An experimental model for slopes subject to weathering

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Abstract. In this paper, an experimental prototype model to study the influence of cracks on the morphologic evolution of natural cliffs subject to progressive retreat induced by weathering is presented. A set of small scale laboratory tests is designed to investigate weathering induced successive landslides. Weathering is applied to the slope model by wetting the slope crest through a rainfall simulator device. The moisture content and the suction of the soil during the tests are monitored by soil moisture sensors and tensiometers that are buried inside the slope model. High resolution cameras record the behaviour of the slope model and GeoPIV is used to analyse the frames and obtain the deformations of the slope model during the tests. After a short time of rainfall, vertical cracks appear in the slope model with significant vertical deformations developing. Experimental results indicate that there is a strong connection between moisture content - thus degree of weathering - and the occurrence of a landslide. A prediction model of slope failures can be introduced based on the observed moisture content response of the slope models.

1. Introduction

An important cause of landslides is weathering, which often leads to the progressive retreat of exposed natural cliffs. Modelling weathering induced cliff retreat has recently received considerable attention by the engineering community due to increasing coastal erosive processes caused by climate change and increased environmental awareness [1-3].

Weathering tend to turn hard rocks into soft rocks characterised by higher void ratios and reduced bond strengths; then soft rocks are transformed into granular residual soils typically by destroying the bonds keeping the rock grains together [4]. Note that also other natural processes, e.g. methane hydrate dissociation in methane hydrate bearing sands [5], can be conceptualized as weathering. Therefore, a common feature of weathering processes is the degradation of the mechanical properties of the slope’s geomaterials (rocks and soils), which in turn leads to the occurrence of successive landslides. This paper aims at investigating and developing an engineering model of the morphological evolution of natural cliffs with limited tensile strength subject to weathering induced landslides.
There are many studies investigating weathering induced landslides. With regard to numerical methods, stability analyses performed by finite element with strength reduction technique [6, 7] are traditionally employed. However, recent developments in contact detection algorithms for 3D convex blocks [8, 9] have made it possible to use also the discrete element method for the analysis of 3D slopes subject to strength reduction [10]. With regard to experimentation, most laboratory experiments require large slope models [11-14] to realistically simulate weathering induced slope failures. Centrifuge modelling [15-17] is also widely used to investigate the failure of slopes under different conditions. A vibrating sand box in the study of Katz and Aharonov [18] was used to induce cracks in soils and investigate the instability of heterogeneous slopes. Model test is also an important approach, in order to investigate the behavior of a slope under certain conditions. In the case of rainfall induced slope failures, model test provides the opportunity to observe the processes of infiltration, movement of the weathering front, deformation and failure [19, 20]. In each case, different techniques were applied to degrade the properties of the soil, while a number of different monitoring devices were used in order to record soil characteristics and the behavior of the slope during the tests. Sensors were vastly used to record the changes in the characteristics of the soil (moisture content, pore pressure, temperature etc.) and digital cameras to record the displacements and the changes in the slope’s front. The results of most of these studies suggest that measurements of the changes of moisture content can be a factor to predict the slope’s movement, while the initiation of the slopes failure is mainly caused with a decrease of the cohesion of the soil, thus making the cohesion the most critical property of the soil to measure, when it comes to slope stability. Not many examples of field experiment studies are found in the literature as they demand continuous monitoring of the characteristics of the slope and soil and are time and cost intensive.

This paper aims at investigating the morphological evolution of natural cliffs subject to progressive retreat induced by weathering, through a set of small scale experiments, with the ultimate objective of developing an engineering model of the phenomenon. To this end, slope models are built in a transparent flume and the weathering is applied to the slope model through light rainfall. The aim of this experiment is to develop a physical model to replicate retrogressive slope failures due to weathering. A set of experiments is carried out to soil with limited tensile strength; after a short period of rainfall and due to degradation of the soil strength; vertical cracks appear in the slope model and significant vertical deformations start to occur around the crack, until failure is reached.

### Table 1. Geotechnical properties of the materials used in the experiments

| Geotechnical Properties of calcarenite [21] | | | | |
|---|---|---|---|
| $\gamma_d$ (kN/m$^3$) | $\gamma_{sat}$ (kN/m$^3$) | Gs (-) | N (-) |
| $\gamma_d$ (kN/m$^3$) | $\gamma_{sat}$ (kN/m$^3$) | Gs (-) | N (-) | E (-) |
| 13.92 | 18.82 | 2.73 | 0.49 | 0.96 |

| Geotechnical Properties of glass beads | | |
|---|---|
| $\gamma_d$ (kN/m$^3$) | Gs (-) |
| 14.715 | 2.55 |

### 2. Test material

The aim is to develop a model that describes the relation between weathering process and the development landslides, for this reason small scale slope models are employed. Weathering was induced by applying light rainfall on the slope until failure was observed. First a suitable material had to be chosen. To this end, preliminary tests to select the appropriate material were carried out. Small cylindrical soil specimens (13mm diameter and 28mm height) of several different soil mixtures, containing calcarenite powder, gypsum, silica sand, glass beads and water were created and tested under certain load until they collapsed. The small size of the specimens, allowed more than 20 alternative mixtures to be tested without spending large amounts of material. Since the main interest
was the response of the material under the influence of water, the specimens were tested under half of their dry collapse load, while at the same time water was added gradually at the base of the specimen, starting from 2 mm for the first two minutes. The material that fitted the desired characteristics was selected to carry out the main experiments for this research.

The mixture for the slope model consists of 43.5% w/w calcarenite, 43.5% w/w glass beads and 13% w/w water. The geotechnical properties of the calcarenite and the glass beads used for the formation of the slope models are illustrated in Table 1.

![Grain Size Distribution Curve](image1)

**Figure 1.** Grain Size Distribution Curve

![Weathering](image2)

**Figure 2.** Weathering of calcarenite and glass beads mixture – different moisture contents.

The Grain Size Distribution performed with sieve analysis is presented in Figure 1. The effective particle size $D_{10}$ of the mixture is 0.12mm, the average particle size $D_{50}$ is 0.6mm and the uniformity
coefficient $Cu=\frac{D_{60}}{D_{10}}$ is 5.83. The coefficient of permeability can be estimated using Hazen’s approximation ($k=100D_{60}^2$) and is $k=1.44\times10^{-2}$ cm/s.

Direct shear box test were performed in the laboratory to identify the relation between the degree of saturation and the strength characteristics of the material. As stated in [22], soil strength can be expressed by two parameters, cohesion $c$ and internal friction angle $\phi$, according to the Mohr-Coulomb yield criterion and weathering causes mainly a decrease in the cohesion and to a much lesser extent a decrease in the friction angle of the soil. The direct shear box tests justify how weathering can be applied in the mixture through the addition of water. Specimens of the exact same characteristics (ingredients and density) as those used in the main experiments and with different moisture contents, therefore various degrees of weathering were tested and the failure envelopes were obtained and are illustrated in Figure 2. As shown in Figure 2, an increase in water content results in a decrease of the strength characteristics of the material. The decrease of the cohesion is greater than that of the friction angle.

3. Dimensional analysis

Since a model test is employed to study the progressive failure mechanism of a slope, a number of physical parameters that are used have to be related between the model and the real slope. The parameters include soil and geometric properties, rainfall intensity, velocity of the weathering front and characteristic times. To ensure complete similarity between the model test and the real case, the model and prototype must be geometrically similar, and all the independent parameters must be identical between the model and the real slope [23].

In Table 2, the relationship between the physical quantities of the model and the real slope, obtained by dimensional analysis is illustrated. The scaling factor ($\lambda$) between the length of the real slope ($L_r$) and the slope model ($L_m$) is $\lambda = \frac{L_r}{L_m}$ and the materials used in the model slope have the same unit weight with the real slope.

Weathering processes can have different velocities depending on the type of weathering. The changes and the evolution of natural slopes range from decades to thousands years depending on the type of soil and the weathering processes. To manage to model the weathering of a slope in the laboratory, a scaling factor should be chosen that will allow the progressive failure of the slope model to occur in laboratory time.

| Table 2. Dimensional analysis of the physical quantities in model test |
|--------------------|------------------|
| Physical Quantity | Relationship      |
| Length             | $L_m = \left(\frac{1}{\lambda}\right) L_r$ |
| Slope angle        | $\theta_m = \theta_r$ |
| Unit weight        | $\gamma_m = \left(\frac{1}{\rho}\right) \gamma_r \gamma_l$ |
| Friction angle     | $\phi_m = \phi_r$ |
| Pore water pressure| $u_m = \left(\frac{1}{\lambda}\right) u_r$ |
| Strain             | $\varepsilon_m = \varepsilon_r$ |
| Time               | $t_m = \left(\frac{1}{\lambda}\right) t_r$ |
| Rainfall intensity | $i_m = i_r$ |
| Hydraulic conductivity | $k_m = \left(\frac{1}{\lambda}\right) k_r$ |

Note that $\lambda$, and $\rho$ are the scaling factors for length and unit weight respectively. In this study the value of chosen to be $\lambda$ was equal to 100 and $\rho$ was equal to 1.

4. Experimental Setup

4.1. Main test apparatus

The experimental apparatus is illustrated in Figure 2. The main apparatus consists of a soil container made of 10mm thick Plexiglas walls and 20mm Plexiglass underlying layer supported by a steel
frame, a rainfall simulation device, soil moisture sensors, tensiometers and two high speed cameras to record the movement of the slope model during the tests. The container, with transparent sides, is 120 cm long, 12 cm wide and 50 cm high (inner dimensions).

Starting at longitudinal distance \( x = 25.00 \) cm from one end of the flume and at latitudinal distance \( y = 38.00 \) cm from the top of the flume, a mesh of small holes is drilled. The holes are located 3.00 cm far from one another (vertically and horizontally) and are used to place the soil moisture sensors and the tensiometers. The rainfall simulator is placed above the container to provide steady and uniform rainfall on the model. The high resolution cameras are also used to monitor the test process from both sides of the flume.

![Figure 3. Arrangement of the experimental apparatus and soil moisture sensors’ location.](image)

### 4.2. Rainfall simulation device

Two different systems are used to generate the artificial rainfall, depending on the desired rainfall intensity. One system consists of a 1x12v diaphragm pump, a control set including a pressure gauge and a pressure regulating valve, plastic pipes and two M1 - Mini nozzles and the other system consists of two GSC Air atomizing nozzles connected to a water tank with liquid flow controlled by suction height. Both systems are placed directly above the container and guarantee uniformity and accuracy. The uniformity of the nozzles for both systems was tested using small containers and measuring the flow rate at different pressures / suction heights.

### 4.3. Slope model

For the experiments, homogeneous slope models made of the material described above are constructed. Although non planar slope profiles are more common in nature and they may be more stable than planar ones [24], all the experiments were performed with planar slopes for sake of simplicity. The dimensions of the slope models are: height: varying between 10 and 25 cm, width: 12 cm and length: 35 cm. For the construction of homogeneous slope models, the materials are manually mixed and layered inside the box in 15 layers of certain weight. Each layer is compacted into 1.00 cm to achieve uniformity of the slope model, obtaining a wet density of 1.70 g/cm³. The soil moisture sensors and the tensiometers are buried inside the slope model during the construction phase, so as to cause the least possible disturbance to the soil.

Transparent silicon oil is applied on the sides of the container to avoid friction between the slope model and the container. When the model is prepared, rainfall is induced to the model by applying low intensity rainfall to the slope’s surface through the rainfall simulation device set directly above the slope model.
Three different slope angles will be tested. For the preliminary results only vertical slopes with different slope heights are examined to verify the repeatability of the procedure and that it is not scale dependent.

4.4. Measurements

4.4.1. GeoPIV analysis
During the event, two high resolution cameras are aimed at both sides of the container, to record the process of the test and the movement of the soil. The cameras have a video resolution of 1920 x 1080 pixels and a maximum frame rate of 25 fps. The main reason for using two cameras is verify that the wetting front is moving homogeneously through the model at both sides; the displacement vectors are obtained by analysing the images of the video from one side via Particle Image Velocimetry (PIV). Frames are extracted every second from the video and are analysed in order to measure the displacement vectors of the soil and the velocity of the wetting front, without causing any disturbance to the slope model.

The displacement vectors are obtained using GeoPIV, a Matlab module that implements Particle Image Velocimetry (PIV) in a manner suited to geotechnical testing [25, 26]. The analysis technique used is based on the principles of PIV, which is a digital image-based surface displacement measurement method that compares a reference image to a series of deformed images. It measures whole velocity fields by taking two images in successive time instants and calculating the distance individual particles travelled within these instants. Since the accuracy of displacement measurements, using particle image analysis is strongly dependent on the surface contrast of the soil, some of the glass beads were painted blue and white to be used as markers, in order to have unique and easy to track patches.

4.4.2. Matlab Image Processing
Red coloured water is used for the rainfall and its movement can be tracked through Matlab image processing, giving the velocity and the position of the water front (Figure 4) at any time. This analysis is necessary to confirm that the water front is moving homogeneously inside the slope model by comparing the height of the ‘red region’ at a certain time at different locations along the slope. These results are also compared to the readings from the soil moisture sensors to validate their accuracy.

![Figure 4. Water front movement through matlab image processing during the test.](image)

4.4.3. Soil moisture sensors
VH400 Soil moisture sensor probes are buried horizontally in one side of the slope model at the locations shown in Figure 3. The accuracy of these sensors is 2% at 25°C and they measure volumetric
soil moisture content, using transmission line techniques to detect the dielectric constant of the soil. The size of these sensors is very small, 9.4 cm long and 0.7 cm thick, thus causing minimal disturbance to the surrounding soil. Since reliable measurements are very important while performing experiments, two SM300 soil moisture and temperature sensors are also buried inside the slope model for independent measurements. These sensors are even smaller than the VH400 sensors causing least disturbance to the soil, their accuracy is 2.5% for the moisture content and 0.5°C for the temperature and they give continuous reading. The SM300 sensors are used in combination with the others to ensure correct readings. The water content of the soil is recorded at frequency 1/s.

Soil moisture content tests took place in the laboratory to calibrate the output voltages of the sensors prior to the main tests. Moreover, some preliminary tests for the response time of these sensors were conducted, using small samples of the same density as that of the slope model and with known water contents which showed that the sensors responded accurately in less than 1 s of contact with the soil.

4.4.4. Tensiometers

The suction of the soil can have a considerable influence on the slope stability [27]; therefore it is essential to determine the suction of the slope during the test to evaluate the likelihood of a slope failure. In order to capture the changes in the soil suction during the tests, it is crucial to use reliable miniature sensors that will cause the least disturbance to the slope models. Two SWT-5x tensiometers, that are specially designed for point measurements monitoring both positive and negative pore pressures, are employed; the accuracy of these tensiometers is ± 0.5 kPa, over the range +100 to -160 kPa, while the small size of the shaft (5 mm diameter and 5 mm length) causes very little disturbance to the soil.

5. Preliminary tests

Fourteen experiments have been carried out to test the designed apparatus and the experimental procedure, and given the procedure described in this paper, up to two progressive failures are observed. Results suggest that the procedure is repeatable and not scale dependent. Tests were performed for slopes with different heights, under different rainfall intensities, with and without sensors or soil particles glued on the bottom of the tank to observe the effect of all these parameters on the behaviour of the soil slope. Successive failures are observed for some combinations of H and I_r (where H is the height of the slope model and I_r, the rainfall intensity) in laboratory times. When rainfall intensity is too low, especially for short heights, only one failure is observed.

![Displacement vectors at the initiation of a. the first and b. the second failure event for a vertical slope by GeoPIV analysis](image-url)

**Figure 5.** Displacement vectors at the initiation of a. the first and b. the second failure event for a vertical slope by GeoPIV analysis

An example of the displacement vectors of the failure events according to the GeoPIV analysis during a test on a vertical slope with H=15 cm and I_r=18 mm/h is plotted in Figure 5. The formation of two cracks is observed. Cracks can significantly reduce slope stability [28]. Through the analysis the location of each crack and failure mechanism can be tracked, the deformation of the slope and the
velocity of the sliding mass can be calculated. From all the analyses it turns out that vertical deformations at the initiation of the failure are greater than horizontal ones.

Combining the time histories of the volumetric moisture content of the slope from the soil moisture sensors with the displacements from the GeoPIV analysis useful information can be extracted for the relation between the moisture content (thus the degree of weathering) and the deformation of the slope.

6. Conclusions
A series of small scale tests for the investigation of the successive failures of soil with limited tensile strength has been designed and tested under different conditions to verify that the procedure is repeatable and not scale dependent. A soil container to accommodate the slope models has been constructed as well as a rainfall simulator device to provide homogeneous wetting of the slope surface. Soil moisture sensors and tensiometers have been carefully selected and tested to ensure reliable measurements, while GeoPiv and Matlab image analyses were employed to carefully track the movement of the water and investigate the deformation of the slope during the tests.

The described setting is satisfying to study the retrogressive retreat of the slope, as up to two successive failures are observed on the slope model during the tests. The behaviour of the slope and the effect of weathering on the retrogressive retreat of soil slope are modelled. Crack formation is observed just before the failure occurred. Given the decrease on the soil strength with the increasing moisture content a prediction model of slope failure due to weathering can be introduced based on the observed moisture content.

7. References
[1] Utili S. and Crosta G., "Modeling the evolution of natural cliffs subject to weathering: 1. Limit analysis approach," Journal of Geophysical Research: Earth Surface (2003–2012), vol. 116, p. F01016, 2011.
[2] Bray M. J. and Hooke J. M., "Prediction of soft-cliff retreat with accelerating sea-level rise," Journal of Coastal Research, vol. 13, pp. 453-467, 1997.
[3] Utili S. and Crosta G., "Modeling the evolution of natural cliffs subject to weathering: 2. Discrete element approach," Journal of Geophysical Research-Part F-Earth Surface, vol. 116, p. F01017, 2011.
[4] Nova R., Castellanza R., and Tamagnini C., "A constitutive model for bonded geomaterials subject to mechanical and/or chemical degradation," International Journal for Numerical and Analytical Methods in Geomechanics, vol. 27, pp. 705-732, 2003.
[5] Jiang M., Zhu F., Liu F., and Utili S., "A bond contact model for methane hydrate-bearing sediments with interparticle cementation," International Journal for Numerical and Analytical Methods in Geomechanics, vol. 38, pp. 1823-1854, 2014.
[6] Huang M. and Jia C. Q., "Strength reduction FEM in stability analysis of soil slopes subjected to transient unsaturated seepage," Computers and Geotechnics, vol. 36, pp. 93-101, 2009.
[7] Zheng H., Liu D., and Li C., "Slope stability analysis based on elasto-plastic finite element method," International Journal for Numerical Methods in Engineering, vol. 64, pp. 1871-1888, 2005.
[8] Boon C., Houlsby G., and Utili S., "A new algorithm for contact detection between convex polygonal and polyhedral particles in the discrete element method," Computers and Geotechnics, vol. 44, pp. 73-82, 2012.
[9] Boon C., Houlsby G., and Utili S., "A new contact detection algorithm for three-dimensional non-spherical particles," Powder Technology, vol. 248, pp. 94-102, 2013.
[10] Boon C., Houlsby G., and Utili S., "New insights into the 1963 Vajont slide using 2D and 3D distinct-element method analyses," Geotechnique, vol. 64, pp. 800-816, 2014.
Bachmann D., Bouissou S., and Chemenda A., "Influence of weathering and pre-existing large scale fractures on gravitational slope failure: insights from 3-D physical modelling," *Natural Hazards and Earth System Science*, vol. 4, pp. 711-717, 2004.

Jia G., Zhan T. L., Chen Y., and Fredlund D., "Performance of a large-scale slope model subjected to rising and lowering water levels," *Engineering Geology*, vol. 106, pp. 92-103, 2009.

Tohari A., Nishigaki M., and Komatsu M., "Laboratory rainfall-induced slope failure with moisture content measurement," *Journal of Geotechnical and Geoenvironmental Engineering*, vol. 133, pp. 575-587, 2007.

Huang C. C., Lo C. L., Jang J. S., and Hwu L. K., "Internal soil moisture response to rainfall-induced slope failures and debris discharge," *Engineering Geology*, vol. 101, pp. 134-145, 2008.

Ling H. I., Wu M. H., Leshchinsky D., and Leshchinsky B., "Centrifuge modeling of slope instability," *Journal of Geotechnical and Geoenvironmental Engineering*, vol. 135, pp. 758-767, 2009.

Wang R., Zhang G., and Zhang J. M., "Centrifuge modelling of clay slope with montmorillonite weak layer under rainfall conditions," *Applied Clay Science*, vol. 50, pp. 386-394, 2010.

Zhang G., Qian J., Wang R., and Zhang J. M., "Centrifuge model test study of rainfall-induced deformation of cohesive soil slopes," *Soils and foundations*, vol. 51, pp. 297-305, 2011.

Katz O. and Aharonov E., "Landslides in vibrating sand box: What controls types of slope failure and frequency magnitude relations?," *Earth and Planetary Science Letters*, vol. 247, pp. 280-294, 2006.

Wang G. and Sassa K., "Factors affecting rainfall-induced flowslides in laboratory flume tests," *Geotechnique*, vol. 51, pp. 587-599, 2001.

Chen R. H., Kuo K. J., and Chien W. N., "Failure Mechanism of Granular Soil Slopes under High Intensity Rainfalls," *Journal of GeoEngineering*, vol. 7, pp. 021-031, 2012.

Castellanza R., Parma M., Pescatore V., and Silvestro G., "Model footing load tests on soft rocks," *ASTM geotechnical testing journal*, vol. 32, pp. 262-272, 2009.

Kimmane G., "Computer aided risk analysis of open pit mine slopes in kaolin mined deposits," Ph. D thesis, Imperial College London (University of London), 1988.

Cengel Y. A., *Fluid mechanics*: Tata McGraw-Hill Education, 2010.

S. Utili and R. Nova, "On the optimal profile of a slope," *Soils and foundations*, vol. 47, pp. 717-729, 2007.

White D. and Take W., "GeoPIV: Particle Image Velocimetry (PIV) software for use in geotechnical testing," 2002.

White D., Take W., and Bolton M., "Soil deformation measurement using particle image velocimetry (PIV) and photogrammetry," *Geotechnique*, vol. 53, pp. 619-631, 2003.

Fredlund D., Morgenstern N., and Widger R., "The shear strength of unsaturated soils," *Canadian Geotechnical Journal*, vol. 15, pp. 313-321, 1978.

Utili S., "Investigation by limit analysis on the stability of slopes with cracks," *Geotechnique*, vol. 63, pp. 140-154, 2013.