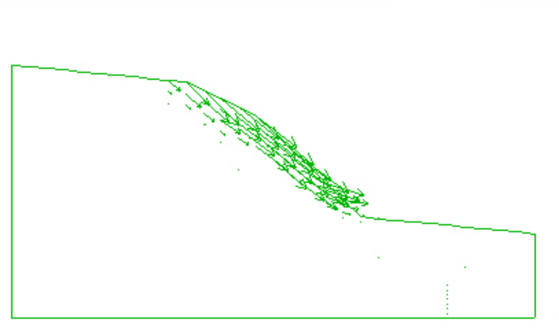
Stability of a slope in unsaturated conditions



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Context

Slope stability

Rainfall event

- low intensity, long duration → stable slope

- high intensity, short duration → slope failure

Capillary forces

Background

Capillary forces

- hold fine particles together

- can provide additional cohesion to the soil

Observation

apparent cohesion provided by capillary forces

→ decreases as soil saturation increases

Thus, build up of saturation can induce slope failure

Objective

Demonstrate FLAC ability to model this behavior

Modeling technique

FLAC - 2 phase flow module

water $\rightarrow$ wetting phase
air $\rightarrow$ non-wetting phase (inert)

Capillary pressure law – van Genuchten

$$-P_w = P_0 \left(S_w^{-1/a} - 1 \right)^{1-a}$$

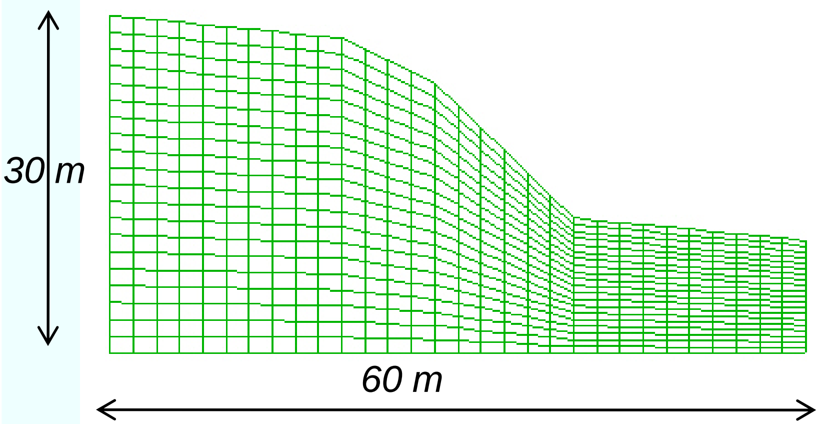
Relative permeability law – van Genuchten

$$\kappa^w = S_w^b \left[1 - \left(1 - S_w^{1/a} \right)^a \right]^2$$

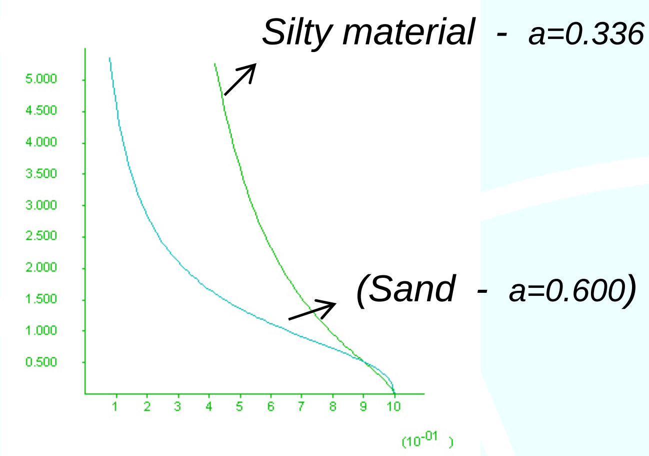
Mechanical coupling – Bishop effective stress

$$\sigma^b = \sigma - S_w P_w$$

Model setup



FLAC grid



Capillary pressure curve

Table 1. Fluid flow properties.

Porosity	0.1
Saturated mobility, *k*	10^{-9} m^2 / (Pa · sec)
Reference capillary pressure, P_0	$1.5 \cdot 10^4$ Pa
Van Genuchten, a	0.336
Van Genuchten, b	0.0
Residual saturation	0.0
Water density	1000 kg/m^3

Unsaturated flow properties – silty material.

Model specifications

Silty material

Mohr-Coulomb model

cohesion → zero

friction → 30 degrees

Initial saturation 0.54

First rainfall event:

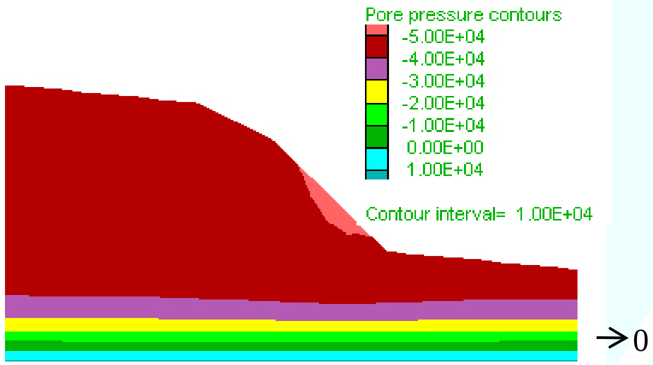
84 mm/month for 7 months (~23 inches over 7 months)

Second rainfall event:

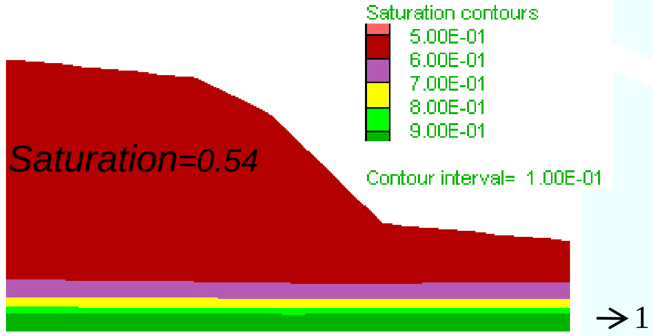
228 mm over 4 days (~9 inches over 4 days)

Initial conditions

Hydraulic conditions

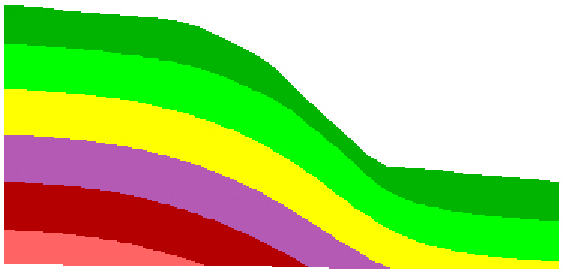


Initial pore pressure distribution



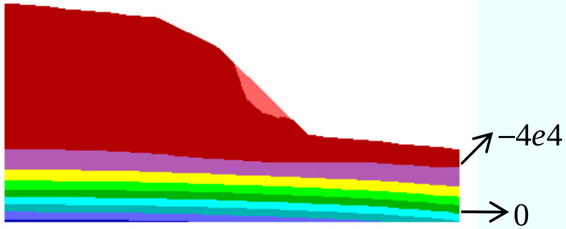
Initial saturation contours

Mechanical conditions

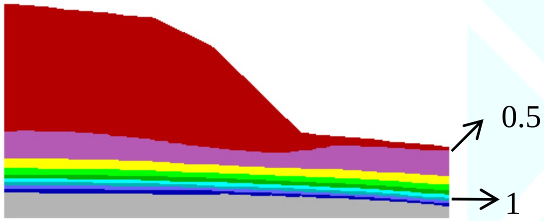


Initial contours of vertical stresses

First rainfall event
low intensity - long duration

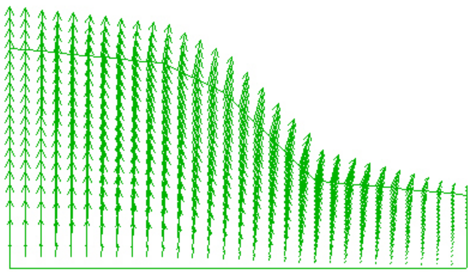


Pore pressure contours



Saturation contours

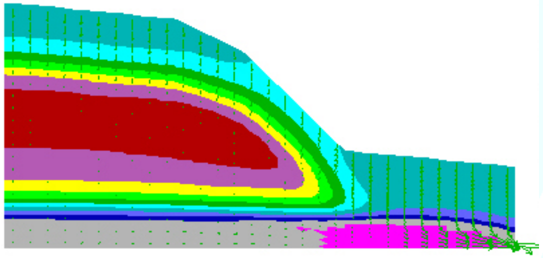
Max value ~ 0.3mm



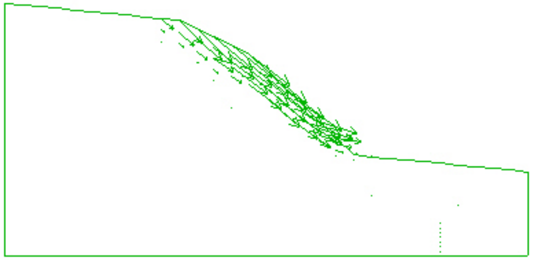
Induced displacements

58 cm (3 inches) over 7 months → Stable slope

Second rainfall event
high intensity - short duration



Saturation contours and flow vectors



Velocity vectors

23 cm (9 inches) over 4 days → Slope failure

Why is stability compromised …

Mohr-Coulomb failure criterion - 2 phase flow module

$$\tau^{\max} = \sigma^{b} \tan\phi + C \qquad (1)$$

Bishop effective stress

$$\sigma^{b} = \sigma - S_w P_w \qquad (2)$$

$$\Rightarrow \quad \tau^{\max} = \sigma \tan\phi + S_w \left(-P_w\right) \tan\phi + C$$

Capillary pressure law – van Genuchten

$$-P_w = P_0 \left(S_w^{-1/a} - 1\right)^{1-a}$$

‘Additional’ cohesion

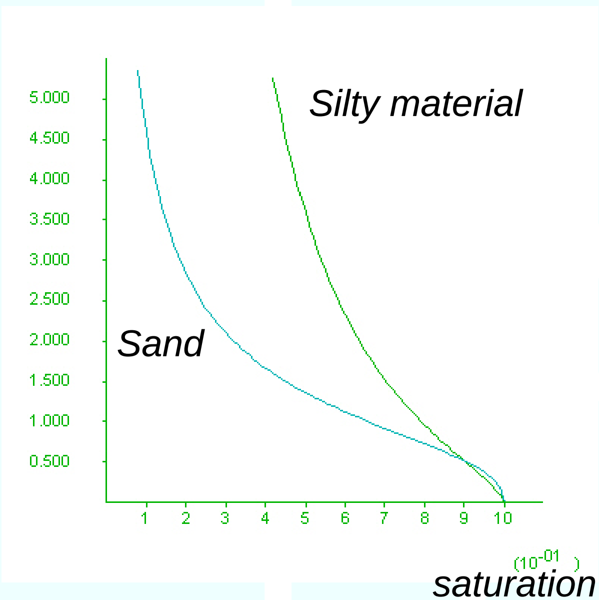
$$C_c = S_w \left(-P_w\right) \tan\phi$$

Cohesive strength

Capillary curve

$$-P_w = P_0 \left(S_w^{-1/a} - 1 \right)^{1-a}$$

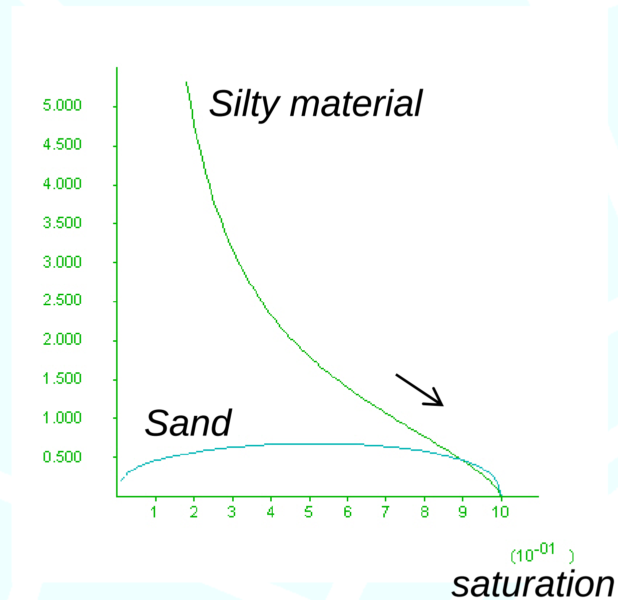
$$-\frac{P_w}{P_0}$$



'Additional' cohesion

$$C_c = S_w \left(-P_w \right) \tan \phi$$

$$\frac{C_c}{P_0}$$



Conclusions

Coupled numerical simulations of unsaturated seepage flow were carried out to show the impact of intensity and duration of a rainfall event on the stability of a slope.

Generic geometry and material properties were used for the slope.

It was shown that a rainfall event of low intensity and long duration was not detrimental to slope stability, provided the additional cohesion provided to the soil by the capillary forces was sufficient.

On the other hand, a rainfall event of high intensity-short duration was responsible for slope failure. In this case, the behavior was explained by an increase in soil saturation, accompanied by a decrease in the capillary forces intensity, causing an apparent decrease in soil cohesion.