ABSTRACT: In January 2006 the interdisciplinary research project "Coupled Modelling of Flow and Deformation Processes at Creeping Hillslopes", funded by the German Research Foundation (DFG), was established. Rapid infiltration processes are observed at a hill slope located in the proximity of the town of Ebnit, Vorarlberg, Austria. Rapid water infiltration at upper slope positions generates a fast increase of soil water saturation in sections of the subsurface several hundred meters down gradient. It is postulated that the seeping soil water leads to a rapid increase in head and hence to buoyancy forces in the lower regions of the slope resulting in slope deformations, observable in the form of slow slope creeping. In order to systematically investigate and quantify the development of slope failure processes, a laboratory experiment was performed at the Research Facility for Subsurface Remediation (VEGAS) at the Universität Stuttgart. It consists of a 100 cm high, 200 cm long and 80 cm wide steel container. One long side of this flume is constructed by a glass pane. At the both short sides it is possible to maintain constant head boundary conditions in order to control the flow of groundwater or to adjust a steady state groundwater table. The soil material in the flume is shaped to a slope. On the upper side of the slope a hydraulic cylinder is installed to simulate a load on the slope. Varying either the load on the slope or the location of the groundwater table provides important information on the factors affecting the stability of the slope and their interdependence. In a first set of experiments, the effect of saturation on the slope stability was investigated. It was shown that in the case where the water along the whole shear band was at negative pressure the slope could sustain 20% more load than in the case where parts of the shear band were underneath the groundwater level.

1 INTRODUCTION

1.1 Motivation

In recent years, the failure of natural slopes or hillslopes has led to catastrophic consequences for population, environment and nature. In cohesive soils, the damage or a sudden failure of the natural slope often occurs due to heavy rainfall following a long-lasting creeping which caused a weakening of shear zones. Runoff, infiltration, interflow, groundwater flow as well as evaporation contribute to a very different measure and on very different space and time scales to the elastic and visco-plastic soil deformations. This superposition of hydrological, subsurface hydraulic and soil mechanical processes over a large bandwidth of scales is poorly understood today.

In January 2006 the interdisciplinary research project "Coupled Modelling of Flow and Deformation Processes at Creeping Hillslopes", funded by the German Research Foundation (DFG), was established. Rapid infiltration processes were observed at a hill slope located in the proximity of the town of Ebnit, Vorarlberg, Austria (Lindenmaier et al. 2005). The rapid infiltration at upper slope positions generates a fast increase of soil water saturation in sections of the subsurface several hundred meters down gradient. It is postulated that the seeping soil water leads to a rapid increase in head and hence to buoyancy forces in the lower regions of the slope resulting in slope deformations, observable in the form of slow slope creeping.

1.2 Goals

The approach of the research is to combine improved process models with coupling, averaging and upscaling processes on the one hand and with improved experimental methods on the other. The tools to be developed will need to be verified based upon the controlled experiments in the laboratory before being transferred to larger scales. Therefore, benchmark experiments to investigate shear failure need to be conducted. Model parameters determined in these controlled experiments will be upscaled using geostatistical methods.
These systematical experimental investigations of slope failure processes are carried out at the Research Facility for Subsurface Remediation (VEGAS) at the Universität Stuttgart. In this paper the behavior of slope failure under two different groundwater regimes resulting in different saturation conditions within the slope will be addressed.

2 MATERIALS AND METHODS

2.1 Properties of the porous media

For all experiment series we used the same fine sand (trade name GEBA) with a grain size distribution from 0.03 mm to 0.3 mm (Fig. 1). With a retention $d_{10}$ of 0.09 mm and $d_{60}$ of 0.11 mm, the sand shows a degree of uniformity of $U = 1.22$, indicating a very uniform porous media.

The capillary pressure - saturation relation is shown in Figure 2, the air entry pressure is $h_{cd} \approx 50$ cmw. The saturated hydraulic conductivity was measured to be $k_f = 2.2 \times 10^{-4}$ m/s.

2.2 Experimental set up

Based on numerical sensitivity studies the laboratory experiment was designed and built. It consists of a 100 cm high, 200 cm long and 80 cm wide steel container (Figs. 3, 4). One long side of this flume is constructed by a glass pane. At the both short sides it is possible to install constant head boundary conditions in order to control the flow of groundwater and to adjust the steady state groundwater table.

The flume was filled layer by layer under saturated conditions. By this filling procedure a bulk density between 1.50 and 1.55 g/cm³ was obtained. Then the water was drained and soil material in the flume was shaped to a slope.

On the upper side of the slope a hydraulic cylinder is installed to press on a plate (30 x 80 cm) to simulate a load on the slope. Figures 3 and 4 show a sketch and a photo of the set-up, respectively. The hydraulic cylinder is moved such that the force on the pressure plate is always imposed vertically. Ultrasonic distance sensors not only control its movement, they also measure and monitor the horizontal and vertical movement of the plate as well as its tilting.

Figure 1. Grain size distribution of the GEBA fine sand.

Figure 2. Capillary pressure - saturation relation for the used GEBA fine sand. $S_w$ = water saturation and $h_c$ = capillary head.

Figure 3. Sketch of the laboratory slope failure experiment. The distance from the bottom of the flume to the pressure plate is 90 cm. $h_{cd}$ and $h_{wr}$ indicate the constant head boundary conditions.

Figure 4. Picture of the laboratory flume for slope failure experiments.
2.3 Experimental procedure

Varying either the load on the slope or the location of the groundwater table will provide important information on the factors affecting the stability of the slope and their interdependence. In the first series of experiments we wanted to compare two approaches. In case A a static groundwater level was established underneath the slope \( h_{wl} = h_{wr} \) resulting, due to capillary forces, in a very high saturation under negative pressure in the slope. In case B steady state groundwater flow was realized, partially within the slope \( h_{wl} > h_{wr} \) as shown in Figure 3. In both cases the load of the pressure plate was increased stepwise until the slope failed. The experiments are listed in Table 1.

<table>
<thead>
<tr>
<th>Experiments</th>
<th>Case</th>
<th>Plate width</th>
<th>Slope angle</th>
<th>Heads</th>
</tr>
</thead>
<tbody>
<tr>
<td>A_30_40a</td>
<td>A</td>
<td>30</td>
<td>40</td>
<td>10</td>
</tr>
<tr>
<td>A_30_40b</td>
<td>A</td>
<td>30</td>
<td>40</td>
<td>10</td>
</tr>
<tr>
<td>B_30_40a</td>
<td>B</td>
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<td>40</td>
<td>70</td>
</tr>
<tr>
<td>B_30_40b</td>
<td>B</td>
<td>30</td>
<td>40</td>
<td>70</td>
</tr>
</tbody>
</table>

3 RESULTS

3.1 Shear plane development

Every experiment is divided into two phases. In the first phase the slope body is stable but it is being deformed due to the stepwise increase of load. In the second phase the slope fails. In this phase the necessary shear strength is reached and a shear plane develops. In our experiment we can observe the development of the shear band over the glass pan side of the flume (Fig. 5).

3.2 Vertical load and vertical displacement of the load plate

Figure 6 shows the vertical displacement of the load plate as a function of pressure. In case A (groundwater table static underneath slope) the load was increased to approximately 350 kN/m² before the slope failed. In case B where the slope or at least parts of the expected shear band was under positive water pressure due to the established groundwater flow, a load of approx. 285 kN/m² was necessary to induce slope failure (see Tab. 2).

<table>
<thead>
<tr>
<th>Experiments</th>
<th>Failure load</th>
<th>Vertical displacement</th>
<th>Bulk density</th>
<th>Porosity</th>
</tr>
</thead>
<tbody>
<tr>
<td>A_30_40a</td>
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<td>12.5</td>
<td>1.55</td>
<td>0.42</td>
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<tr>
<td>A_30_40b</td>
<td>350</td>
<td>12.4</td>
<td>1.52</td>
<td>0.43</td>
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<tr>
<td>B_30_40a</td>
<td>280</td>
<td>14.0</td>
<td>1.51</td>
<td>0.43</td>
</tr>
<tr>
<td>B_30_40b</td>
<td>288</td>
<td>15.5</td>
<td>1.52</td>
<td>0.43</td>
</tr>
</tbody>
</table>

Figure 6. Load \( q \) – vertical displacement \( u \) diagram for two experiments of each case A and B.

4 CONCLUSIONS

Slope failure experiments on slopes built from homogeneous fine sands were conducted. In a first set of experiments, the effect of saturation on the slope stability was investigated. In both cases, the water saturation in whole experimental set-up was very high (near saturation) due to capillary forces. Nevertheless, it was shown that in the case where the water along the whole shear band was at negative pressure the slope could sustain 20% more load than in the case where parts of the shear band were underneath the groundwater level. While it can be seen that capillary forces contribute to this increase in strength and that the positive water pressure destabilizes the slope, it is assumed that the magnitude of the groundwater flow has no or at most an insignificant effect on the slope stability.

The slope experiments give a first hint regarding the validity of the reasons for slope failure postulated at
the introduction to this article. The experimental results will be used to verify a numerical model (Avci & Ehlers 2007 & 2008). Simultaneously, additional experiments will be conducted to investigate the effect of a dynamic groundwater change on slope stability.

REFERENCES

