

Numerical analysis of rainfall-induced landslides.

The case of Camaldoli hill, Naples:
test case nr.1 - October, 2004;
test case nr.2 - September, 2005

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Summary

This report shows the results of some numerical analyses aimed to simulate two rainfall-induced landslides events, recorded on October 13th, 2004 and on September 17th, 2005, which involved the pyroclastic deposits of the south-eastern side of a hill, known as Camaldoli hill, set inside the western sector the urban district of Naples.

The analyses of the transient infiltration due to the rainfall have been performed by means of a commercial finite element code, devoted to 2D analyses of soil water flow in saturated and unsaturated condition.

Keywords: rainfall-induced landslide, slope stability analysis, numerical simulation.

JEL Classification:

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1. Foreword

Some numerical analyses have been performed in order to simulate the triggering of rainfall-induced landslides that involved the shallow pyroclastic deposits of an area set inside the western sector of the urban district of Naples, known as Camaldoli hill. The two chosen test cases, occurred along the south-eastern side of the hill on October 13th 2004 and on September 17th 2005, were characterized by the activation of shallow slides (depth ranging between 0.5 m and 2.0 m) that triggered within very steep deposits and then travelled until a distance of about 90 m, involving the other deposits set downslope (Figs. 1.1 and 1.2)

Stability analyses have been coupled with seepage analyses. These last have been performed by the use of the finite element program SEEP/W code, produced by the GEO-SLOPE International Ltd, which is useful to model both saturated and unsaturated 2D seepage. The geotechnical properties assigned to the soil have been derived by laboratory tests.

The rainfall data have been taken from the hourly rainfall measurements made by a pluviometer installed by the Civil Protection of the Campania Region. Besides, in order to check the model performed by the meteorological task of C.I.R.A., the hourly rainfall coming from the results of the analyses performed with the “COSMO LM” have also been used as input data.

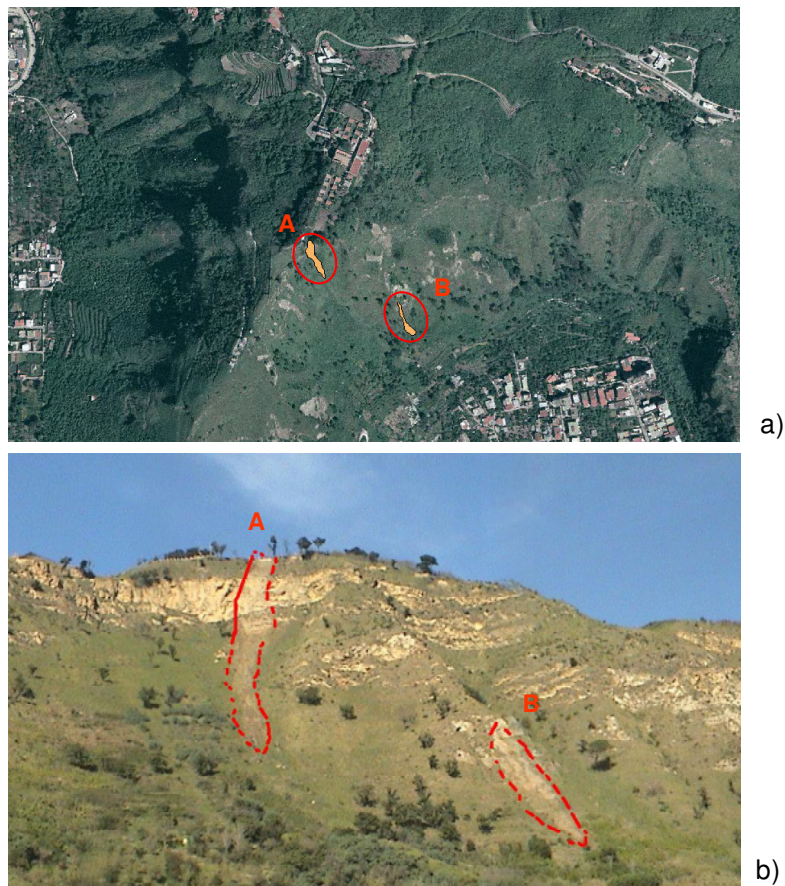


Figure 1.1. Landslides occurred on October 13th, 2004

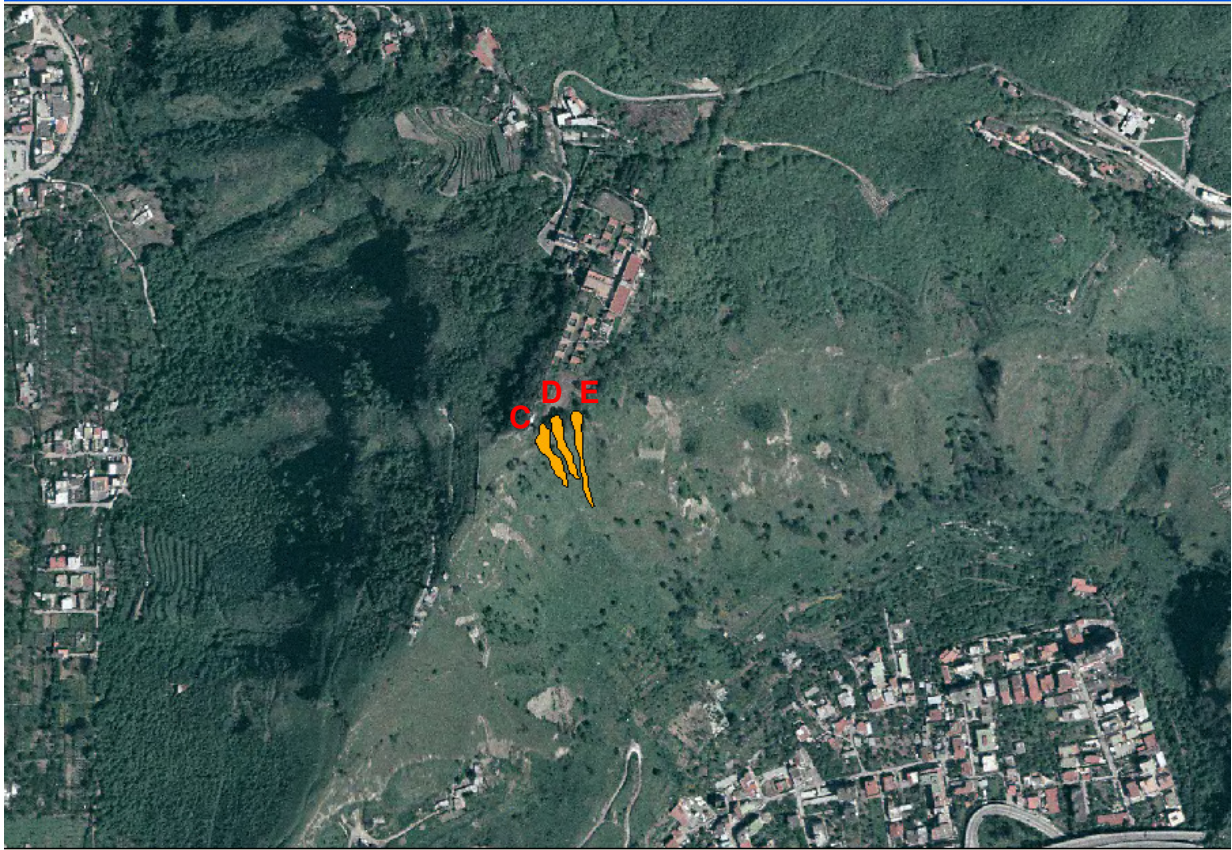


Figure 1.2. Landslides occurred on September 17th, 2005

2. Input data

The input data required by the code regard:

- a) geometrical characteristics;
- b) mechanical and hydraulic properties;
- c) initial hydraulic conditions;
- d) time-varying rainfall intensity.

a) *Geometrical characteristics*

Agreeing with the available topography map of the Camaldoli hill, the analysed slope has been modelled through two differently inclined slopes. The one set upslope is 27 m long, has an inclination equal to 66° and a constant thickness equal to 0.65 m. The second slope, 103 m long, is less steep (38°) and presents a thickness growing from 0.65 m to 5.00 m.

The bottom and the two lateral boundaries have been considered impervious; in particular, the downslope lateral boundary has been set very far (200 m) from the upslope lateral boundary in order to not influence the results of the analyses.

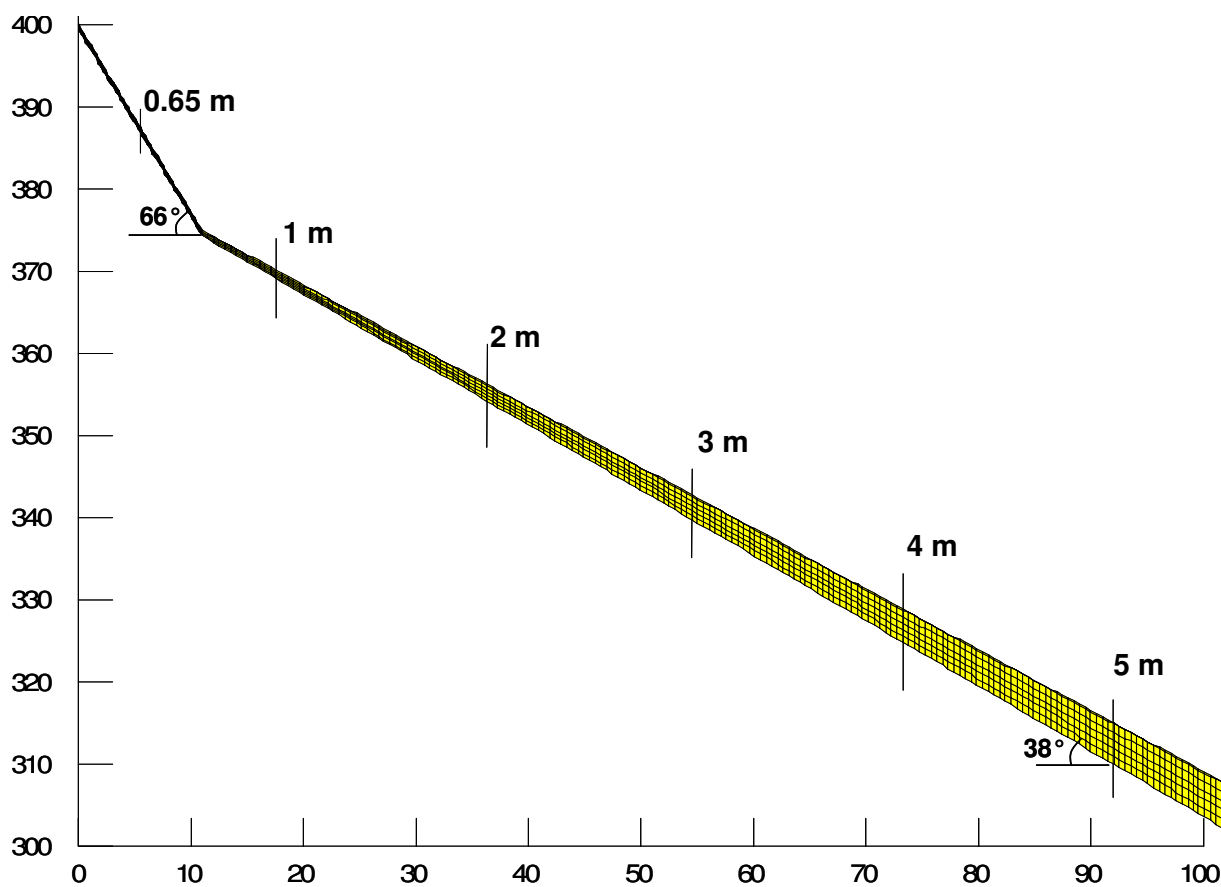


Figure 2.1. Modelled slope



b) Mechanical and hydraulic properties

The studied landslide events involved the pyroclastic ashes typical of the Phlegraean deposits. Their properties have been derived from results coming from laboratory tests. In particular, permeability k_w has been assigned as a function of matric suction $u_a - u_w$ (Fig. 2.2a), using the formulation proposed by Mualem (1976)

$$k_w = \begin{cases} k_{ws} & \alpha \cdot (u_a - u_w) \leq 1 \\ k_{ws} \cdot [\alpha \cdot (u_a - u_w)]^{-(2+5\lambda/2)} & \alpha \cdot (u_a - u_w) > 1 \end{cases} \quad [2.8]$$

where k_{ws} is the saturated permeability, α is the reciprocal of the air-entry suction $(u_a - u_w)_e$ and λ is a dimensionless parameter. Table 2.1 contains the parameters that have best fitted the experimental data.

Table 2.1. Hydraulic properties of Phlegraean pyroclastic deposits

k_{ws} [m/s]	θ_{ws}	θ_{wr}	λ	α [kPa ⁻¹]	$(u_a - u_w)_e$ kPa
$5.40 \cdot 10^{-5}$	0.45	0.00	0.4019	0.1053	9.5

The water content has been considered dependent from suction (Fig. 2.2b) by means of the characteristic curve equation proposed by Brooks and Corey (1964)

$$\theta_w = \begin{cases} \theta_{ws} & \alpha \cdot (u_a - u_w) \leq 1 \\ \theta_{wr} + (\theta_{ws} - \theta_{wr}) \cdot [\alpha \cdot (u_a - u_w)]^{-\lambda} & \alpha \cdot (u_a - u_w) > 1 \end{cases} \quad [2.9]$$

where θ_w is the volumetric water content (ratio of water volume to the total soil volume), θ_{ws} is the saturated volumetric water content and θ_{wr} is the residual volumetric water content.

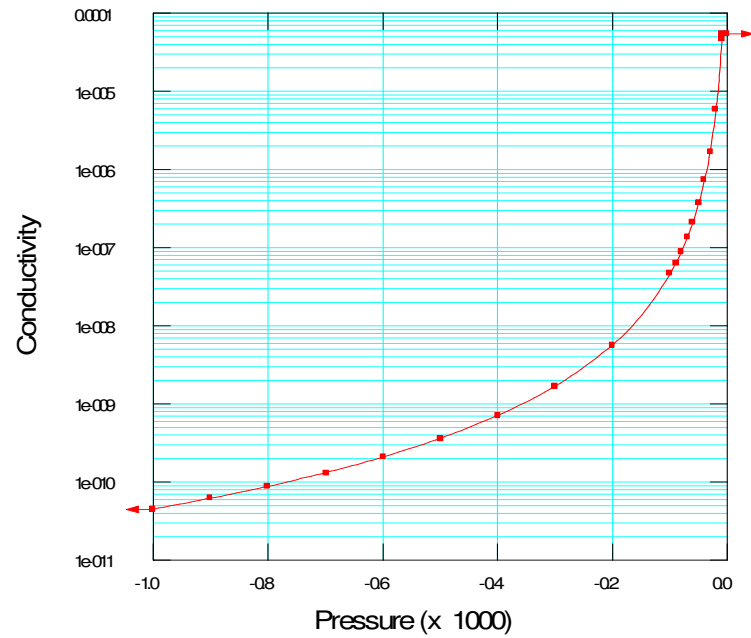
According to Fredlund (1979), the shear strength envelope is given by

$$\tau_{lim} = c + (\sigma - u_a) \cdot \tan \varphi' \quad [2.10]$$

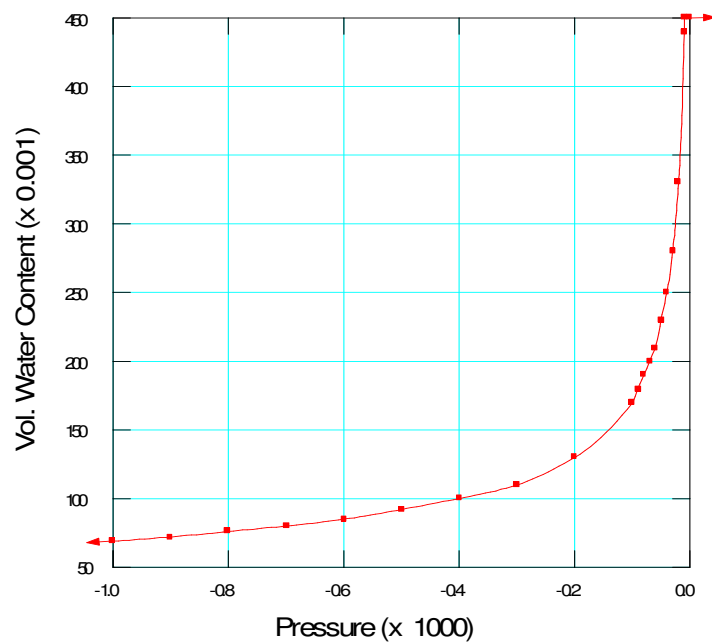
where $(\sigma - u_a)$ is the net normal stress, the friction angle $\varphi' = 35^\circ$, c is the intercept of cohesion that is a function of the matric suction according to the relation (Vanapalli et al., 1996)

$$c = (u_a - u_w) \cdot \Theta^k \cdot \tan \varphi' \quad [2.11]$$

where $\Theta = \frac{\theta - \theta_r}{\theta_s - \theta_r}$ is the relative volumetric water content and $k = 2$ is a fitting parameter.



a)



b)

Figure 2.2. Permeability function (a) and soil-water characteristic curve (a) of the soil



c) Initial hydraulic conditions

Numerical results are always very sensitive to the assigned initial conditions. In particular, with regard to infiltration analyses, the initial condition coincides with a transient state which represents the effect of a meteorological history characterized by alternating time periods of precipitation and evaporation.

We have decided to test the sensitivity of the code, starting the seepage analyses one month before the landslide event (i.e. from 13/09/2004 to 12/10/2004 for the 1st test case and from 17/08/2005 to 16/09/2005 for the 2nd test case), hypothesizing an initial hydrostatic distribution of the pore water pressure along every sections of the slope, characterized by the same initial minimum value $u_{w,0}$ at each point of the ground surface. Starting from that condition, we have assigned at the ground surface the rainfall history (Figs. 2.3 and 2.4) recorded during this period (the evaporative effects have been neglected) by a pluviometer installed by the Civil Protection of the Campania Region next to the landslide zone at an altitude equal to 384 m a.s.l., which registers at hourly frequency from October 18th, 2000.

So doing, different distributions of suction (univocally determined) correspond to both test cases. In particular, although the initial pore water pressure at ground surface $u_{w,0}$ is constant at each point of the upper boundary, the corresponding values at the end of the calibration-month, $u_{w,1}$ (which act at the beginning of the landslide event), systematically decrease along the slope (Figs. 2.5 and 2.6).

Because the hydraulic and mechanical properties of the pyroclastic soils depend on different suctions, the initial conditions may strongly influence the response of a slope subjected to a determined rainfall history.

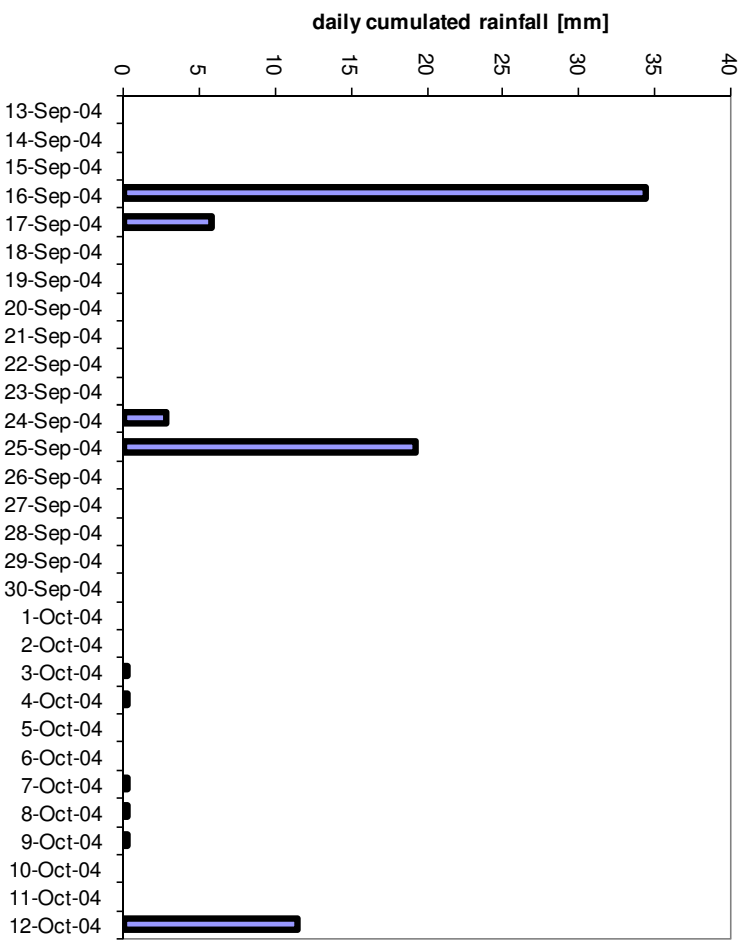


Figure 2.3. Test case nr. 1 (13/10/2004): daily rainfall measured from 13/09/2004 to 12/10/2004

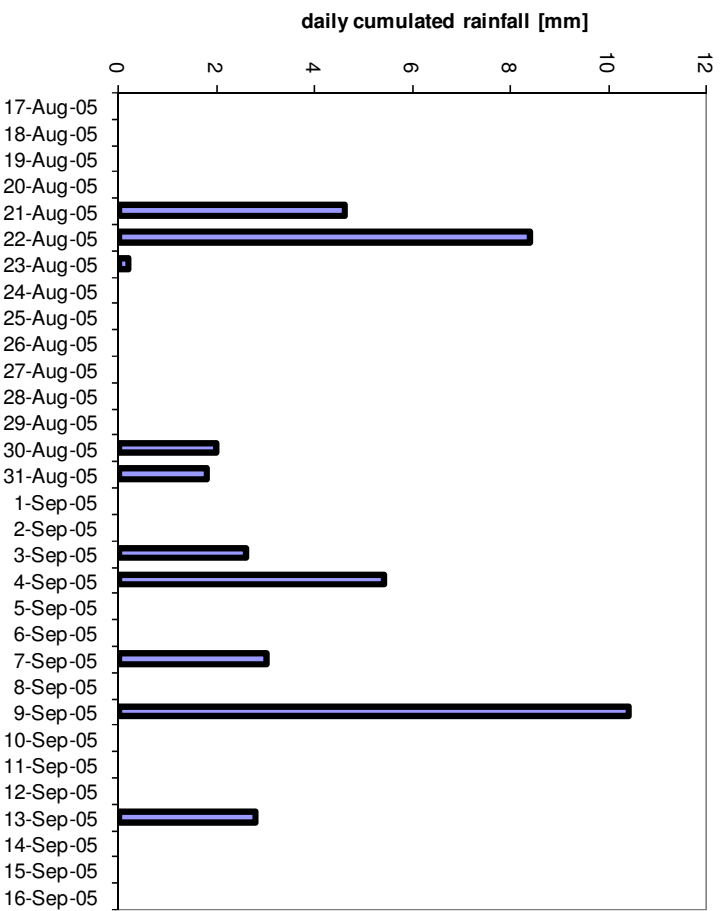


Figure 2.4. Test case nr. 2 (17/09/2005): daily rainfall measured from 17/08/2005 to 16/09/2005

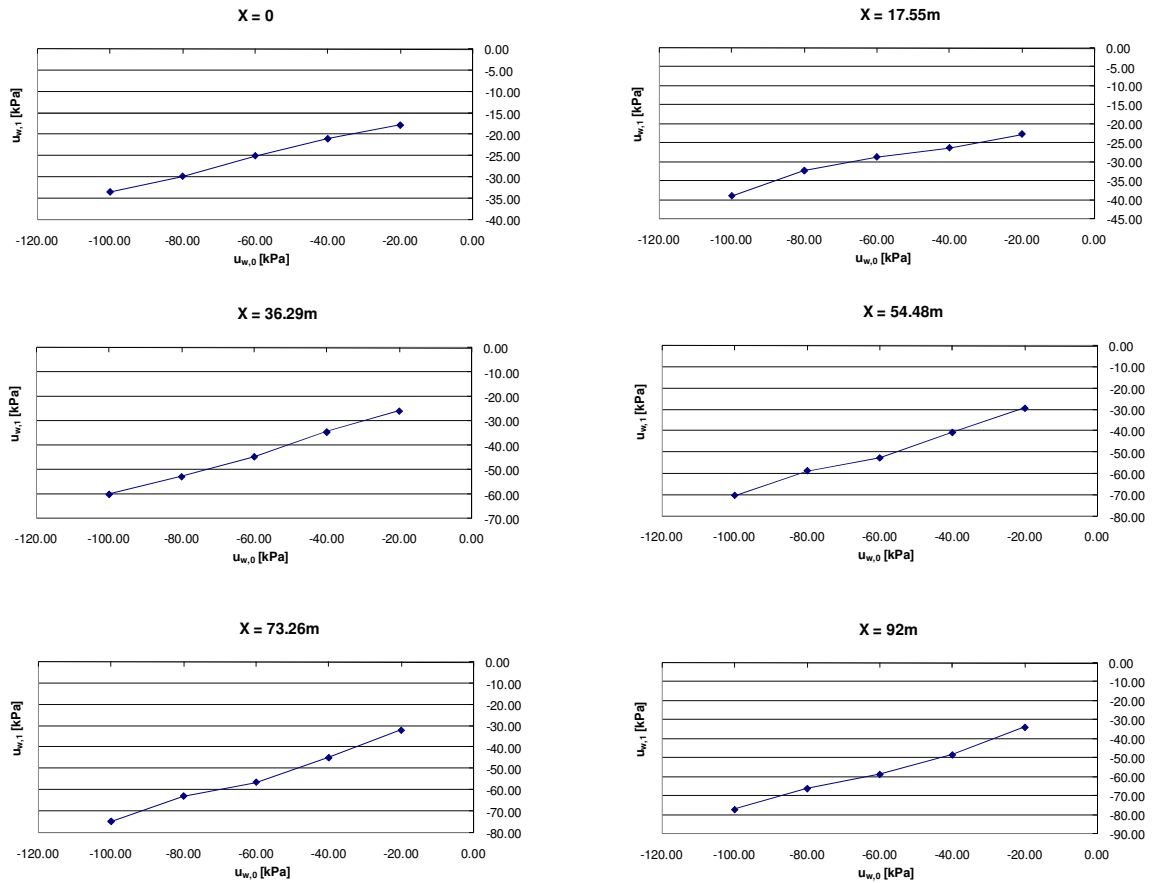


Figure 2.5. Test case nr.1 (13/10/2004): pore water pressure $u_{w,1}$ calculated at the ground surface along the slope at the end of the 30 days preceding the landslide event ($u_{w,0}$ represents the initial pore water pressure imposed at the ground surface)

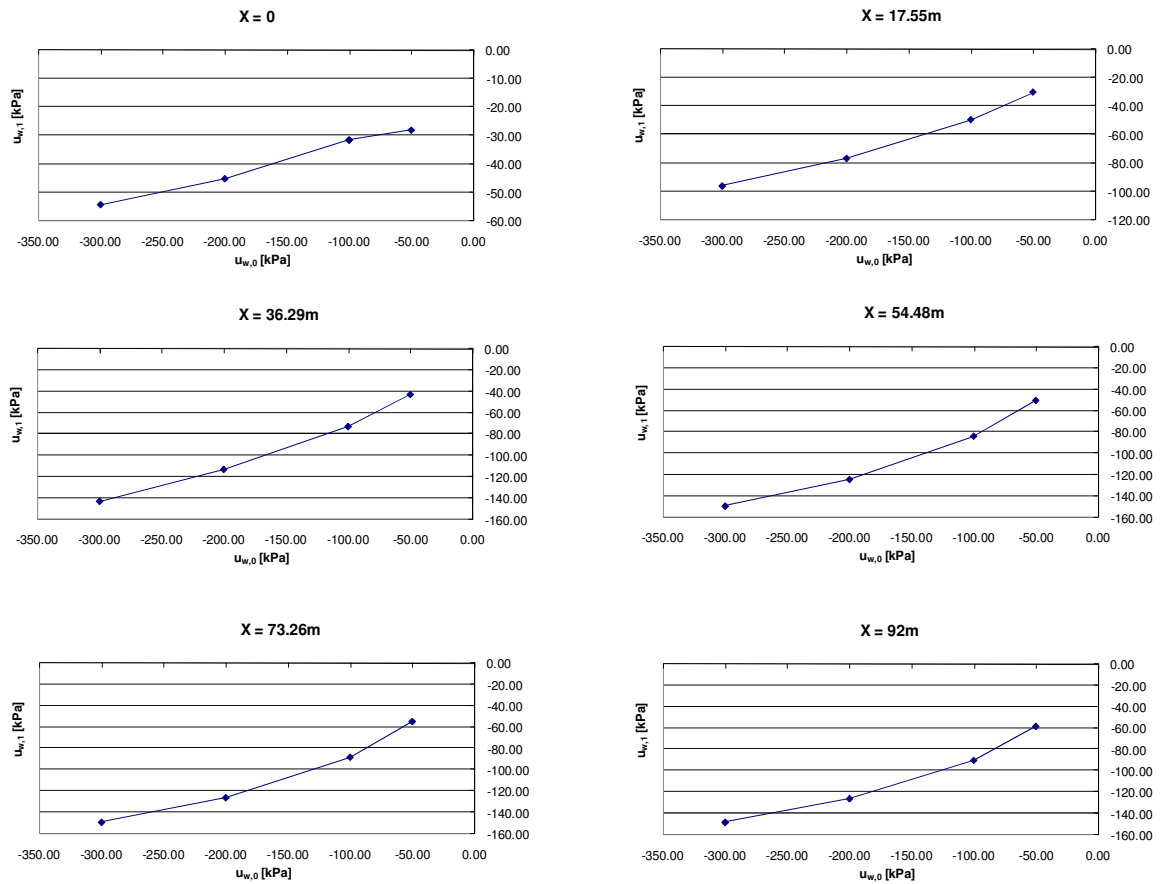


Figure 2.6. Test case nr.2 (17/09/2005): pore water pressure $u_{w,1}$ calculated at the ground surface along the slope at the end of the 30 days preceding the landslide event ($u_{w,0}$ represents the initial pore water pressure imposed at the ground surface)



d) *Time-varying rainfall intensity*

Test case nr. 1: October, 2004

The rainfall cumulated on 13/10/2004 concentrated during a rather short period (7 hours) distributed between 16:00 and 23:00 (Fig. 2.7a): the hourly peak (19.2 mm) was registered between 18:00 and 19:00. Unfortunately, the exact time when landslides have been activated is unknown.

Taking into account the hourly rainfall, we have imposed as boundary condition a rainfall history constituted by seven periods, which are characterized by an hourly duration and the following different intensities (Fig. 2.7b):

- 1st period → intensity $I_1 = 0.6 \text{ mm/h}$ ($1.67 \cdot 10^{-7} \text{ m/s}$), duration $\Delta t_1 = 1 \text{ h}$;
- 2nd period → intensity $I_2 = 6.8 \text{ mm/h}$ ($1.89 \cdot 10^{-6} \text{ m/s}$), duration $\Delta t_2 = 1 \text{ h}$;
- 3rd period → intensity $I_3 = 19.2 \text{ mm/h}$ ($5.33 \cdot 10^{-6} \text{ m/s}$), duration $\Delta t_3 = 1 \text{ h}$;
- 4th period → intensity $I_4 = 4.4 \text{ mm/h}$ ($1.22 \cdot 10^{-6} \text{ m/s}$), duration $\Delta t_4 = 1 \text{ h}$;
- 5th period → intensity $I_5 = 10.8 \text{ mm/h}$ ($3.00 \cdot 10^{-6} \text{ m/s}$), duration $\Delta t_5 = 1 \text{ h}$;
- 6th period → intensity $I_6 = 4.0 \text{ mm/h}$ ($1.11 \cdot 10^{-6} \text{ m/s}$), duration $\Delta t_6 = 1 \text{ h}$;
- 7th period → intensity $I_7 = 1.8 \text{ mm/h}$ ($5.00 \cdot 10^{-7} \text{ m/s}$), duration $\Delta t_7 = 1 \text{ h}$.

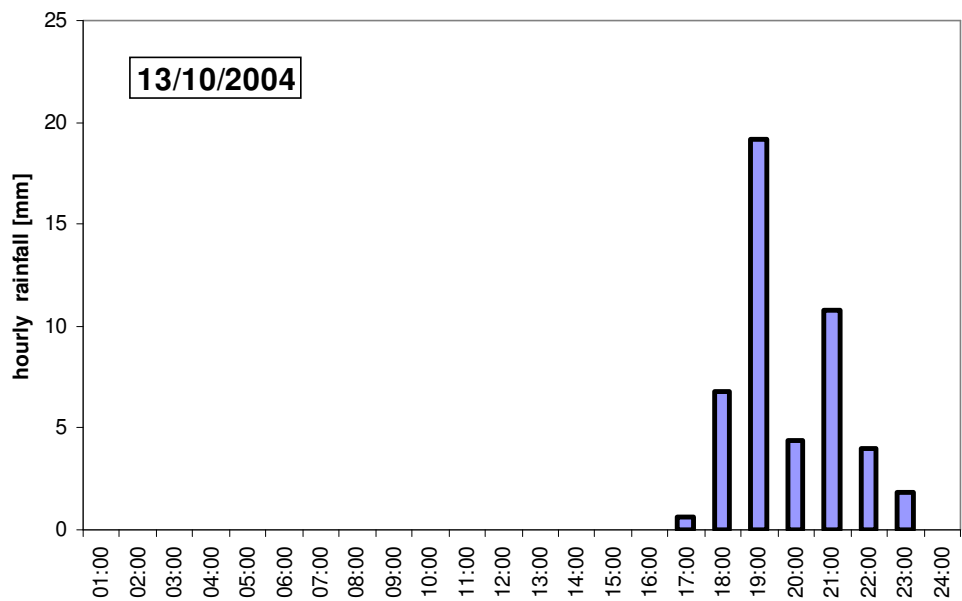
Besides, we also have used as rainfall history the maximum hourly rainfall coming from the temporary results of the meteorological analyses performed by C.I.R.A. with the “COSMO LM” set at the 2.8 Km configuration. These values, which have been calculated at six grid points (Fig. 2.8) set next to the landslide area (the distance ranges between 1 and 5.5 Km), are reported in Table 2.2. The corresponding input rainfall are reported in Figure 2.9.

Test case nr. 2: September, 2005

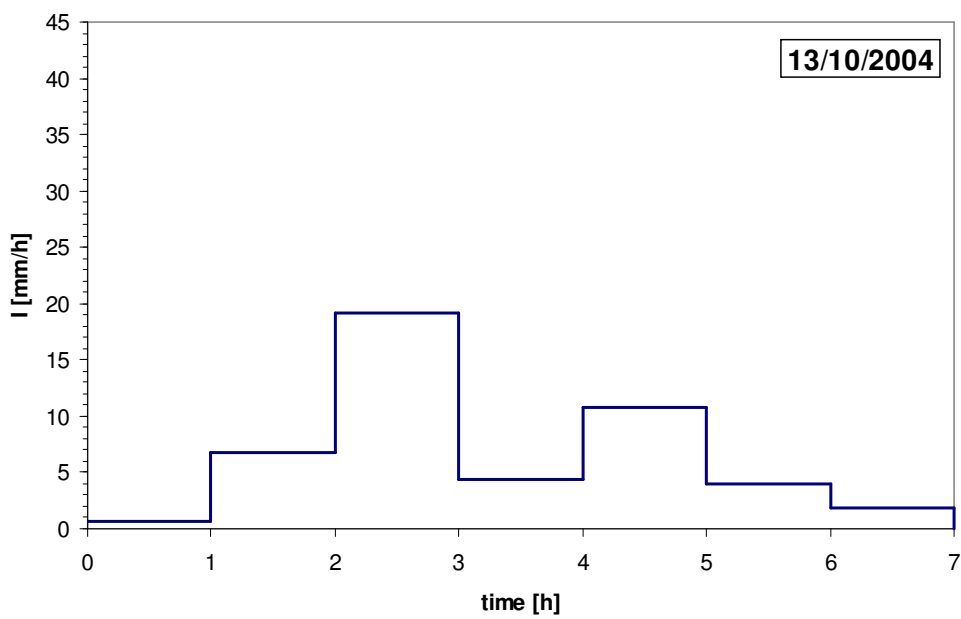
During the night between September 17th and 18th, 2005, three slides were triggered by one of the most intense rainfall events registered by the pluviometer. In particular, the hourly peak measured between 23:00 and 24:00 (44.2 mm) (Figs. 2.10a and 2.10b) has been overcome only two times. We have no data about the timing of landslides triggering.

The rainfall history imposed at the ground surface is given by the following seven periods (Fig. 2.10c):

- 1st period → intensity $I_1 = 0.4 \text{ mm/h}$ ($1.11 \cdot 10^{-7} \text{ m/s}$), duration $\Delta t_1 = 1 \text{ h}$;
- 2nd period → intensity $I_2 = 8.0 \text{ mm/h}$ ($2.22 \cdot 10^{-6} \text{ m/s}$), duration $\Delta t_2 = 1 \text{ h}$;
- 3rd period → intensity $I_3 = 44.2 \text{ mm/h}$ ($1.23 \cdot 10^{-5} \text{ m/s}$), duration $\Delta t_3 = 1 \text{ h}$;
- 4th period → intensity $I_4 = 4.0 \text{ mm/h}$ ($1.11 \cdot 10^{-6} \text{ m/s}$), duration $\Delta t_4 = 1 \text{ h}$;
- 5th period → intensity $I_5 = 2.0 \text{ mm/h}$ ($5.56 \cdot 10^{-7} \text{ m/s}$), duration $\Delta t_5 = 1 \text{ h}$;
- 6th period → intensity $I_6 = 0.2 \text{ mm/h}$ ($5.56 \cdot 10^{-8} \text{ m/s}$), duration $\Delta t_6 = 1 \text{ h}$;
- 7th period → intensity $I_7 = 0.4 \text{ mm/h}$ ($1.11 \cdot 10^{-7} \text{ m/s}$), duration $\Delta t_7 = 1 \text{ h}$.



a)



b)

Figure 2.7. Test case nr.1 (13/10/2004): measured hourly rainfall (a) and assigned rainfall history (b)

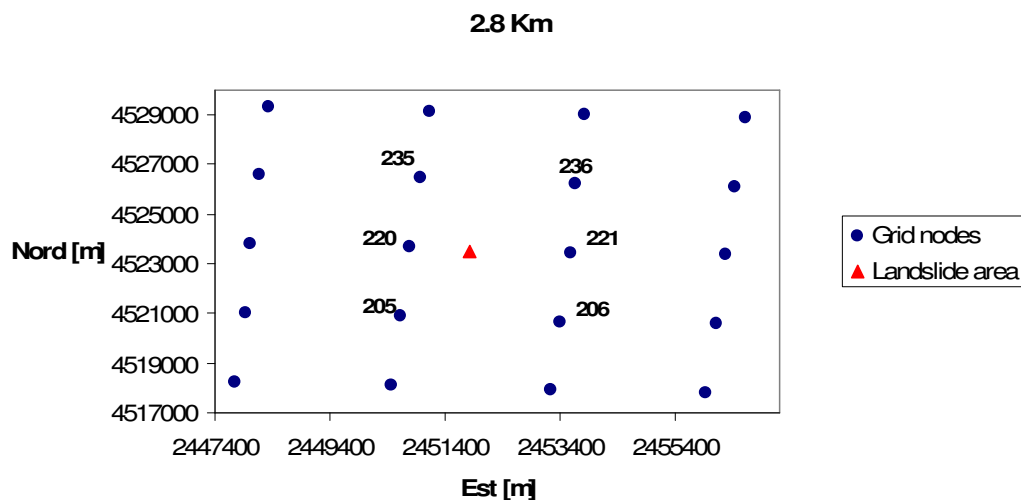


Figure 2.8. Test case nr.1: grid nodes (blue points) of the analyses performed by meteorological task of C.I.R.A. with the COSMO LM model set at the 2.8 Km configuration. Red triangle is the landslide area.

Table 2.2. Test case nr.1: maximum hourly rainfall calculated on 13/10/2004 by meteorological task of C.I.R.A. at points set next to the landslide area

time [h]	MAX [mm]
17.00	0.00
18.00	0.00
19.00	0.00
20.00	0.00
21.00	0.72
22.00	3.36
23.00	12.17

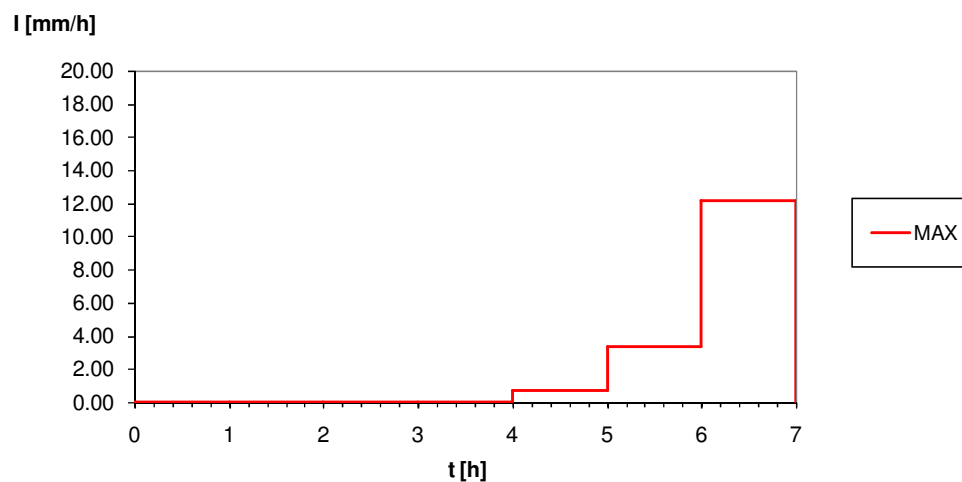


Figure 2.9. Test case nr.1: assigned rainfall history based on the maximum hourly rainfall calculated by meteorological task of C.I.R.A.

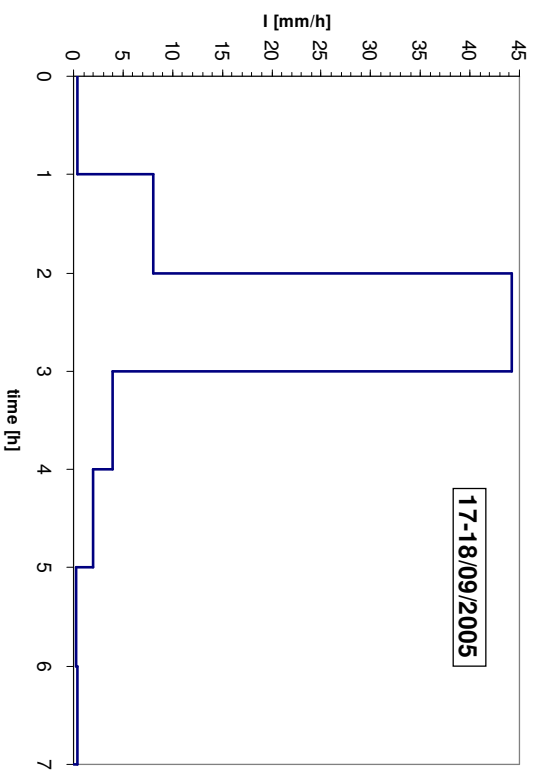
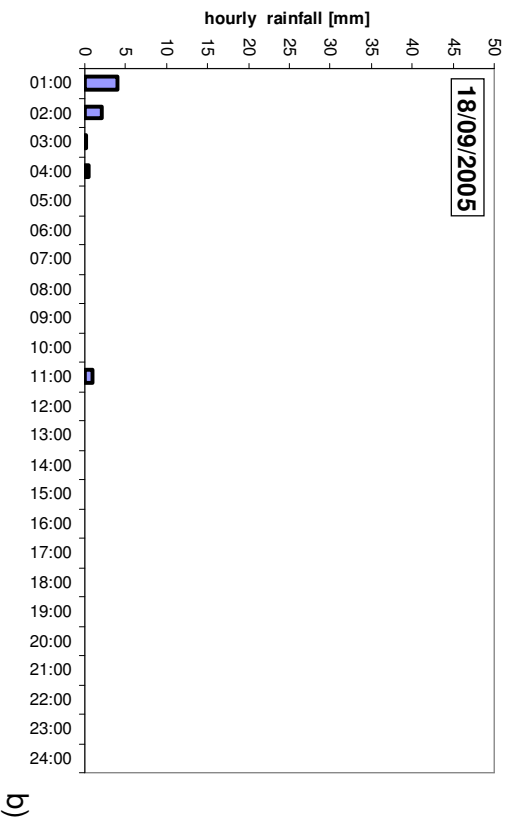
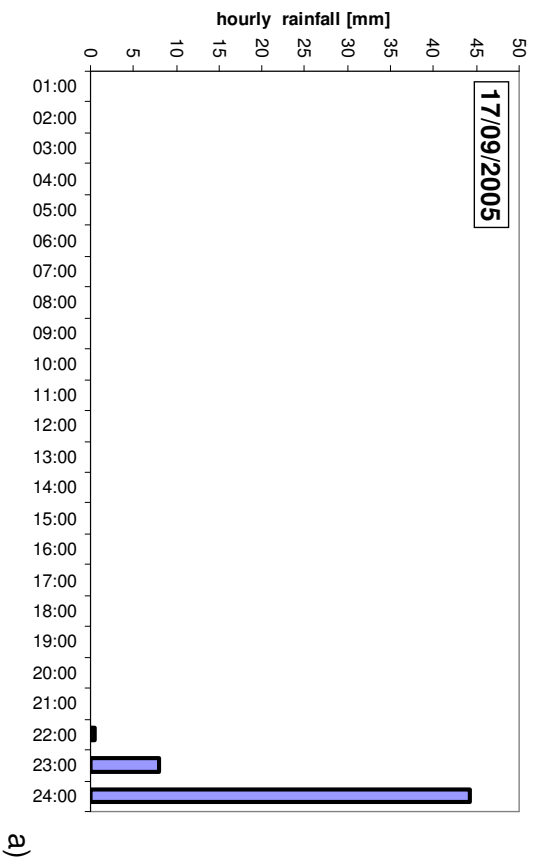


Figure 2.10. Test case nr.2 (17/09/2005): measured hourly rainfall (a,b) and assigned rainfall history (c)

3. Results of the analyses

Several analyses depending on different initial distributions of pore water pressure at the ground surface $u_{w,1}$ (derived from the previously described calibration) have been performed.

In the follow, we will report the results coming from the cases characterized by the $u_{w,1}$ values that have allowed the occurrence of the failure.

The results will be reported in terms of changing with time of:

- relative volumetric water content Θ ;
- pore water pressure u_w ;
- local factor of safety FS (calculated by means of the infinite slope model).

3.1 Test case nr. 1

The distribution of pore water pressures along the ground surface $u_{w,1}$ (Fig. 3.1) which have allowed the onset of failure on 13/10/2004, range between -18 kPa (upslope) and -35 kPa (downslope). This distribution comes from the hypothesis that suctions along each point of the ground surface are constantly equal to 20 kPa on 13/09/2004. This result means that failure doesn't verify for suctions higher than this value.

As reported from Figure 3.2 to Figure 3.8, the failure occurred upslope along the first 27 m of the slope, characterized by the highest inclination and the lowest depth (0.65m) of the impervious bedrock, at the end of the 5th hour of the measured rainfall event, which doesn't correspond to the maximum peak (coinciding with the 3rd hour). On the other hand, the local factor of safety FS remains higher than 1 along the other vertical sections of the slope, so inducing to retain that the failure didn't occur at the same time along the entire slope and so that these sections could have been involved by the landslide only through after-failure processes.

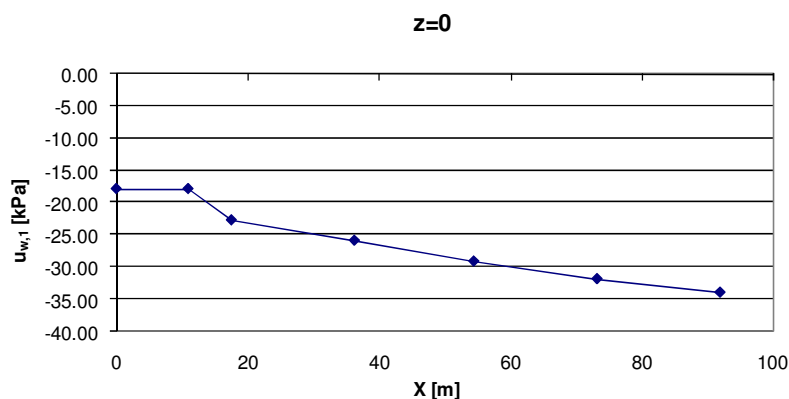


Figure 3.1. Test case nr.1 (13/10/2004): initial distribution of pore water pressure $u_{w,1}$ along the upper boundary of the modelled slope ($z=0$)

We have also assigned the rainfall history based on the maximum hourly rainfall calculated by meteorological task of C.I.R.A. (Fig. 2.9). Differently from what previously observed, we have not recorded any local failure at the different sections, in fact the factor of safety FS everywhere remains higher than one (Figs. from 3.9 to 3.15).

We have not been amazed at this result, because the meteorological results are only temporary (further studies in depth are already in progress).

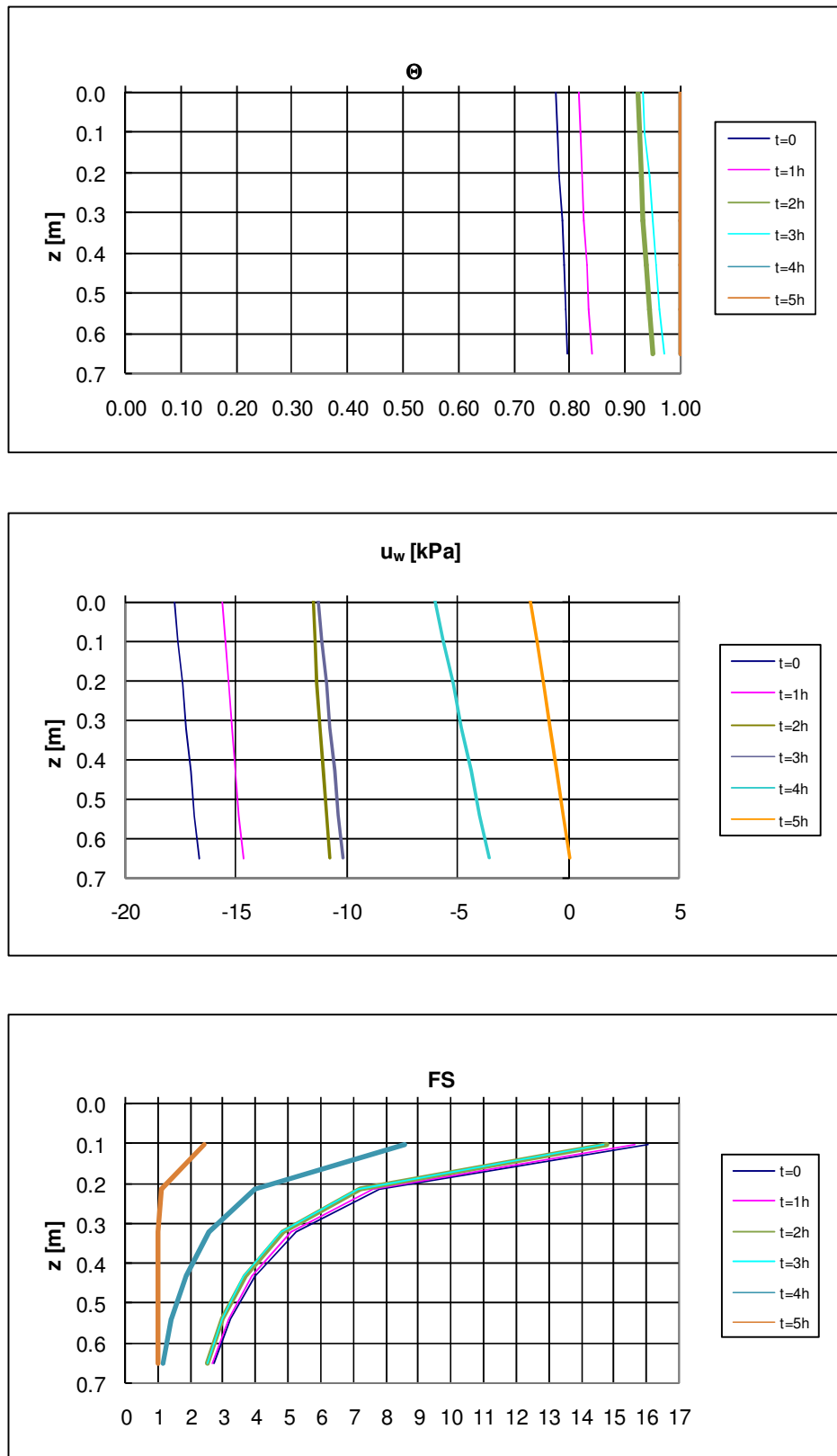


Figure 3.2. Test case nr.1 (measured rainfall) - Section nr.0 ($z_{\max} = 0.65$ m): changing with time of the relative volumetric water content Θ , the pore-water pressure u_w and the local factor of safety FS along the depth z .

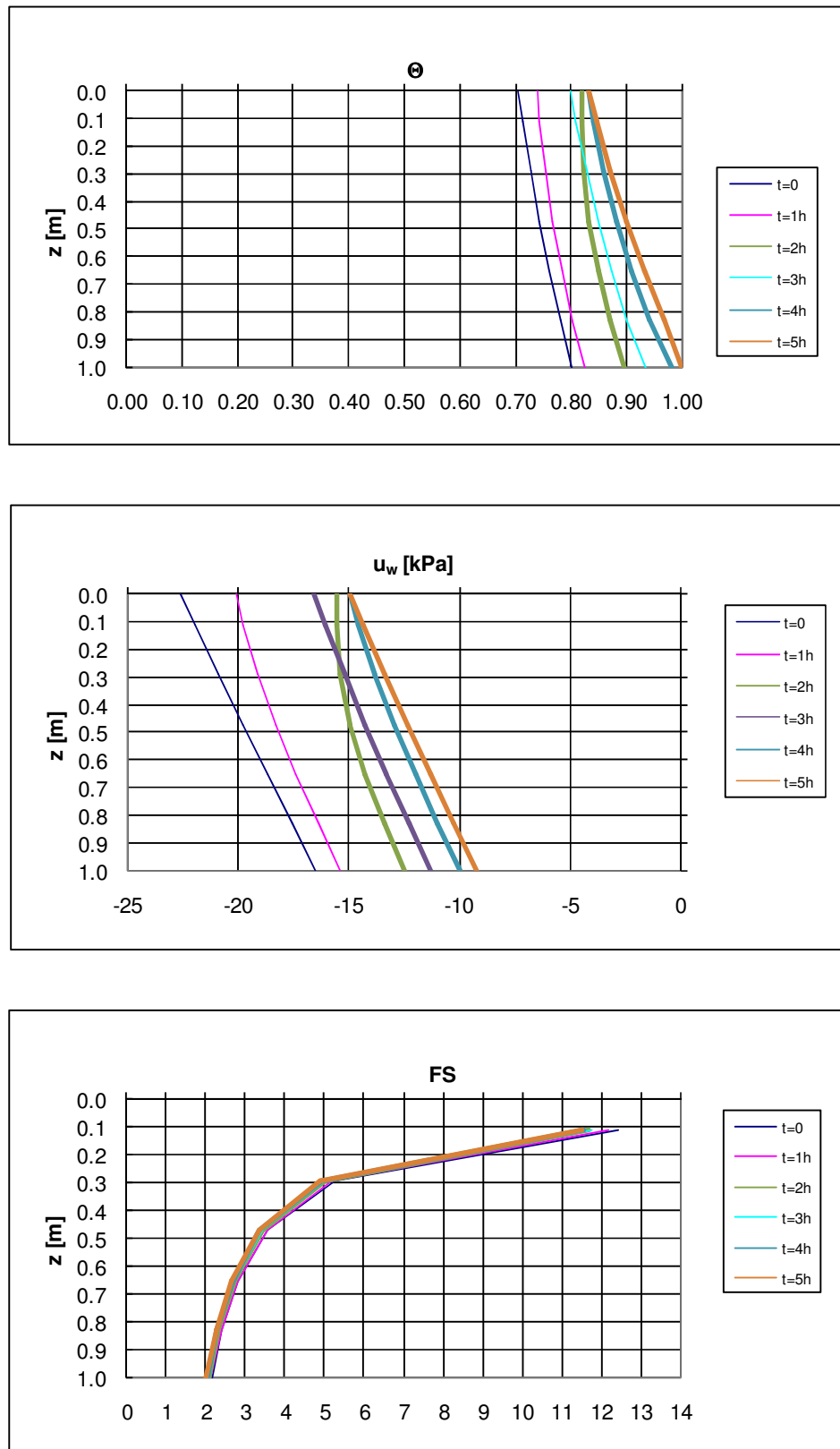


Figure 3.3. Test case nr.1 (measured rainfall) - Section nr.1 ($z_{\max} = 1\text{m}$): changing with time of the relative volumetric water content Θ , the pore-water pressure u_w and the local factor of safety FS along the depth z.

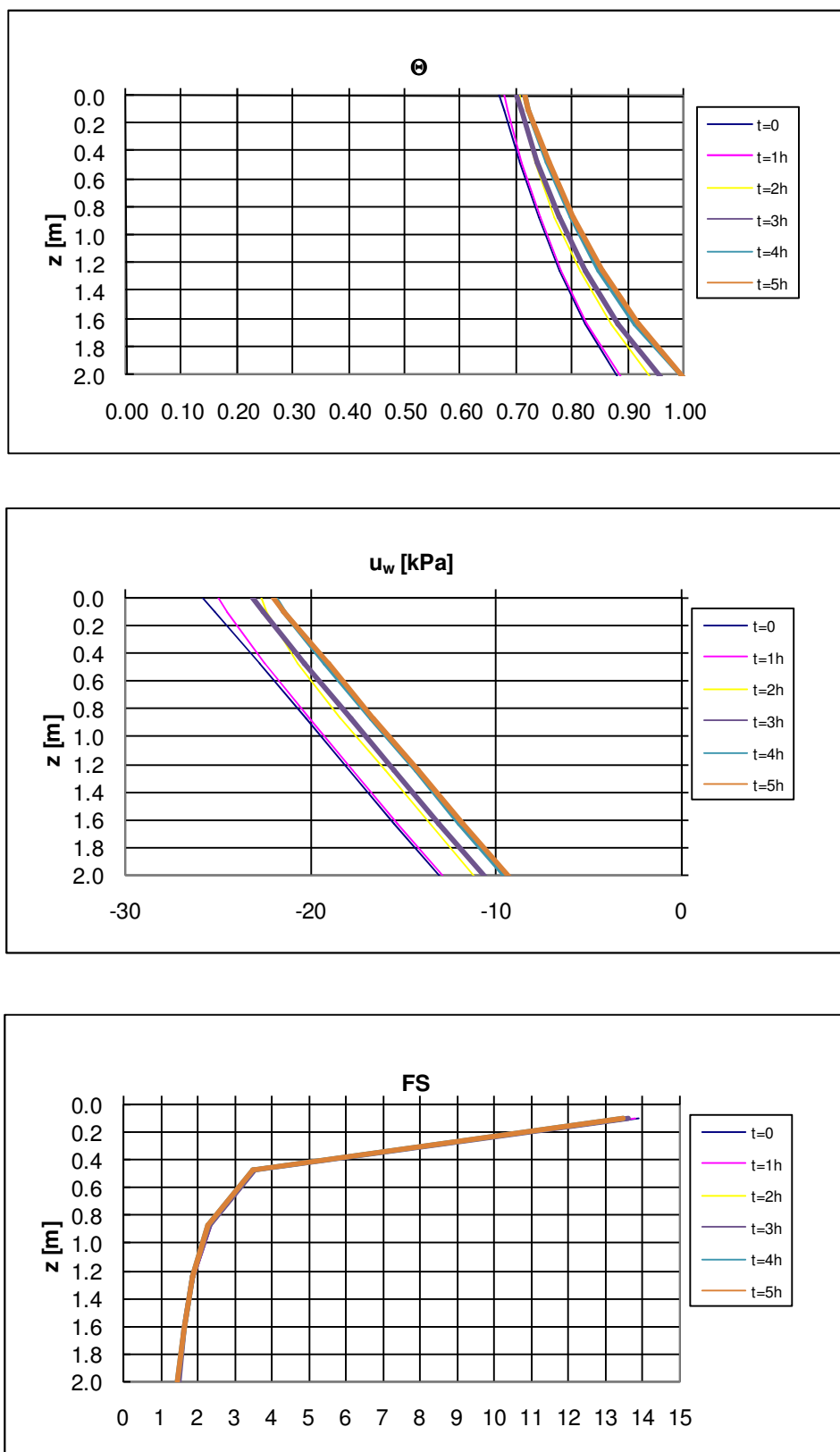


Figure 3.4. Test case nr.1 (measured rainfall) - Section nr.2 ($z_{\max} = 2\text{m}$): changing with time of the relative volumetric water content Θ , the pore-water pressure u_w and the local factor of safety FS along the depth z .

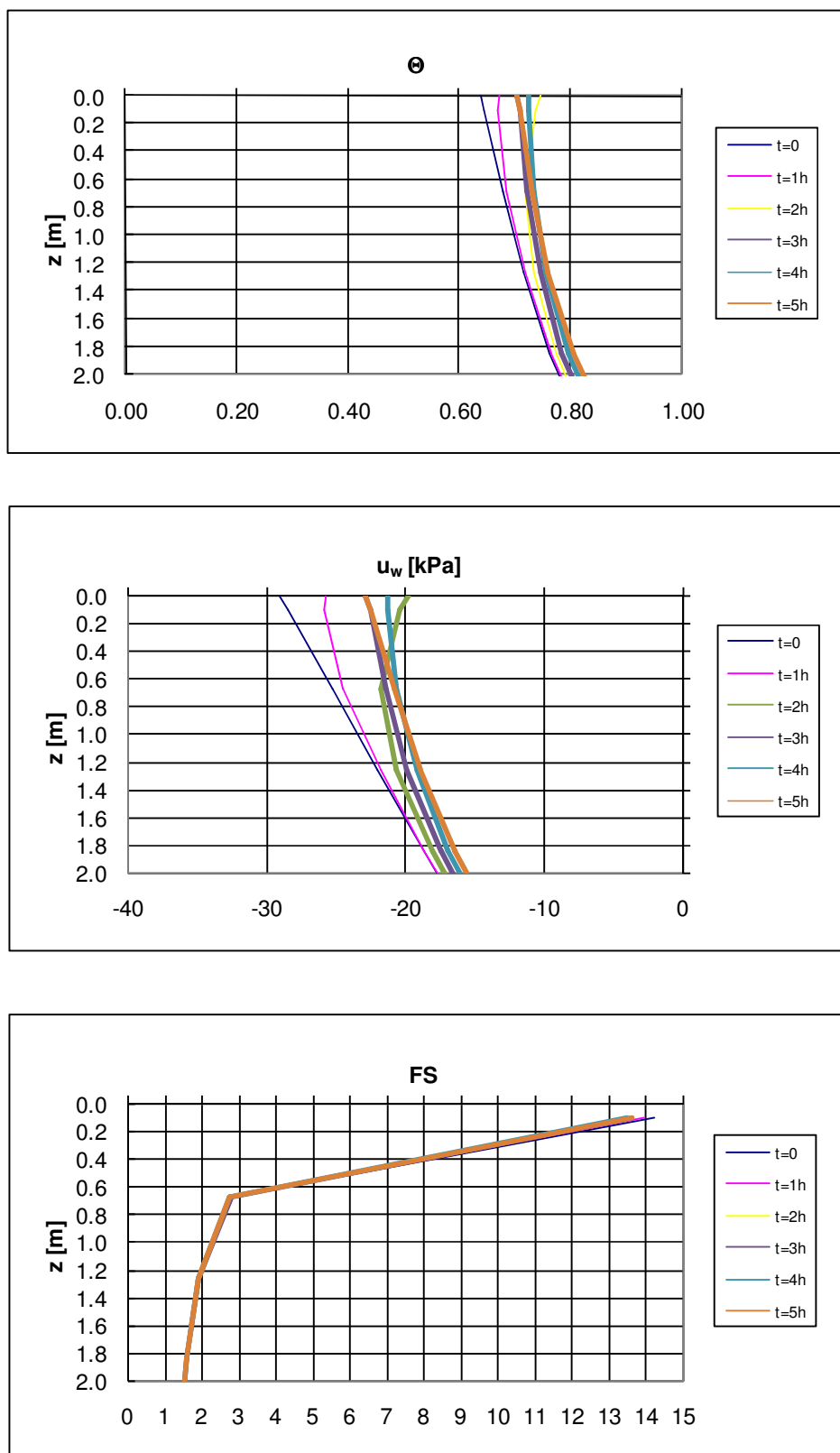


Figure 3.5. Test case nr.1 (measured rainfall) - Section nr.3 ($z_{\max} = 3\text{m}$): changing with time of the relative volumetric water content Θ , the pore-water pressure u_w and the local factor of safety FS along the depth z .

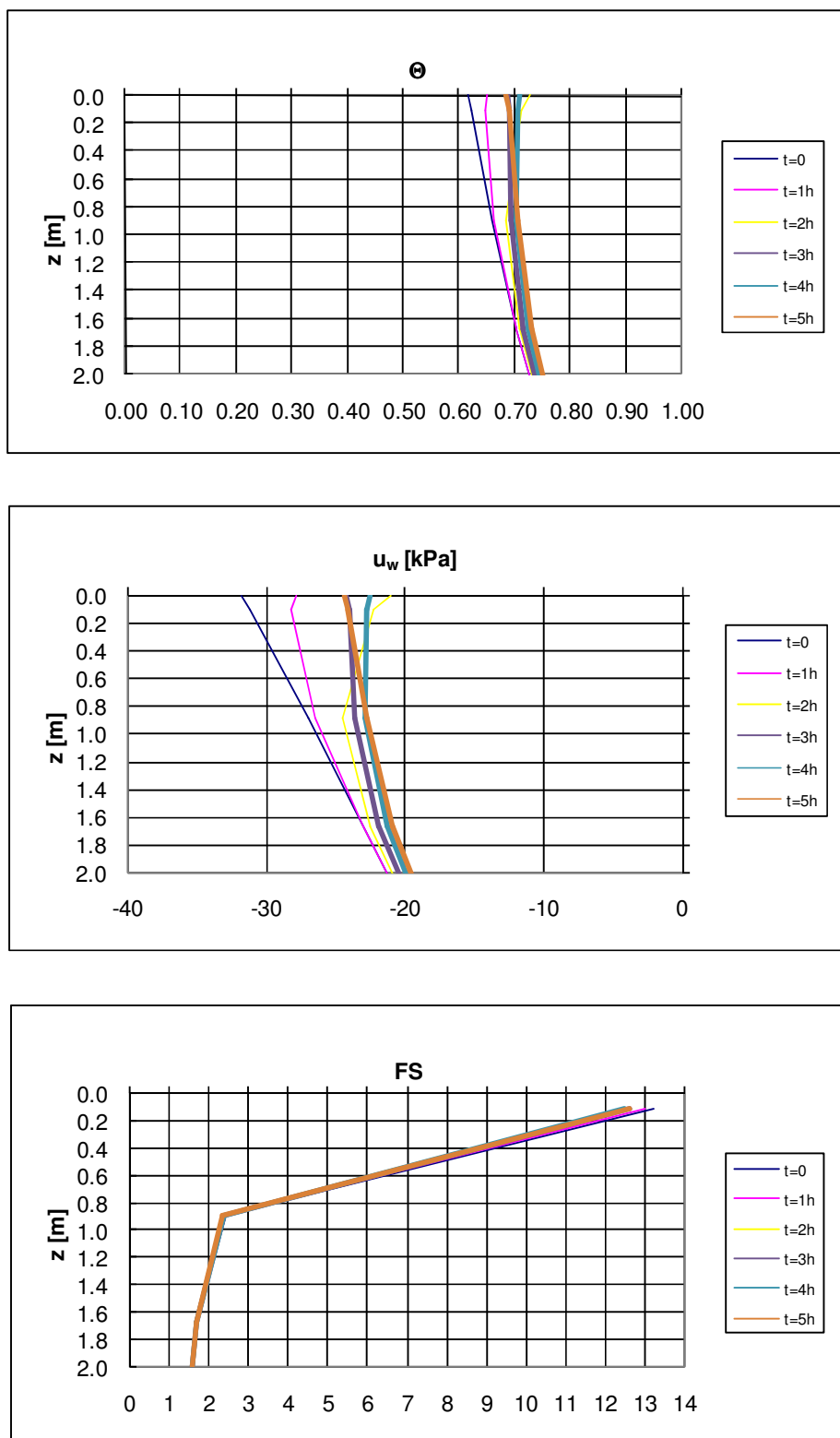


Figure 3.6. Test case nr.1 (measured rainfall) - Section nr.4 ($z_{\max} = 4\text{m}$): changing with time of the relative volumetric water content Θ , the pore-water pressure u_w and the local factor of safety FS along the depth z .

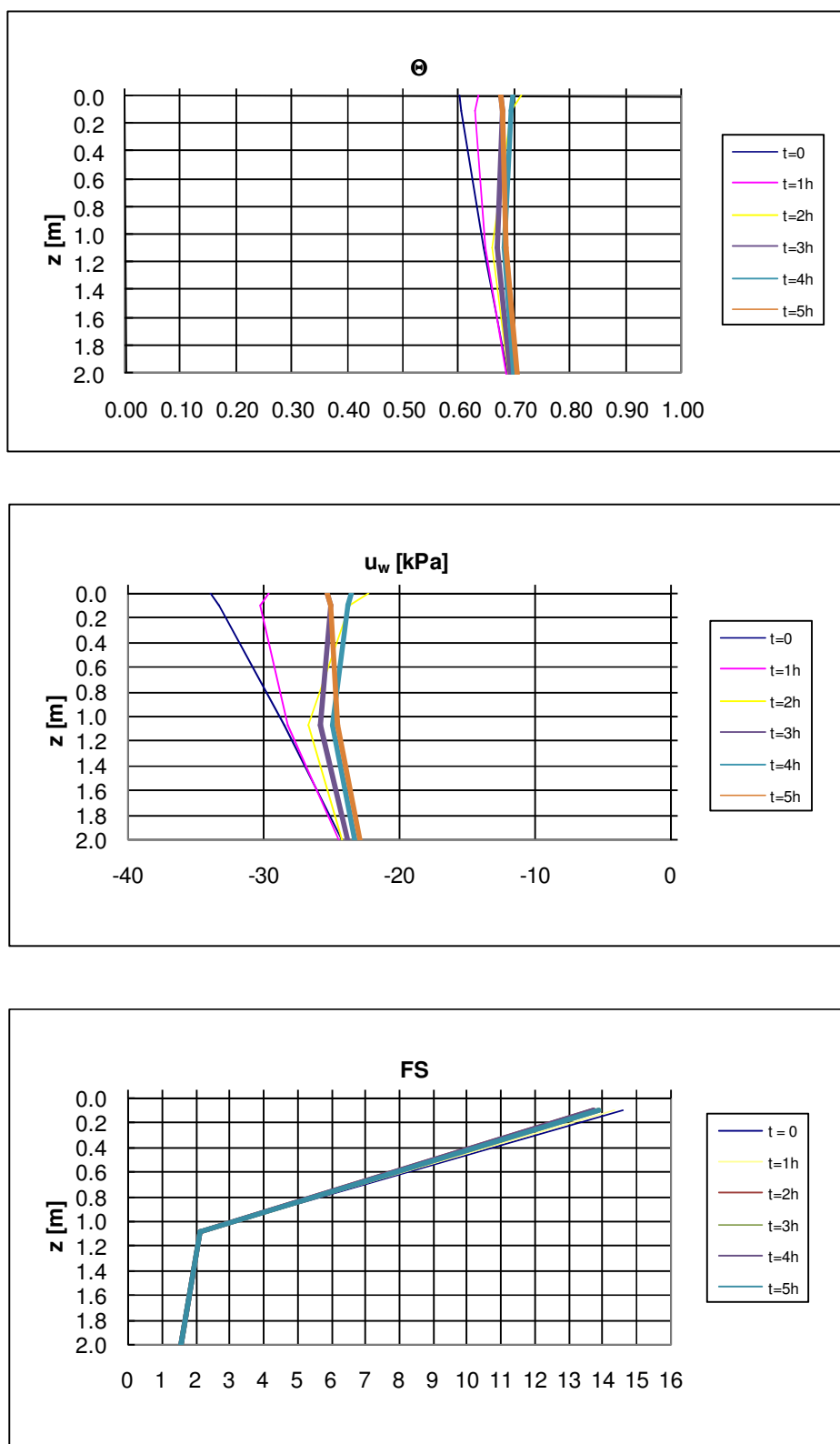


Figure 3.7. Test case nr.1 (measured rainfall) - Section nr.5 ($z_{\max} = 5\text{m}$): changing with time of the relative volumetric water content Θ , the pore-water pressure u_w and the local factor of safety FS along the depth z.

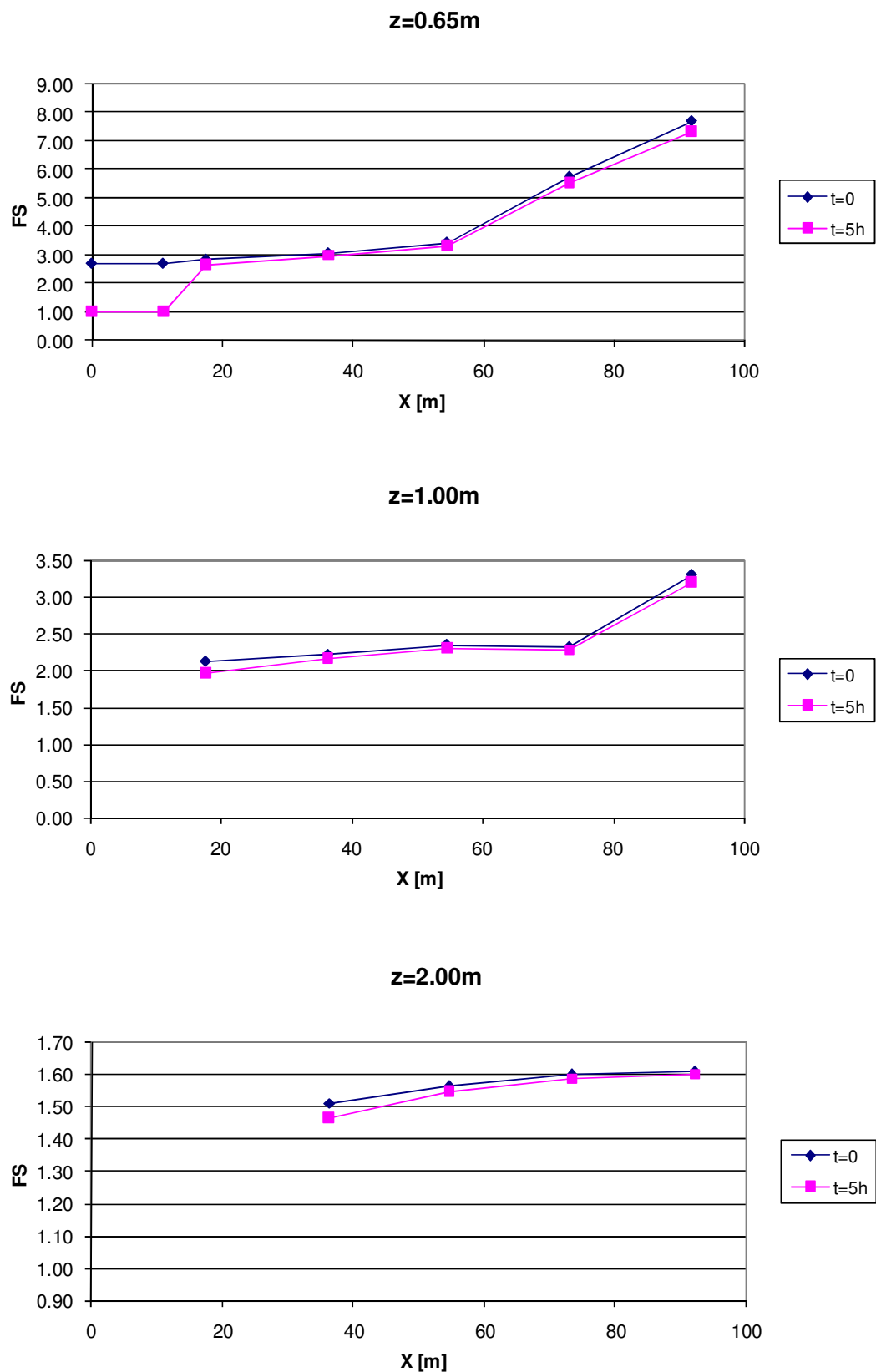


Figure 3.8. Test case nr.1 (measured rainfall) - Changing with time of the local factor of safety FS at the depths 0.65m, 1m and 2m.

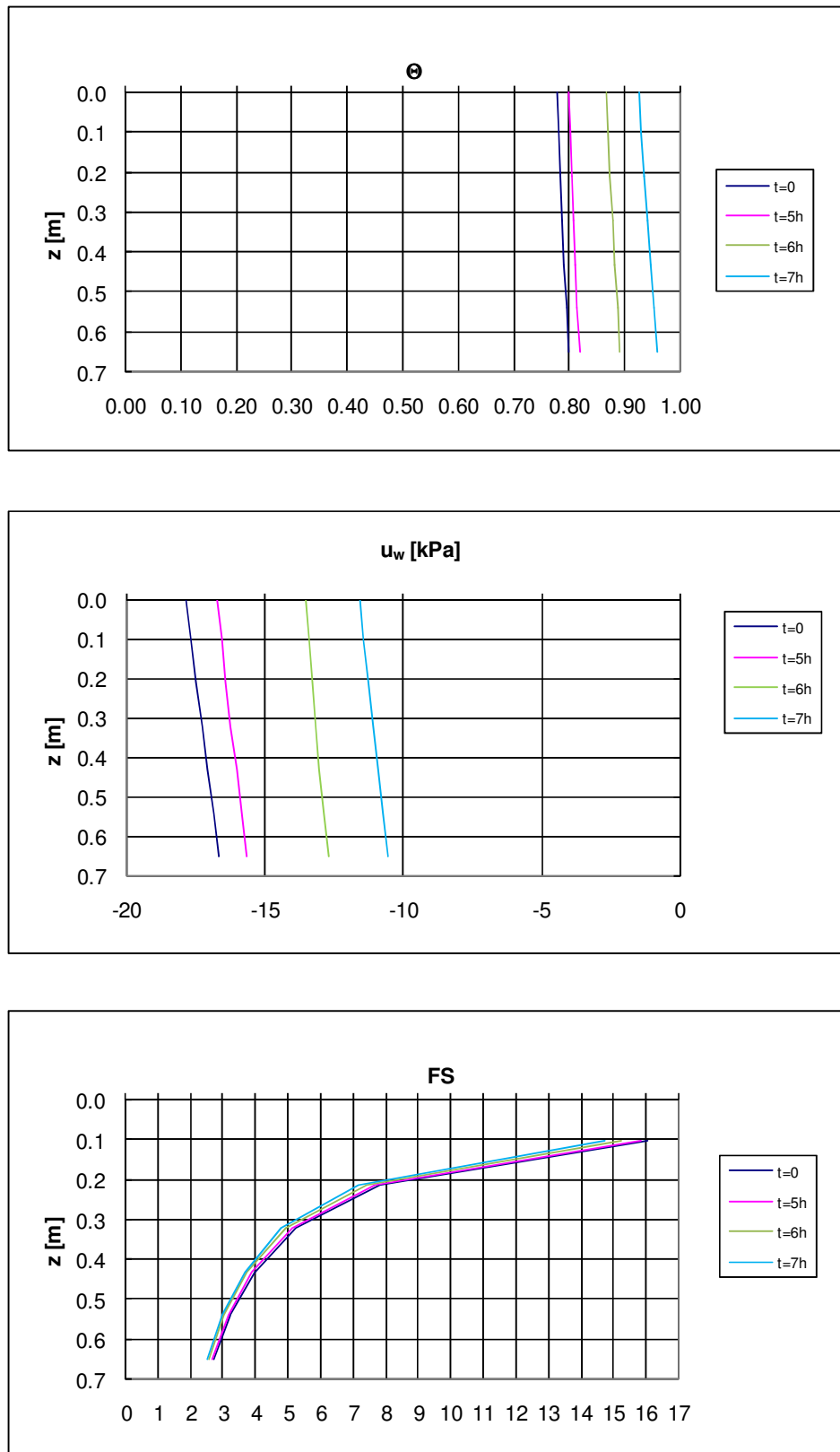


Figure 3.9. Test case nr.1 (calculated rainfall) - Section nr.0 ($z_{\max} = 0.65\text{m}$): changing with time of the relative volumetric water content Θ , the pore-water pressure u_w and the local factor of safety FS along the depth z .

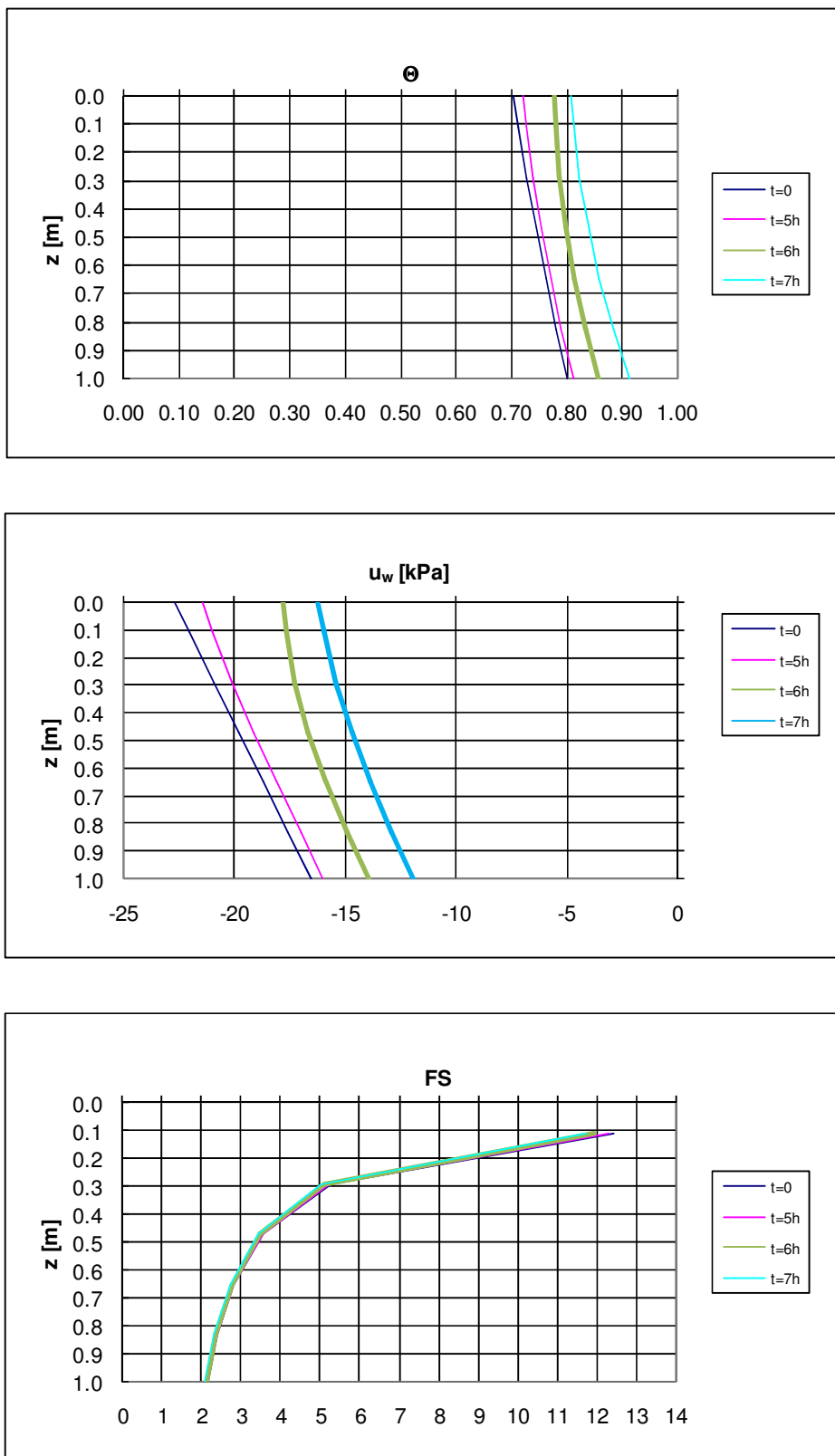


Figure 3.10. Test case nr.1 (calculated rainfall) - Section nr.1 ($z_{\max} = 1$ m): changing with time of the relative volumetric water content Θ , the pore-water pressure u_w and the local factor of safety FS along the depth z .

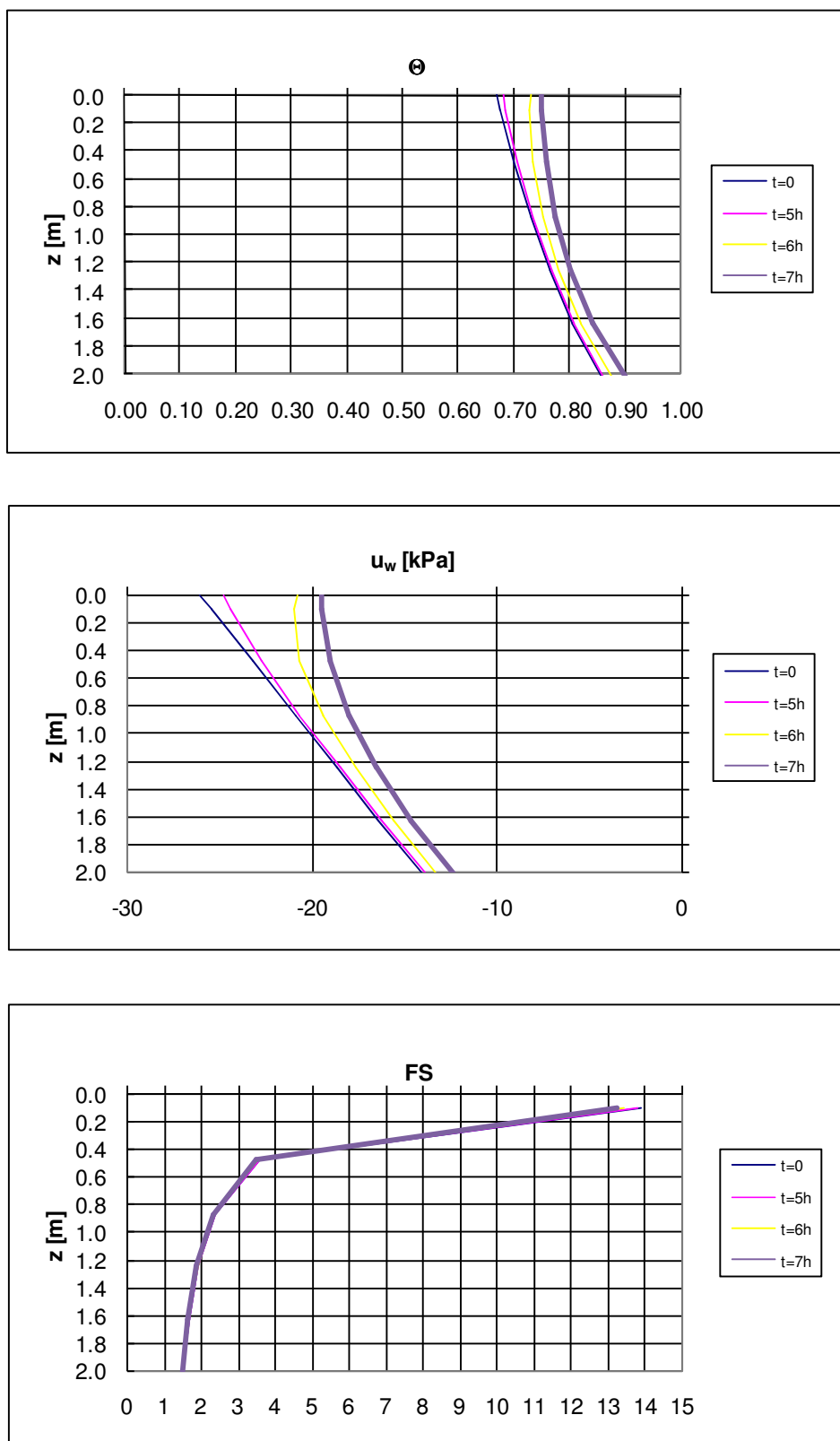


Figure 3.11. Test case nr.1 (calculated rainfall) - Section nr.2 ($z_{\max} = 2\text{m}$): changing with time of the relative volumetric water content Θ , the pore-water pressure u_w and the local factor of safety FS along the depth z .

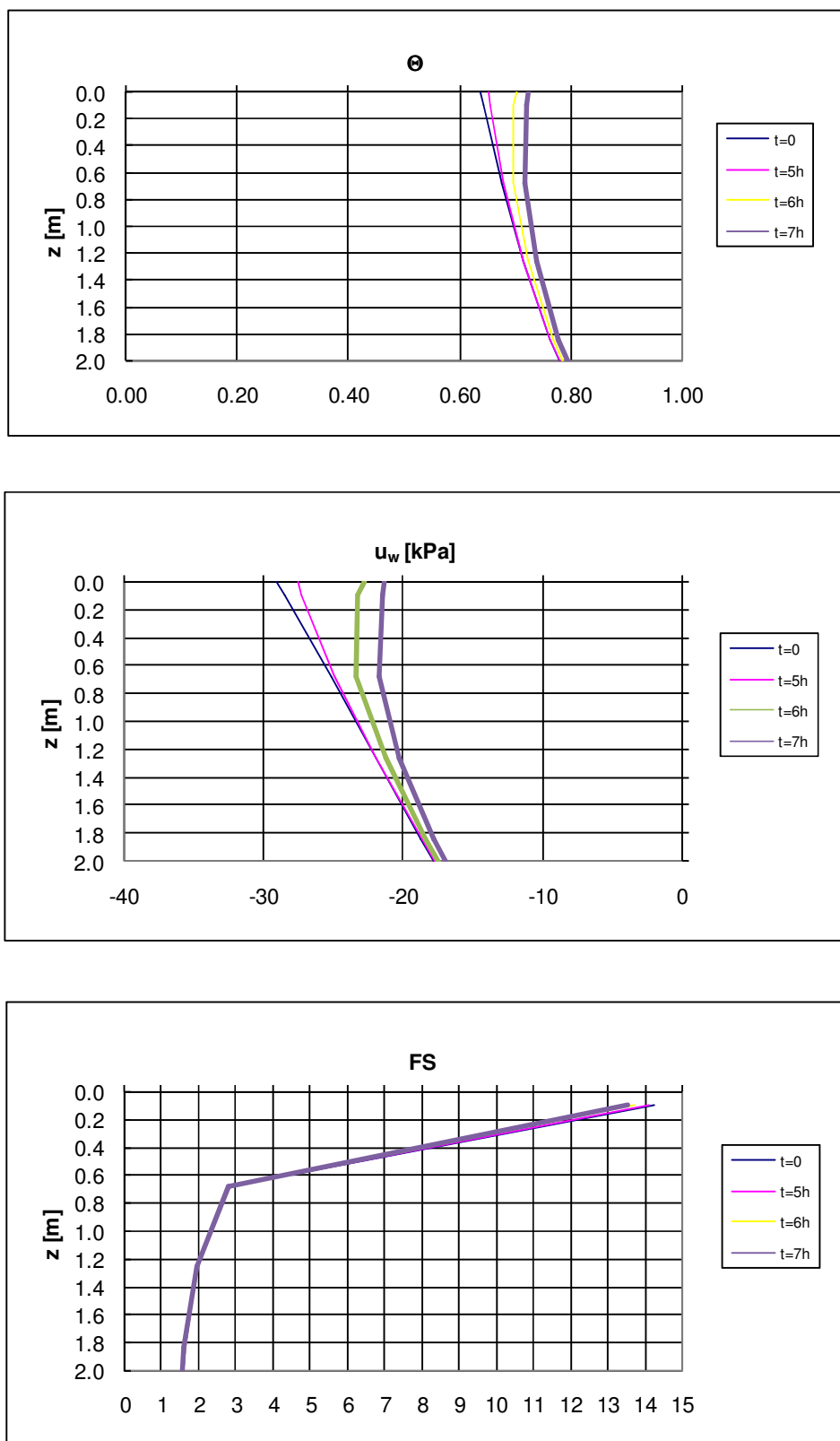


Figure 3.12. Test case nr.1 (calculated rainfall) - Section nr.3 ($z_{\max} = 3m$): changing with time of the relative volumetric water content Θ , the pore-water pressure u_w and the local factor of safety FS along the depth z .

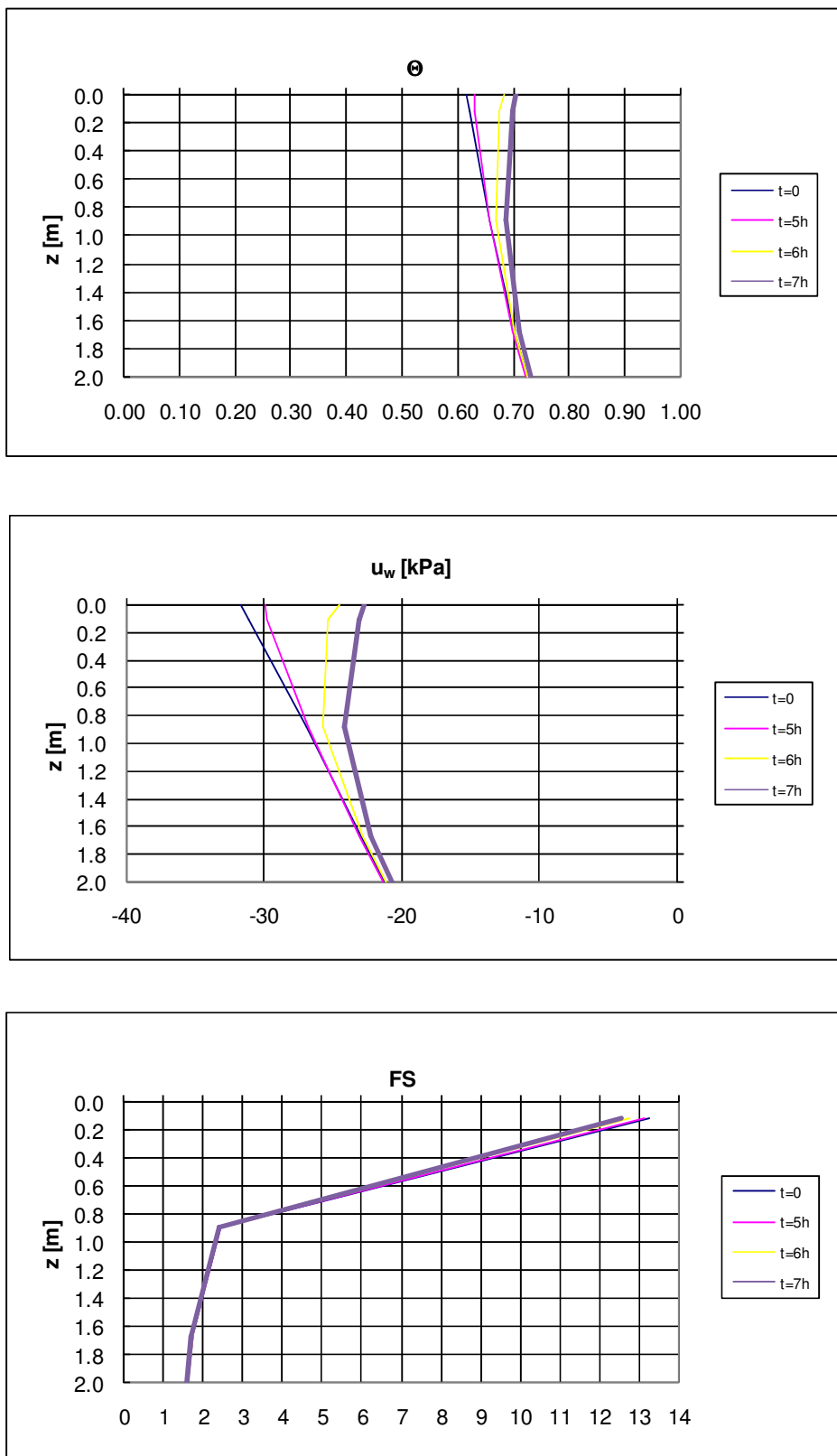


Figure 3.13. Test case nr.1 (calculated rainfall) - Section nr.4 ($z_{\max} = 4\text{m}$): changing with time of the relative volumetric water content Θ , the pore-water pressure u_w and the local factor of safety FS along the depth z .

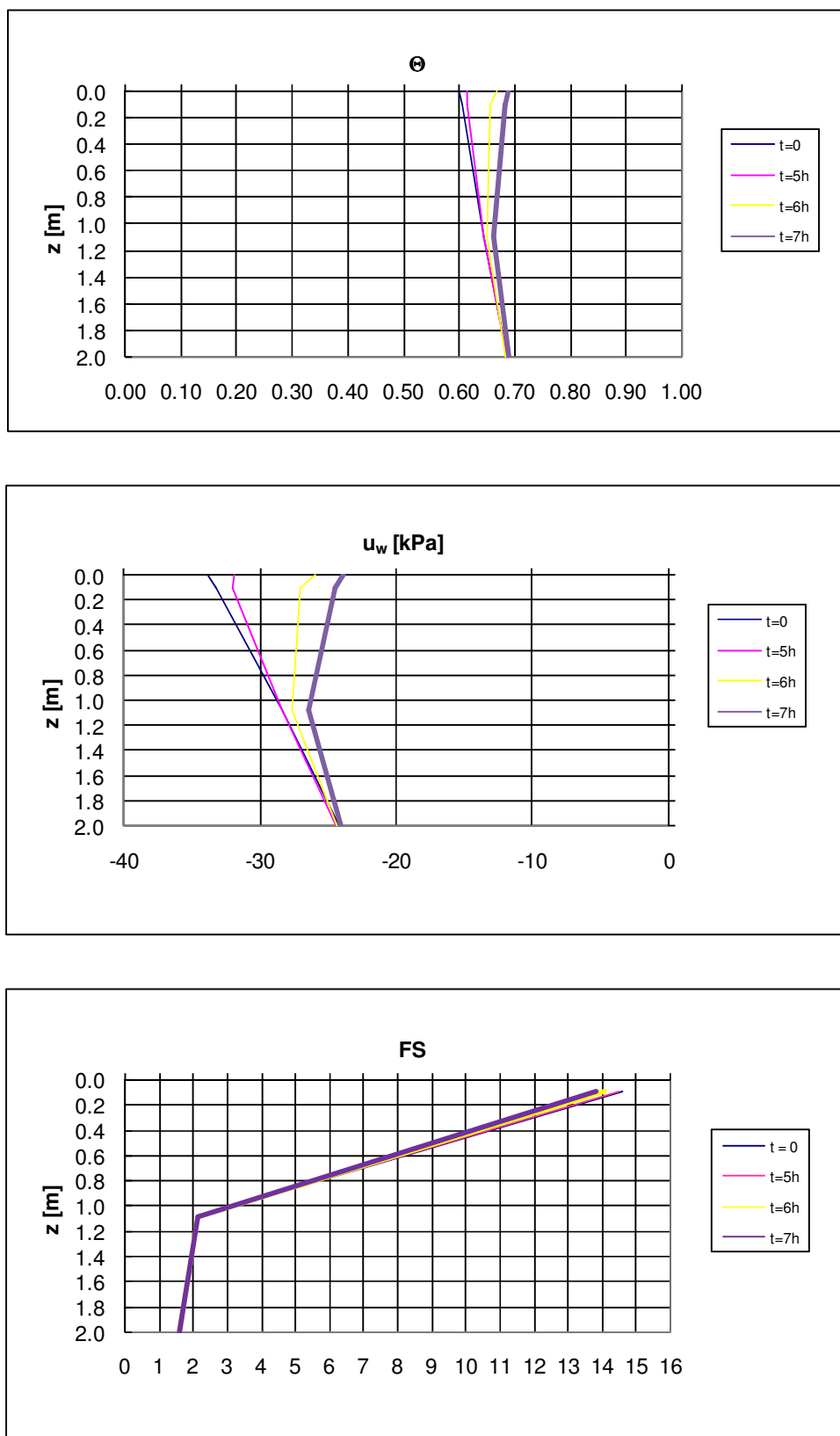


Figure 3.14. Test case nr.1 (calculated rainfall) - Section nr.5 ($z_{\max} = 5\text{m}$): changing with time of the relative volumetric water content Θ , the pore-water pressure u_w and the local factor of safety FS along the depth z .

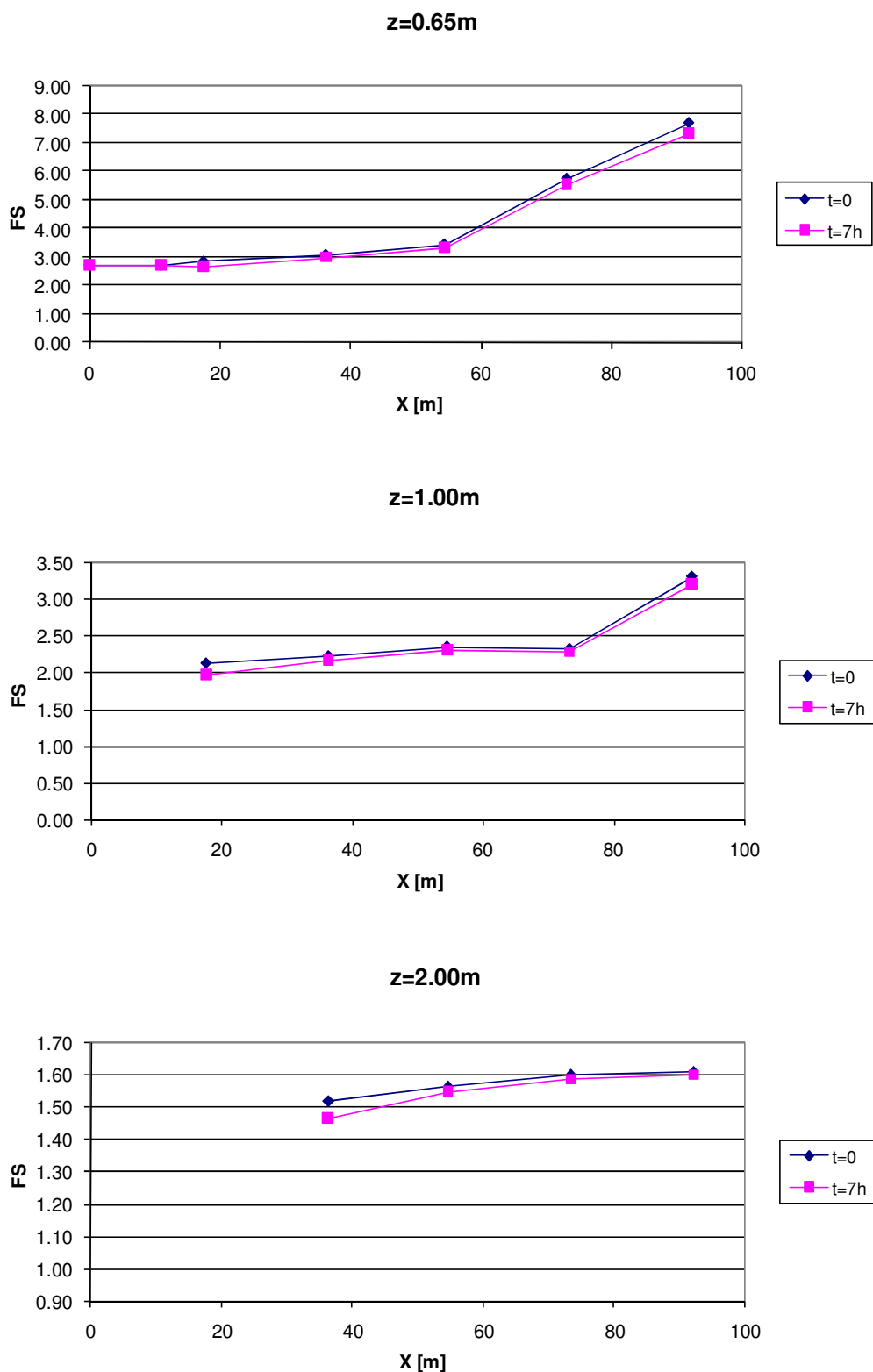


Figure 3.15. Test case nr.1 (calculated rainfall) - Changing with time of the local factor of safety FS at the depths 0.65m, 1m and 2m.

3.2 Test case nr. 2

According to the results, the landslide would be justified for values of suction lower than 200 kPa on 17/08/2005 (one month before landslide), which induces the distribution of pore water pressures along the ground surface to attain values ranging between -45 kPa (upslope) and -126 kPa (downslope) on 17/09/2005, before the rainfall event (Fig. 3.16).

As reported from Figure 3.17 to Figure 3.23, only the most inclined portion of the slope attained failure at the end of the 3th hour of the measured rainfall event, which corresponds to the maximum peak. Therefore, the local factor of safety FS remains higher than 1 along the other vertical sections of the slope, so inducing to retain, also for this case, that the failure didn't occur at the same time along the entire slope and so that only after-failure processes could have induced the landslide to develop downslope.

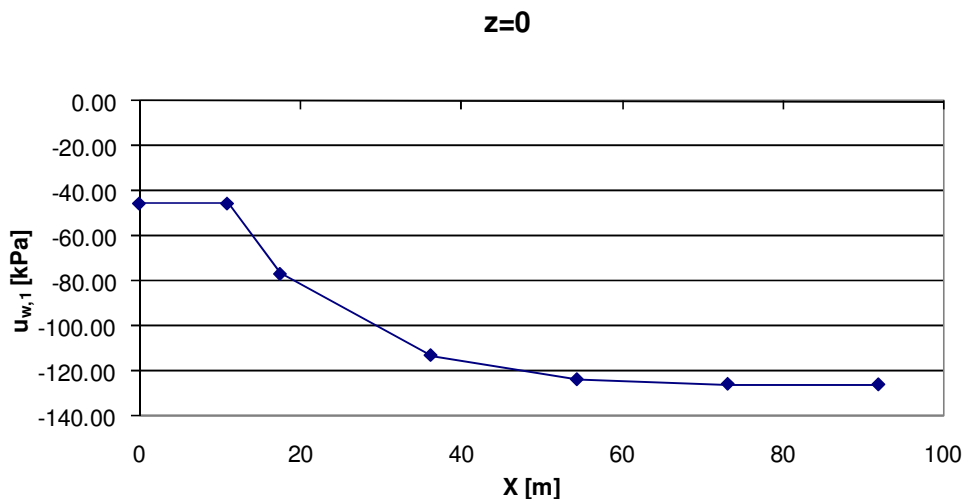


Figure 3.16. Test case nr.2 (17/09/2005): initial distribution of pore water pressure $u_{w,1}$ along the upper boundary of the modelled slope ($z=0$)

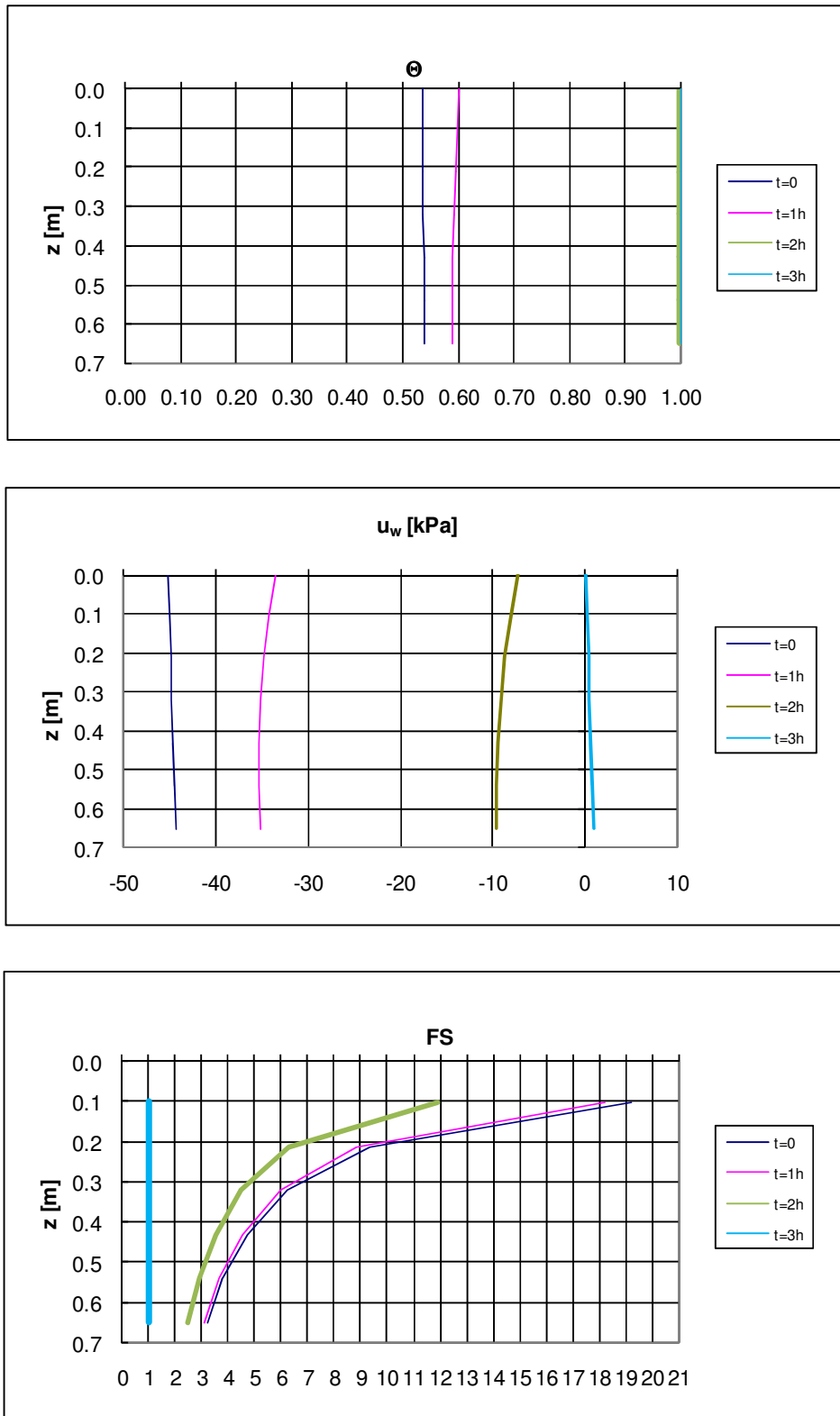


Figure 3.17. Test case nr.2 (measured rainfall) - Section nr.0 ($z_{\max} = 0.65\text{m}$): changing with time of the relative volumetric water content Θ , the pore-water pressure u_w and the local factor of safety FS along the depth z .

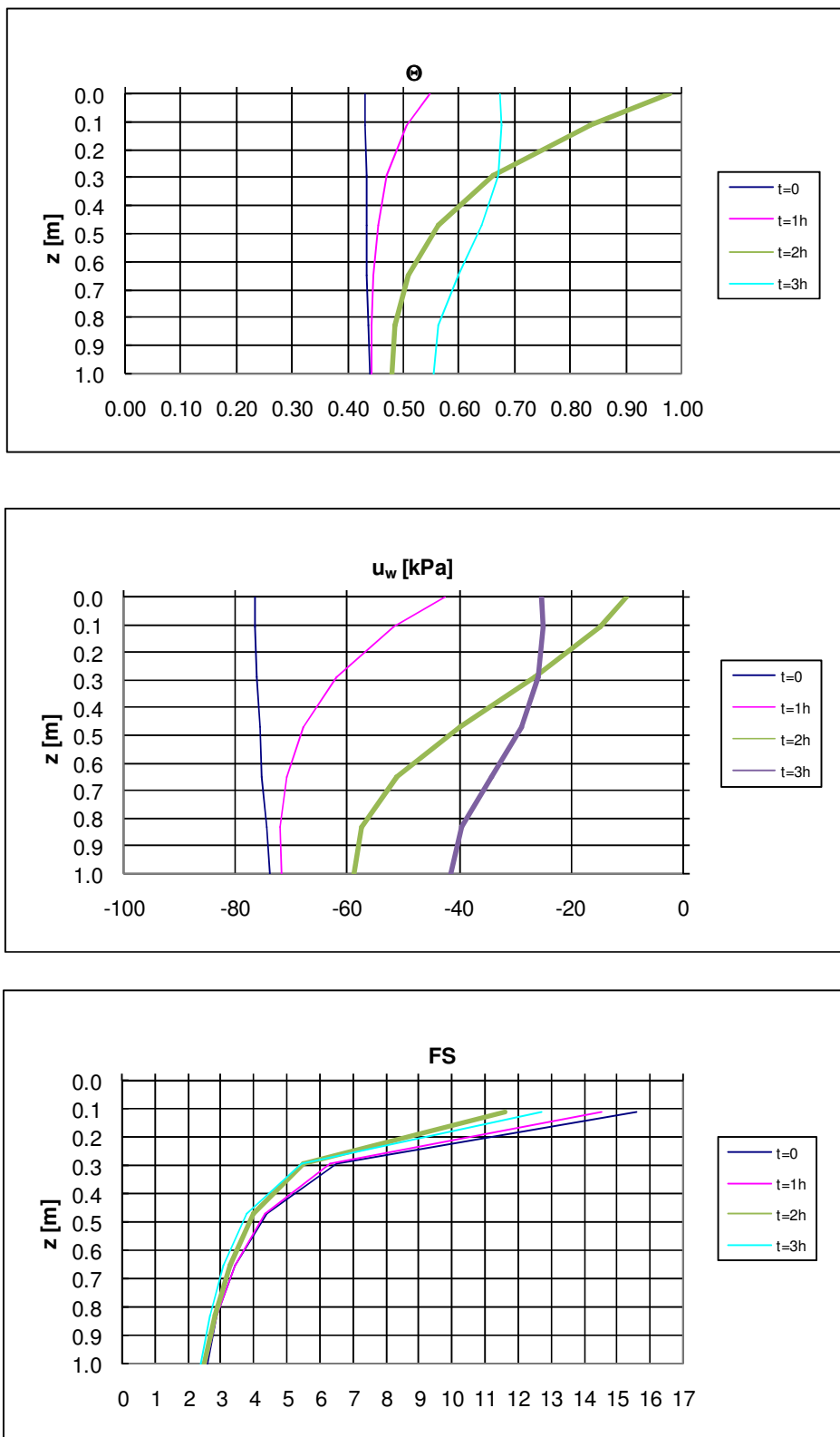


Figure 3.18. Test case nr.2 (measured rainfall) - Section nr.1 ($z_{\max} = 1\text{m}$): changing with time of the relative volumetric water content Θ , the pore-water pressure u_w and the local factor of safety FS along the depth z .

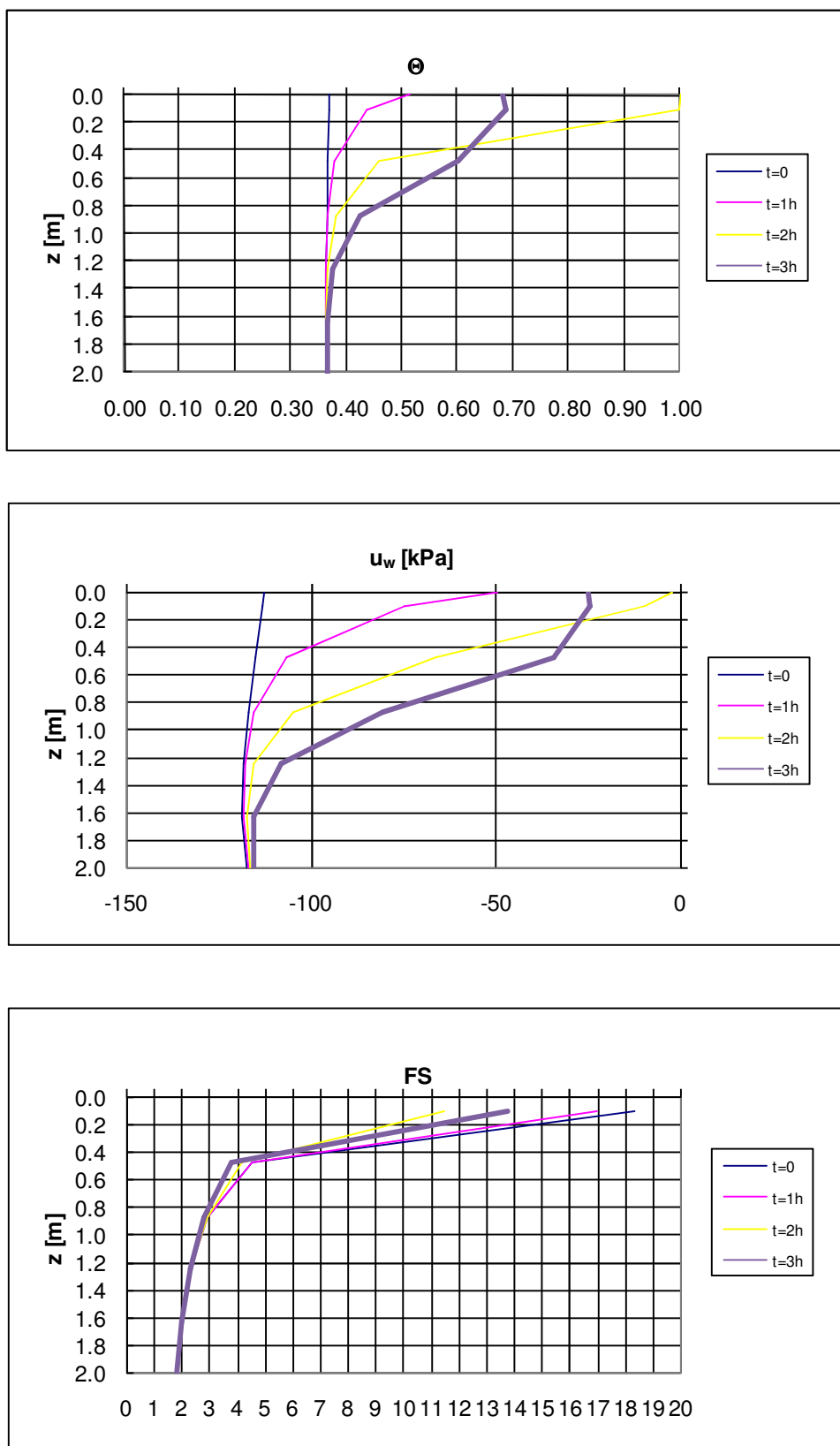


Figure 3.19. Test case nr.2 (measured rainfall) - Section nr.2 ($z_{\max} = 2m$): changing with time of the relative volumetric water content Θ , the pore-water pressure u_w and the local factor of safety FS along the depth z .

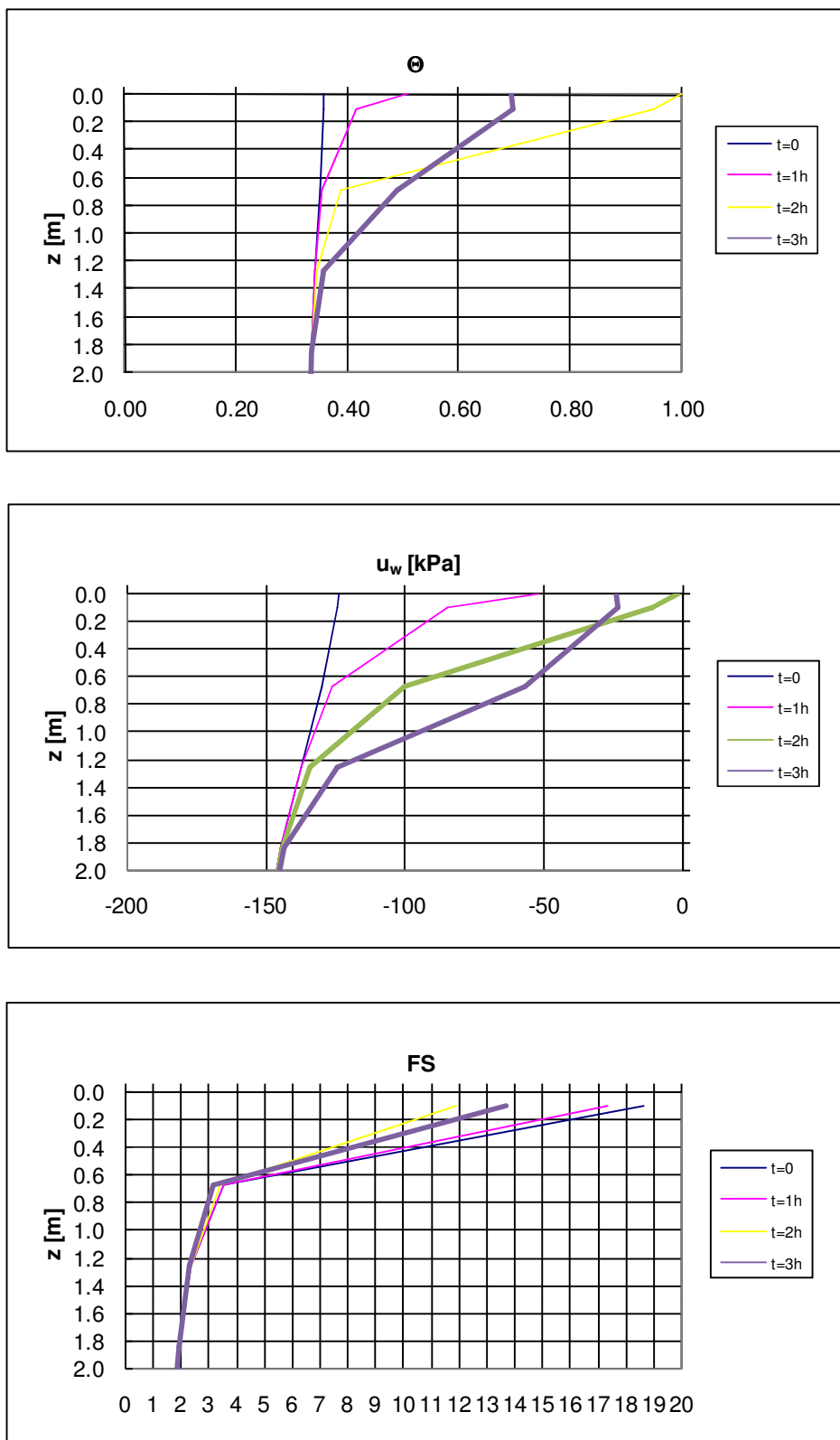


Figure 3.20. Test case nr.2 (measured rainfall) - Section nr.3 ($z_{\max} = 3$ m): changing with time of the relative volumetric water content Θ , the pore-water pressure u_w and the local factor of safety FS along the depth z .

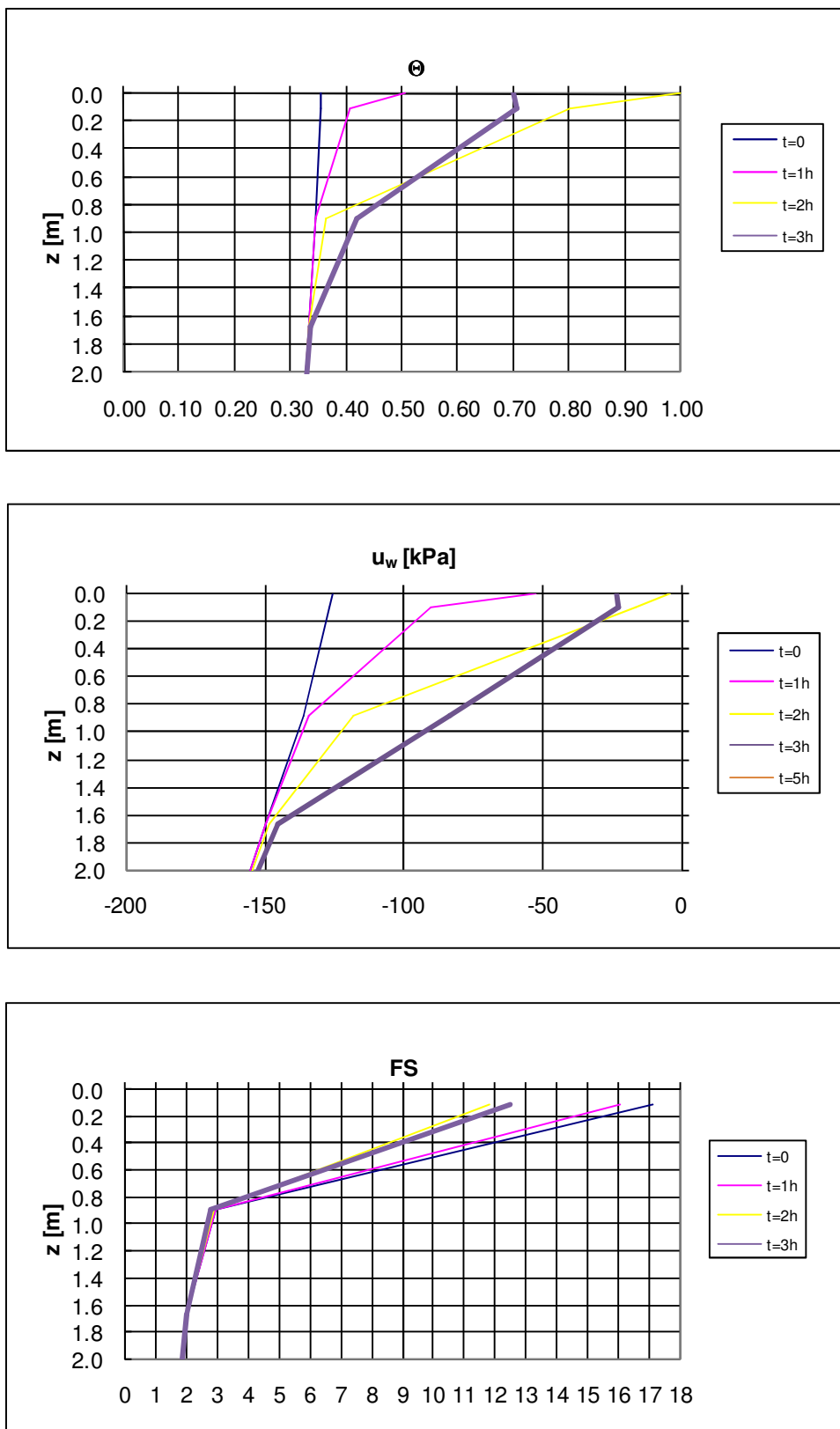


Figure 3.21. Test case nr.2 (measured rainfall) - Section nr.4 ($z_{\max} = 4\text{m}$): changing with time of the relative volumetric water content Θ , the pore-water pressure u_w and the local factor of safety FS along the depth z .

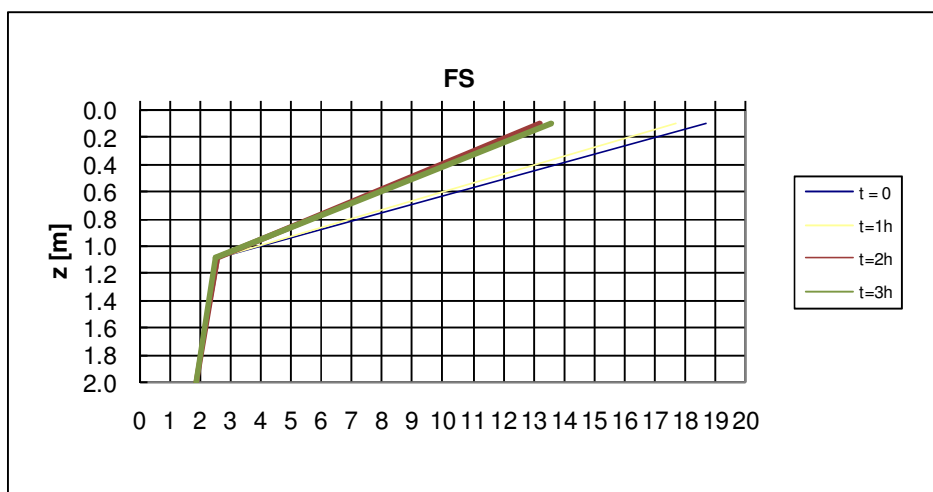
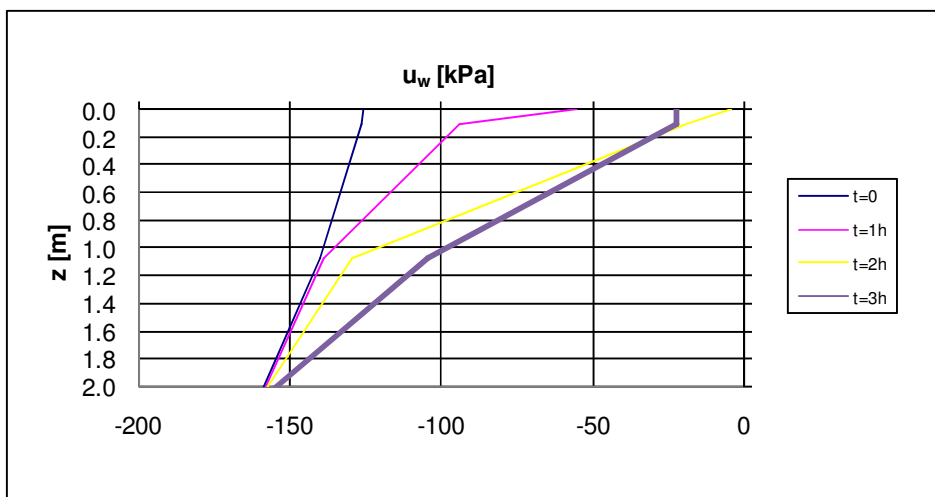
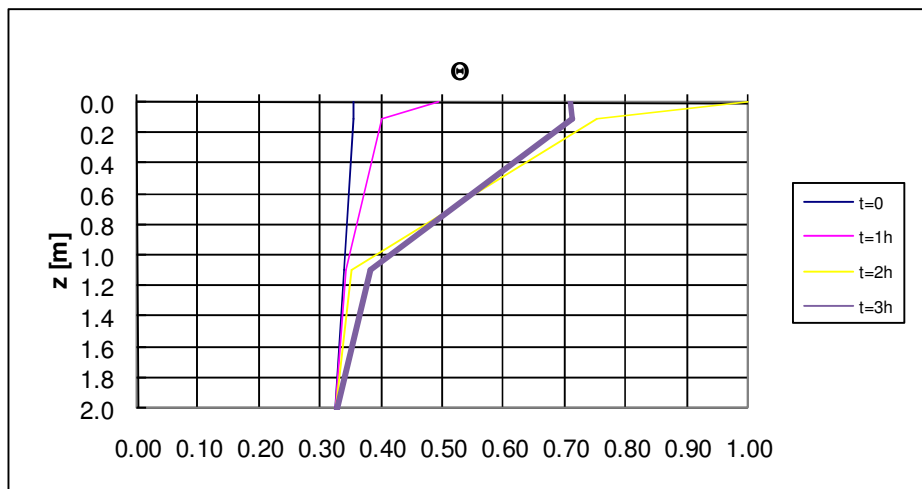


Figure 3.22. Test case nr.2 (measured rainfall) - Section nr.5 ($z_{\max} = 5\text{m}$): changing with time of the relative volumetric water content Θ , the pore-water pressure u_w and the local factor of safety FS along the depth z .

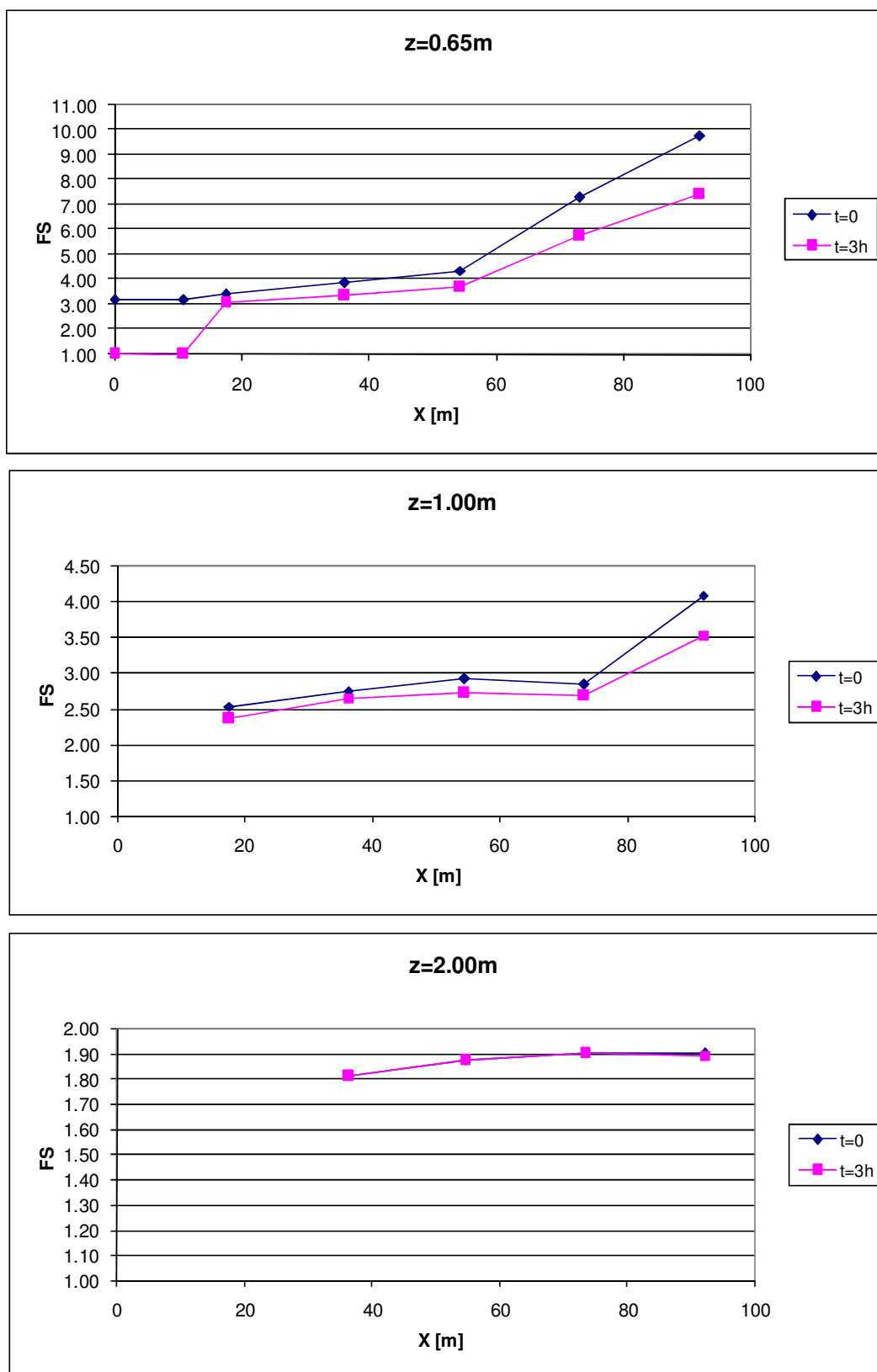


Figure 3.23. Test case nr.2 (measured rainfall) - Changing with time of the local factor of safety FS at the depths 0.65m, 1m and 2m.



4. Conclusive remarks

This report contains the results of 2D numerical analyses performed with the goal to simulate two rainfall-induced shallow landslides events, which occurred on October 13th, 2004 and on September 17th, 2005 along the south-eastern side of the Camaldoli hill, set inside the western sector of the urban district of Naples.

The analyses of the transient infiltration due to the rainfall have been performed by means of the finite element SEEP/W code (produced by the GEO-SLOPE International Ltd.), which needs detailed data about geotechnical properties of the soil (derived from laboratory tests) and about the geometry of the problem. Seepage analyses have been coupled with stability analyses.

The characteristics of the rainfall events which triggered the landslide events, have been derived from the hourly rainfall measurements made by a pluviometer installed next to the landslide area by the Civil Protection of the Campania Region, which registers without any interruption from October 2000.

With regard to the initial conditions (which directly influence the initial properties of the soil), we have decided to obtain the initial transient distribution of the suctions along the slope, starting from a hydrostatic condition and assigning as upper boundary condition the rainfall history which occurred during the monthly period which preceded the landslide event. This procedure has allowed to check the sensitivity of the program to the hypotheses regarding the assigned initial conditions. In particular, we have deduced that the landslides regarding the 1st test case could be justified for initial suctions of about one order of magnitude lower than those related to the 2nd test case.

Again, both the cases were characterized by the activation of the upper portion of the slope, which is the most inclined and characterized by the lowest depth of the impervious bedrock. Therefore, the local factor of safety FS remains higher than 1 along the other parts of the slope, which has induced to deduct that for both the events after-failure mechanisms could have provoked the downslope development of the landslide.

Besides, in order to check the model performed by the meteorological task of C.I.R.A., we have also used as boundary condition the rainfall event based on the maximum hourly rainfall coming from the results of the meteorological analyses performed with the "COSMO LM" set at the 2.8 Km configuration. The lack of correspondence between results coming from the stability analyses (we have not recorded any local failure along the slope) and the reality, has highlighted the temporary aspect of these data and the necessity of further studies, which are already in progress.



5. References

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