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Seepage numerical simulations in test case of Nocera Inferiore

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Summary

This technical report aims to describe numerical results obtained from seepage analyses concerning landslide event occurred in pyroclastic deposits of Nocera Inferiore (Sa) on March 4th, 2005.
The analyses have been carried out using the finite element software SEEP/W (Geo-Slope International Ltd.,2004).
During previous simulations, water pressure values are suffering from kinks due to software numerical problems. So we tried to find out and delete the reason of these oscillations.
Lastly, sensitivity analyses have been made in order to analyze the soil response in terms of pressure at changing of permeability.

Keywords: seepage, kinks, sensitivity analyses, permeability

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1. Foreword

Hydrological risk prevention is one of CMCC purposes.
In the research activity concerning the test case of Nocera Inferiore 2005, seepage studies are required in order to investigate slope stability.
Rainfall-induced landslide involved on the 4th March, 2005 is considered in this technical report.
Groundwater flow in a unsaturated soil (like pyroclastic soil in Nocera Inferiore) is governed by a differential equation that can be solved by means of a finite element method.
Analyses have been implemented by the finite element software Seep/W, developed by Geo-Slope International Ltd. (2004); it is a finite element program to model water infiltration into partially saturated soils.
SEEP/W gives results in terms of water pressure values, degree of saturation, conductivity and water flow velocity.
Nocera Inferiore landslide event has already been examined in technical report “2D seepage process simulation: preliminary analyses”; in that case unrealistic pressure values were risen because of boundary conditions imposed at bottom.

2. Model input data

As in saturated soils the flow of water in unsaturated soils can be assumed to fallow Darcy’s Law (Richards,1931). In this case the coefficient of hydraulic conductivity is a function of the degree of saturation or negative pore-water pressure in the soil. The governing partial differential equation for the flow of water through a 2D unsaturated soil element is given as fallows:

$$\frac{\partial}{\partial x}\left(k_x \frac{\partial H}{\partial x}\right)+\frac{\partial}{\partial y}\left(k_y \frac{\partial H}{\partial y}\right)+Q=m_w \gamma_w \frac{\partial H}{\partial t}$$

where:
H is the total head;
k_x and k_y are the hydraulic conductivity in the x and y direction;
Q is the applied boundary flux;
m_w is the slope of the soil-water characteristic curve;
γ_w is the unit weight of water; and
t is the time.

In the simulations it was assumed seepage flow at lateral boundaries and two boundary conditions at the base of the scheme: unit gradient and impervious base.
Both conditions are realistic for Nocera Inferiore slope: the first simulates free drainage in fractured carbonaceous bedrock under pyroclastic layer, whereas it is possible to have the second one when smaller particles of soil are dragged along by the intense rainfalls. They may plug up limestone fractures so as make impermeable the bottom of pyroclastic deposits.

Seepage analyses extend from August 2004 to March 2005 in order to investigate the role of previous rainfalls in the slope instability.
Rainfalls data input have been deduced from measures of pluviometric station next to the highway A3.
Into finite element methods the time steps size is related to element size. If you don' t set the correct combination of them, convergence problems can occur.
Time step assumed was one day, and it was set an adaptive time step of one hour when the nodes heads between successive time steps were changing by more than 5%.
Elements size is 100x36 cm, but to numerically deal with rapid boundary changes (like rainfalls) it is necessary to have fine discretization near the ground surface; so on the upper part of the scheme, mesh are 100x4 cm thick.

Material properties have been deduced from tests performed in laboratory of D.I.G.A. (Dipartimento di Idraulica e Geotecnica Ambientale) of University of Naples "Federico II".
In a unsaturated soil, the volume of water stored within the voids will vary depending on the negative water pressure within the pore-water. There is no fixed water content in time so a function is required to describe how water contents change with different pressures into the soil.
The amount of water stored or retained is a function of the pore water pressures and the characteristics of the soil structure and is described by the volumetric water content function.
This curve has been deduced from laboratory tests employing pyroclastic soil samples of Nocera Inferiore (Zingariello C., 2007).
During the test water content is estimated as the soil pressure changes: incremental increases in air pressure result in incremental decreases in water content within the soil sample.
The adsorption curve (wetting phase) differs from the desorption curve (drying phase) as a result of hysteresis. The end point of the adsorption curve may differ from the starting point of the desorption curve because of air entrapment in the soil.
Seep/W doesn't allow to use two different curve for drying and wetting, so it needs to set only one of these.
Partially saturated soil, owing to water seepage, increases its water content, so into the analyses it was chosen an interpolating curve closer to the adsorption curve. Volumetric water content is shown in Fig. 1.

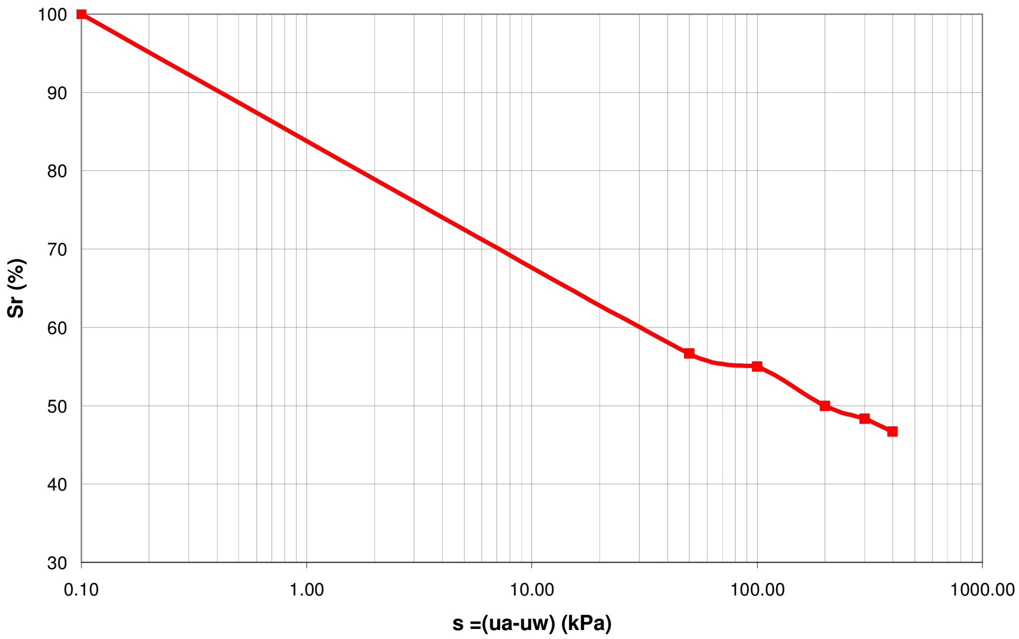

Fig. 1 Volumetric water content

Hydraulic conductivity function has been estimated from van Genuchten relation (1980), assuming $k_{sat}=10^{-7}$ m/s, as literature suggests for pyroclastic soils in Campania Region.

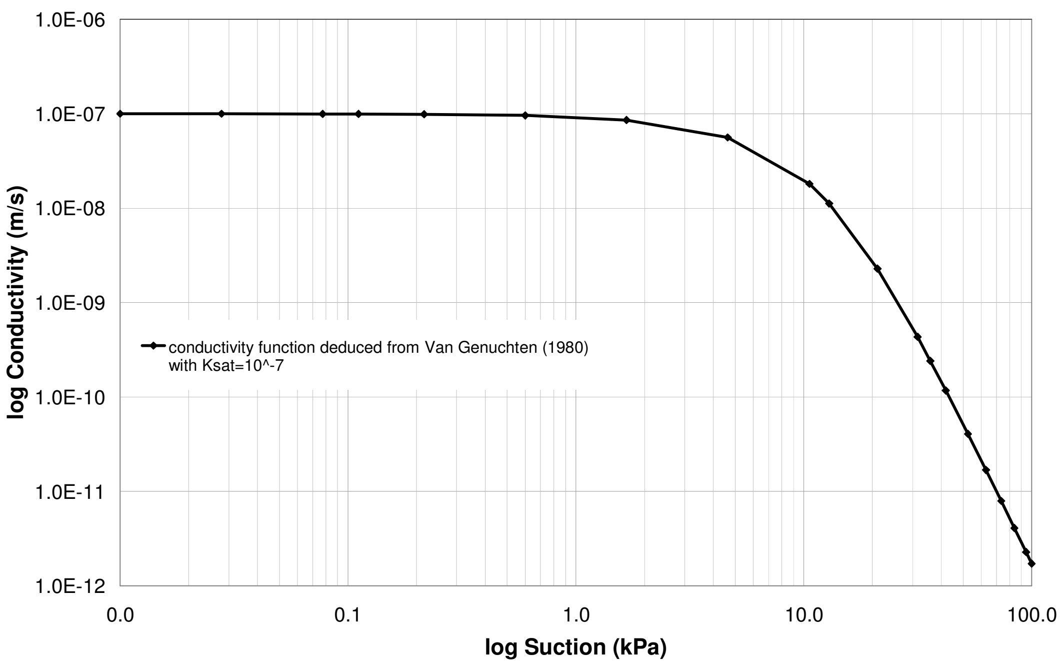

Fig. 2 Hydraulic conductivity function

3. Analyses results

If impervious base is imposed at bottom of the scheme, results are realistic (see technical report “2D seepage process simulation: preliminary analyses”), but when free drainage is assumed, results are suffering from oscillations of pore-water pressures especially near the free drainage boundary (blue curves in Fig.3, Fig.4, Fig.5).

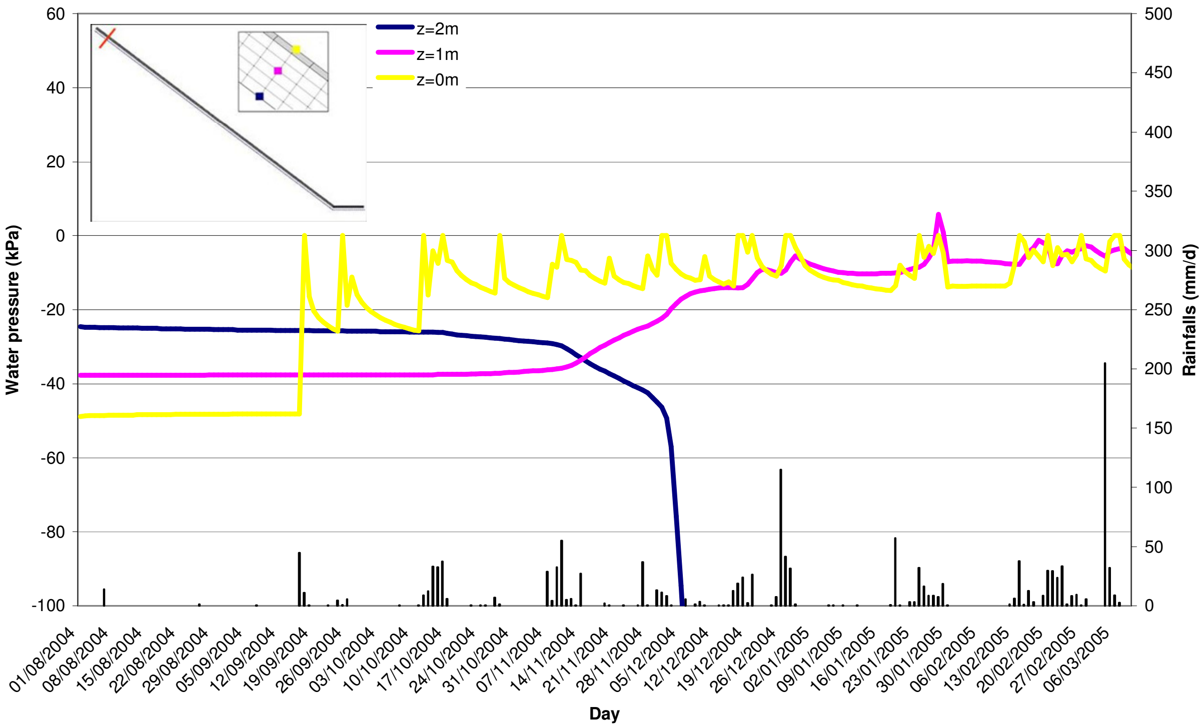

Fig. 3 Water pressure trends, section A

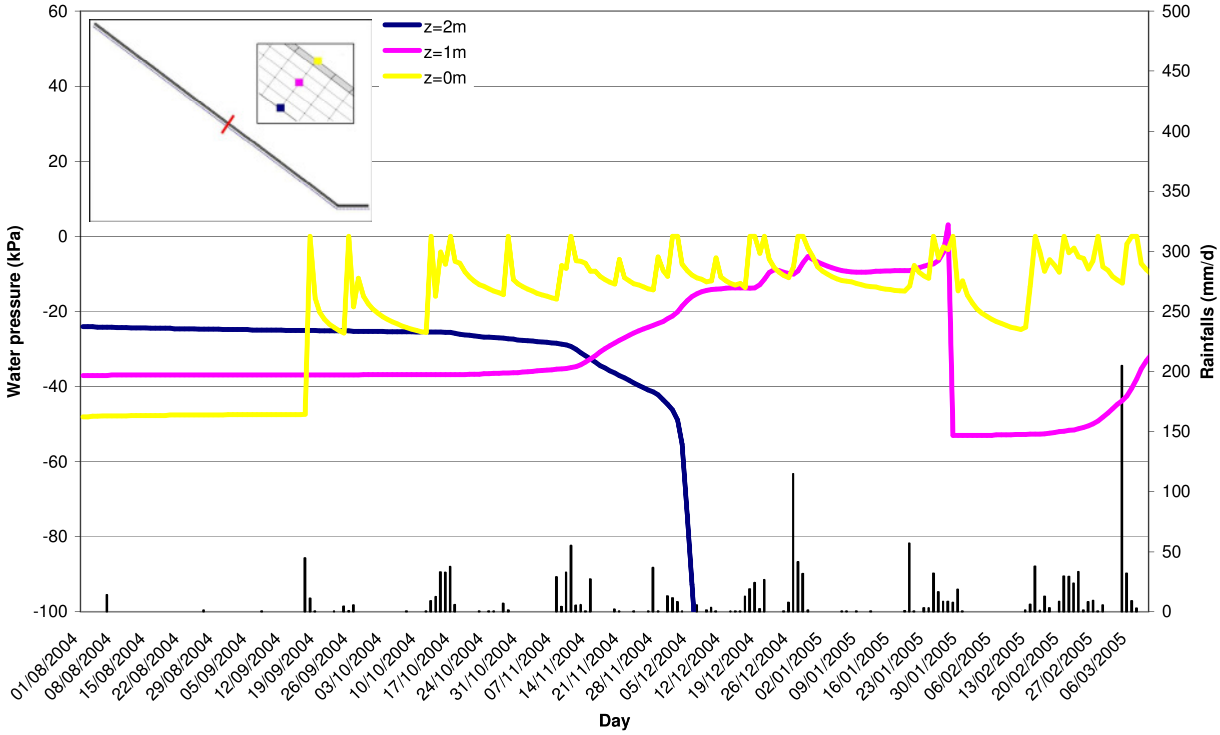

Fig. 4 Water pressure trends, section B

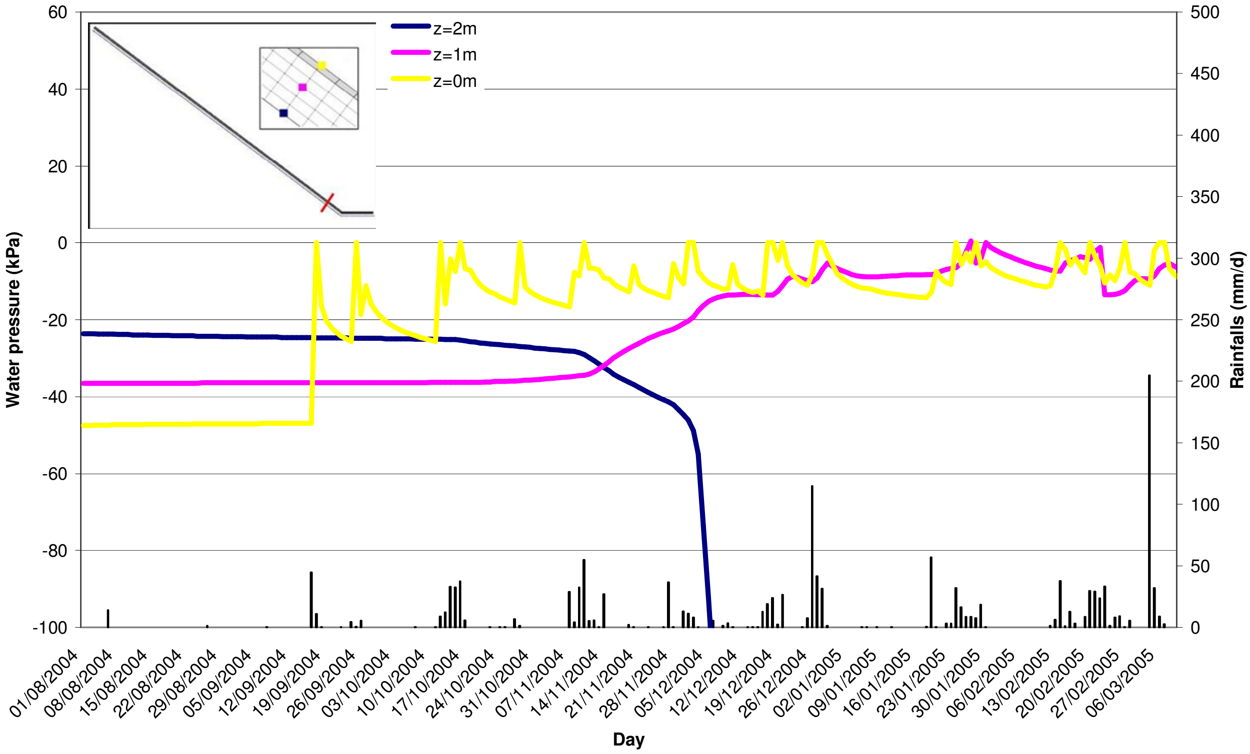

Fig. 5 Water pressure trends, section C

At bottom pressure values become more and more negative. This trend is unrealistic because it means:

1. The flow leaves the soil faster than filtering from above;

2. The soil is emptying following rain water and it is not possible with such conductivity values. Rather soil should saturate, even if more slowly than the upper layers.

Probably this unrealistic trend is given by numerical convergence problem because drainage flux at bottom depends on the changes in water pressure.
The unit gradient boundary condition is obtained by setting the Q flux boundary to be equal to the actual hydraulic conductivity value present at the nearest point from the previous iteration multiplied by the contributing edge boundary length.
Therefore, the solution of the correct Q to apply is closely controlled by the initial or previous time step and actual pressure conductivity conditions in the finite element at the point of application.
We are in effect applying an unknown Q boundary with unknown conductivity values at the base of the problem and the solution can oscillate.

4. Ways to avoid fluctuations

Depending on specific problem complexity, numerical oscillations may arise in finite element software because of:

- boundary condition inappropriate;
- time step too long or too short compared to analysis period;
- elements size too big or too small compared to domain sizes.

4.1 Boundary condition verify

In the simulations we assumed seepage flow at lateral boundaries.
Further analyses have been performed in order to verify if such condition can influence pressure values into entire domain.
Therefore different conditions are assumed: free drainage (like at bottom) and infinite elements.
The first condition was previously explained: it imposes exit flux equal to hydraulic conductivity present at last step.
The second one is useful when boundary condition cannot be correctly defined. These types of elements make it possible to greatly extend the position at which the boundary conditions are effective without actually extending the mesh. The conditions far from the main area of interest are referred to as far field boundary conditions.

Results of these simulations are shown for cross section in the middle of domain (Fig.6, Fig.7, Fig.8).

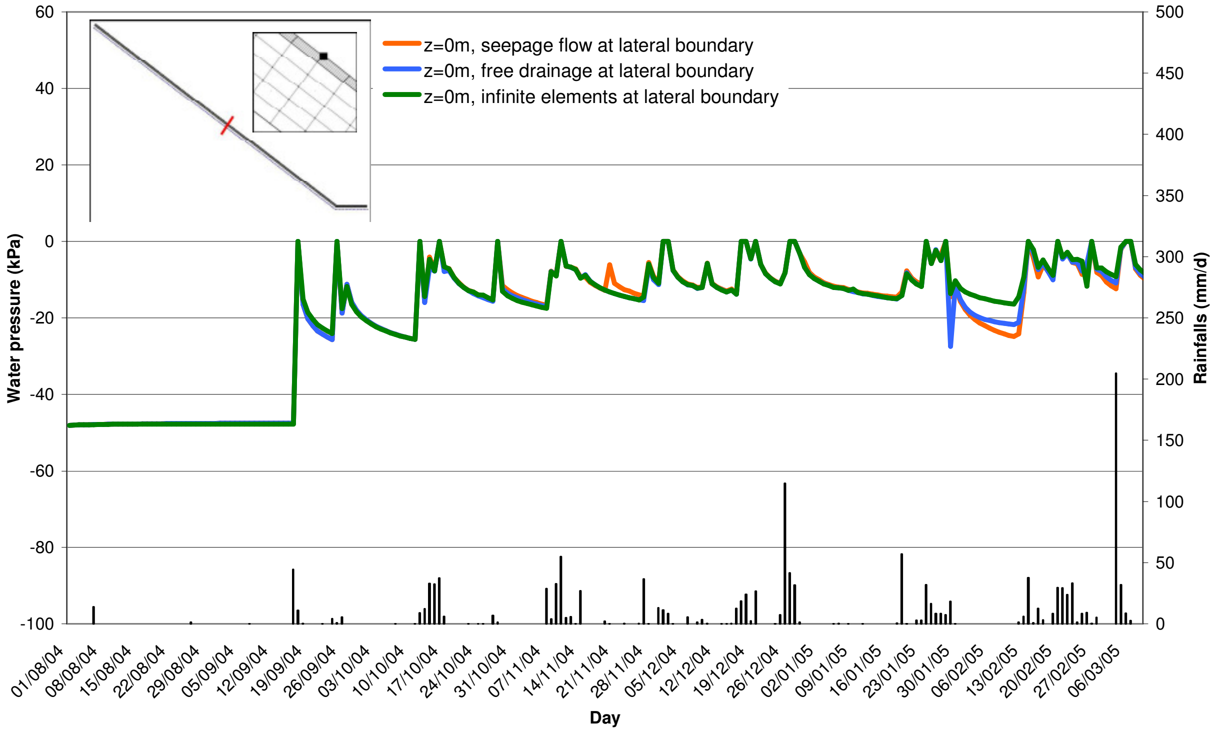

Fig. 6 Water pressure trends, lateral boundary verify, section B, z=0m

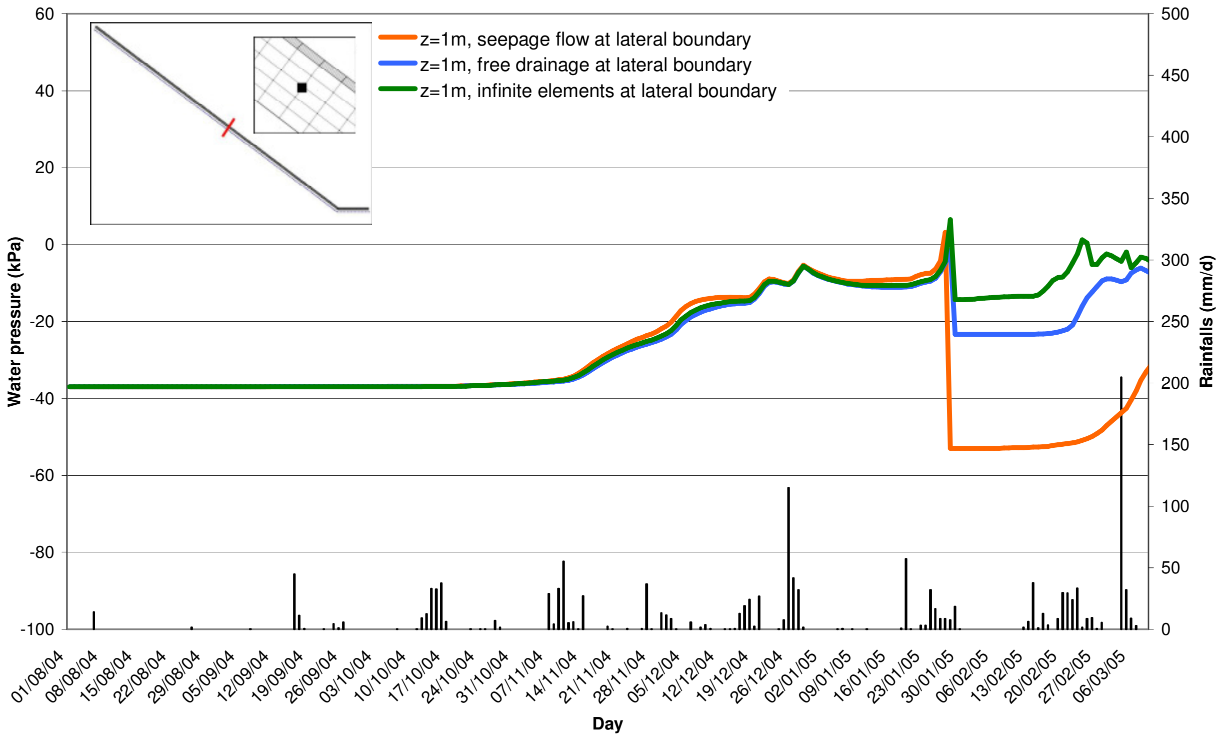

Fig. 7 Water pressure trends, lateral boundary verify, section B, z=1m

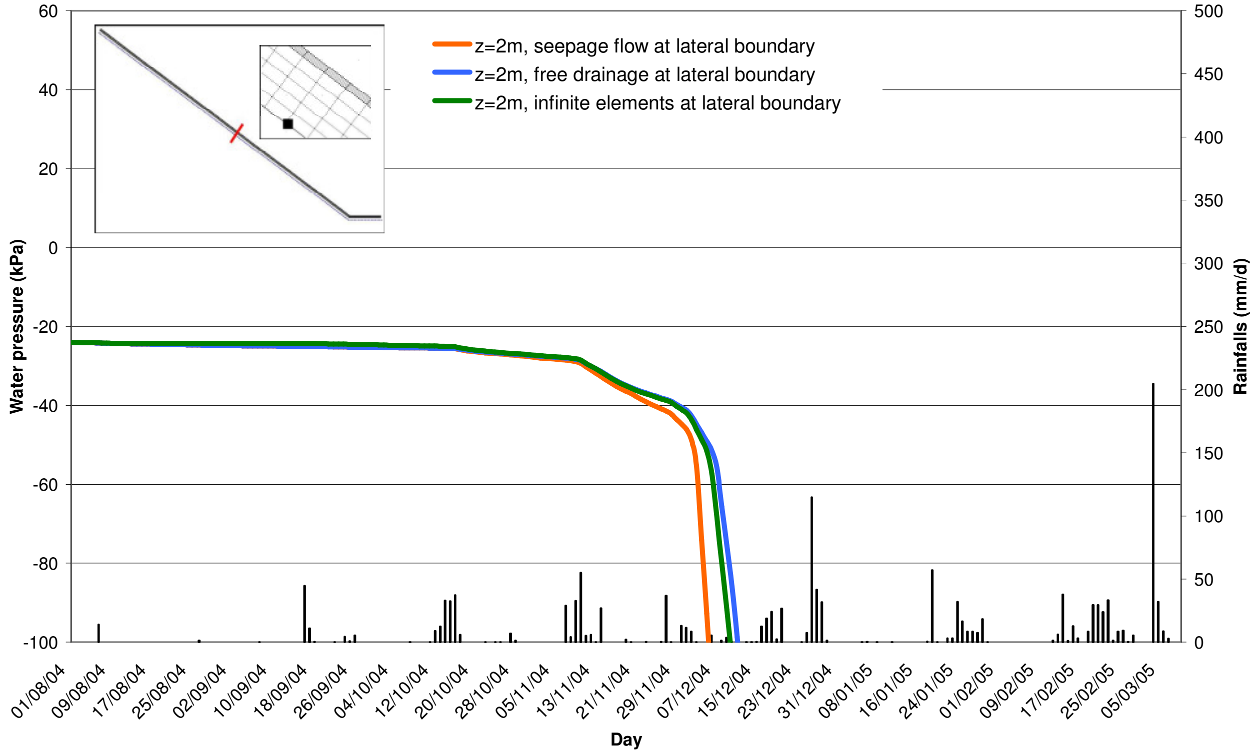

Fig. 8 Water pressure trends, lateral boundary verify, section B, z=2m

Also these results suffering from visible fluctuations especially near the bottom of the scheme. So it stands to reason lateral boundary condition is not the cause of water pressure oscillations.

4.2 Time step size verify

Smaller time steps can sometimes help to bring about convergence, but also too small time step involves unrealistic computed pore-water pressures.
Among the contributions present in literature oscillatory phenomena can be observed in the seepage analysis conducted by and Rahardjo and Leong (1997), in which pore water pressure profiles show visible kinks near the wetting front.
As well in one-dimensional consolidation problems of Vermeer and Verruijt (1981) oscillations were observed near the drainage boundary.
In this instance oscillations are given by too small time-step size.
Thomas and Zhou (1997) derived two minimum time-step size criteria to avoid numerical oscillations in 1-D and 2-D heat diffusion problems.
Since differential equation for heat flow is similar to unsaturated seepage flow one, these criteria may be applied to unsaturated seepage flow problems to remove numerical fluctuations.
Criteria correlate time step size to the element size, the soil water characteristic curve and the hydraulic conductivity.
Therefore, using this criteria, we have checked that oscillations aren't given by time step too short.

Besides we have also verify if time step of one day was too long; therefore we have assumed time step of two days, but oscillations arise again (Fig. 9, Fig.10, Fig.11).
Also this time results are unacceptable, moreover fluctuations arise since ground surface.

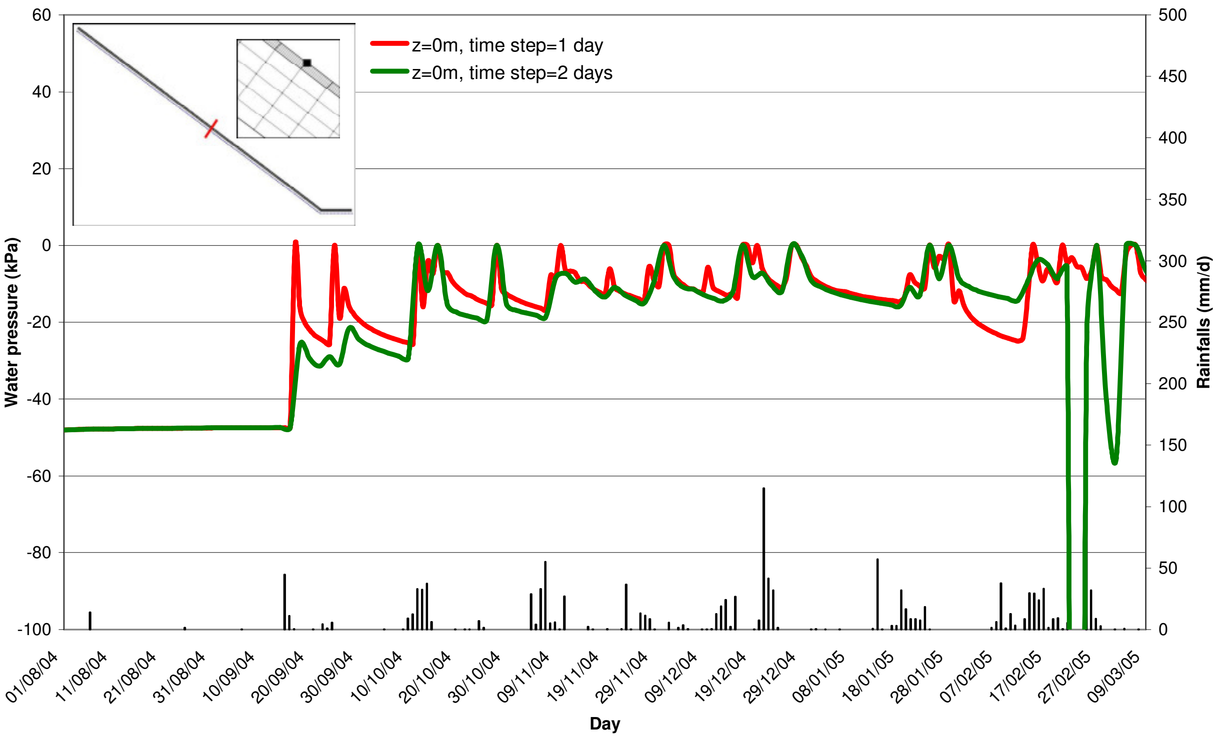

Fig. 9 Water pressure trends, time step verify, section B, z=0m

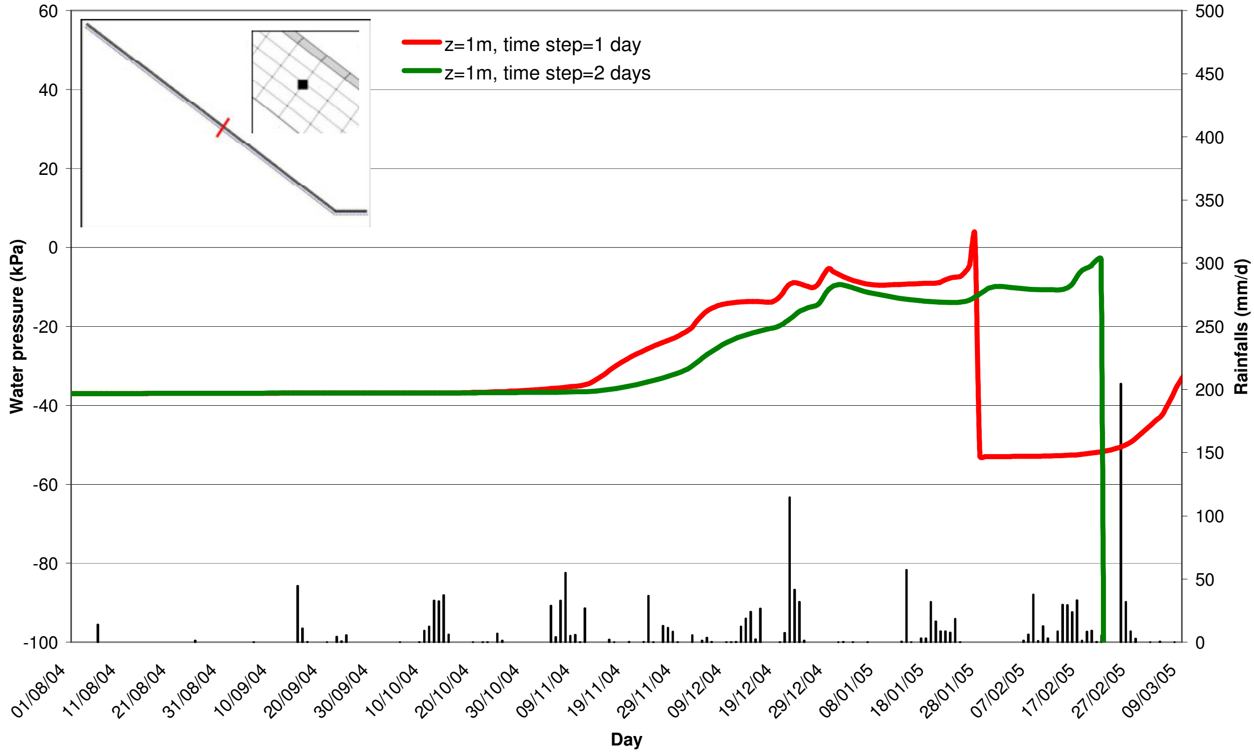

Fig. 10 Water pressure trends, time step verify, section B, z=1m

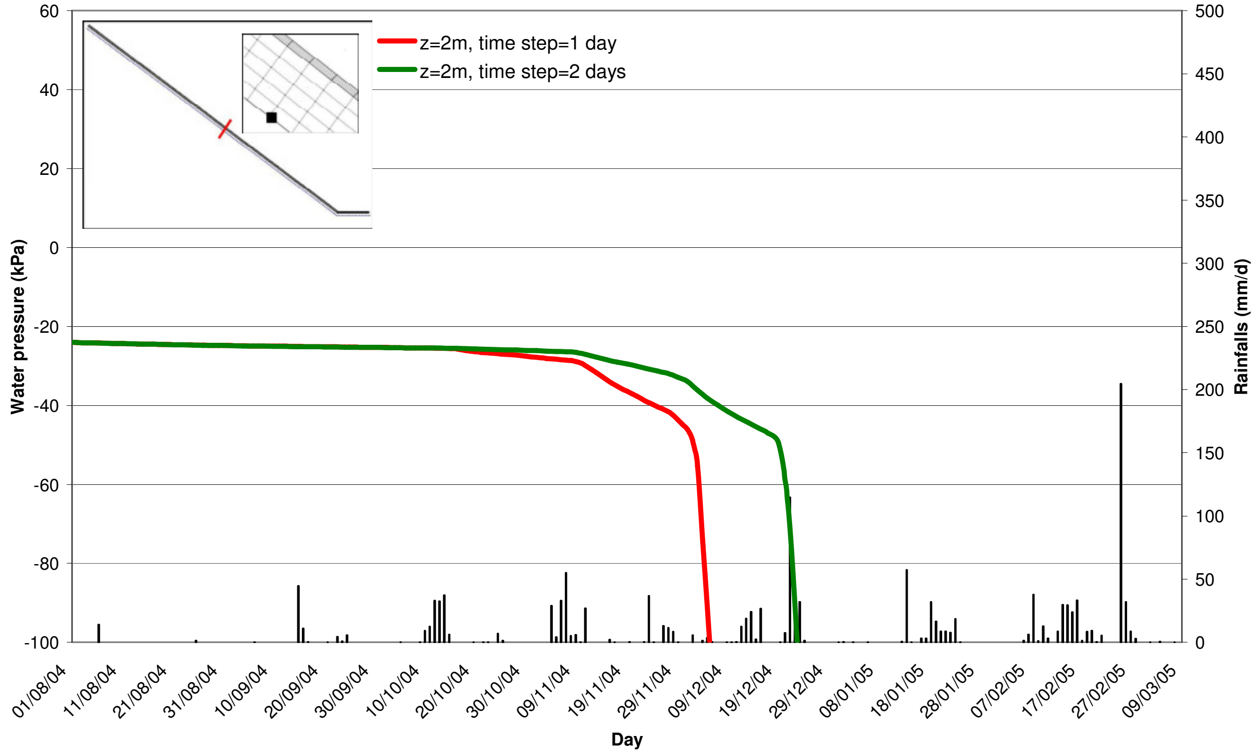

Fig. 11 Water pressure trends, time step verify, section B, z=2m

4.3 Elements sizes verify

In order to try to avoid oscillations near the drainage boundary a more dense mesh is assumed at bottom.
Actually refinement of the finite element mesh in areas of steep hydraulic gradients it might be helpful to reduce convergence problems.
Further numerical simulations are performed changing the elements sizes at bottom.
Mesh sizes are modified like the surface ones (100x4 cm) and, as it is shown in the next figures, results are not suffering from oscillations.

The differences are clearly visible if you compare both simulations results at the same depth (Fig. 12, Fig.13, Fig.14) into the same cross section in the middle of scheme.

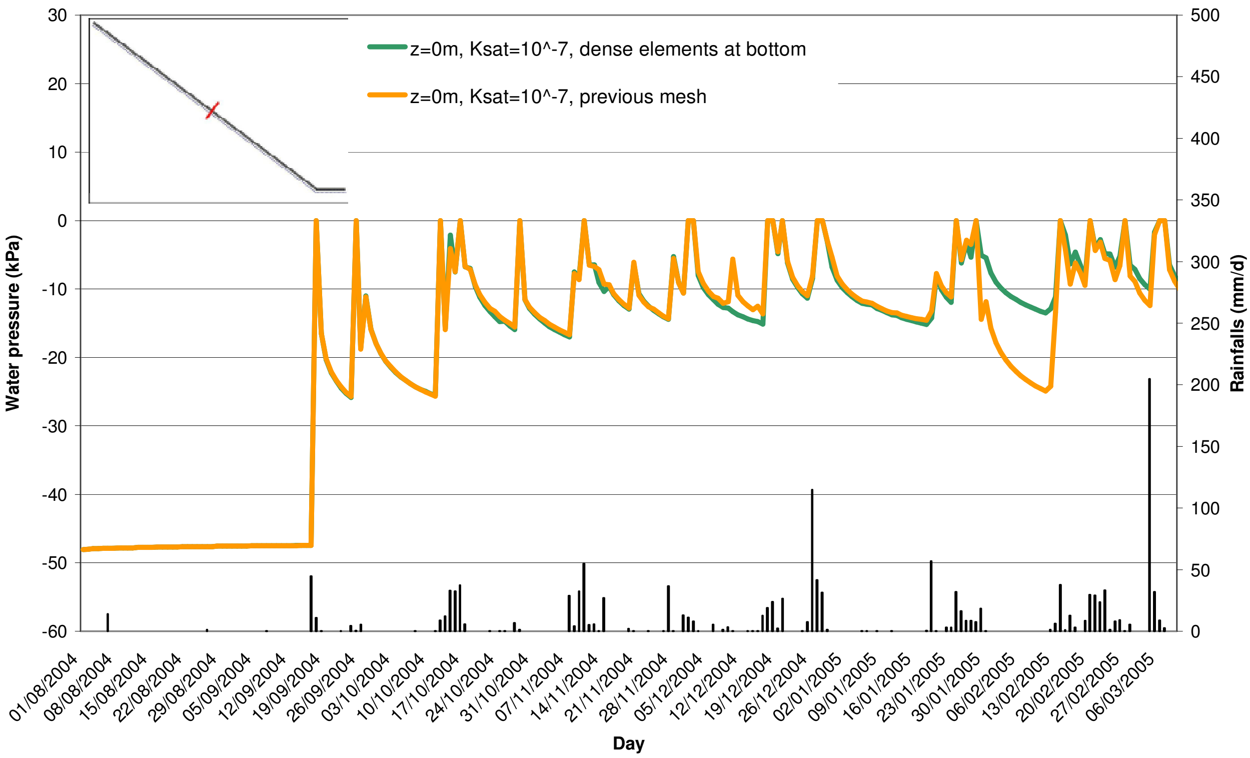

Fig. 12 Water pressure trends, mesh verify, section B, z=0m

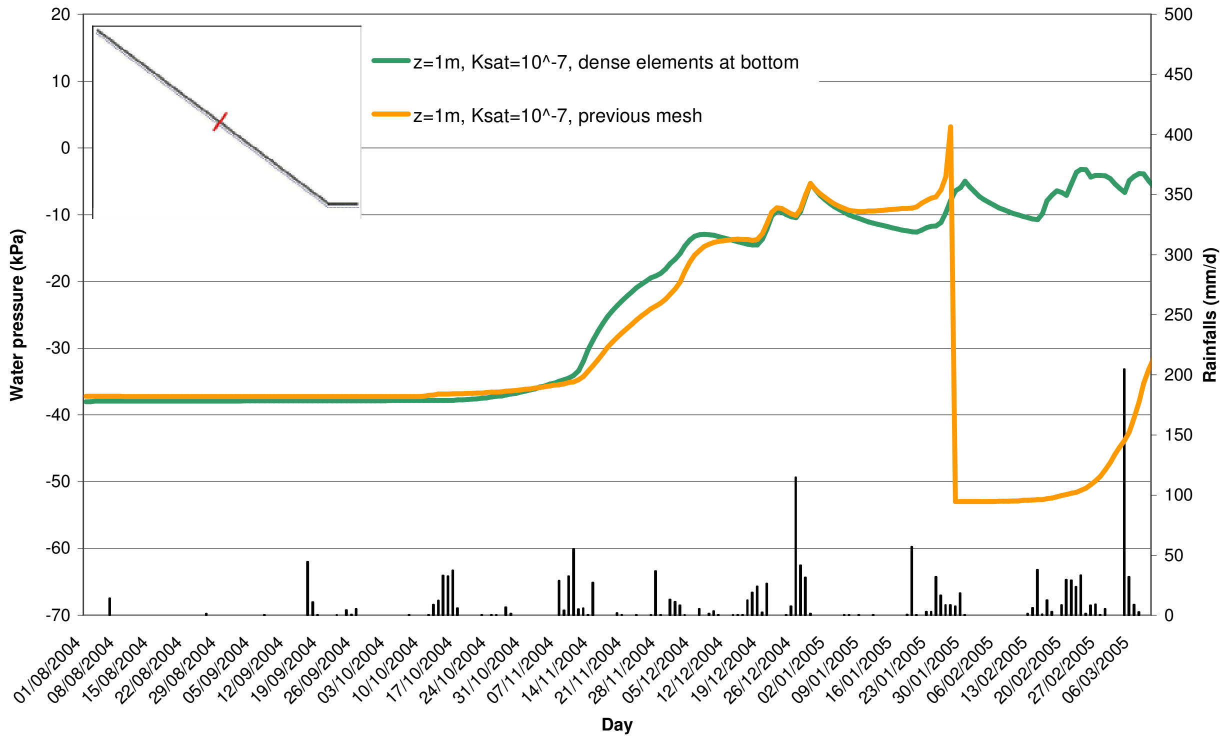

Fig. 13 Water pressure trends, mesh verify, section B, z=1m

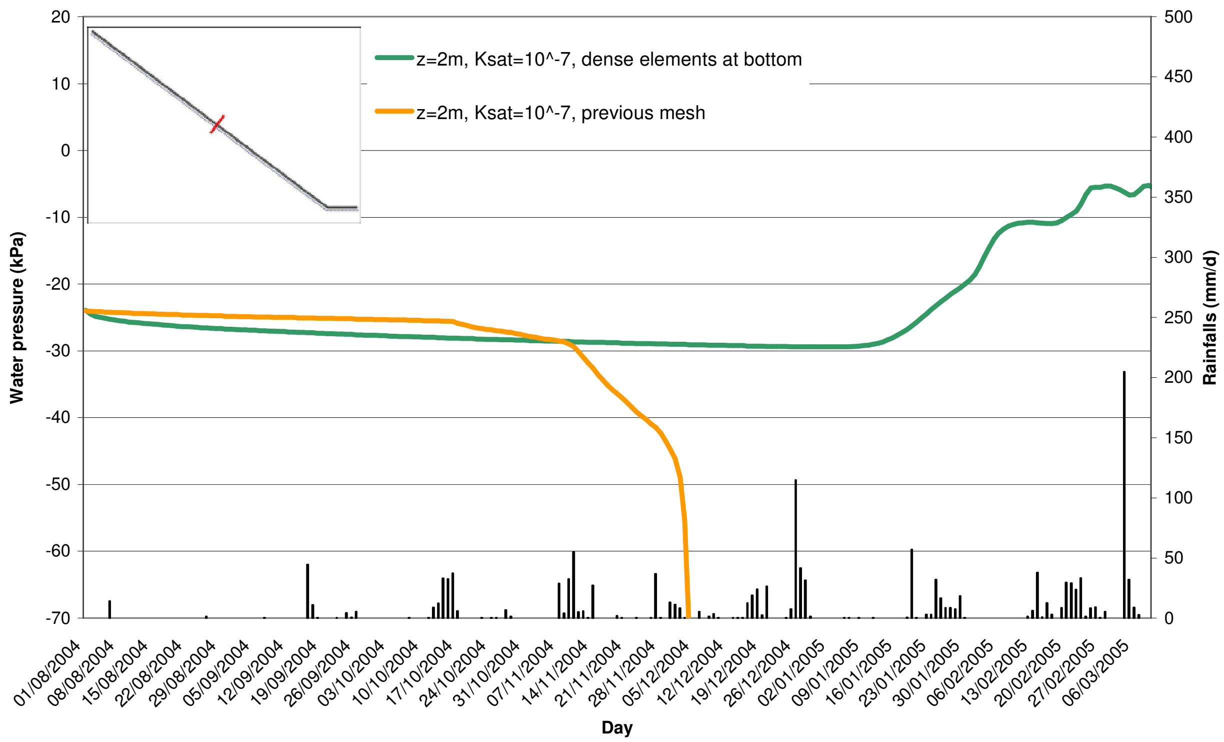

Fig. 14 Water pressure trends, mesh verify, section B, z=2m

This time it stands to reason at ground surface there aren't considerable variations of pressures values (Fig. 12) because the elements at bottom are changing in sizes, not at surface ones.

At one metre in depth (Fig. 13) and at drainage boundary (Fig. 14) it is possible to see that refining the element mesh, oscillations has been avoided.

5. Sensitivity test about hydraulic conductivity of the soil

After having solved oscillatory phenomenon into seepage simulations, sensitivity analyses have been performed using corrected scheme.
Hydraulic properties of pyroclastic deposits in Nocera Inferiore are not well-defined, because results of lysimeter tests are not available yet.
So the goal is to test the behaviour of soil with changes in permeability.
When a soil is partially saturated, the coefficient of permeability is a function of negative pore water pressure (suction) into the soil.
The hydraulic conductivity function has been estimated by means of the predictive method proposed by Van Genuchten (1980).
Permeability is deduced once the volumetric water content function and a k_{sat} value have been specified.
The closed form equation to describe the hydraulic conductivity of a soil as a function of matric suction is:

$$k_w = k_s \frac{\left[1-\left(a\Psi^{(n-1)}\right)\left(1+\left(a\Psi^{n}\right)^{-m}\right)\right]^2}{\left(\left(\left(1+a\Psi\right)^{n}\right)^{\frac{m}{2}}\right)}$$

where:
k_s is the saturated hydraulic conductivity;
a, n, m are a curve fitting parameters;
n = 1/(1-m) , and
Ψ is the suction.

The curve fitting parameters can be estimated graphically based on the volumetric water content function of the soil (Fig. 1).
Previous analyses are carried out, assuming the conductivity constant at saturation k_{sat} = 10^{-7} m/s. Further simulations has been performed, assuming in van Genuchten relation k_{sat}=10^{-6} m/s.

In Fig. 15 the two conductivity functions are shown.

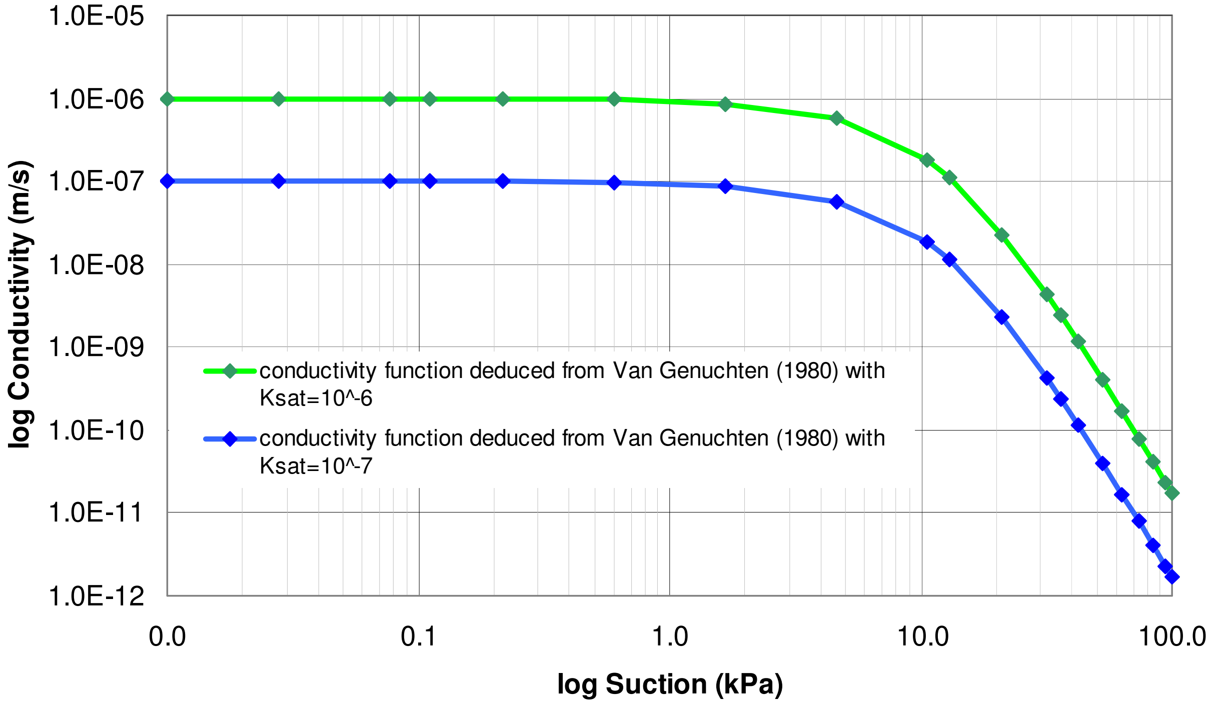

Fig. 15 Hydraulic conductivity functions

Blue curve represents a less conductive material.
In this instance water seeps through the soil hardly, so water pressure values are always higher than those developed if a more permeable soil is assumed (Fig.16, Fig.17, Fig.18).

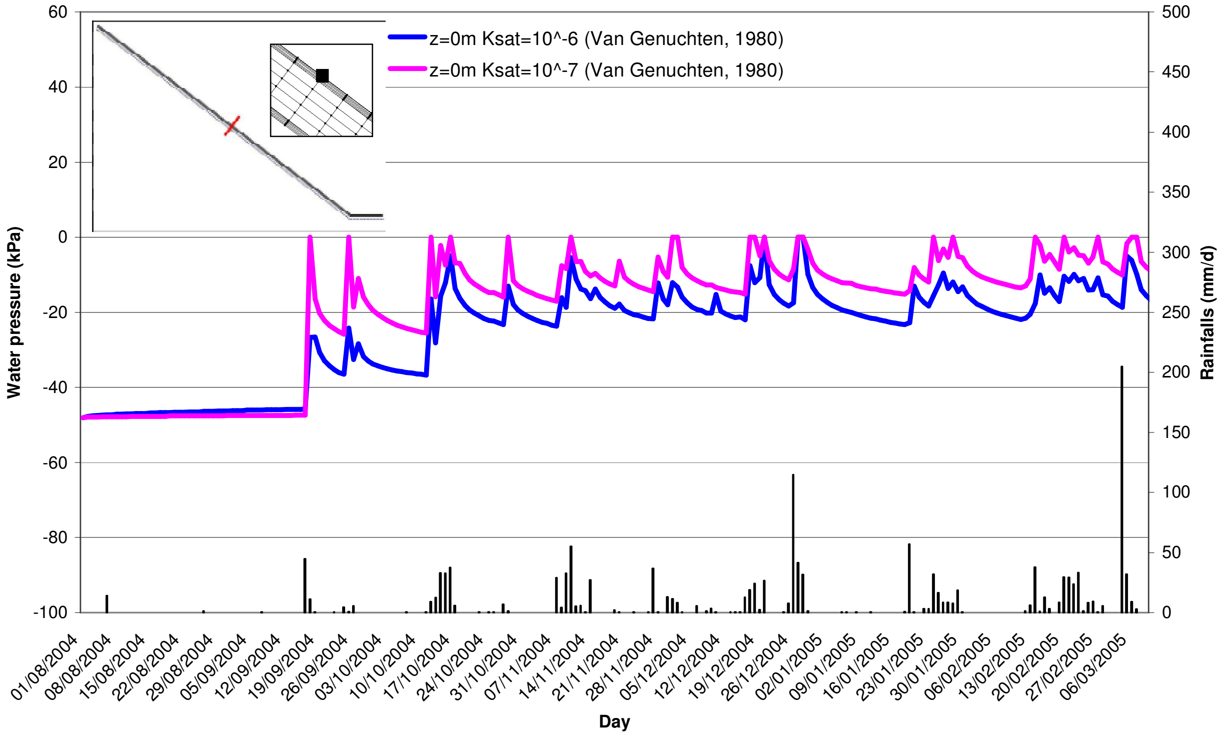

Fig. 16 Water pressure trends in changing of permeability, z=0m

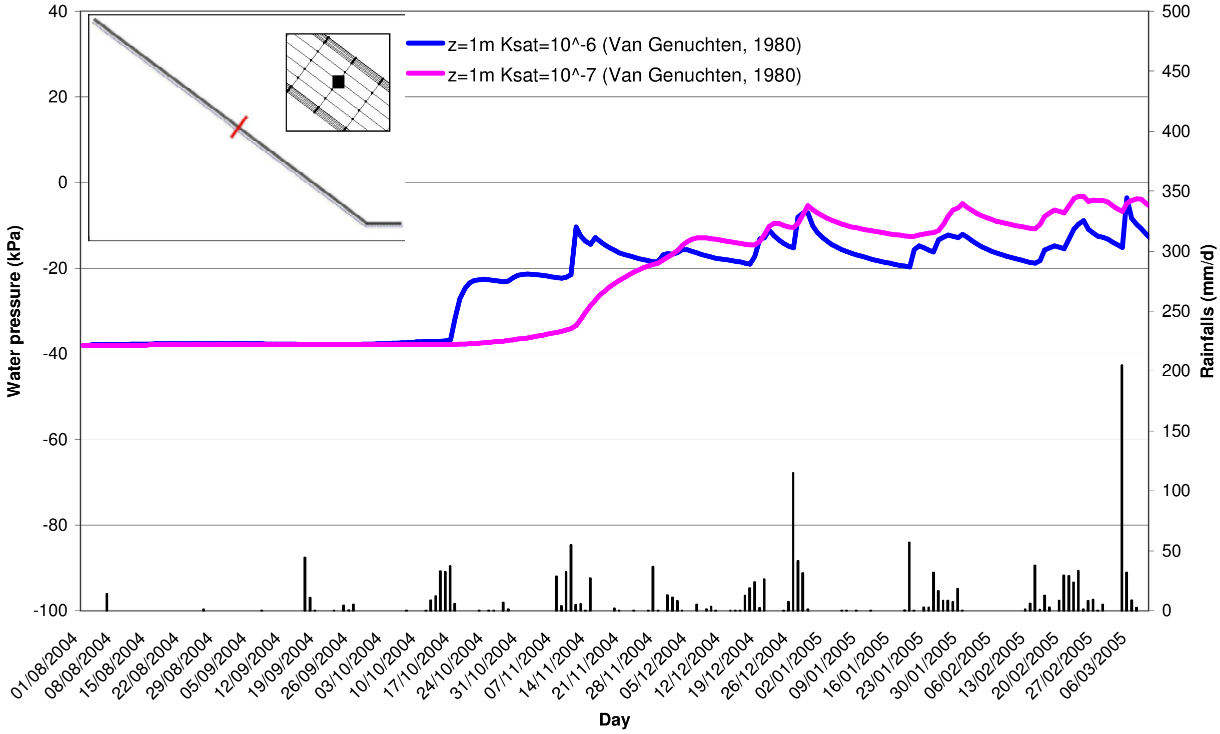

Fig. 17 Water pressure trends in changing of permeability, z=1m

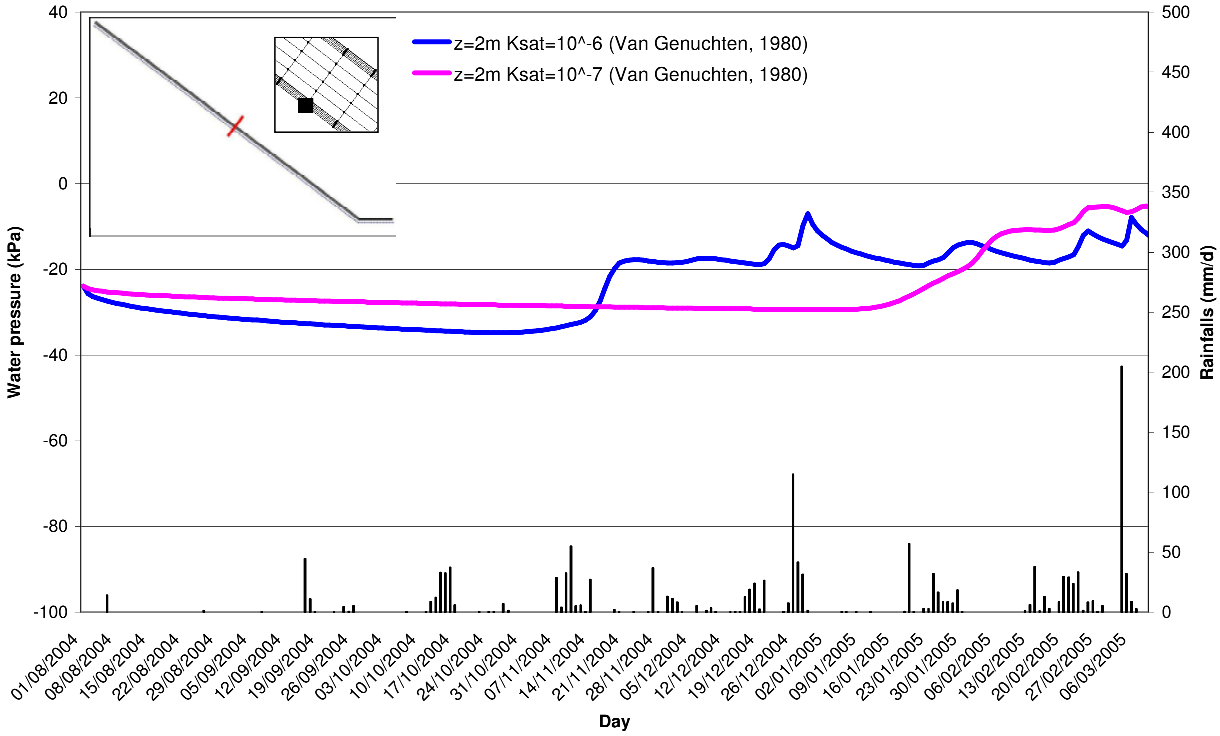

Fig. 18 Water pressure trends in changing of permeability, z=2m

In the first month, when there are few rainfalls, soil is almost unsaturated; the suctions are high (about 40 kPa at one metre in depth, Fig. 17) and the unsaturated conductivities functions are pretty close (Fig. 15). It is easier for the water to flow through the both material, so pink and blue curves are approximately the same (Fig. 17).
When rainfalls become considerable, infiltration rate is big and suction decreases (pressure values closer to zero).
In suction range of 0.1÷10 conductivity values are more different (Fig. 15) so pressure trends as well.

6. Conclusions

This technical report describes numerical results of the analyses, carried out in order to study seepage processes into partially saturated soil.
In the CMCC activity research, test case of Nocera Inferiore concerns landslide event involved the shallow pyroclastic deposits on 4th march 2005.
Simulations performed by means of software Seep/W, a FEM that give results in terms of water pressure or degree of saturation.
Pyroclastic deposits in Nocera Inferiore slope are based on carbonaceous bedrock, so the bottom may be considered both impervious and draining.
Free drainage condition causes oscillatory phenomena into results, especially near the wetting front.
In order to avoid this numerical problem, a few ways are considered: different conditions to impose at lateral boundary, shorter and longer time step sizes, smaller elements sizes. The latter it seems to be the greatest solution to avoid oscillations in water pressure values.
With the correct mesh, sensitivity analyses are carried out waiting for experimental results; the aim is to investigate pressures values developed in changing of hydraulic conductivity.
Software response is in accordance with conductivity function imposed to material.

7. References

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