creep of up to 10 cm per year. High annual precipitation values of 2100 mm strongly influence surface, unsaturated and saturated water conditions.

Movement characteristics were observed with inclinometers, terrestrial and GPS survey. The surface movement was observed with 34 GPS points and 13 terrestrial survey points. A distinct movement pattern is seen with annual movement rates of 10 or more centimeters. In some parts, the surface movement is in close relation to the subsurface movement: a year-wise periodicity is seen with peak displacement in August to November (Lindenmaier 2008). Movement observation with a recently installed inclinometer chain shows deformation peaks in spring and fall, see the presentation of Wienhöfer et al. in this conference.

Our approach includes a thorough investigation of the fast hydro-meteorological processes encountered in the setting of the Vorarlberg Alps. Fast hydrological processes, i.e. infiltration, surface and subsurface lateral flow are observed, despite low matrix permeability of the soils which consists of stagnic gleysols with a silty-clay loam matrix.

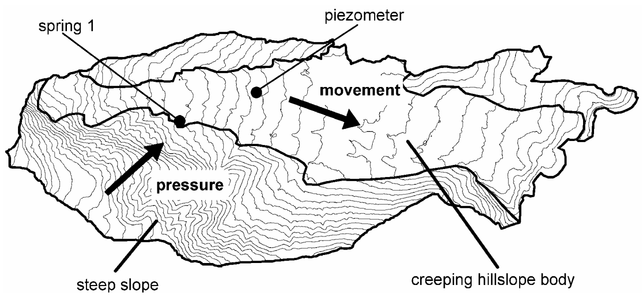

Figure 1. Pressure propagation from adjacent hydrological active hillslopes towards the creep mass which moves towards the east on the Heumös Slope.

The spatial pattern of these interacting processes is determined by dominating heterogeneities, i.e. preferential pathways like shrinkage cracks and coarser grained strata in the generally fine-grained slope body. These fast processes dominate hydrotopes adjacent to the creeping hillslope body (called steep slope in Figure 1), whereas the creeping mass is governed by a fast surface runoff response in contrast and no deep percolation of water. The preferential infiltration processes and their direct reaction in a debris spring on adjacent steep slopes (Fig. 1) are correlated to fast pore pressure responses of a piezometer in a depth of 5.5 m within hours to days after heavy precipitation events in the hillslope body. This lateral pressure propagation (Lindenmaier et al. 2005), is thought to be an essential link towards the observed creep movement. New observation data helps to better identify the processes and non-linear reaction behind this pressure propagation. Our scope in this presentation is to use the concept of aquifer deformation to get an idea of the loading and unloading of the sediment column as well as to further quantify the non-linear pressure propagation from the steep slope towards the creeping mass.

2 GEOLOGICAL SETTING

The geological setting of the Heumös Slope is shown in Figure 2a and b: the hillslope body is surrounded by a rim of marlstone bedrock from several formations of the Late Cretaceous with slightly differing rock properties, mainly in their carbonate content. The Amden marlstones are finely shattered marlstones with about 40 % of carbonate content. These rocks are considered to act as an aquitard. The overlying Wang marlstones exhibit higher carbonate contents and are considered to show a lesser degradation than the Amden marlstones as rock fragments in the sediment body mainly consist out of Wang rocks.

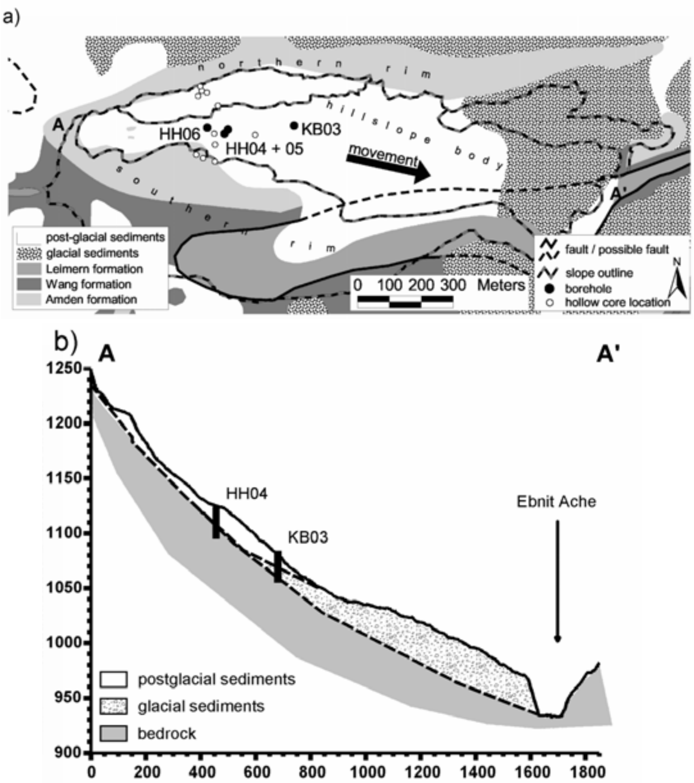

Figure 2. a) Geological map of the mass movement and adjacent hydrological relevant areas (northern and southern rim), arrow indicates direction of movement. b) Cross section in east-west direction and location of boreholes, the river Ebnit flows at the tow of the Heumös Slope.

The Wuerm glaciation resulted in the accumulation of subglacial till and endlake sediments on the Heumös Slope. The west-east profile (Fig. 2b) shows that the subglacial till is eroded by the river taking away the counter bearing of the hillslope. In post glaciation time, an approximate 22 m deep mass of debris accumulated on top of the subglacial till and the Amden marlstones, the debris sediment is hence named post glacial sediments.

A first borehole (KB03, 1075 m) has been drilled in 1996 (Schneider, 1999): In general there are interchanging layers of post glacial sediments with different content of clay matrix and marlstone fragments. The layers show changing consistency values from very soft to hard up to a depth of 9.8 m. Subglacial till, which also includes other rock fragments than marlstones, then follows down to an approximate depth of 22.7 m. The lowest 1.3 m were lost in the borehole and bedrock was presumably just not reached.

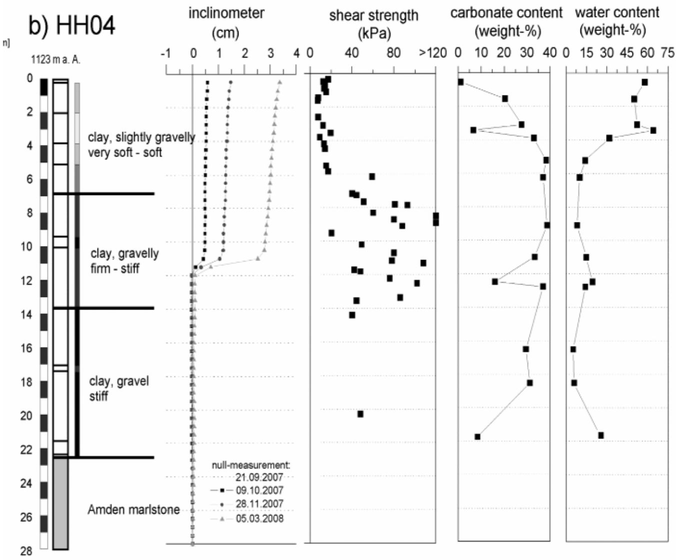

Figure 3. Simplified borehole log of HH04 with three major layers and results of field and laboratory investigations. A clear shear zone is detected in 11-12 m depth.

The newly drilled borehole HH04 (2007, 1123 m) is located 220 m uphill from KB03: there, only post glacial sediments were found in three major layers before marlstones were reached in 22.5 m (Figure 3). The uppermost layer (0-6.8 m) consists of loose, very soft to soft, silty to clayey material with only a few marlstone fragments, sometimes containing wood. Beneath, there is a layer of similar grain size distributions (6.8-13.6 m) that is more compacted and has a lower consistency (firm to stiff). The lowest sediment layer (13.8-22.7 m) has similar consistency values as the middle layer but features larger marlstone fragments with grain sizes of approximately 0.5 m in diameter which are bedded in a silty to clayey matrix.

Samples with low carbonate content in the borehole log indicate phases with soil development

(Fig. 3). Wood directly at the transition to the bedrock indicates that the subglacial till was removed there, before post glacial sediments were deposited.

3 AQUIFER CHARACTERISTICS OF HEUMÖS SLOPE

3.1 Borehole KB03

In KB03, a confined groundwater body was found but details were not recorded (Schneider, 1999). Piezometers in 5.5 m depth and 12.2 m depth show distinct pressure rises in relation to precipitation events in 1998 and also in 2008 (Fig. 4).

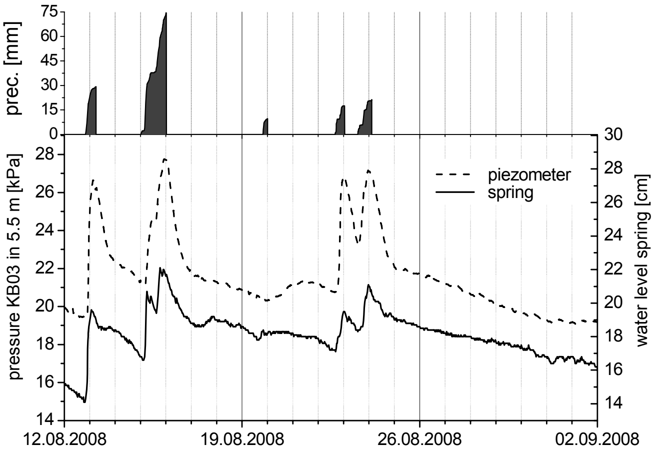

Figure 4. Relation of cumulative precipitation of single events, spring discharge (1127 m) and pressure changes about 300 m downhill in KB03 (1075 m) (see also Figure 1).

These pressure changes coincide with water level changes in the debris spring at the border of the mass movement 51 m uphill. Unfortunately, the data logger failed in 1998 just after spring and surface runoff observation started but could be reactivated in 2008.

In Figure 4, a close relation can be depicted for the spring discharge and the piezometer observation signals. The correlation coefficients for 6 single events in July and August 2008 are between 0.8 and 0.9. Cross correlation gives no time lag for single events or the whole time series, which would mean that an instant reaction of piezometer and spring is feasible.

However, visual estimation of beginning times and peak times shows a varying time lag of 0-4 hours for single events. Simple linear storage coefficient calculation (Tallaksen, 1995) for the August 28th recession results in similar values of about 16 days of depletion for each observation signal. It is noteworthy that both spring and piezometer seem to have an upper limit which is not surpassed, even when precipitation exceeds a certain value of approximately 20 mm.

3.2 Borehole HH04, HH05 and HH06

During the drilling process in borehole HH04, an upper groundwater body was reached in a depth of 2.5 m but water dissipated in a depth of 5.3 m. Then, in a depth of 8.5 m, a sudden rise of water was observed: the water level rose about 7.2 m in 1-2 hours and stayed there until drilling was finished. It has to be noted that drilling went on with water cooling from about 14 m on. Piezometers were installed in the nearby borehole HH05 in a depth of 8.1, 14.6 and 19.1 m. The lower pressure observations show similar behavior as the spring discharge observation. This is not the case at all the time but seem to happen in rather dry general soil moisture conditions of the whole hillslope. For instance, spring and piezometer time series show similar signals in October 2007 (beginning of measurements) and also in fall 2008 (Fig. 5).

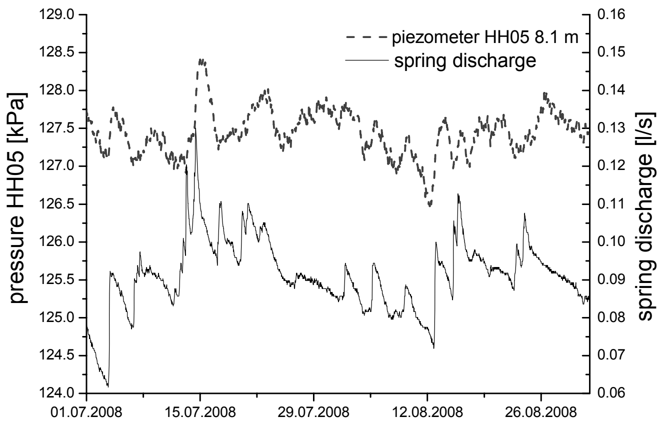

Figure 5. Concordance of pressure signal in HH05 and spring discharge is less than for piezometers of KB03, probably because both are located on the same topographic height.

3.3 Aquifer characteristics

Defining clear aquifer or aquitard properties to the sediments in the borehole log in HH04 is difficult, as source material is similar for all layers and differences only account in different grain size compositions, i.e. the proportion of matrix to rock fragments.

However, the lowest sediment layer observed in HH04 could account for a possible aquifer as rock fragments get more dominant. Still, matrix is considered to enclose these fragments. This layer could coincide with a gravelly layer in KB03 in a depth of 7-9 m, though this layer probably is also matrix dominated.

A second option is, that the shear zone encountered in a depth of 8 and 12 m respectively functions as a confined aquifer, reducing the aquifer depth dimensions drastically. This would also explain the rapid rise of water while drilling near the shear zone in HH04. To conclude, aquifer dimensions vary within 2 m (KB03) to 8.9 m (lowest layer in HH04) or are reduced to shear zone dimensions (less than 1 m ?).

Porosity values in the uppermost layer of HH04 are high with n~0.6; values decrease towards the lower layers to n~0.4. Hydraulic conductivities could not be derived in greater depths but K_f-values in 1-2 m depth, derived with slug-tests, are low with $K_f \sim 1*10^{-8}$ m.s^{-1} to $1*10^{-9}$ m.s^{-1}.

The material is close to wet consistencies in the uppermost 6.8 m of the sediment column in HH04, this means water saturation and consequently no interaction in between the upper and lower sediment column (Lindenmaier, 2008). It can be stated that the upper layer functions as an aquitard for any lower lying possible groundwater bearing strata.

4 UNDERSTANDING THE PRESSURE PROPAGATION IN THE CONFINED AQUIFER

Water level fluctuations in wells in relation to external loading or unloading have been reported numerously (see Domenico & Schwartz 1990, p 126). The pore pressure coefficient (Domenico & Schwartz 1990), also called tidal efficiency (Jacob 1940) relates the height of the tide and a response in an observation well with compressibility factors of water and pores:

$$T.E. = \frac{dP}{\gamma_w dH} = \frac{\beta_P}{\beta_P + n\beta_w} \quad (1)$$

where dP = the change in piezometric level; γ_w = specific gravity of water; n = porosity; β_w compressibility of water and β_P compressibility of pores.

The close relation of the spring and piezometer time series of KB03 as described in section 3.1 can be used to calculate the compressibility of pores, with n, β_w, and γ_w given. The relation of dP to dH is calculated out of the height of the rising limbs of five events in July/August 2008. The compressibility β_P is the reziprocal value of the modulus of elasticity E_s.

It is interesting to apply this concept on the Heumös Slope as well, where the spring discharge is a signal showing external loading and unloading of the confined aquifer in the mass movement. One distorting effect is that the pressure does not experience an attenuation but an increase of amplitude. Two additional circumstances need to be considered here: the spring water level is not a true boundary condition as a tidal effect would be and there is a height difference of the spring in relation to the borehole of 51 m. Calculated values for the modulus of elasticity lie in between $4.42*10^5$ kN.m^{-2} to $5.02*10^5$ kN.m^{-2} which is very likely too high even for stiff to hard clays as encountered in borehole HH04. Stiff to hard clays rather have a modulus of elasticity ten times smaller than calculated.

With more reliable information about the modulus of elasticity or other geomechanical properties or the knowledge of a specific storage coefficient, derived by pump tests, a better link between loading and unloading and hydrogeological reaction could be established.

There is a relationship of aquifer deformation and the withdrawal of groundwater from confined aquifers (Domenico & Schwartz 1990, Walton 1970 Jorgensen 1980). Calculation of consolidation and subsidence in confined aquifers is based on the specific storage coefficient S_s, which can be set in relation with the coefficient of compressibility β_p, hence the elasticity $E_s = 1/\beta_P$.

$$S_s = \rho_w g(\beta_w n + 1/E_s) \quad (2)$$

where ρ_w = density of water; g = gravitational acceleration; α_w = compressibility of water; n = percentage of voids.

5 OUTLOOK

Reducing the pressure level in a confined aquifer means that a decompression of water and parallel to that a compression of the granular structure is achieved.

In a confined aquifer of a mass movement the opposite effect can occur: the pressure level rises and a decompression of the granular structure is achieved. This can lead to the destabilization of clay mineral particles in the shear zone and hence to a localized deformation. The approach mentioned in section 4 can be a first step for understanding the pressure propagation on Heumös Slope, though some essential information about geomechanical properties are still missing.

Also, the high values for the modulus of elasticity yet pose additional uncertainty on the applied equations. Despite the highly compacted matrix in the lower sediment column, the fast rising of water level during drilling of HH04 might be the reason for a highly conductive layer and hence a more pronounced water flow. This would exceed the assumptions for the tidal efficiency (Domenico & Schwartz 1990).

Our aim is to use the concept of aquifer deformation to get an idea of loading and unloading of the sediment column, respectively in a highly pressurized thin shear zone in the hillslope body. This could be a clue for stabilizing and destabilizing of the mass movement and hence on the effect of maximum displacement in the months August to November (Wienhöfer et al., this conference).

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