Influence of barometric pressure changes on slope stability – measurements and geotechnical interpretations

Hans-Jürgen Köhler, Roland Schulze & Ingo Feddersen
Federal Waterways Engineering and Research Institute, Karlsruhe, Germany


ABSTRACT: For measurements of pore water pressure and their geotechnical interpretation the fact needs to be acknowledged that changes of barometric air pressure play an important role concerning soil behaviour especially in low permeable soils. A connection between falling barometric pressure and landslide triggering in unstable slopes is shown. Open gauge and absolute pressure datum transducers are compared in regard to obtain the correct pore pressure from instrument readings and using the evaluated measurements in slope stability analysis. Possible improvements in the technical instrumentation layout are suggested. To explain unsaturated soil conditions in ground water (below the piezometric line) a three-phase-model consisting of gas, water and soil particles is applied: The compressibility of the pore fluid in a submerged subsoil is to a great extent directly dependent on a small but not negligible quantity of microscopic gas bubbles, which are always present in natural pore water. Excess pore water pressure may occur, leading to slope failure.

1 INTRODUCTION

Observations of unstable slopes often show time dependent movements which may be highly variable. In general those variations in movement are often explained with changing water levels behind and in the slope resulting from rainfall events.

In engineering practice this dependency is commonly accepted to be valid also in low permeable soil. But experience shows, that in such 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 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 may be enhanced by including time dependable effects of external pressure variation and its influence on the soil below the piezometric line. Especially the influence of barometric air pressure on pore water pressure and the consequences for geotechnical applications are described.

The terms 'high permeability' and 'low permeability' will be defined in this paper as follows: If a pressure drop is slow enough to enable local pore water pressure to respond without excess pore water pressure being confined, this soil will be rated as 'high permeable'.

2 DISCUSSION OF TYPE OF TRANSDUCER

Pressures are usually measured in relation to reference pressures. The reference pressure might be either constant or variable. At constant reference pressure (absolute pressure datum, type A) an arbitrary but known constant pressure is used. If a variable reference pressure is chosen (open gauge pressure datum, type G) measurements will be relative to barometric air pressure. Both systems are suitable for measurement of pore water pressures, but care should be taken in evaluation of the readings. In 'low permeable' soil the reading of type A transducers represents directly the acting pore water pressure which is a function of time, location, barometric pressure and other factors (Fig. 1a). The reading of type G transducers includes the time dependent change in barometric pressure due to this pressure acting directly on the measuring membrane via vent. If measured against a constant pressure u* the readings will vary according to Figure 1b.
Figure 1. Comparison between absolute pressure (type A) and relative pressure (type G) transducers.
Thus the readings need to be modified in order to obtain the correct pore water pressure $u^*$. For slope stability analysis in most cases knowledge of barometric pressure changes is necessary for correct interpretation of measurements of any type of both transducers. No barometric pressure needs to be included in analysis, if type G transducer are used in 'high permeable' soil.

Assuming barometric air pressure to act without pressure loss through the soil above the piezometric line the barometric air pressure might be considered to act directly on the piezometric line in the analysis. For long term measurements stability of the reference pressure inside the transducer needs to be assured. If this stability can be provided, type A transducers seem to be more suitable for applications in soils because the measured pore water pressures can directly be used in slope stability analysis.

Readings of type G transducers often need to be modified before being introduced into calculations as shown in Figure 1b: In very low permeable soil under ideal conditions (perfect working vent) the difference in barometric pressure $\Delta p_{\text{barom}}$ between the currently acting barometric pressure $p_{\text{barom}}(t)$ and mean barometric pressure $p_{\text{mean}}$ needs to be added (if $p_{\text{barom}}(t) > p_{\text{mean}}$) or subtracted (if $p_{\text{barom}}(t) < p_{\text{mean}}$) from the reading to obtain the correct pore water pressure $u^*$. If the permeability of the soil is greater only a percentage of the barometric pressure difference needs to be considered (see also Fig. 3c and 'transition zone' in chapter 4). A design chart dealing with this specific case can be found in Schulze & Köhler 1999.

Under field conditions experience shows that in time the atmospheric vent gains mechanical resistance due to e.g. condensed water blocking the vent in some unknown extend or other effects. Thus a realistic modification of the readings will be increasingly difficult in time therefore decreasing accuracy of the measurement.

Again it is emphasised that barometric pressure acting at the slope needs to be included in back-analysis using measured pore water pressures unless type G transducers are used in 'high permeable' soil.

Table 1. Requirement of modification of readings and consideration of barometric pressure depending on type of transducer and soil.

<table>
<thead>
<tr>
<th>Transducer</th>
<th>Soil permeability*</th>
<th>Type A</th>
<th>Type G</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>'low'</td>
<td>'high'</td>
<td>'low'</td>
</tr>
<tr>
<td>Barometric pressure required to be included in slope analysis</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td>Reading required to be modified to obtain correct pore pressure $u^*$</td>
<td>no</td>
<td>no</td>
<td>yes</td>
</tr>
</tbody>
</table>

*) see definition in chapter 1

3 LAYOUT OF INSTRUMENTATION

In an unstable old cutting slope in clay the location of the shear zone had been detected by inclinometer measurements. With the location of the shear zone being known, pore water pressure transducers have been placed in the shear zone, above and below the shear zone. The position of the transducers is shown in Figure 2. Type G transducers had been selected for this project because long term stability of the reference pressure inside the transducer could not be sufficiently assured at the time of installation. The transducers were installed under temporary water coverage in deaired water to ensure best contact to the pore water.

The inclinometer casings have been equipped with in-place inclinometers positioned directly into the shear zone. Readings have been taken twice an hour by an automatic data acquisition system for more than one year. Further details on the soil, the instrumentation and measurement data of selected sensors located at the east bank of the navigable canal at km 3.55 may be found in Schulze & Köhler 1999. In this paper a second slope situated on the opposite bank of the canal at km 2.95 is shown in Figure 2. It seems to be noteworthy that in both slopes under investigation which are located at Lühnde (Germany) movements have been repeatedly triggered simultaneously.

4 MECHANICAL ASPECTS OF PORE WATER PRESSURE CHANGES

Submerged soil below water level is commonly regarded to be saturated, consisting of two materials, soil particles and water filled voids. In general engineering practice pore water is viewed to be incompressible.

The introduction of a three-phase-system consisting of gas, water and soil particles assumes a small but decisive part of gas bubbles, always contained in natural pore water. Mechanically the compressibility of the gas-water mixture is highly sensitive regarding a small change of the gas content. Due to external fluctuating pressures, such as pressure changes induced by water waves, water level draw down or meteorological variations in barometric air pressure, the gas bubbles inside the gas-water mixture would like to react immediately in volume change, causing local transient flow. This process is hampered by low permeability depending on boundary conditions and other factors thus creating a time dependent excess pore water pressure. In Central Europe barometric pressure drops of up to about 5 kPa below mean barometric pressure have been observed. The
resulting excess pore water pressure may lead to slope failure.

Figure 2. Instrumentation of an unstable slope close to Lühnde (located on the west bank of the canal at km 2.95).

Regarding the pore fluid of submerged soils as a compressible medium the change in pore water pressure is governed by a delayed pressure spreading process. This time dependent pressure spreading leads to a different mechanical behaviour of the soil which turns out to be often decisive in unstable slope conditions. Figure 3 explains the possible transient situations occurring due to fluctuating pressure loadings such as piezometric head or barometric pressure changes. It is considered that barometric pressure changes will travel through the pores of an unsaturated soil above the piezometric line with almost no delay and pressure loss. Therefore the barometric pressure may be taken into account as an active loading on the piezometric line. Additionally the changes in piezometric line and/or fluctuating air pressure will induce changes in water pressure head \( u^* \) in the submerged soil.

As long as the soil is considered 'high permeable' the external pressure change will penetrate instantaneously into the water filled pores without noticeable delay. Any change in external pressure will be transferred to the shear zone. Since the external pressure acts on all planes of the soil prism it need not be taken into consideration at all (Figure 3b).

In the case where the soil is rated as being 'low permeable', pressure changes cannot spread as fast as the pressure changes occur. In Figure 3c the possible time dependent pressure distributions below piezometric line are shown for the loading of oscillating barometric pressure variations. In the depth \( z \) below piezometric head no pressure change can be measured (using type A transducers). Exactly this type of loading may cause excess pore water pressure, which will be kept confined in 'low permeable' soils such as clay or even silt, when barometric pressure drops below the mean pressure \( p_{\text{mean}} \). Possible shear zones may easily reach failure conditions. The physical model of such behaviour of the deforming soil structure below water level can be explained by volume changes of microscopic small gas bubbles dispersed in the pore fluid of submerged soils, which are always present in nature (Köhler et al. 1999). Due to the gas content in the pore water, pressure changes induce local microscopic flow conditions which will be hampered in low permeable soils. Therefore no pressure release will be observed in certain soil depth levels below the piezometric line. Thus the relatively small and slow external barometric pressure variations cannot reach certain soil depth levels in 'low permeable' soils.

According to engineering judgement the confined mean barometric pressure, which continuously counteracts inside the soil below a certain soil depth has to be rated as excess pore water pressure \( \Delta u (z,t) \) when pressure drops below mean pressure level occur. In the transition zone between this certain depth level and the piezometric line pressure dissipation will be possible depending on soil permeability, soil stiffness and pore fluid compressibility.

5 SUGGESTED IMPROVEMENTS

If pore water transducers (piezometers) are placed in 'low permeable' soil close to inclinometer casings pore water pressure might dissipate into the incli-
nometer casing or a water pressure inside the casing that happens to be higher than the local pore pressure might also influence the local pore pressure.

In Figure 3 (a-c), Influence of barometric pressure $p(t)$ on pore pressure changes in submerged soils

Thus the measured pore water pressure might not truly represent the actual pore pressure. To counteract this process an improved inclinometer casing should be connected by hermetically (air- and watertight) sealed couplings which are still flexible enough to keep excessive strain off the casing after movements in the slope have occurred. By using hermetically sealed couplings incorrect readings can be avoided as shown in Figure 4. This can be achieved quite easily during construction. Also care should be taken in selecting adequate grout permeability.

A conventional standard inclinometer casing which might cause intolerable pressure leaks will be costly to replace or seal after construction of the inclinometer is finished.

6 CONCLUSIONS

A new mechanism is introduced which is valid especially in soils with 'low permeability': Rapid falling barometric pressure may be the decisive factor leading to landslide triggering in unstable slopes. Combined with appropriate weather forecast information the quality of slope failure prediction may be substantially improved.

Regarding pore water pressure measurements basic differences in evaluating readings from type A and type G transducers have been explained.

- Generally both types of transducers are suitable for application in pore water measurements.
- Barometric pressure needs to be included in back analysis of slopes using data from pressure transducers with the exception of type G transducers in 'high permeable' soil.
- Readings from type G transducers used in 'low permeable' soil need to be modified to obtain a correct pore water pressure $u^*$.
- Sufficient time should be allowed for the pore water pressure to recover after installation of the transducer. In the described slope in clay 2 to 3 months were required. Attention should be paid to this time frame when determining zero readings ahead of construction projects.

Permanent disturbance of the local pore water pressure in 'low permeable' soil is to be avoided. Disturbances may be caused by instruments which allow water or barometric air pressures to act randomly, thus local measurements of pore pressure may not be representative.

- inclinometer casings need to be equipped with hermetically sealed couplings and base caps
permeability of the grout surrounding the inclinometer casing should be equal or lower than the soil permeability. The influence of external pressure fluctuations seems to be an important additional factor to be included in slope stability analysis.

Figure 4. Influence of inclinometer casing in regard of nearby placed piezometers in 'low permeable' soil

REFERENCES

