Landslides Triggered in Clayey Soils
– Geotechnical Measurements and Calculations

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INTRODUCTION
Unstable slopes often show time dependent movements which may be highly variable. In general these variations are often explained with changing water levels behind and in the slope resulting from rainfall. In engineering practice this dependency is commonly accepted. But experience shows, that in low permeable soils heavy rainfall will more likely run off at the surface rather than penetrating into the subsoil at a substantial rate. Thus the influence of rainfall on the piezometric line in low permeable soil should be expected to be minor and delayed in time.

Because variations in pore water pressure control effective shear stress (Terzaghi & Peck 1948) this accepted soil mechanical principle has been enhanced by including time dependent effects of external pressure variation and its influence on the soil below the piezometric line. So far accepted external pressure variation may originate in changes of water level (e. g. tidal effects in estuaries, water level draw down effects in reservoirs or waterways).

In this paper it is proposed, that variations of barometric pressure acting on a slope may also influence pore water pressure conditions. Under certain conditions this effect may be decisive in triggering landslides. Own extensive field measurements have been performed in unstable clay slopes. In this paper recent results will be presented of these measurements in progress as well as results of back calculations. Further information on this topic has already been published recently (Schulze & Köhler, 1999; Köhler et. al.; 1999a; 1999b).

INSTRUMENTATION OF SLOPES AT LÜHNE
For a navigable canal (Stichkanal Hildesheim-SKH-) a cut has been constructed in Lias clay close to Lühnde (Germany) in the 1920s. After major failures in the beginning due to extremely steep slopes (1 : 1.5) the slopes still remain unstable at slope inclinations presently ranging at about 1 : 2.5 to 1 : 3.5. In 1996 inclinometer casings have been installed and periodically read. After identification of the position of the shear zone, two slope profiles located at SKH-km 2.95 (west bank) and SKH-km 3.55 (east bank) have been selected to be instrumented. Pore water pressure transducers have been positioned into the shear zone as well as several meters below and above the shear zone and behind the crest of the slope. Four in-place inclinometers have also been installed directly into the shear zones. The installation of the instruments was completed in November 1997 (SKH-km 3.55) and February 1998 (SKH-km 2.95). At each profile a separate automatic data acquisition system is taking readings of all instruments every 30 minutes.
DISCUSSION OF THE RESULTS OF MEASUREMENTS

After adequate time (up to three months) had passed to allow the pressure transducers to adjust to local pore water pressures, the results of the measurements enabled to construct a plausible piezometric line for each profile. The speed of sliding has been found to be slow enough (up to about 1 mm per day) to observe the slide for longer periods of time. From April 1996 to May 1999 a maximum horizontal deformation of at least 28 cm (SKH-km 3.55) and at least 9.5 cm (SKH-km 2.95) has been measured.

The readings from the instrumented profile at SKH-km 2.95 are depicted in Fig. 1. The data shows a period of major movements of the slope between early November 1998 and May 1999 which resulted in a maximum horizontal deformation of at least 3.7 cm. In both slope profiles little activity was detected during the summer months of 1998. In late October and early November the barometric pressure dropped several times to very low levels. Those typical autumn storms brought considerable amounts of precipitation, but no rise of the piezometric line behind the crest could be registered. Every time major movements of the slopes occurred, mainly the pressure transducers installed in the shear zone (W19, W20, W23 and W24) showed a very quick drop of pore water pressure, followed by increased pressure (up to 15 kPa), which normally will dissipate to the original pressure at rest. This reaction indicates time dependent changes of volume in the moving soil mass which can be directly associated with slope deformation (increasing inclination of inclinometers I3 and I4). This typical situation for instance at time t1 is depicted in Fig. 1. It has been observed, that movements of the entire slope will be noticed at all transducers positioned in the shear zone. Local movements will be noticed in neighbouring transducers only. Obviously the observations can be correlated: Acceleration of movements (times t1, t2, t3 and t4) when barometric pressure falls below mean barometric pressure and vice versa deceleration as soon as barometric pressure rises above mean barometric pressure.

The slope located at SKH-km 3.55 started to move at the same time (late October) as the slope located at the opposite bank shown in Fig. 1. The following major movements were also detected almost simultaneously in both slopes. Due to a common dip of the joint system in the Lias formation such behaviour was not to be expected. Simultaneous movement in combination with a common dip of the joint system at opposite slopes also weakens speculations of water filled fissures that may decisively control movements of the slopes.

Additionally it was observed that the shown slope movements took place exactly in the predicted period of time (Schulze & Köhler, 1999). This had been concluded from the meteorological fact, that major barometric pressure drops (up to almost 5 kPa below mean barometric pressure) occur in Central Europe between about October and April. The remainder of the year fluctuation in barometric pressure is much smaller. It is also noteworthy that precipitation depicted in Fig. 1 from December to May is distributed quite evenly. Thus a deceleration of the slope movements in May 1999 may be difficult to explain by a dry period of time.

MECHANICAL ASPECTS AND CALCULATIONS

In engineering practice soils below piezometric line commonly are still considered to be saturated and the pore fluid is rated being incompressible. But in natural pore water small quantities of fine dispersed small gas bubbles are always present. Even smallest quantities of gas bubbles change the physical properties of the pore fluid in an extreme way and need to be
taken into account in many cases. These gas bubbles inside the pore fluid of the submerged soil will counteract variations of external pressures by inflating or deflating the gas volume, thus causing local transient micro flow. In low permeable soils such as clay or even silt this

Figure 1. Data from SKH-km 2.95 from October 20th, 1998 to June 4th, 1999
process is hampered. Therefore transient excess pore pressure may easily be initiated, when fast pressure changes act on such soils. Regarding the pore fluid as a compressible medium under stress strain controlled deforming soil conditions, lead to new insight of the mechanical behaviour of such treated soils, especially in unstable slope conditions. Oscillating pressure changes will travel trough such unsaturated submerged soil with more or less delay in time and their amplitudes can only reach certain depth levels. Average pressure levels will therefore be kept confined in the deeper soil areas. Regarding such considerations in a typical engineering calculation scheme, the difference between low barometric and mean barometric pressure (which continuously counteracts inside the soil below a certain soil depth \(z[m]\)) needs to be rated as excess pore water pressure \(\Delta u(z,t)\), if barometric pressure drops below the mean pressure level. In the upper transition zone between this certain depth \(z[m]\) and the piezometric line, pressure dissipation may be observed, depending on soil permeability, soil stiffness and pore fluid compressibility.

Two types of calculations have been carried out to simulate the sliding of the slopes under observation in order to investigate the influence of such fluctuating pressure loading (falling barometric pressure and canal water level draw down): Figure 2 shows the results of traditional taylor-type slip circle analysis under limit state condition (Mohr-Coulomb) for the slope at SKH-km 3.55 (east bank). The upper part (Fig. 2a and 2b) shows the circles representing the minimum factor of safety \(f_s\) located at the toe of the slope for stationary and transient pore pressure conditions. The stationary condition (Fig. 2a) describes the uninfluenced piezometric line. No excess pore pressure is acting, neither resulting from falling barometric pressure \(\Delta h_{atm} = 0\) nor from water level draw down \(\Delta h_{water} = 0\). Under transient condition (Fig. 2b) excess pore pressure is acting, resulting from falling barometric pressure \(\Delta h_{atm} = 0.35 \text{ mWH}\) and water level draw down \(\Delta h_{water} = 0.2 \text{ m}\) in the navigable canal. In the lower part (Fig. 2c and 2d) the results of the global slip circle analysis are presented for both conditions. Comparing the safety factors of global and local failure sliding begins at the toe of the considered slopes. Further calculations separating the influence of water level draw down and falling barometric pressure show, that local toe stability is mainly influenced by water level draw down effects. But the global failure of the slope is almost completely caused by excess pore pressure initiated by falling barometric pressure. Combination of both failures (local and global) leads to a modified shape of the shear zone which can be investigated by using finite element (FE) calculation.

Secondly a FE code (PLAXIS 7.1) has been used to analyse the slopes in order to compare with conventional slip circle calculation schemes. Using the same shear parameters as in slip circle analysis, the safety factor \(f_s\) of the slope under stationary condition without acting excess pore water pressure would be marginally above \(f_s = 1.0\). The position of the calculated shear zone fits the measurements better than depicted in Fig. 3. In order to show the effect of reduced effective shear stress due to the acting excess pore water pressure of \(\Delta u(z,t) = 3.5 \text{ kPa}\) (resulting from falling barometric pressure 35 hPa below mean barometric pressure) the shear parameters had to be increased for reasons of numerical stability only (results in FE calculations can only be obtained if the safety factor is not much smaller than unity). Compared to \(\Delta u(z,t) = 0\) the safety factor decreases by 0.035 which coincides well with results of slip circle analysis, but shows a much better correlation to the measured position of the shear zone than a circle (see Fig. 3). In both analyses a single set of shear parameters has been used representing an average shear strength along almost the entire length of the shear zone (Fig. 4, soil 2) because the shear strength rises from a low value.
Figure 2. Results from slip circle analysis at SKH-km 3.55 (local and global failure)

Figure 3. Results from FE-analysis (barometric pressure drop of 35 hPa) at SKH-km 2.95

representing residual shear strength at the toe of the slope (where the maximum deformation has been detected) to higher strength close to the crest.
In Figure 4 (left) results at SKH-km 2.95 are shown together with possible effects caused by suction pressures in the capillary zone above the piezometric line (Fig. 4, right) in soil 1 (Fig. 4, left). Only the depicted suction zone may be directly influenced by rain events, but the effect on global stability is small. Also this effect is superimposed by changing barometric pressure acting in the opposite direction weakening this possible effect. More important is the effect of water filled fissures, but they are difficult to track in natural slopes.

Figure 4. Results of slip circle analysis at SKH-km 2.95 (left side) and possible additional influence of suction acting in the soil above the piezometric line (right side)

CONCLUSIONS
Measurements and calculations suggest falling barometric pressure to be a new and important factor in slope stability. If the permeability of the soil is low enough to allow an excess pore water pressure to be kept confined as barometric pressure decreases, the effect gains importance.

REFERENCES