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Influence of pore-water pressure and deformation effects on the long-term stability of cut slopes in overconsolidated clay

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Abstract

Assessing the long-term stability of cut slopes in overconsolidated clay is a geotechnical issue which is still not well understood. A concept of several characteristic pore-water pressure states is applied to describe the stability of cut slopes in low permeable ground like clay: Starting from typical states of pore-water pressure and stress-strain characteristics and their impact on soil fabric, which were identified earlier concerning EDZ (Excavation Damaged Zone)[1] around tunnels, this approach is now transferred to slopes. The three-phase-system (solid, water, gas) below the piezometric level and other approaches can be included in the analysis. Additionally, typical changes in soil fabric (states) may occur after the unloading process is initiated by excavating a cut slope:

As suggested, this effect is applied to slope stability, being directly linked to profound changes in soil fabric, a state related to the opening of fissures or similar deformation effects – possibly leading to sudden collapse. At first the pore-water pressures in the slope will decrease (e. g. below atmospheric pressure). After some time, if the opening of micro-joints occurs (EDZ), pore-water pressures rapidly approach atmospheric pressure. If the slope stays stable in this phase, well-known procedures towards equilibration of pore pressure will be followed – later failure may or may not occur. Applying new insight about the state-changes indicated above, derived from in-situ pore-water pressure measurements in tunnels, explanation of sudden failure of slopes may be improved, especially when collapse occurs after long periods of apparent stability. This concept, which is elaborated in detail, may lead to new approaches to assess long-term behaviour of such instable slopes. Within the proposed soil-mechanical framework based on the concept of effective stress the understanding of such critical slopes may be enhanced.

Additionally, guidance is provided on pore-water pressure measurements and compensation of atmospheric pressure effects.

Keywords: slope stability, pore pressure, atmospheric pressure, three-phase-system, excavation damaged zone

1. Introduction

Cuttings in soil or rock are constructed for transport infrastructure like roads, railways, navigable canals etc. at a level below the original ground surface. Stability of such cut slopes is linked to mechanical properties of the local ground, primarily concerning strength and hydraulic characteristics as well as the geometry of the slope. Cuts in overconsolidated clay are especially prone to instability in the long-term – failures like deep-seated rotational slides cannot be excluded. Even slopes, that seemed to be stable for many years or even decades, failed without or only little pre-warning, obstructing or even disrupting traffic at the affected infrastructure.

Such failures are often attributed e. g. to rainfall or seasonal events (which indeed may directly trigger instable slopes). Still the underlying complex processes leading to instabilities in the long-term are not well understood, in spite of considerable advances in research, e. g. Skempton (1964), Vaughan & Walbancke (1973), Potts et al.

[1] In this paper the definition of the Excavation Damaged Zone (EDZ) proposed by Tsang et al. (2005) is used: EDZ is a zone with hydromechanical and geochemical modifications inducing significant changes in flow and transport properties. These changes can, for example, include one or more orders of magnitude increase in (effective) flow permeability.
To clarify, in contrast to EDZ, the excavation disturbed zone (EdZ) is defined by the same authors as zone with hydromechanical and geochemical modifications, without major changes in flow and transport properties. EdZ is not referred to in this paper.

(1997), Cooper et al. (1998), Tsiampousi et al. (2017). The delayed failure of slopes is generally explained by initial unloading and the resulting equilibration of stresses leading to strain softening in combination with re-adjusting pore pressure distribution in accordance to consolidation theory (often linked in a simplified way to the development of a rising piezometric line).

In underground engineering the excavation damaged zone (EDZ) is a feature around subsurface openings (e. g. shafts or tunnels): Under certain conditions time-dependent fundamental changes of soil fabric and associated mechanical properties may occur rapidly (Bernier et al. 2007), influencing local properties such as permeability, and stiffness thus affecting stress-deformation characteristics and pore pressure distribution. In the presented paper, the concept of EDZ is applied to cut slopes as a novel approach, that may influence stability of the slope.

In order to calculate time-dependent pore-water pressure distributions more realistically, soil should be regarded to consist of a three-phase-system (solid, water, gas). Since small amounts of gas are ubiquitous in untreated water, even below the piezometric line conditions are not fully saturated - in the sense, that the pore-volume is filled with such a pore-fluid consisting of water and gas. The presence of entrapped gas is also referred to by terms such as “nearly saturated” or “quasi-saturated”. If the pore-fluid consists of a water-gas mixture, even a very small percentage of gas leads to a significant increase in fluid compressibility (Fredlund et al. 2012, p. 790 f), in low permeable ground resulting in consequences concerning the time-dependent stress-deformation behaviour. Examples of application and further information are given in Schulze & Stelzer (2015). Verifying model predictions with field measurements is essential, so the next chapter briefly provides basic information in order to clarify terminology, measurement procedures and interpretation of sensor readings.

2. General remarks

2.1 Pore-water pressure measurements

Generally, pressures may be expressed in absolute pressure p_{abs} or relative pressure p_e (relative to atmospheric pressure) as indicated in Fig. 1. This leads to implications concerning the interpretation of readings taken from a pore-water pressure sensor.

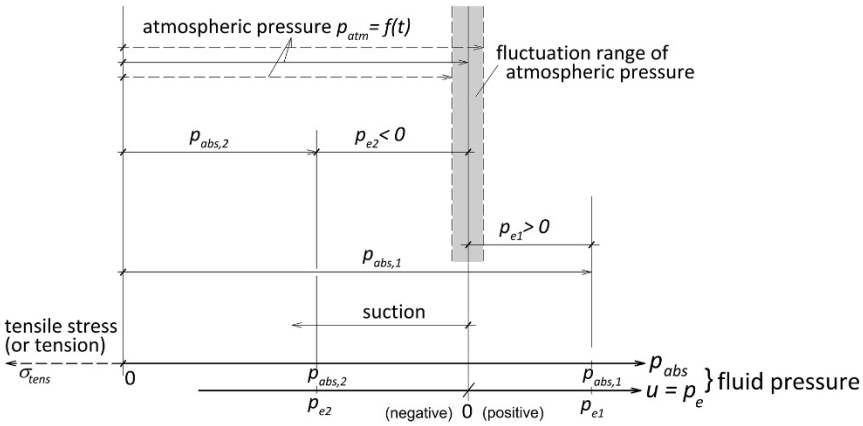

Figure 1: Definitions of pressure terms related to pore-water pressure (modified from EAG 2022, p. 46).

Applying equilibrium condition to the groundwater level (e. g. in a piezometer tube) leads to the definition of pore-water pressure u relative to atmospheric pressure p_{atm}: The groundwater level is defined to be the elevation level, where pore-water pressure $u = 0 = p_e$ (or: $p_{abs} = p_{atm}$). Thus pore-water pressure u may be defined as pressure difference compared to the atmospheric pressure p_{atm}. Positive values represent pressure higher than atmospheric pressure and negative values lower than atmospheric pressure – the latter also known as “suction” (suction values are positive values per definition, please note the reversed axis-direction in Fig. 1).

$u > 0$	positive pore-water pressure
$u < 0$	negative pore-water pressure (also known as “suction”)
$\sigma_{tens} < p_{abs} = 0$	tensile stress (or: tension)
$p_{abs1,2}$ and $p_{e1,2}$	arbitrary selected pressures indicating mutual interrelation of absolute and relative pressure

Pore-water pressure measurements are covered in the recently introduced standard ISO 18674-4:2020 "Piezometers", where pore-water pressure u (also: pore pressure) is defined as pressure of the water in the voids of the ground (or a fill). According to the principle of effective stress (Terzaghi 1943) pore-water pressure u is derived from

$\sigma = \sigma' + u$ with $u = h \cdot \gamma_w$ h … height of water column (pressure head) γ_w … unit weight of water

Thus, with $u = \sigma - \sigma'$ the pore-water pressure u is the difference between the total normal stress σ and the effective normal stress σ'. Please note, pore-water pressure u is defined as pore pressure relative to atmospheric pressure p_{atm}. Although this definition is valid for many classical geotechnical applications, often the absolute pore-water pressure p_{abs} may be required in selected equations (e. g. Boyle-Mariotte law).

In ISO 18674-4 "Piezometers" several methods to measure pore-water pressure are described, e. g. by using open or closed (piezometer) systems. An example for an open system is a piezometer tube (hydraulically connected to the groundwater at a certain depth), where the water level inside the tube (which is directly connected to the atmospheric pressure) is assumed to indicate the piezometric level of groundwater. In contrast a closed system would be a pressure sensor separated from direct contact to the atmosphere, e. g. traditionally installed in a sand pocket and sheltered by an impermeable seal placed into the bore hole above the sand pocket.

A special variant of a closed system is the installation according to the fully grouted method (Vaughan 1969, Marefat et al. 2019), which may offer economical and technical advantages and has now found its way into current standards (e. g. ISO 18674-4 "Piezometers", British Standard BS 5930 "Code of practice for ground investigations"): The sensor is fixed in the borehole, later the borehole is filled with a specific grout (water, cement and bentonite).

Electronic sensors installed in closed systems cannot be retrieved easily to check their function, thus redundant installation of at least two identical sensors at the same depth can be considered. For further information on pore-water pressure measurement methods refer to Dunnicliff (1988).

2.2 Compensation of atmospheric pressure

Atmospheric pressure is always acting on the ground surface, respectively on the surface of the groundwater. In general, atmospheric pressure p_{atm} is fluctuating with time ($p_{atm} = f(t)$). In many cases compensation for atmospheric pressure is necessary to determine pore-water pressure u, which is prevailing at the measuring point. An overview to compensate a sensor reading p concerning atmospheric pressure is given in Table 1, depending on the type of the applied sensor and site-specific conditions.

Type of sensor	absolute pressure sensor		relative pressure sensor		gauge pressure sensor	
Permeability of ground (prevailing conditions)	„low" (undrained)	„high" (drained)	„low" (undrained)	„high" (drained)	„low" (undrained)	„high" (drained)
Compensation required	yes	yes	yes	no	yes	yes
Compensation of sensor reading p(t)	$-\bar{p}_{atm}$ = constant (average value)	$-p_{atm}(t)$ (fluctuating)	$+\varepsilon(p_{atm}(t) - \bar{p}_{atm})$	N/A	$+p_{const} - \bar{p}_{atm}$	$+p_{const} - p_{atm}(t)$
Pore-water pressure u(t)	$u(t) = p(t) - \bar{p}_{atm}$	$u(t) = p(t) - p_{atm}(t)$	$u(t) = p(t) + \varepsilon(p_{atm}(t) - \bar{p}_{atm})$	$u(t) = p(t)$	$u(t) = p(t) + p_{const} - \bar{p}_{atm}$	$u(t) = p(t) + p_{const} - p_{atm}(t)$

Table 1: Compensation of atmospheric pressure to determine pore-water pressure u from sensor reading p.

Annotation to Table 1: The constant value $\bar{p}_{atm}$ is the average atmospheric pressure acting at the specific site. The case of using a relative pressure sensor at undrained conditions is rather theoretical and not recommended; the required correction factor ε ($0 \leq \varepsilon \leq 1$) needs to be derived for each measuring point, considering non-perfect vent conditions: e. g. totally blocked vent: 0, perfectly open vent: 1

A pressure sensor typically captures pressure differences, and often consists of two chambers separated by a membrane: The inner chamber (according to ISO 18674-4) is connected to the measuring point via fluid, while the pressure in the outer chamber is either known (and constant) or connected to the atmosphere. The difference of the two pressures is indicated by the deflection of the membrane, which can be measured. The term “relative pressure sensor” refers to a sensor where the outer chamber of the measuring device is connected via vent to the atmosphere, “absolute pressure sensor” refers to a sensor reading relative to $p_{abs} = 0$. A subtype of an absolute pressure sensor is a “gauge pressure sensor”, where the reference pressure in the outer chamber is calibrated referring to a pre-selected constant value p_{const} (e. g. $p_{const} = 100$ kPa > $p_{abs} = 0$).

Externally applied (hydraulic and/or mechanic) loading (or unloading) induces pore-water pressure responses, depending on several parameters, such as e. g. rate of external load variation, hydraulic permeability of the soil, stiffnesses of soil and fluid. The result may be a deviation from the hydrostatic pore pressure distribution (e. g. leading to excess pore-water pressure) characterized by undrained conditions. In Table 1 permeability "low" denotes a symbol for external pressure change leading to such a deviation from the hydrostatic pressure distribution. In order to assess the prevailing conditions (undrained or drained), the specific site conditions of the measuring task need to be considered. Thus, any fixed values concerning permeability cannot be specified to determine either case. However, these categories are rather simplistic. Although in clay undrained conditions are to be expected, in certain cases drained behaviour may occur even in clay, if the measuring point happens to be positioned in the vicinity of a fissure with increased permeability (representing short dissipation length). When evaluating field data, as guidance for interpretation may serve, that the resulting pore pressure u is usually expected to be rather stable, when compared to fluctuations in atmospheric pressure.

3. Pore-water pressure in cut slopes

3.1 Effects related to EDZ

Mechanical unloading is initiated by excavation of an underground opening as well as by excavating a cut slope. Typical time dependent phases of pore-water pressure development around underground openings such as tunnels or shafts are shown in a schematic way in Fig. 2a. Such phases have been observed (van Geet 2009 p. 82, Schulze 2011) and can be related to EDZ effects. In Fig. 2b associated typical phases, that may occur at cut slopes are derived as a novel approach.

Fig. 2a is taken from Schulze (2011), where the evidence of EDZ is elaborated in detail, based on pore-water pressure measurements from the vicinity of a tunnel. Here a short summary is given: The readings acquired in the beginning of the measurements (phase 0) are somewhat arbitrary and depend on the original undisturbed pore-water pressure. In phase 1 pore pressure strives asymptotically towards a new equilibrium, possibly even falling to suction. Depending on factors like e. g. permeability, the distance from the tunnel wall, stiffnesses of soil and tunnel lining this phase may last from about a few days to several months. In phase 2 the pore pressure suddenly increases to atmospheric pressure when the fabric of the ground changes radically to increased permeability, e. g. by the opening of micro-joints (EDZ). Phase 3 is characterized by atmospheric pressure reaching far into the soil. This phase may last for several months or even years. Finally, in phase 4 increasing pore pressure is observed which may be explained by joints which have been closed again with time. Influenced by the tunnel, pore-water pressure may finally approach a new equilibrium.

In Fig. 2b the phases of Fig. 2a are applied to the case of a cut slope: Depicted is the time dependent development of pore-water pressure at a measuring point below the future ground surface of a cut starting prior to the excavation. Phase 0 represents undisturbed, equilibrium pore-water pressure before the excavation started. While excavation takes place (in the beginning of phase 1), pore pressure decreases due to unloading, possibly even falling below atmospheric pressure depending on site-specific conditions, because of low permeability pore-water cannot flow fast enough from the surrounding ground to respond to deformation. Corresponding to decreasing pore-water pressure, gas bubbles tend to expand, which may always be present in natural pore-fluids, resulting in non-trivial time-dependent deformation processes. Later in phase 1 (post construction of the cut) pore pressures tend to equilibrate with time due to dissipation. Obviously falling pore-water pressures increase effective stresses and thus the stability of the slope, at least temporarily. Phase 1 may last a few days to years or even decades, depending on permeability and/or strength/deformation characteristics of the ground. Classical theory (e. g. continuum mechanics) would predict, that after phase 1 pore pressures continuously increase. This may eventually lead to failure with time.

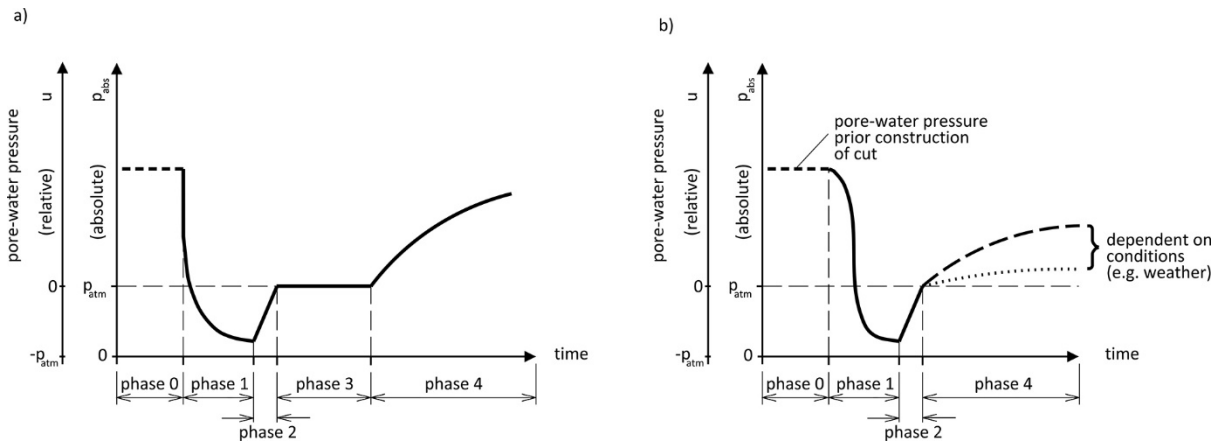

Figure 2: Schematic sketch of time dependent pore pressure development in clay at a) underground opening, b) cut slope.

Applying EDZ to cut slopes (Fig. 2b) opens the possibility that deformation during phase 1 reaches a point, when a sudden transition of the original soil fabric implies significant changes of geotechnical properties of the ground concerning stiffness and permeability e. g. by opening micro-joints or micro-cracks. This radical change of fabric characterizes phase 2, when atmospheric pressure is enabled to reach into the ground, leading to a sudden increase of pore pressure (e. g. loss of suction). Additionally, if newly opened micro-joints are connected directly to the surface of the slope, allowing run-off water from rainfall events to enter easily the soil body (phase 4). With (and after) phase 2 the probability of failure of the slope is increased because of occurrence of the opening of fissures, directly followed[2] by phase 4. Phase 4 is characterized by further equilibration of pore-water pressure and water infiltrating into micro-joints, which adds extra load to the slope. All those effects decrease the stability of a slope, possibly leading to failure. As a result, applying phase 2 (EDZ) to unloading processes associated with cut slopes, may explain frequent practical observations claiming that slopes which remained apparently stable for a long time (even for several decades) suddenly failed without pre-warning.

3.2 Effects related to shearing

Delayed failure at cut slopes in overconsolidated stiff clay tends to start at the toe of the slope, working its way upward along the potential shear zone to its crown (Potts et al. 1997, p. 965 ff). Cooper et al. 1998 (p. 97 f) observed an onset of failure at the toe also, as well as decreasing pore pressure close to the toe at the shear zone, that might be explained by dilatancy. Experience also identified decreasing pore pressure in the shear zone and vicinity as a sensitive indicator for the detection of movements in the soil.

It can be derived from the potential geometry of a failing slope, that the displacements near the toe of the slope are likely to be mainly horizontal. However, at the crown of the slope mostly vertical displacements will occur, as soon as the shear zone has advanced close enough toward the top. In order to detect slope movements as early as possible, preferably the lower part of the slope should be observed. Since the detection of small horizontal displacements is not a trivial task in the field, pore-water pressure measurements can be deployed as a sensitive indicator to detect movements of the slope. Such measurements should be positioned as close as possible to the potential shear zone, if early detection is needed preferably in the lower part of the slope near the toe. Movements are often indicated by relatively low pore pressure (might be fluctuating at a scale of hours to weeks). Such low pore pressures result from dilatancy in the shear zone, that is not consistent to pore pressure distribution in the far-field, away from the shear zone. For comparison the piezometric level is decisive.

The main body of a larger instable slope rarely moves as a massive block. Rather parts of the instable soil mass will move along the rupture surface like a caterpillar: Starting from the toe a part moves downwards, allowing the neighbouring part to follow as soon as mechanical conditions permit and so forth. Because of disaggregation, the permeability of soil in the rupture zone tends to increase (leading to diminished dilatancy-induced pore

[2] In Fig. 2b phase 3 of Fig. 2a is omitted because in practice it may just last for a relatively short time. This is to be expected, because (unlike in an underground opening) at a cut slope located in wet climate, rainfall may provide enough run-off water at ground level to enter and fill the micro-cracks. An underground opening is protected from rainfall, thus open micro-cracks cannot be infiltrated by rain. After some time, the deformation of soil eventually causes cracks to close and pore-water pressures might increase slowly.

pressure), while the shear strength of the soil is likely to decline. In the course of time the rupture zone may develop toward the top of the cut.

3.3 Pore-water pressure below atmospheric pressure

Concerning slope stability, especially in low permeable slopes negative pore-water pressure like e. g. suction may be pivotal for processes following unloading. The same is valid when looking directly at the shear zone while shearing (see 3.2). Suction is also influenced seasonally by rainfall patterns and vegetation - details on a lightly vegetated slope in London clay are given by Smethurst et al. (2012).

Contrary to a common interpretation concerning cavitation (formation of vapour cavities), stresses in pore-water may indeed reach below $p_{abs} = 0$ (Take & Bolton 2003), such stress is referred to tensile stress. Further information concerning pore-water reaching temporarily 755 kPa tensile stress (tension) is described by Khaledi et al. 2021 focussing on Mont Terri clay shale: The issue of pore-water linked to various nuclei that may cause cavitation before reaching tensile stress is addressed by "*the pore size distribution of Opalinus clay may control cavitation and facilitate negative pore pressures upon unloading"*. In other words, water is capable of withstanding tensile stresses, if such stresses can be transferred to the fluid[3].

4. Conclusions

In order to understand the processes affecting the long-term stability of cut slopes in clay, a sound knowledge of the evolution of time-dependent pore-water pressure distribution and effective stress is crucial. Thus briefly

- definitions of pressures are given. Pore-water pressure u (relative to atmospheric pressure) which is traditionally applied in classical soil mechanics and absolute water pressure p_{abs} are distinguished,
- methods to measure pore-water pressure are mentioned (open and closed systems), including the fully grouted method because of its relevance concerning measurements in clay,
- compensation of atmospheric influence on sensor readings p to determine pore-water pressure u is explained. Guidance is given, depending on the type of the sensor and site-specific conditions.

Pore-water pressure measurements are proposed as a sensitive indicator for movements of a slope.

The main topic is the introduction of a novel aspect to evaluate long-term stability of slopes in clay: Application of EDZ as a mechanism to explain sudden failure of a cut slope in overconsolidated clay. This process of sudden change in soil fabric (permeability, stiffness etc.) resulting in fast change of pore pressure that may occur in the long-term, during the unloading process initiated by excavation of the cut. Further research is needed to assess the conditions under which rapid fabric changes occur in cut slopes. The discussed contribution may improve understanding of cut slope behaviour pursuing the goal to ensure safe and intact traffic links as long as possible and keep traffic closures to a minimum.

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[3] Tensile stresses do also occur at or close to full saturation (quasi-saturated pore-fluid). Under such conditions, the upper bound of suction seems to be roughly 5 MPa (Prime et al. 2016), about 0,6 to about 4 MPa have been observed at several occasions (Temperley & Chambers 1946, Prime et al. 2016), although much higher suction (150 MPa and more) has been observed at drying conditions associated with much lower degrees of saturation (Prime et al. 2016).

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