Increasing safety of unstable slopes by unconventional pore pressure release technique

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ABSTRACT: Transient pore pressure distributions may be estimated by regarding submerged soil as a three-phase medium (gas, water and solids). Thus new approaches to release pore water pressure have been developed in order to stabilise endangered slopes in low permeable soil. The applied concept of using reversely inclined bore holes to release pore pressure in the vicinity of potential shear zones is described. The proposed way of pore pressure release in order to increase safety of unstable slopes is widely applicable. Examples of applications to increase safety include cut slopes as well as river dikes. Additionally results of calculations and field measurements are provided and discussed.

1 INTRODUCTION

In this paper pore water pressure release techniques are described, which may be used to increase slope stability in low permeable soils. Transient pore pressure distributions are initiated by applying such concepts. This paper will focus on the practical estimation of the increase of slope stability.

First a cut slope will be discussed. Pore pressure measurements have been undertaken to observe the effectiveness of bore holes allowing dissipation of pore pressure. Results of the measurements are presented providing input for safety assessment calculations.

The second example describes pore pressure reduction in order to increase slope stability of existing river dikes, used for flood protection. Improvements of existing structures are often requested due to increasing probability of higher flood waves than originally anticipated.

2 PORE PRESSURE RELEASE TECHNIQUE

It is widely assumed that drainage pipes need to withdraw water visibly in order to be effective. Thus apparently dry drainage pipes are often viewed falsely as being ineffective. Especially in low permeable soil even the removal of small quantities of water (e. g. evaporation into the pipe) will reduce pore water pressure surrounding the drainage pipe.

Pore pressure reduction has been applied in the past at many occasions usually considering steady state conditions. To increase slope stability the following aspects are applied in this paper.

Pore pressure reduction may occur regardless of the inclination of the bore hole or the water level inside the bore hole. Furthermore a new approach and main target is the estimation of the transient development of pore pressures covering the gap between the steady state conditions of the initial and final state. The method which is based on the application of the three-phase-model is described in Schulze et al. (2003). Even reversely inclined bore holes or bore holes entirely filled with water may be able to decrease pore pressures.

Removing water from the bore holes increases effectiveness, because barometric pressure is allowed to be transferred directly into the soil. A successful application of this concept depends on the original magnitude of the pore pressures to be reduced.

Looking at a bore hole filled entirely with water the piezometric level all over the bore hole is constant and solely determined by the geodetic level of the bore hole mouth (flow velocity in the bore hole assumed to be negligible). In a bore hole which is filled with air (water removed), the local piezometric level (hydraulic boundary condition along the bore-hole) will be the local geodetic level.

In many practical cases these facts allow a much more effective placement of the drainage pipes into the shear zone. In accordance with Terzaghi’s principle of effective stress the stability of the slope will be increased directly as pore water pressure is reduced.
3 STABILISING AN ENDANGERED CUT

3.1 General information and soil properties

The instable cut is about 20 m deep and located at a navigable canal nearby Lühnde (Germany). Indications of slope movements led to the current geotechnical investigations, which were initiated in 1995, resulting out of the intention to deepen the canal to allow larger ship vessels to pass. Pore water pressures, slope movements and rainfall are observed by automated data acquisition systems.

Falling barometric pressure has been identified to be a decisive factor being able to trigger slope movements (Schulze et al. 1999). Using this factor, forecasts as to when movements of the slope will be accelerating have repeatedly been successful in the field. Further details referring to that specific aspect, as well as soil properties, instrumentation and data, have been published (Köhler et al. 1999, 2000, 2002a).

The cut is located in stiff, fissured Lower Lias clay, \( w_L = 0.58, w_p = 0.22 \), clay 40%, silt 60%. Narrow limestone bands are embedded occasionally. The permeability is considered to be about \( 10^{-10} \) to \( 10^{-11} \) m/s, although fissures and limestone bands increase the large scale permeability of the soil.

3.2 Field test and pore pressure measurements

A field test has been designed and performed to verify the anticipated effectiveness of the proposed method. The test field has been located at a section that had already been used for several years to monitor slope movements.

In a test field located within the endangered slope a pattern of three differently inclined pore pressure reduction borings was selected. Figure 1 shows sections and ground plan. The geometry of three inclined bore holes depicted in the general section is repeated at a distance of about 6 m and has been chosen in order to influence significant parts of the shear zone.

To enhance an existing monitoring scheme additional pore pressure sensors have been positioned in between the bore holes. The location of seven sensors (including sensor W30) is indicated in Figure 1. It was intended to place the sensors at the furthest distance from the bore holes in order to measure at locations least influenced by the bore holes.

Sensors measuring absolute pressures were installed. As described in previous papers a packer system was used to measure pressures with an extremely small time lag. The pressure sensors have been installed months ahead of the installation of the bore holes to allow general equilibration of the pressures.

The bore holes (diameter 178 mm) were drilled and equipped with drainage pipes according to DIN 4262-1 (2001): DN 100, circular type R2, in general totally perforated pipes were installed. Prior to installation the drainage pipes were wrapped with a geosynthetic filter material.

During drilling most drains appeared to be dry. After drilling about 40 m of bore hole D1, water was reported discharging from the bore hole at a rate of 20-30 l/h. When D4 was being drilled at a depth of about 20 m, water appeared here as well at about the same rate and discharge from D1 diminished. This observation may be explained with water bearing strata (limestone bands) which are occasionally embedded in the clay formation. Another observation which supports this explanation is a highly variable pore pressure measured at pressure sensor W30. Presumably this sensor is located in or in close vicinity of a water bearing limestone band.

![Figure 1. General section and ground plan of test field.](image-url)
Occasionally the drains have been visited to check for water discharge. According to those observations water flow varies with the seasons. At D2 and D6 water discharge of about 10 l/h (each) has been observed in mid-December 2002. Most other bore holes rarely discharge water visibly, but all have been found filled with water to high levels.

In Figure 2 the development of the measured pore water pressures with time is presented. An average of the piezometric level of all 7 pore pressure sensors is shown. Because of extreme fluctuations of the sensor W30, a second line is presented showing average values omitting W30. Measurements were taken every 30 minutes by an automated data acquisition system. Those original readings have been modified by subtracting the barometric pressure which was acting at the time of the measurement, assuming 100 % of the barometric pressure having actually reached the sensor. As described in a previous paper (Köhler et al. 1999) fluctuating barometric pressure may not reach beyond certain depth levels. This is due to delayed pressure spreading which depends on the velocity of barometric pressure changes and the soil permeability. Due to this effect the piezometric level depicted in Figure 2 is accurate within about ±0.20 m, which is perfectly acceptable regarding the subject of this paper. Small data scatter (e.g. in February 2002) may be explained by this effect.

Originally piezometric levels of about 79.5 m NN have been measured. The pore pressures had been fairly steady before drilling started and relate to the initial piezometric line (see Fig. 1). Drilling of the bore holes and installation of the drainage pipes took place between December 17th, 2001 and January 9th, 2002. Work had been interrupted between Christmas and New Years Day. During drilling fluctuating pore pressures have been observed, which may be mainly a result of volume changes due to the drilling process or the interconnection of water bearing limestone bands. While drilling a considerable drop in pore pressure was observed.

Following the installation period, Figure 2 shows a noteworthy phase of relatively continuous decline of pressures until mid-October. Increases have been recorded in April 2002, mid-June, mid-July and in August which corresponds to extremely wet weather causing flooding elsewhere in Germany. Evidently sensor W30, which may be located in or in the vicinity of a water bearing limestone band recorded major pressure differences due to extensive rain, while the remaining sensors are influenced much less by such events. Starting in late October and continuing into spring 2003 the pressure sensors show an increase averaging about 5 kPa which corresponds to wet winter conditions.

In mid-May 2002 a pumping test was performed. Water was removed from the bore holes repeatedly and the velocity of the rising water levels in the bore holes was measured. These measurements allow conclusions regarding hydraulic properties of the water bearing limestone bands and possible hydraulic connections to the canal water.

During all times the piezometric line above the drains has not yet changed. This has been measured with additional sensors which have not been covered in this paper. The piezometric line is expected to be extremely lowered approaching final steady state conditions. The measurements continue to observe the size of seasonal deviations of the pore pressures which have to be taken into account concerning slope stability.
3.3 Calculations

Safety assessments have been performed by using PLAXIS (1998), a finite element (FE) code. The geometry of the model and dimensions are depicted in Figure 3. The bore holes are simplified modelled as continuous layers. The Mohr-Coulomb soil model has been selected. Shear parameters used by the program are constant. Thus the input shear parameters represent a value averaging conditions along the shear zone.

Pore pressures acting in the soil are generated depending on the position of the assigned piezometric line. Compared to pressure distributions resulting from flow calculations this procedure remains on the safe side concerning safety assessments. Above the piezometric line pore pressures are assumed to be zero (equalling barometric pressure). Remaining on the safe side, negative pore pressures (pressures below barometric pressure) which might exist in the field (Köhler et al. 2002a) are not considered in the calculations.

In a first step the model was validated by analysing a situation before the bore holes existed. Pore pressures were assigned according to the measured piezometric line. In Figure 4a contour lines of incremental displacements are shown, giving the geometry of the potential shear zone. Comparing the geometry of the calculated potential shear zone with the position of the measured shear zone (dotted line) shows good agreement. The safety factor $f_s \approx 1.0$ represents the unstable initial situation. Attempts to deepen the canal would result in global failure.

To calculate the safety for a transient state, pore pressures acting in the soil have been modified. In a region encircled by a dotted line pore pressures have been assigned corresponding to a piezometric level of 75.0 m NN (see Fig. 4b). This specific level was reached in late August 2002 (see Fig. 2). The region is estimated to reach 2 m beyond the limits of the outer bore holes (see Fig. 4b). This estimation is based on observations of pore pressures sensors not covered by this paper. It remains on the safe side since pore pressure reduction will spread with time.

Figure 3. Finite element model of the endangered cut slope.

Figure 4. Contour lines of incremental displacements resulting from FE calculations.
At transient state an increased safety factor will be reached by drilling the drains deeper into the ground. In the potential shear zone pore pressures will be reduced earlier. Additional calculations performed with higher piezometric levels (up to about 77 m NN) show the potential shear zone still forced into a position shown in Figure 4b. The safety factor remains almost unchanged. Thus seasonal fluctuations of the piezometric level seem to have no decisive influence in the case under consideration.

When the piezometric line reaches the final steady state (which might take a long period of time) the safety factor will reach about 1.18 (see Fig. 4c). Deepening the canal will reduce this factor of safety by about 0.05. Thus safety will remain at a very low level but will minimise movements of the slopes. To add security the observational method will continuously be applied.

4 STABILISING EXISTING RIVER DIKES

Safety assessment investigations have been carried out for case study reasons (Köhler et al. 2002a, 2002b) in order to compare slope stability of a river dike caused by seepage at high water level and in a worst case situation of a high crest water level.

Figure 5 shows the water level history, which has been assumed to act on the river dike, rising from high water level at 50.3 m NN to high crest water level at 52.3 m NN within 20 h, staying at this level for 8 days.

In order to model a worst case scenario, in which the highest possible water level may reach the elevation of the dam crest level of 52.3 m NN, the crest water level is assumed to remain unchanged at this level within the following next eight days. Such a loading situation may usually not be expected at a natural flooding event. Even under such extreme loading conditions a dam break ought to be prevented.

Figure 6 describes different seepage situations with and without the installation of reversely inclined drain borings, showing the acting pore pressure distribution at initial (Fig. 6 a-1 and b-1) and final (Fig. 6 a-2 and b-3) steady state seepage conditions.

Figure 6 b-2 describes a pore pressure condition at transient state at the time step t = 70 h, after rising the water level from 50.3 m NN (see Fig. 6 a-1) to 52.3 m NN (see Fig. 6 b-2) taking place within 20 h. During the phase of rising water level, reversely inclined drain borings have been activated.

As depicted in Figure 6 a-1 the factor of safety f_s has remarkably dropped down to f_s ≥ 1.1 already at flood situation with a high water level at 50.3 m NN. With a further increase in water level up to high crest situation at 52.3 m NN bank stability decreases rapidly (see Fig. 6 a-2). The calculated safety factor f_s against slope failure reaches values below 1.0 as soon as water infiltration may saturate the whole dam body up to a certain level above the seepage condition shown in Figure 6 a-1. This situation is unsafe leading to failure. A lot of emergency work needs to be undertaken in such flood situations to ensure dam stability under such conditions. Usually the top load of the dam embankment surface is increased by e. g. placing sand bags or additional filter layers on to the downstream side of the saturating dam body. In order to avoid catastrophic events during high crest situations, pre-installed drain borings may be an adequate improvement of existing dikes. Bank stability at the required level of service can be ensured.

As shown in Figures 6 b-1 and 6 b-3, the applied pore pressure release technique by using pre-installed drain borings would provide a significant increase of stability even at steady state condition of a long lasting high flood situation. The drain borings may be entirely filled by sand or gravel fulfilling the requested filtration criteria to ensure long term stability and service. It is recommended to select drain material in the borings with a permeability k which should be about 100 times larger than the permeability of the material to be drained.

In comparison to the occurring discharge at flood situation without the additional drain borings, estimations of the water discharged by the drains, result in an increase of no more than 50 %. Usually such an increase of discharge may easily be handled, even remaining unnoticed.

If the drain borings are installed ahead of a flood event the dam will not saturate to dangerous high levels. Further the direction of seepage flow is redirected toward the drains. Toe erosion is minimised.

In this paper considerations have been limited to simplified homogenous soil conditions in order to draw primarily attention to the efficiency of the presented pore pressure reduction technique.

5 CONCLUSIONS

Possibilities of selecting reversely inclined drain borings are indicated to reduce pore pressures in the region of the potential shear zone. Application of this technique leads to increased slope stability. Submerged soil under water is regarded as a three-phase medium (gas, water and solids). Based on this
concept and on the results of field measurements numerical investigations have been performed for two practical examples regarding transient pore pressure conditions.

Application of drains in low permeable soil are encouraged. Further aspects of technological development need to be considered, e.g.:

- The selection of the type of drain pipes needs to be evaluated. If the bore holes are filled with appropriate filter material (sand, gravel) no pipes are needed at all.
- Continuous removal of water collected in the drains improves effectiveness. With the application of vacuum safety gains are even larger.
- Water discharged from the drains needs to be led away properly, winter conditions should be taken into consideration (freezing etc.).
- Advanced drilling methods may enable to apply curved bore holes, allowing to place drains even more effectively along the potential shear zone.

6 REFERENCES


PLAXIS (1998), Professional Version 7.2
