Slope Stability

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Exercise 9 - Solution

Stability evolution of unsaturated slopes during rainfall infiltration (FEM analysis)

1 Exercise description

The goal of this exercise is to perform soil slope stability analyses using a finite element code in which a coupled hydro-mechanical model is implemented taking into account the partial saturation of the soil.
In particular, it is required to study the stability of the slope reported in Figure 1.a for the following conditions:

a) a rainfall event of low intensity and long duration (0.012 m/h, up to 200 h);
b) a rainfall event of high intensity and short duration (0.12 m/h, up to 20 h).

The problem can be outlined as shown in Figure 1.b, where a simplified geometry is assumed and kinematic boundary conditions are defined. As initial condition, a water table coinciding with the slope toe can be assumed. The entire slope domain can be thought as composed of a Mohr-Coulomb material with the properties indicated in Table 1.

Numerical analyses will be performed in a coupled way (hydraulic and mechanical behavior) by means of the finite element software ZSoil.

ZSoil can be downloaded at the following website: https://www.zsoil.com/student/. Follow the installation instructions on the website to obtain the free student version.
A tutorial is presented in section 2 in order to guide the student through the basic steps of ZSoil. The tutorial refers to ZSoil 2014 version (The link will download a newer version so there might be some small differences compared to this tutorial).

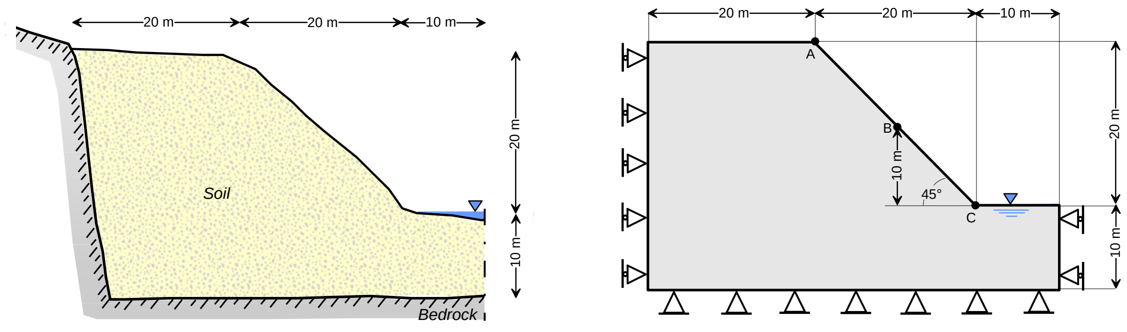


Figure 1: Case to study (a) and problem layout (b).

E	Young's modulus	100'000	kPa
ν	Poisson's ratio	0.3	-
c'	Cohesion	15	kPa
φ'	Shear strength angle	23	°
ψ	Dilatancy angle	0	°
γ	(Dry) soil unit volume weight	14.2	kN/m^3
e_0	Initial void ratio	0.9	-
K_x, K_y	Darcy's coefficient	0.05	m/h
S_{res}	Residual saturation ratio	0	-
α	Saturation constant	0.1	1/m

Table 1: Soil parameters.

Consider that, in the case of unsaturated medium, the definition of effective stress adopted by the software is as follows:

$$\sigma_{ij}^{'} = \sigma_{ij} - S_r p \delta_{ij}$$

Where S_r is the degree of saturation (called by the software "saturation coefficient") and p is the fluid pressure. The relationship between the degree of saturation and the pressure of the fluid is defined as follows

$$S_r = S_r(p) = \begin{cases} S_{res} + \dfrac{1 - S_{res}}{\left[1 + \left(\dfrac{\alpha p}{\gamma_F}\right)^2\right]^{1/2}} & \text{if } p > 0 \\ 1 & \phantom{\text{if }} p \le 0 \end{cases}$$

where S_{res} is the residual degree of saturation (defined by the software "residual saturation ratio"), γ_F is the unit weight of the fluid, and α is a material parameter.

Work to be done

For the initial state:

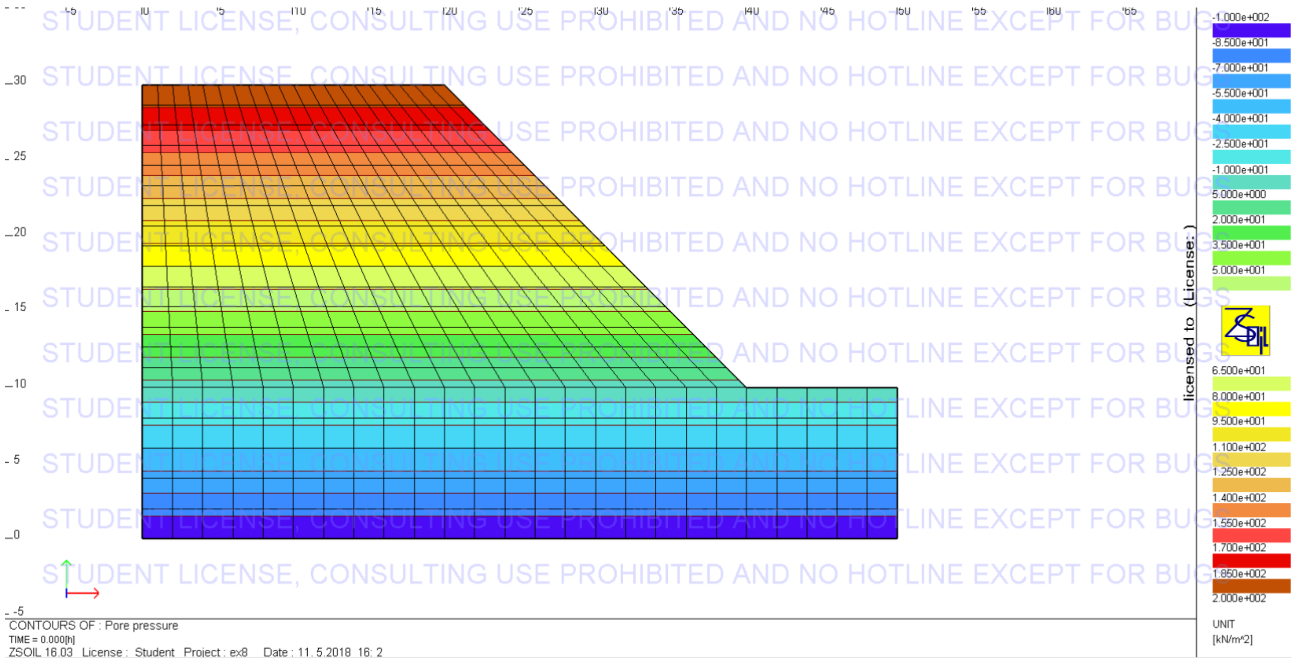
1. calculate the pore pressure, effective stress and saturation degree distributions within the domain;
2. calculate the initial safety factor.

For each of the proposed cases:

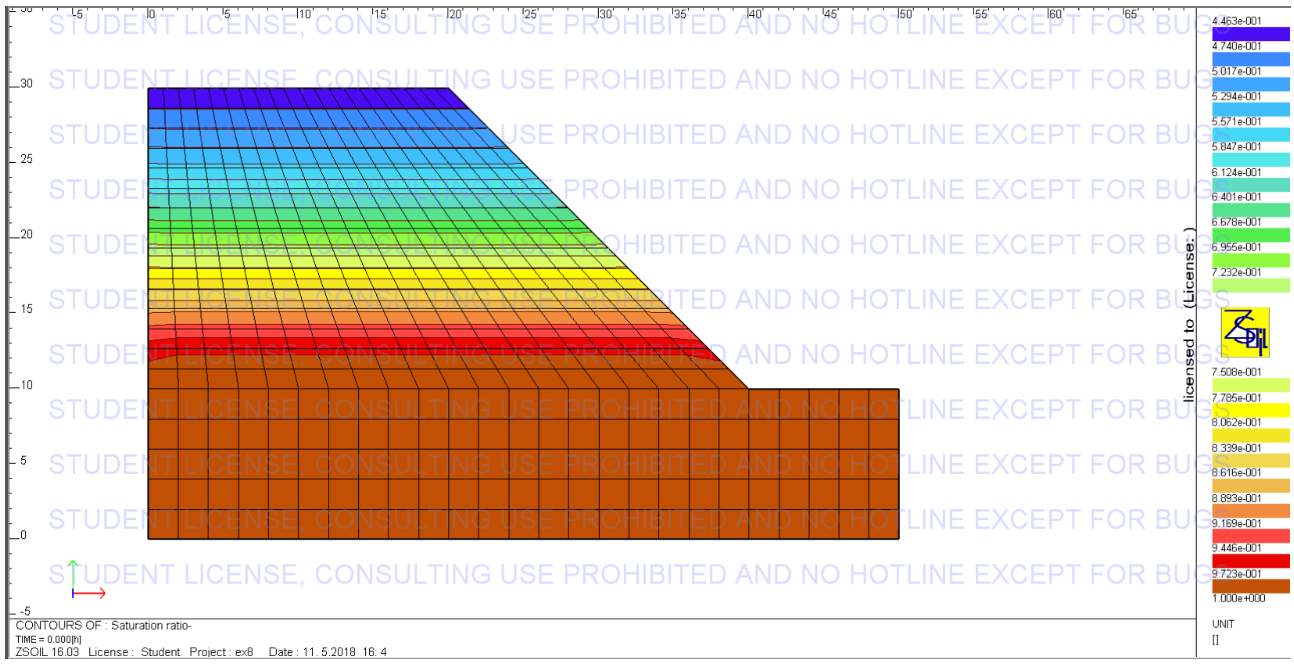
3. calculate the evolution of pore pressure and saturation degree with time within the domain and plot the displacements of some relevant points (A, B and C in Figure 1.b) versus time;
4. identify the failure mechanism;
5. evaluate the evolution of the safety factor with time;
6. identify the maximum rainfall duration that leads to failure.

Results

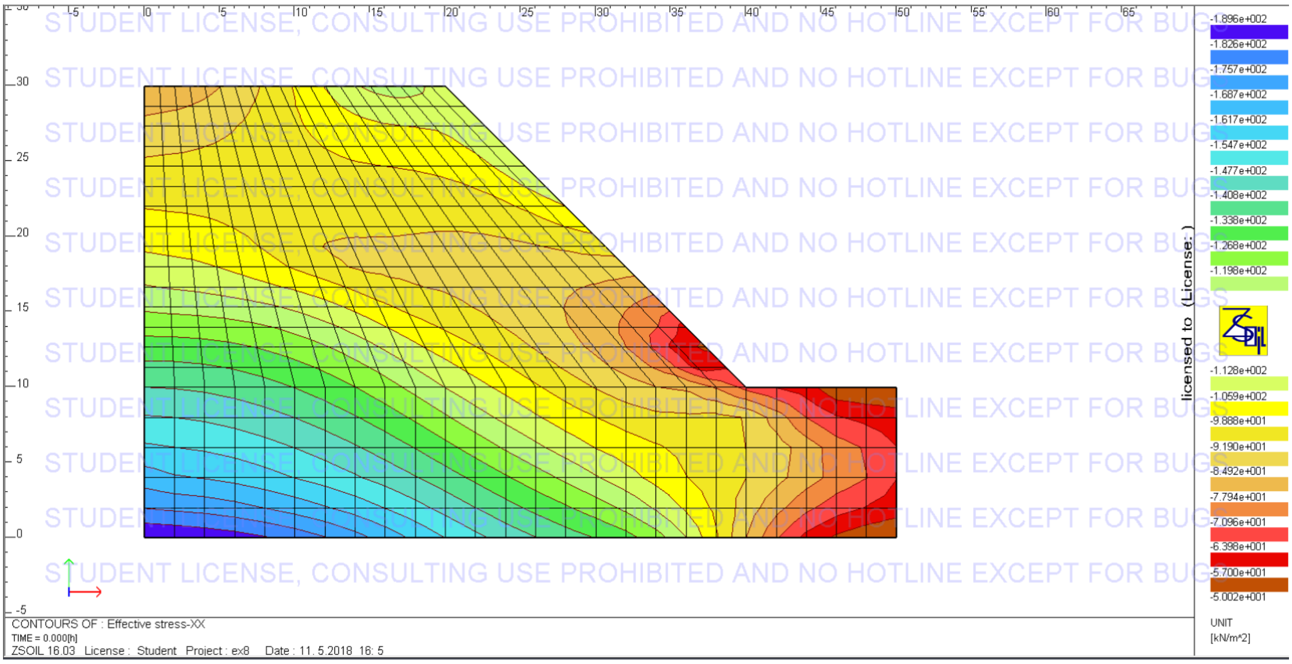
<u>Pore pressure map at the initial state</u>



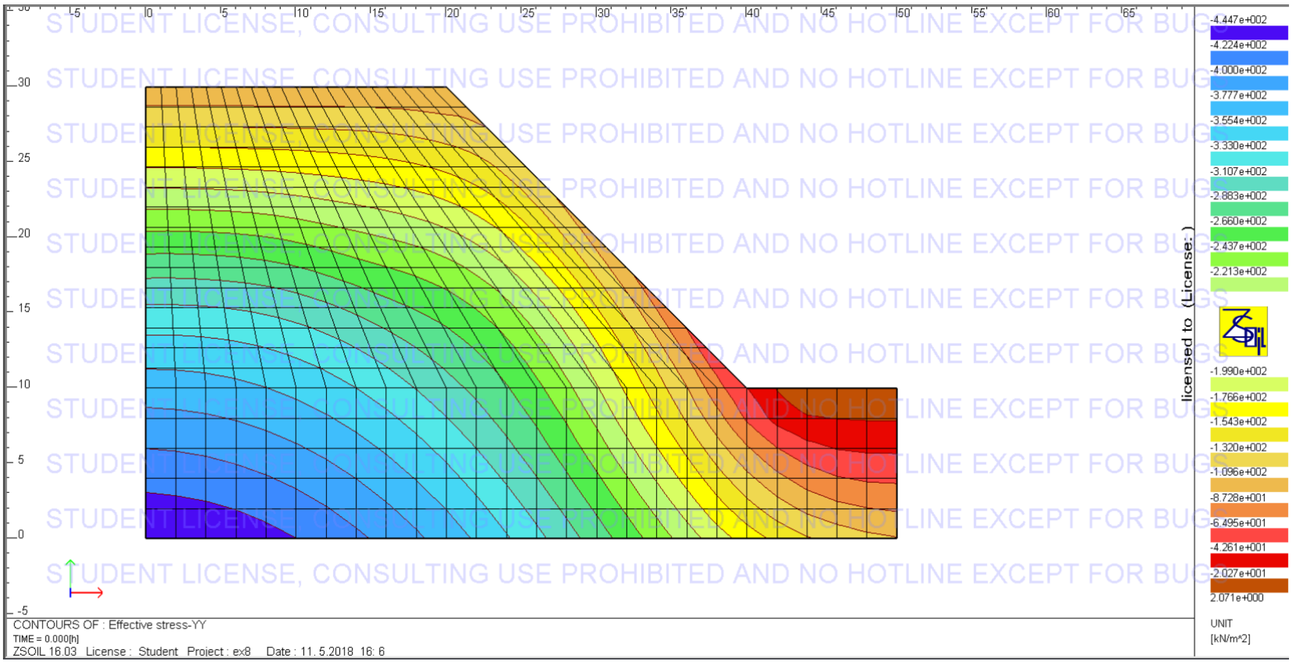
<u>Degree of saturation map at the initial state</u>



Effective stress map – xx component - at the initial state



Effective stress map – yy component - at the initial state



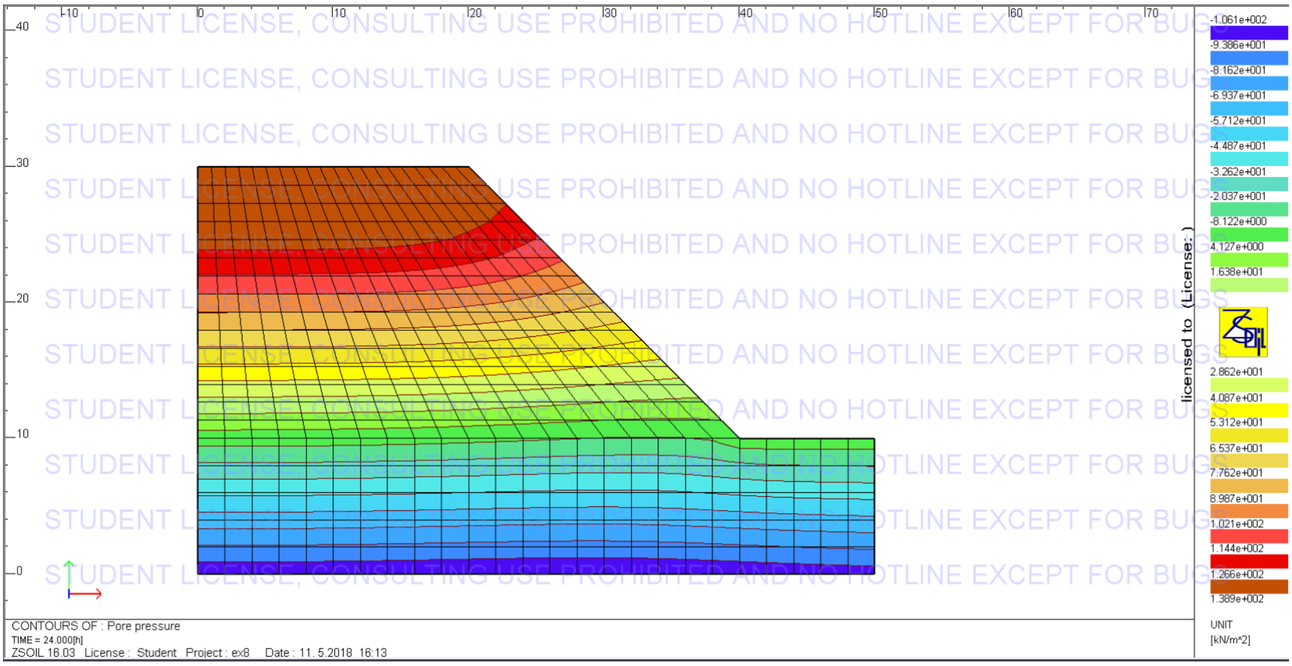
Safety factor at the initial state

The initial safety factor results to be equal to 1.22.

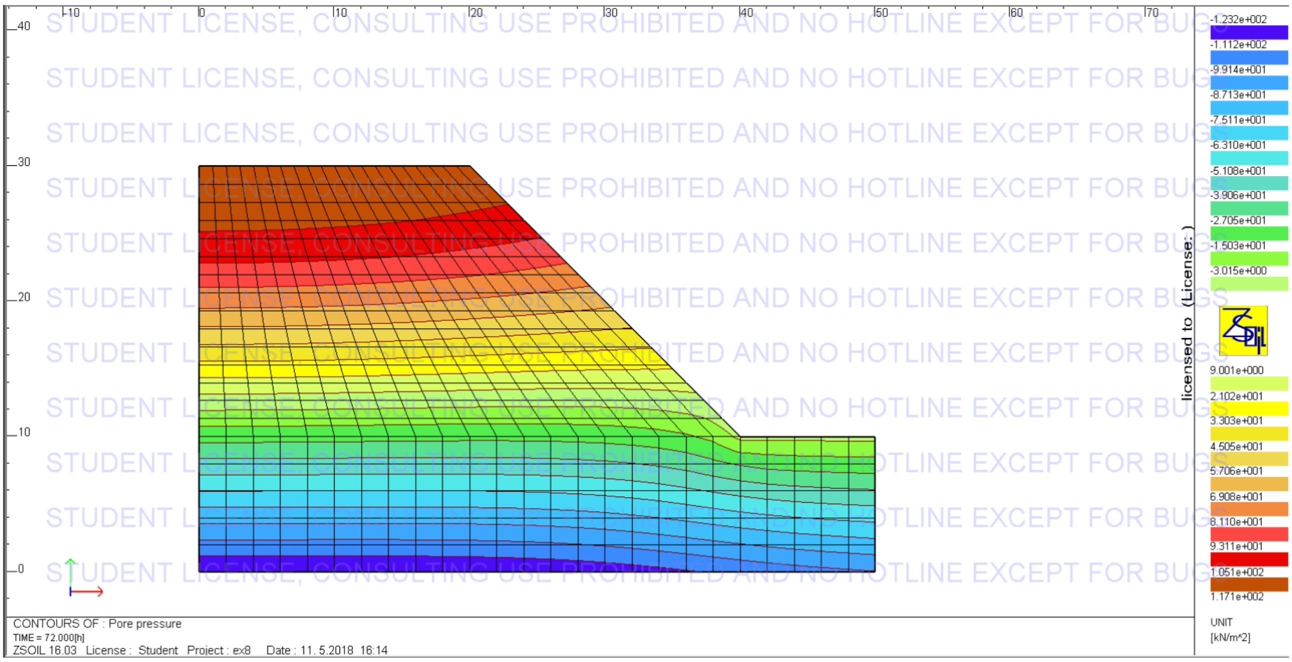
Case A

Evolution of pore pressure with time

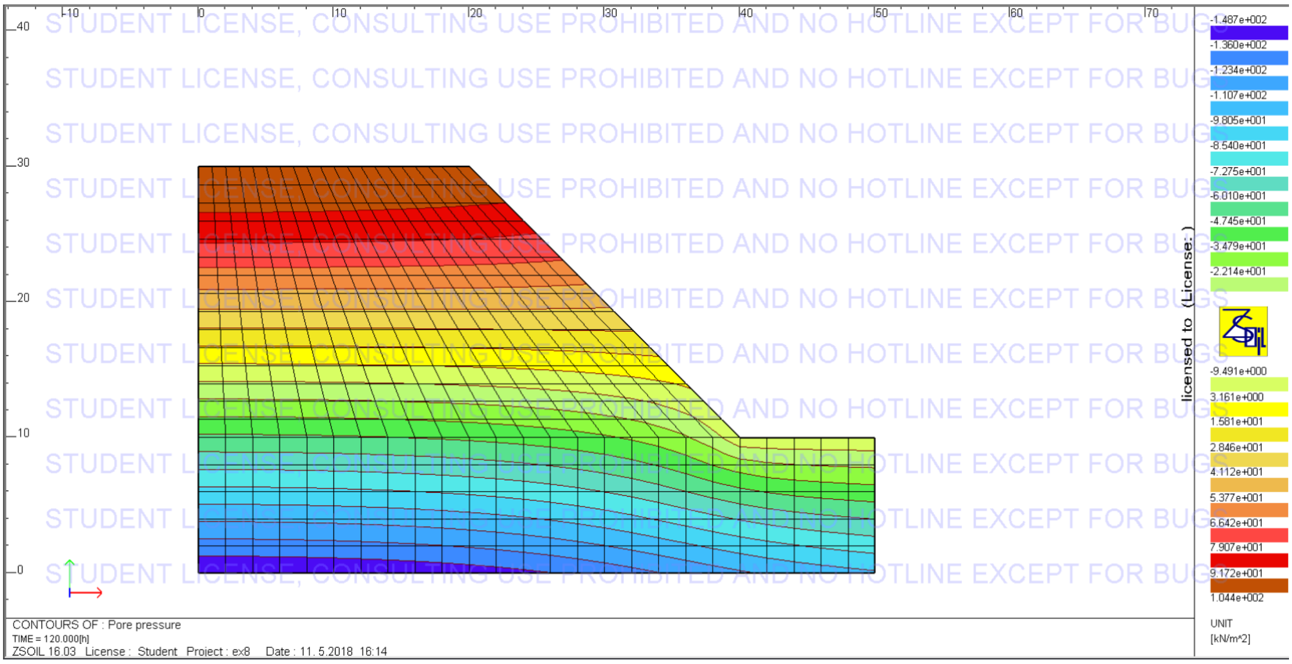
Timestep: 24h



Timestep: 72h

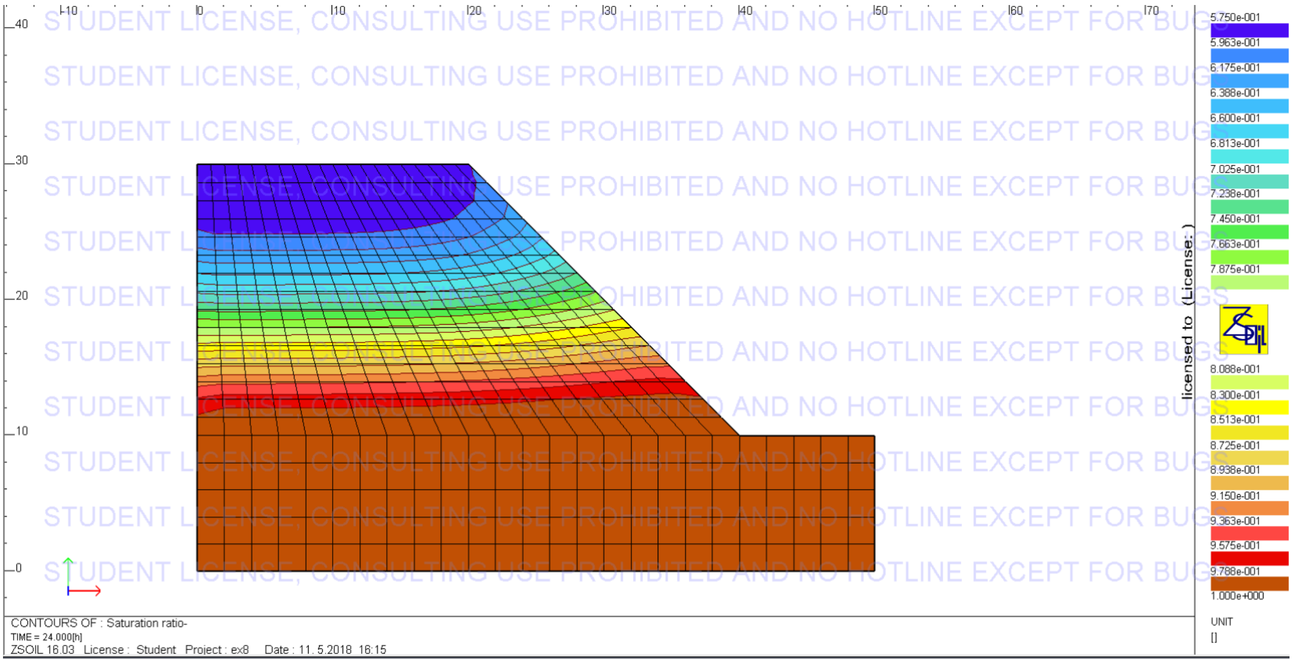


Timestep: 120h

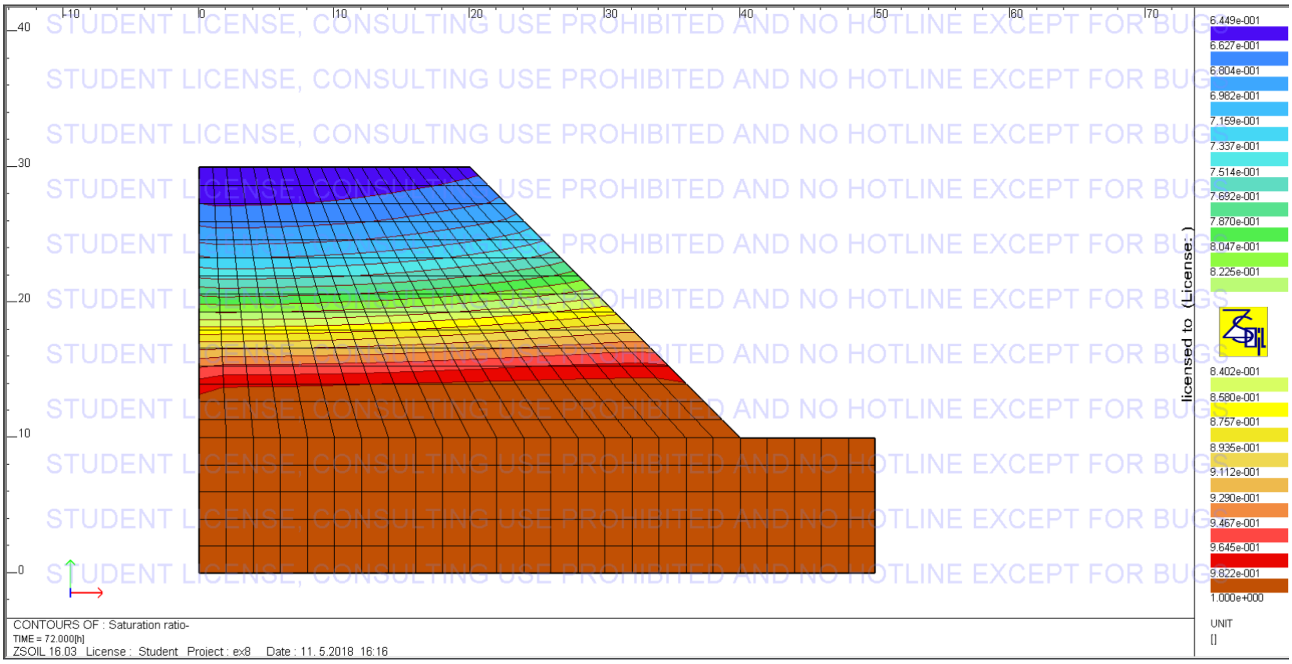


Evolution of degree of saturation with time

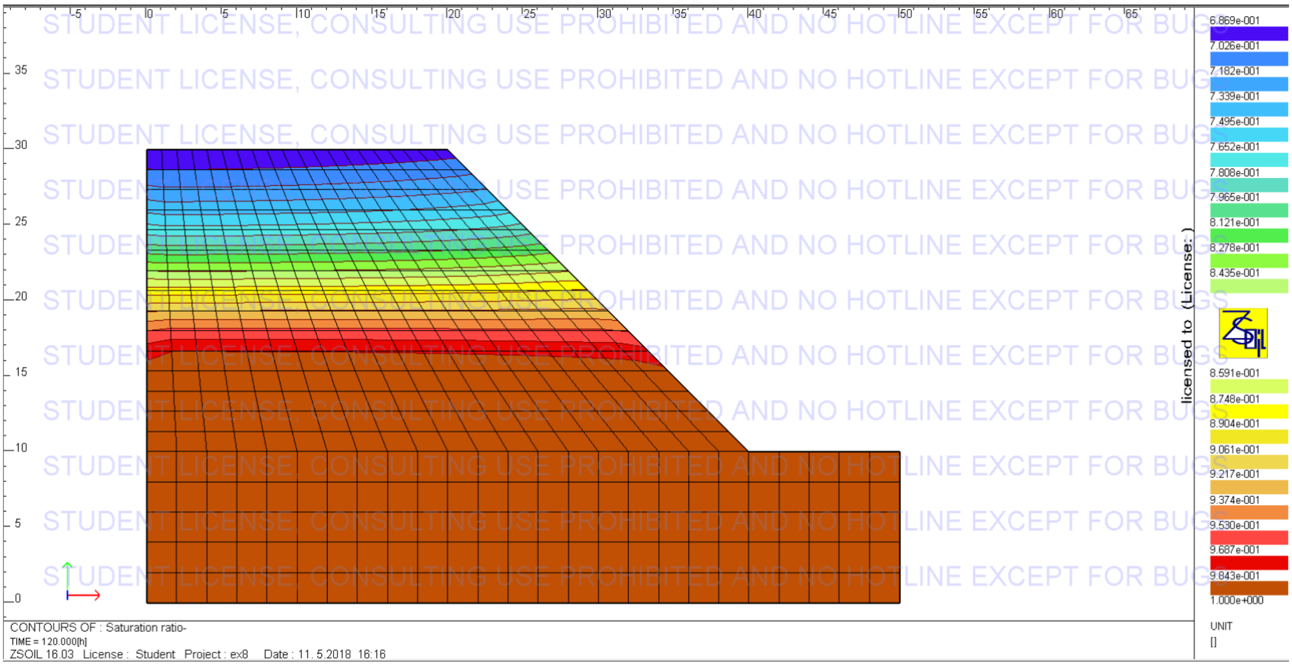
Timestep: 24h



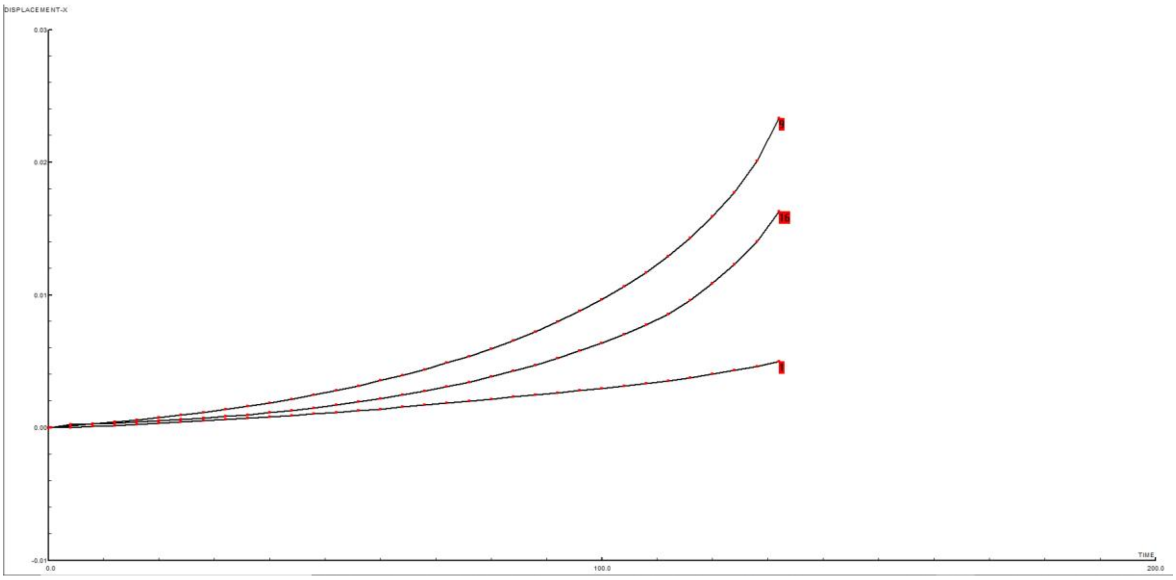
Timestep: 72h



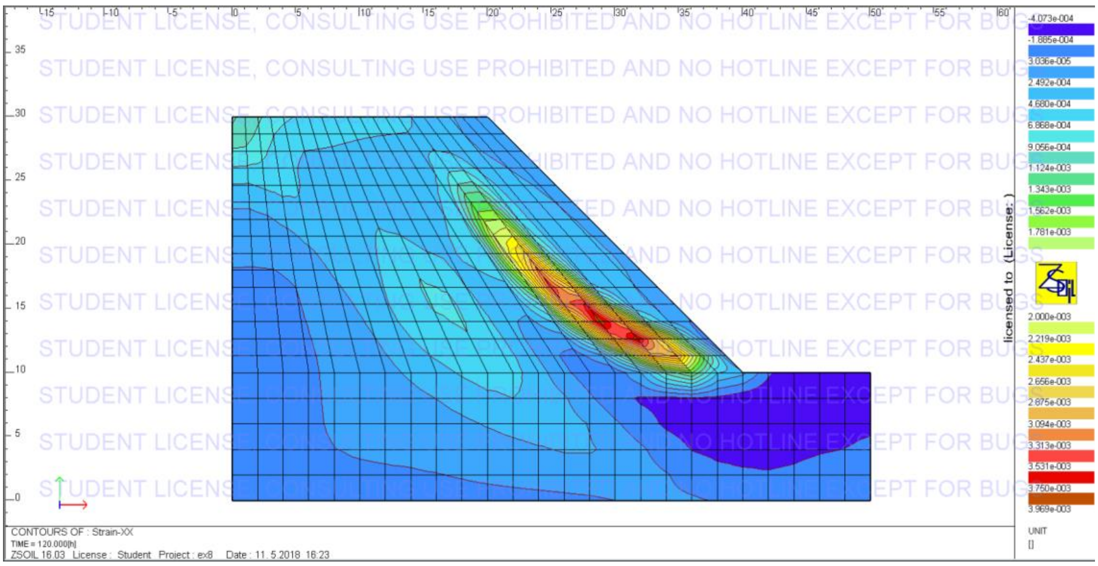
Timestep: 120h



Evolution of displacements with time at three specific points (nodes 1 (C), 9 (B) and 16 (A) in this example)



Failure mechanism – strain map xx component



Evolution of the safety factor with time:

for t = 0, FS = 1.22
for t = 24h, FS = 1.17
for t = 72h, FS = 1.09
for t = 120h, FS = 1.00

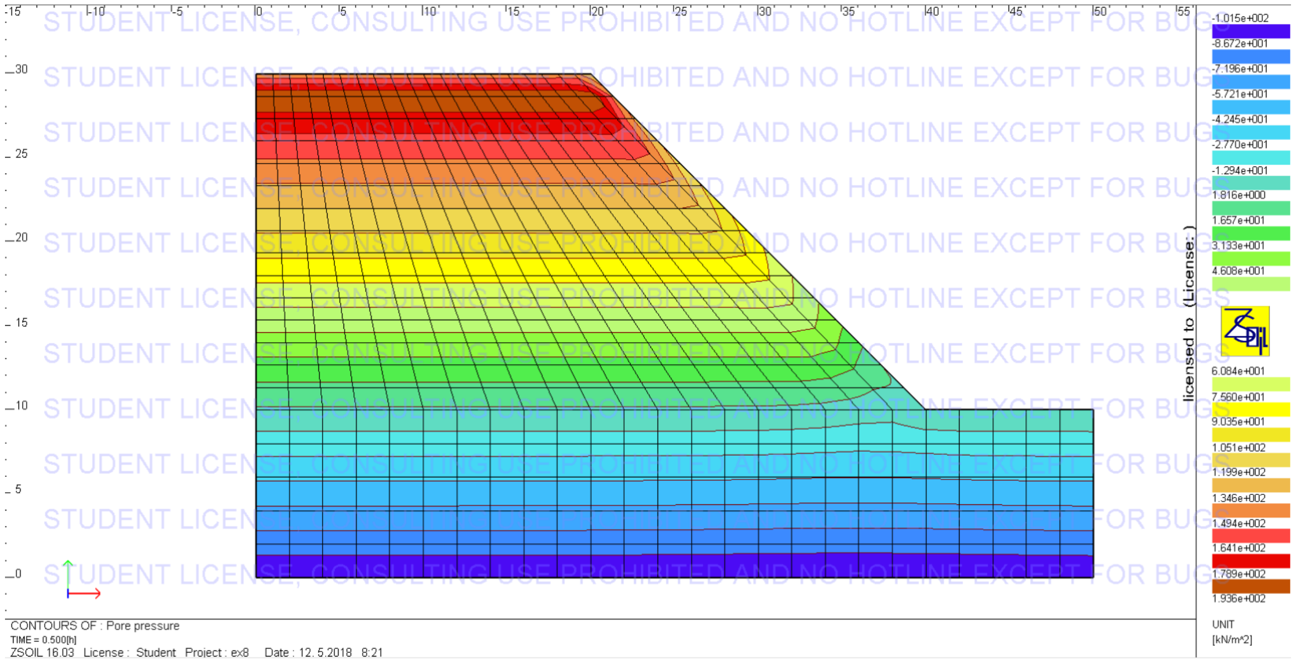
Maximum rainfall duration that leads to failure

t= 120h.

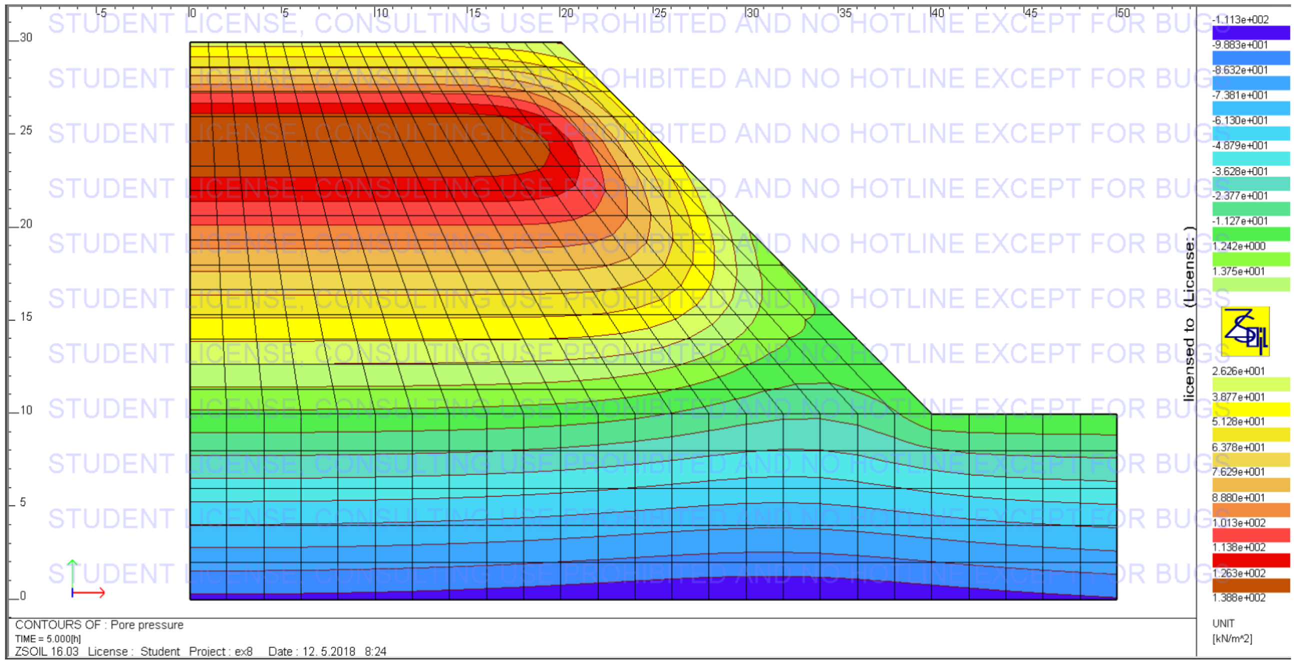
Case B

Evolution of pore pressure with time

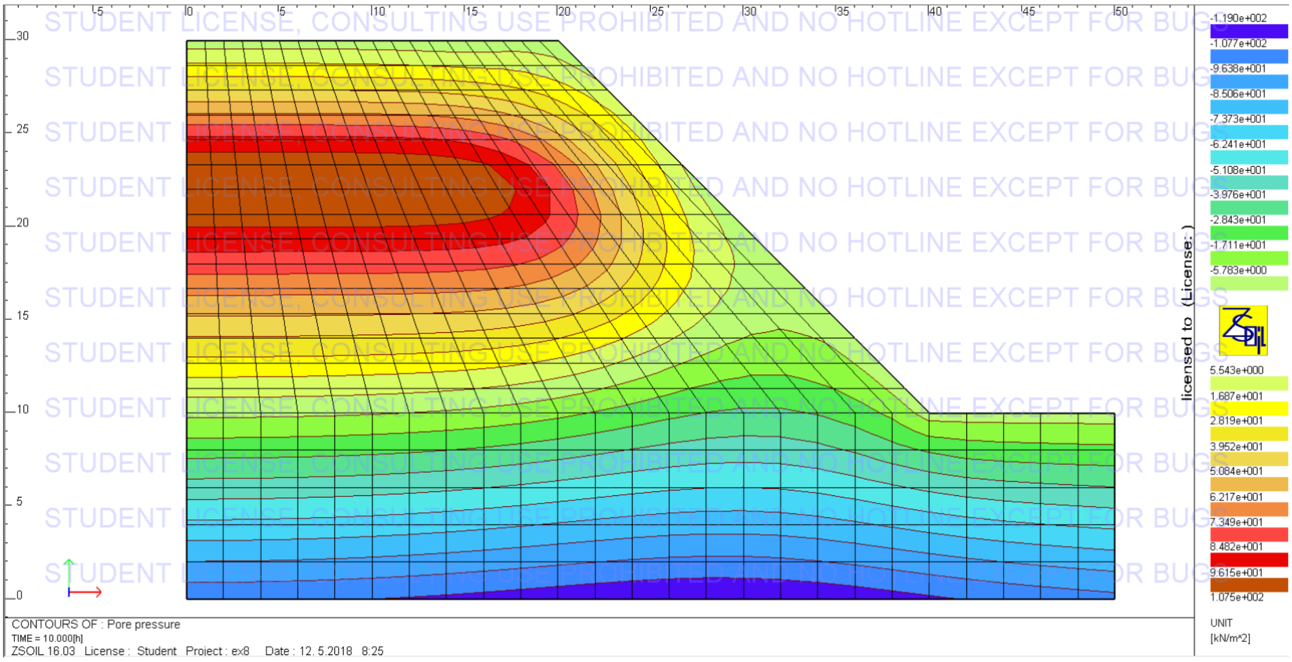
<u>Timestep: 0.5h</u>



<u>Timestep: 5h</u>

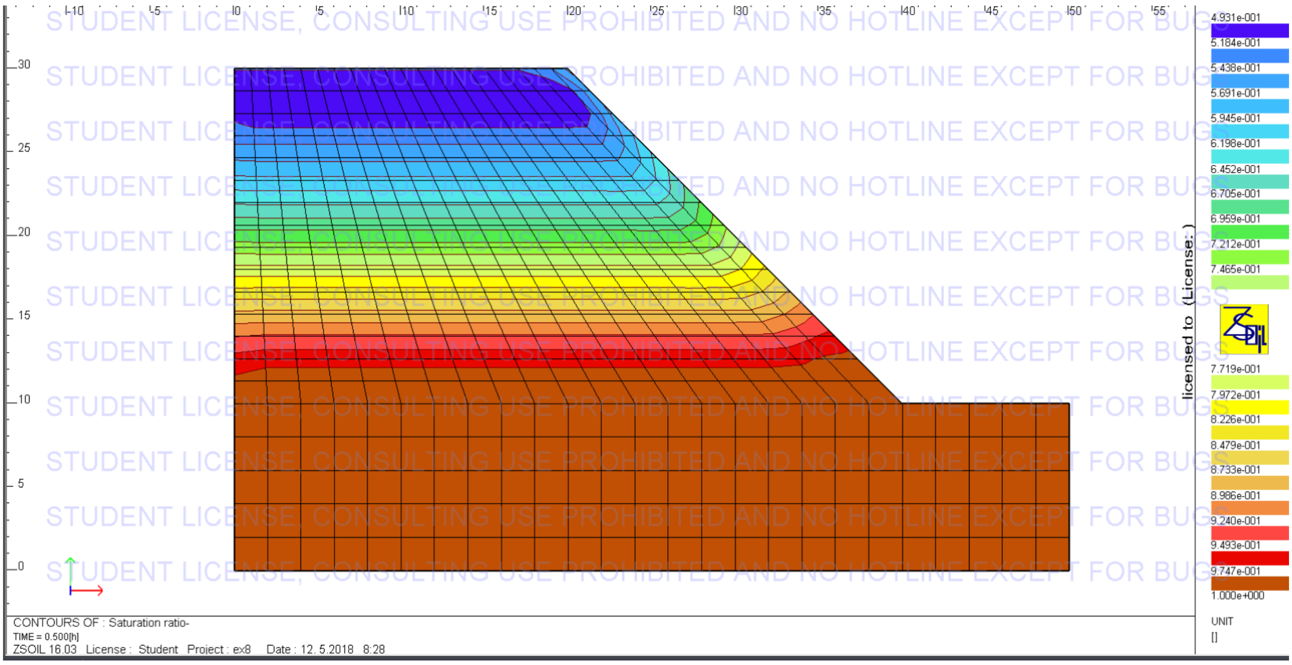


Timestep: 10h

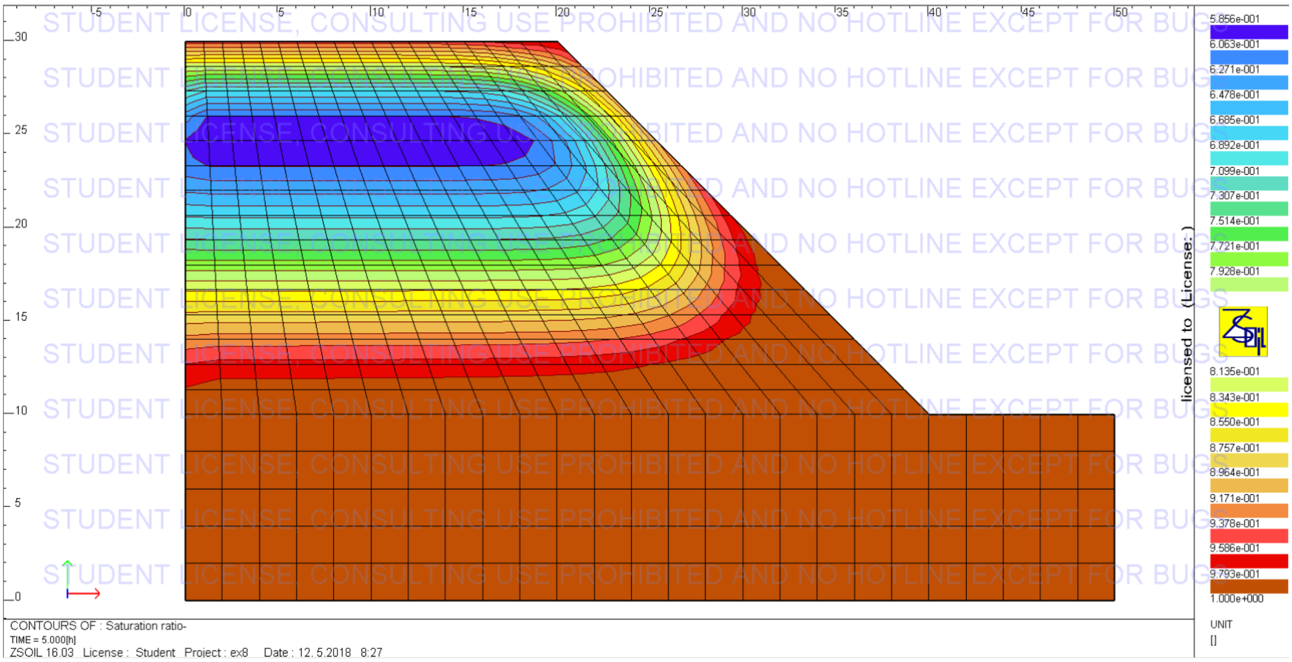


Evolution of degree of saturation with time

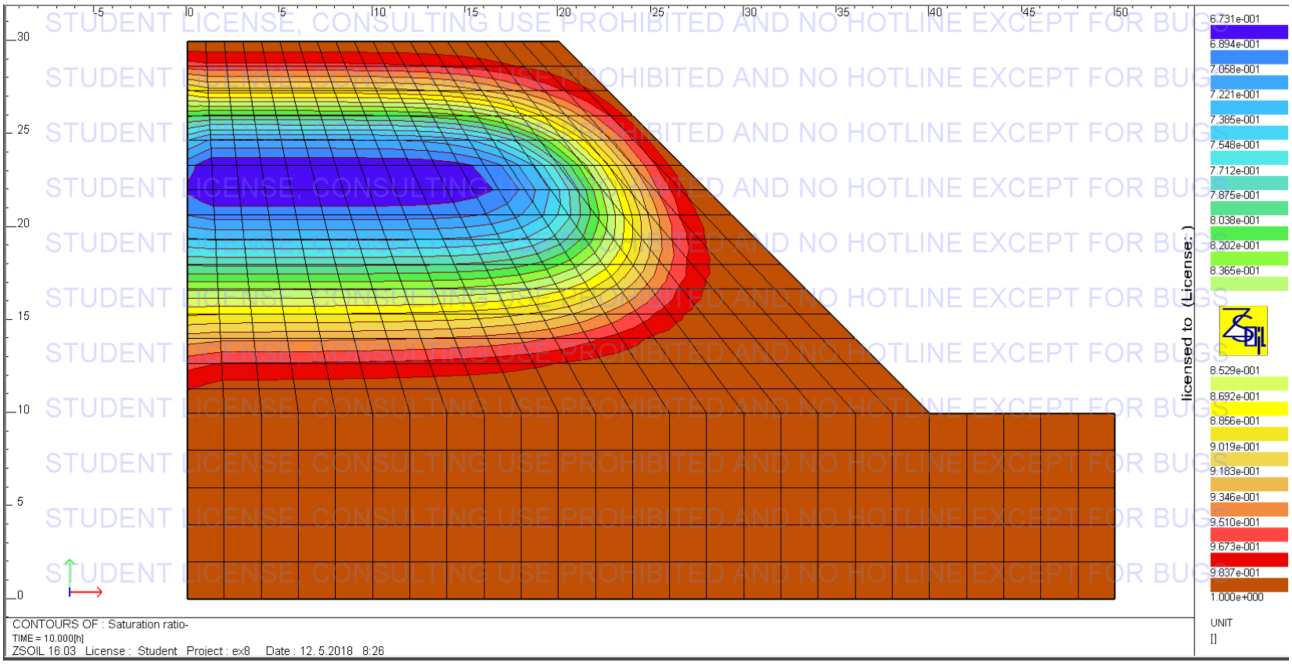
Timestep: 0.5h



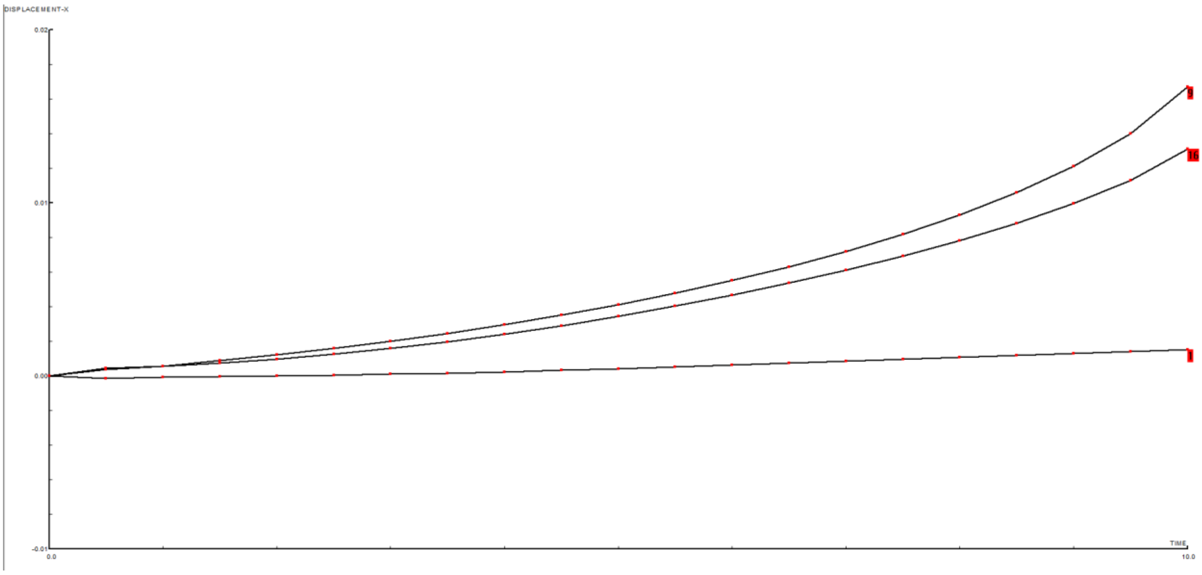
<u>Timestep: 5h</u>



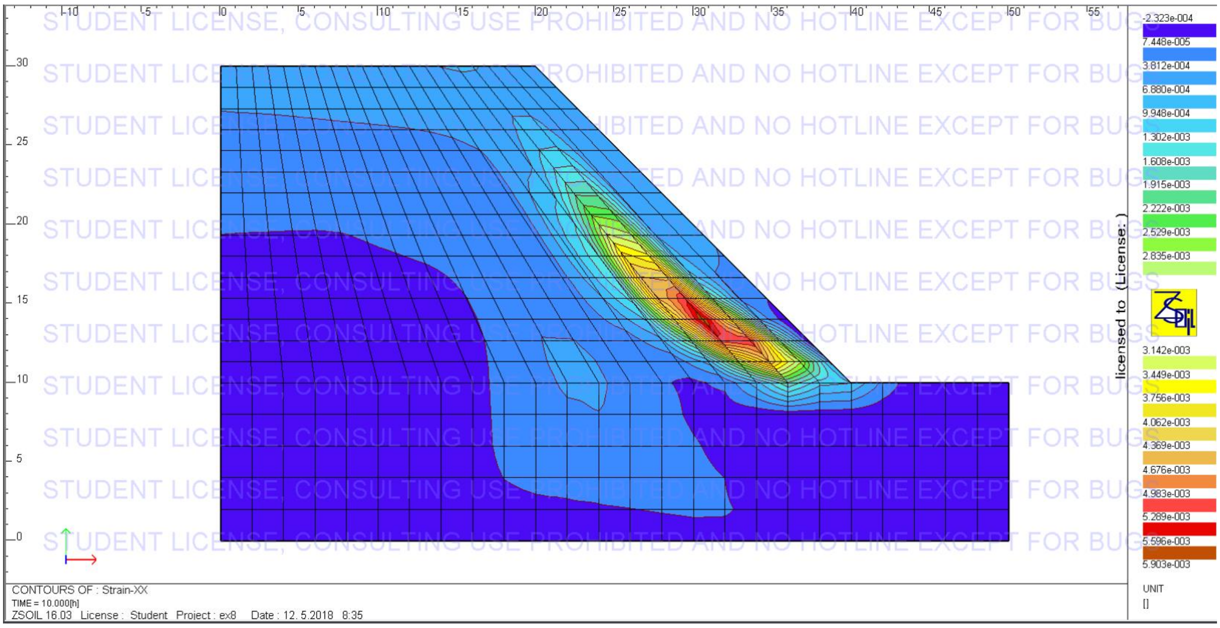
<u>Timestep: 10h</u>



Evolution of displacements with time at three specific points (nodes 1 (C), 9 (B) and 16 (A) in this example)



Failure mechanism – strain map xx component



Evolution of the safety factor with time:

for t = 0, FS = 1.22
for t = 0,5h, FS = 1.20
for t = 5h, FS = 1.12
for t = 10h, FS = 1.00

Maximum rainfall duration that leads to failure

t= 10h.