The role of unsaturated zones in mitigating slope instability

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ABSTRACT: Unsaturated zones significantly enhance slope stability by increasing effective stress and shear strength through matric suction. This study examines the role of unsaturated conditions at the toe of a slope in mitigating instability during the rapid construction of a buttress. Centrifuge tests were performed on loose sand slopes subjected to identical buttress loading but differing toe saturation states. In one test, a small unsaturated region at the toe prevented failure despite high water table conditions and large excess pore pressures, demonstrating the stabilising effect of unsaturated soil. Conversely, when the toe was fully saturated, the slope failed immediately, with rapid displacement and significant pore pressure generation. These findings highlight the heightened vulnerability of slopes with saturated toes under external loading. The study underscores the importance of maintaining unsaturated conditions at the toe to reduce the risk of instability. Drainage systems and regular monitoring of pore pressures and deformations near the toe are recommended, particularly in areas prone to rapid water table fluctuations or loading changes. These measures can provide early warnings and enable pre-emptive stabilisation, improving slope safety and management practices.

1 INTRODUCTION

Slope stability is a critical consideration in geotechnical engineering, particularly in the design and management of slopes and earth structures subjected to changing environmental and loading conditions. Unsaturated zones, where matric suction increases the effective stress and shear strength of the soil, play a vital role in resisting deformation and failure (Basson 2023). However, the transition from unsaturated to saturated conditions, often caused by rising water tables or external loading, can significantly reduce soil strength, increasing likelihood of instability.

Geldenhuys et al. (2021) monitored the stability of a tailings dam during the construction of a buttress. It was shown that if a buttress is constructed too quickly, excess pore pressures are generated and the effective stress reduces in the soil. The factor of safety (FOS) of the slope might reduce sufficiently to trigger instability. This study investigated the influence of unsaturated conditions at the toe of a slope on mitigating instability during the rapid construction of a buttress. Two loose sand slopes were accelerated in the centrifuge and subjected to a rising water table. After establishing the water table, sand was rapidly discharged at the toe, simulating the construction of a buttress.

2 METHODOLOGY

2.1 *Index properties of Cullinan sand*

The model slopes were constructed from a commercially available fine silica sand obtained from a quarry near Cullinan, South Africa. Its particle size distribution is shown in Figure 1. The fines content ($D < 63$ μm) is 23.5%, the average grain size (D_{50}) is 98 μm and the maximum particle size is 400 μm. The coefficient of permeability (k_s) is 6.5×10^{-6} m/s. The specific gravity (G_s) is 2.7. According to Murison & Heymann (2024), the maximum and minimum void ratios (e_{max} and e_{min}) are 0.953 and 0.576, respectively. Table 1 summarises the index properties of the sand.

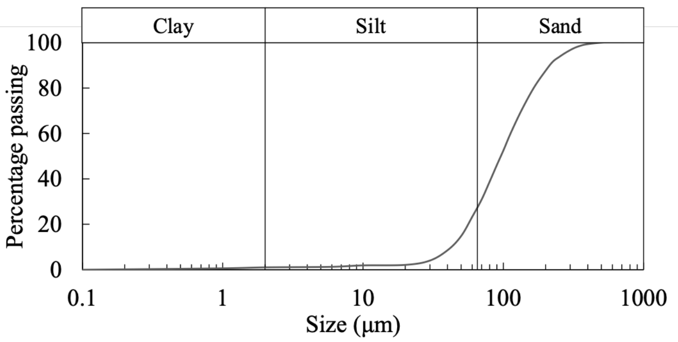

Figure 1. Particle size distribution of Cullinan sand.

Table 1. Index properties of Cullinan sand

Index property	Cullinan sand
Specific gravity, G_s	2.7
Average grain size, D_{50} (μm)	98
Sand content	76.5%
Fines content	23.5%
Saturated permeability, k_s (m/s)	6.5×10^{-6}
Maximum void ratio, e_{max}*	0.953
Minimum void ratio, e_{min}*	0.576

* Murison & Heymann (2024)

Figure 2 shows the effective stress paths of three undrained triaxial compression tests conducted on loose Cullinan sand specimens. The slope of the CSL (M) is 1.329, translating to a friction angle of 33°. Considering the effective stress paths, it is evident that if the sand is sufficiently loose and is sheared under undrained conditions, the soil is susceptible to liquefaction, with the shear strength collapsing to zero. Thus, if a buttress is constructed rapidly enough to induce excess pore pressures, the sand could potentially liquefy, triggering the failure of the slope. Considering the brittle nature of the sand, it was chosen as the material for the centrifuge tests.

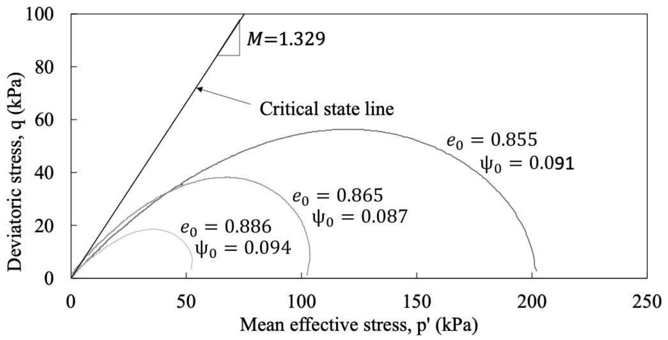

Figure 2. Effective stress paths of three undrained triaxial compression tests conducted on loose Cullinan sand specimens.

2.2 *Centrifuge tests*

The centrifuge tests were conducted at the Geotechnical Centrifuge Facility at the University of Pretoria (Jacobsz et al., 2014). The centrifuge package was similar to that presented by Crous et al. (2022) and Ng et al. (2023). The model slopes were constructed by moist tamping the sand in six 50 mm layers at a moisture content of 4% to a void ratio of 0.9. The moist tamping method creates a soil fabric that is more brittle than other sample preparation methods (Chang et al. 2011).

Figure 3 shows a schematic diagram of the package and the model slopes, along with the instrumentation installed. In both models, six tensiometers were installed in the slopes. However, in Test 1, T4 and T5 malfunctioned, and thus the results from the instruments were omitted. In Test 1, one linear variable differential transformer (LVDT) was installed midslope. In Test 2, an additional LVDT was installed at the crest.

Additionally, a hopper filled with sand was installed at the downstream section of the slope. An opening at the bottom was sealed with an angle, which was attached to an actuator. During the tests, the actuator could be activated, pulling the angle away from the opening, allowing the sand to be discharged onto the toe of the slope.

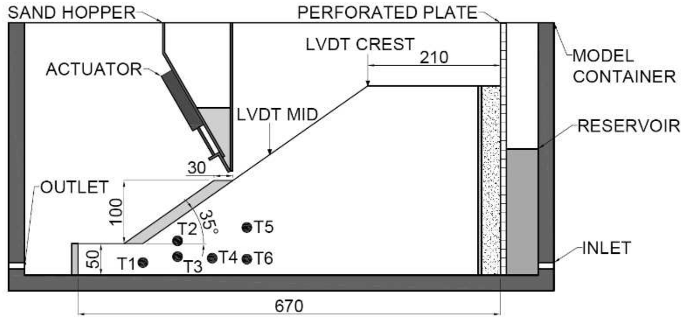

Figure 3. Schematic diagram of the model slopes and instrumentation in the centrifuge tests.

The slopes were constructed to an angle of 35°, which was steeper than the friction angle. However, both slopes settled to approximately 32° during the centrifuge tests.

A reservoir was created at the upstream section of the slope using a geotextile covered perforated plate. This allowed for control over the hydraulic head at the upstream of the slopes. The models were accelerated to 30 g. Once at the elevated acceleration, the reservoir in Test 1 was filled with water, with water seeping through the slope and establishing a water table. When the water table neared the toe of the slope, the hopper was activated and sand was discharged at the toe.

In Test 2, the reservoir was filled with a water-glycerine mixture that was $\sqrt{30}$ more viscous than water (Crous et al. 2022). This was done to correctly scale the triggering of liquefaction (Askarinejad et al. 2015). Additionally, the higher viscosity of the fluid caused the excess pore pressures to dissipate more slowly. The same procedure was followed as with Test 1, only the water table was allowed to saturated the toe in Test 2.

In Test 1, the mechanism was captured using a DSLR camera, which was capable of capturing images once every three seconds. In Test 2, the mechanism was captured using a video camera, capturing the mechanism at 30 frames per second. The DSLR images were of high enough quality for a particle image velocimetry (PIV) analysis. However, the video camera images were not.

3 OBSERVED DEFORMATION AND MEASURED RESPONSE DURING TEST 1

Figure 4a and b present the side profile of the slope in Test 1 before and after the buttress was discharged. Prior to the buttress placement, the slope exhibited no significant signs of distress. As the water table neared the toe, the hopper discharged the sand, during which minor settlement of the crest and small cracks near the crest were observed. Despite this, the slope remained stable.

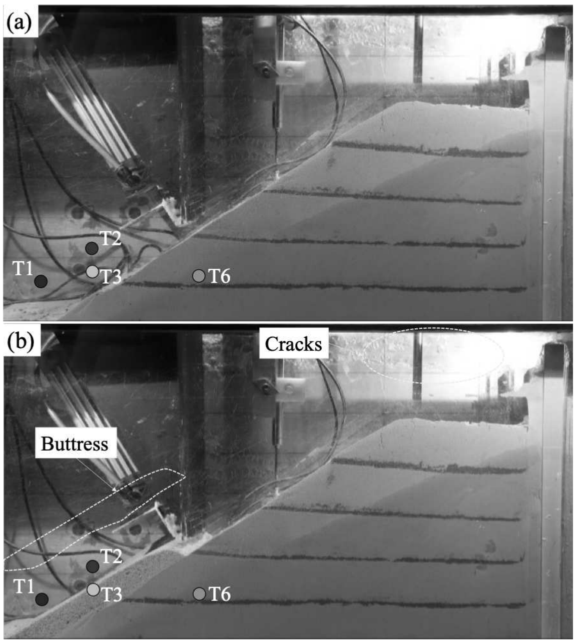

Figure 4. Side profile of slope in Test 1 a) before; and b) after the discharge of the buttress.

A PIV analysis conducted using the two images in Figure 4 confirmed the observed deformation. Figure 5a illustrates the computed displacement vectors following buttress deposition, while Figure 5b and c show the corresponding shear and volumetric strain distributions, respectively. The maximum deformation was less than 1 mm, with two slip planes forming in the slope: a shallow plane near the surface and a deeper one extending from the toe to the crest. Interestingly, the volumetric strain along the deeper slip plane suggests minor dilation, potentially due to shear localisation. This phenomenon can occur even in loose material, as described by Malvick et al. (2006).

Figure 6a and b present the measured excess pore pressures and rate of settlement before, during and after buttress placement. The vertical dashed line labelled “a” corresponds to the moment Figure 4a was captured. Prior to discharge, pore pressures were stable and the settlement rate was approximately 0.1 mm/s. Upon sand discharge, pore pressures increased sharply, with a peak excess pore pressure of 13.2 kPa. This increase momentarily reduced effective stress, as evidenced by an accelerated rate of settlement of 0.4 mm/s. However, the sand’s relatively high permeability, combined with the use of water in the centrifuge test, facilitated rapid dissipation of excess pore pressures, allowing the slope to stabilise.

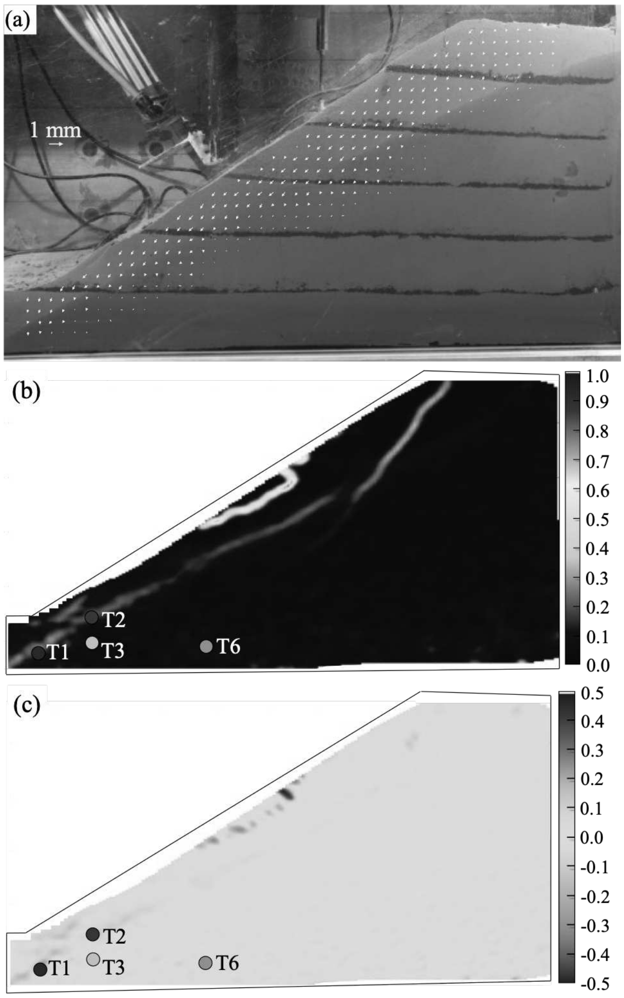

Figure 5. Results from PIV analysis for Test 1 a) displacement vectors; b) shear strain (%); and c) volumetric strain (%).

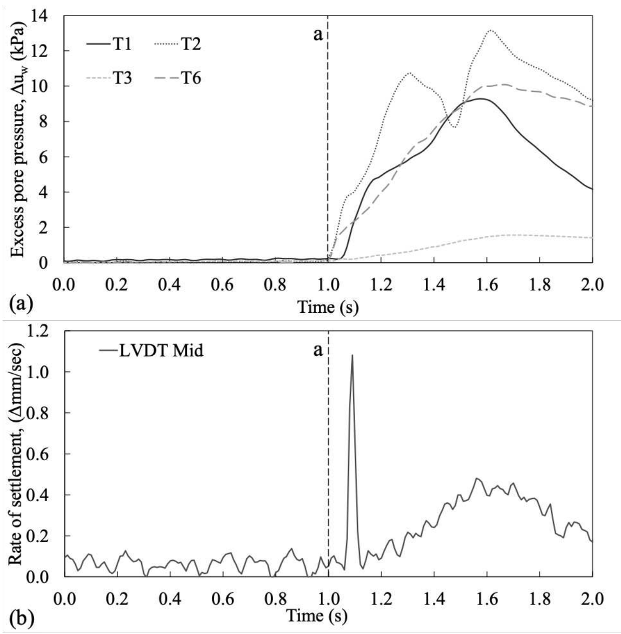

Figure 6. a) Excess pore pressures; and b) rate of settlement measured during the discharge of the buttress in Test 1.

Even with excess pore pressures of between 10 to 13 kPa, this test highlights how the unsaturated region at the toe of the slope sufficiently increased the shear strength of the soil at the toe to prevent instability. It is possible that if a less permeable soil or a more viscous fluid were used that the slope could have failed but in this case it did not.

A critical observation is that shearing was concentrated along these slip surfaces. While undrained conditions were triggered, they remained localised rather than global, contrary to the assumption of global liquefaction as described in the Global Industry Standard on Tailings Management (GISTM) (ICMM 2020).

4 OBSERVED FAILURE AND MEASURED RESPONSE DURING TEST 2

The failure mechanism in Test 2 is depicted in Figure 7. Figure 7a shows the slope just before the sand was discharged at the toe. Upon discharge (Fig. 7b), a small slip failure initiated at the toe, evidenced by the formation of cracks beneath the buttress and soil heave at the toe. Shortly after this initial slip, a crack formed at the crest of the slope, marking the onset of a larger failure mechanism, shown in Figure 7c. The entire failure process unfolded over approximately 0.5 seconds, or 7.5 minutes prototype scale.

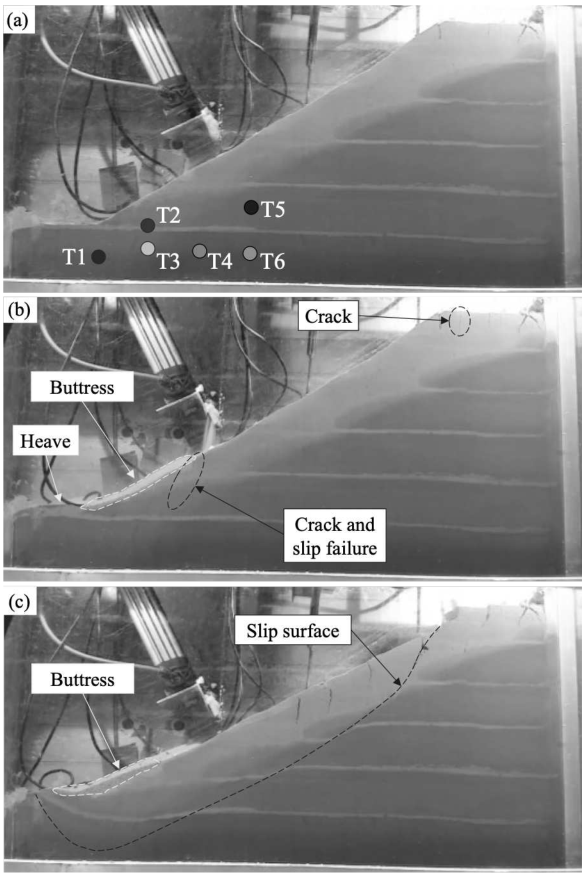

Figure 7. Side profile of failure mechanism in Test 2 at a) 0 seconds; b) 0.31 seconds; and c) 0.51 seconds.

The measured excess pore pressures and rates of settlement during the failure of the slope in Test 2 are shown in Figure 8a and b, respectively. The vertical dashed line marked “a” corresponds to the moment Figure 7a was captured. Before sand was discharged, the pore pressures and settlements remained relatively stable. Upon sand discharge, T1, T2 and T3 (all located beneath the discharged sand) recorded initially small increases in pore pressures of only 2.2 kPa, considerably smaller than the increases in Test 1 (Fig. 6a). Despite the modest magnitude of these excess pore pressures, they were sufficient to trigger the initial slip failure shown in Figure 7b, due to the contractive and brittle tendencies of the loose sand.

Following the initial increases, T1 and T3 recorded sharp decreases in pore pressure due to a loss of confinement. As the buttress deposition continued, and the slope failure progressed, pore pressures at T1, T2 and T3 increased sharply, culminating in a peak excess pore pressure of 17.2 kPa at T1, which was equal to the initial vertical effective stress. Thus, the deposition of the buttress resulted in a complete loss of effective stress. T2 and T3 also measured peaks of 14.5 and 16.1 kPa, respectively.

The peak excess pore pressures generated in Test 2 were significantly higher than those in Test 1. Two factors contributed to this difference. Firstly, during sand deposition, the process was partially drained. While some excess pore pressures dissipated, the use of a more viscous fluid in Test 2 slowed this dissipation, resulting in larger peaks. Secondly, unlike in Test 1, where no rapid failure occurred, Test 2 experienced a rapid slip failure. This induced additional shearing in the loose sand, further generating excess pore pressures.

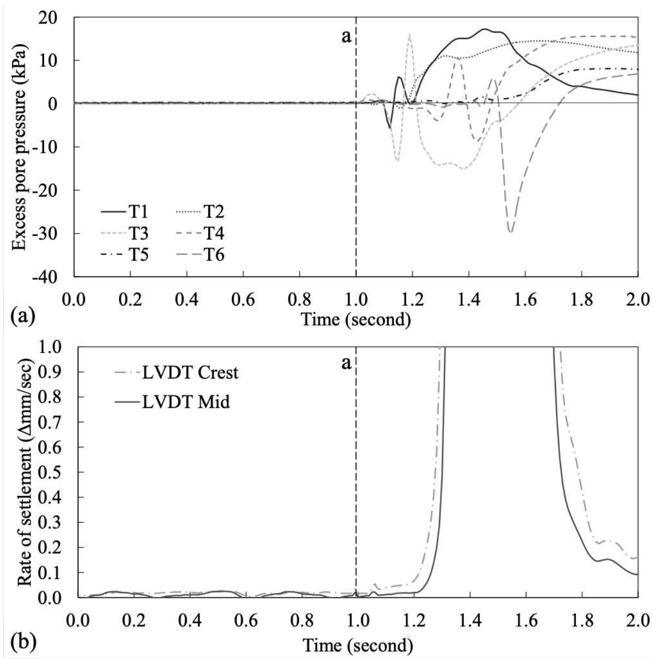

Figure 8. (a) Excess pore pressures; and (b) rate of settlement measured during the failure even in Test 2.

Comparing the results from Test 1 and Test 2, it is evident that the unsaturated region at the toe allowed for the slope to resist instability. Despite large excess pore pressures being measured in Test 1, the slope did not fail. In contrast, in Test 2 the failure was initiated with initially small positive excess pore pressures (~ 2 kPa) and the larger excess pore pressures only occurred following the initiation of the failure. This highlights the importance of preventing the toe of a slope to become saturated, as instability can be triggered more easily.

5 CONCLUSIONS

The management of a water table in a slope has significant influences on the stability of the structure. A rising water table reduces the effective stress in a slope, and thus the shear strength. In slopes with marginal stability, buttresses are often constructed to improve the stability of slopes by increasing the effective stress. However, if buttresses are constructed too quickly, excess pore pressures may be generated, which can also destabilise the slopes. Using centrifuge modelling, this study investigated the influence of an unsaturated zone at the toe on the stability of the slope during buttressing.

Comparing the observed and measured responses from Test 1 (Figs. 4-6) with those from Test 2 (Figs. 7 & 8), several key insights emerge. The most critical observation is that instability was only triggered when the slope's toe was fully saturated. In order to be susceptible to liquefaction, the soil needs to be in a loose, saturated state, and be subjected to an external trigger – all conditions present in Test 1.

Despite the slope in Test 1 being marginally stable under drained conditions, global failure did not occur when the buttress was deposited. Although peak excess pore pressures of 13 kPa were recorded, a portion of the toe remained unsaturated, providing sufficient resistance to prevent failure. It is plausible that using a less permeable material or a more viscous fluid might have caused failure, but under the conditions tested, instability was not triggered.

In contrast, Test 2 allowed the water table to rise further, fully saturating the toe. The use of a more viscous fluid retarded dissipation of excess pore pressures, increasing potential for failure. Instability was triggered by the discharge of sand, though only when the drained factor of safety approached one.

Initial excess pore pressures in Test 2 were approximately 2 kPa at the onset of instability, significantly lower than the 13 kPa recorded in Test 1. Despite the higher values in Test 1, global failure did not occur, only localised distress. This emphasises the critical role of toe stability in preventing failure. Notably, larger excess pore pressures in Test 2 were only measured after the initial slip failure was triggered.

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