P2R2C2

Pavement response to rainfall changes

Report Nr 9

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1 Introduction

The research performed during Working Package 4 was aimed at investigating how the future likely changes in rainfall quantity, duration and pattern can influence the behaviour of a road. As it was observed in WPs 1.2 and 2.1, the presence of excess water in the road structure, in particular in the unbound subbase layer, can reduce its strength and stiffness, up to the point in which it is not able to sustain the traffic load that is transmitted from the surface. The consequences are more or less severe rutting, but also the formation of cracks on the asphalt and so on. Another important consequence is the risk of floods, a problem that is becoming more and more common, especially in coastal roads.

The climate change projections from Working Package 1.1 show that, while in Southern Europe there will be a decrease of rainfall up to 30%, on average Central Europe will not experience any considerable change in annual precipitation compared to now, while Northern Europe will see an increase between 100 and 200 mm/year on average, with peaks of 400 mm/year on the coast of Norway.

Projections made by the Intergovernmental Panel on Climate Change [IPCC, 2007] show that the increase in rainfall will be higher in winter than not in summer. Northern Europe will likely witness an increase in rainfall of the 20% during winter, but only of the 10% during summer; in Central Europe, about 10% during winter and no change in rainfall compared to the present situation during summer. IPCC also predicts an increase of events of heavy precipitations, especially “extreme events” such as storms and surges, with consequent increase of the risk of flooding.

These changes in climate were modelled and compared to a simulation of a simplified model of the present situation. Also, different ways of dealing with the presence of water on the subbase and practical ways to reduce water infiltration into the subbase were simulated.

2 Description of the models

The simulation was performed using MODFLOW-SURFACT, a 3-dimensional finite-difference groundwater flow and contaminant transport program. This was chosen as it allows simulating also water movement in an unsaturated soil, and de-saturation and re-saturation processes. Groundwater Vistas, a software package for 3-D groundwater flow modelling, calibration and optimisation using the MODFLOW codes, was used as a graphical interface. The period simulated is of one year, considered enough to observe a steady situation. It should be noticed that evapo-transpiration is not considered, therefore, even after dry periods, the simulations will show that water can be still found close to the surface.

2.1 Modelling of the materials

The structure of the road was highly simplified for the simulations. The subgrade and surrounding soil was considered to be either clay or sand. The base was chosen to be an unbound material, with permeability relatively low compared to a clean, freshly crushed Type 1 aggregate, in order to simulate an unbound subbase aggregate which, after a few years, gets mixed with soil and other material, as it is usually the case. The asphalt surface and asphaltic base are considered as just one material. Finally, a draining aggregate was considered to be used on the side of the roads as a lateral drain, or as a substitute to the unbound subbase aggregate to create a draining layer (see reports from WP 2.1 and 2.5).

Each material was described, in the simulation, by the following parameters:

- The hydraulic conductivity, which represents the ease with which water can move through the voids between the particles.
- The porosity, which is a measure of the void spaces in a material, equal to the volume of voids over the total volume, thus its value is between 0 and 1.
- The specific yield, less than or equal to the porosity, which is the volumetric fraction of the bulk aquifer volume that a given aquifer yields when all the water is allowed to drain out of it under the forces of gravity. The storage coefficient is the volume of water released from or taken into storage per unit surface area of the aquifer per unit change in the component of head normal to that surface, and, for an unconfined aquifer, is approximately equal to the specific yield.
- α, β and θr are the so called Van Genuchten values, and allow the simulation of an unsaturated mean;
- α represents the inverse characteristic length of the soil pores
- β is the degree if pore-size uniformity
- θr is the residual saturation, i.e. the saturation level below which fluid drainage does not occur.

Table 1 shows the characteristics assigned to each of these materials.

material	hydraulic conductivity (mm/s)	storage/porosity		Van Genuchten values		
		storage coefficient & specific yield	Porosity θs	α (1/mm)	β	Residual sat. θr
clay (subgrade)	0.0001	0.04	0.5	0.0008	1.2	0.068
sandy mat. (subgrade)	0.008	0.21	0.43	0.0147	2.68	0.045
Subbase	0.01	0.25	0.33	0.0063	1.3	0.06
draining aggregate	1	0.22	0.4	0.0058	1.27	0.005
Asphalt	-	-	-	-	-	-
Porous asphalt	1	0.2	0.2	0.01	2	0.1

Table 1: values used to describe the materials' parameters in the model.

The values of Hydraulic conductivity used were taken from Watmove [2008]. Values for porosity were found mostly in Boothroyd [2008] and in http://en.wikipedia.org/wiki/Porosity. The values of specific yield used have been taken from Johnson [1967] (see Table 3). The storage coefficient was considered equal to the specific yield as the aquifer simulated was always unconfined. Finally, the Van Genuchten values of the clay, the sandy material and draining aggregate were taken from Carsel and Parrish (1988), the values of the subbase from Gardner (…).

Texture	θ_r (m^3/m^3)	θ_s (m^3/m^3)	α (1/cm)	n	K_s (cm/day)
(1) Sand	0.045	0.430	0.145	2.68	712.80
(2) Loamy sand	0.057	0.410	0.124	2.28	350.20
(3) Sandy loam	0.065	0.410	0.075	1.89	106.10
(4) Loam	0.078	0.430	0.036	1.56	24.96
(5) Silt	0.034	0.460	0.016	1.37	6.00
(6) Silt loam	0.067	0.450	0.020	1.41	10.80
(7) Sandy clay loam	0.100	0.390	0.059	1.48	31.44
(8) Clay loam	0.095	0.410	0.019	1.31	6.24
(9) Silty clay loam	0.089	0.430	0.010	1.23	1.68
(10) Sandy clay	0.100	0.380	0.027	1.23	2.88
(11) Silty clay	0.070	0.360	0.005	1.09	0.48
(12) Clay	0.068	0.380	0.008	1.09	4.80

Table 2: properties of different soils (from Carsel and Parrish, 1988, and others).

type of material	max (-)	min (-)	average (-)
Clay	0.05	0	0.02
Sandy clay (mud)	0.12	0.03	0.07
Silt	0.19	0.03	0.18
Fine sand	0.28	0.1	0.21
Medium sand	0.32	0.15	0.26
Coarse sand	0.35	0.2	0.27
Gravelly sand	0.35	0.2	0.25
Fine gravel	0.35	0.21	0.25
Medium gravel	0.26	0.13	0.23
Coarse gravel	0.26	0.12	0.22

Table 3: specific yield values used as a reference (Johnson, 1967).

2.2 Modelling of the different types of roads

Pavements are three dimensional objects. However, on level ground, there is a large degree of symmetry in the longitudinal direction, and therefore two dimensional (2D) cross-sections of the pavement can provide a reasonably reliable geometrical description of the whole pavement. For this reason, 2D numerical simulations were performed using the cross-section of typical pavement substructures. Because the pavement cross-section is symmetric, only half of the structure was modelled (see dashed lines in the figures 1, 2, 3 and 4).

Four models of roads have been simulated: a typical European highly trafficked road, a road surfaced with porous asphalt, a low-volume traffic road typical of the Northern European countries and a highly cracked road. The designs of the roads were mostly based on the answers given by the Transport Departments of the European countries to a questionnaire sent out by the project members (see Appendix A). The initial design is described in the following paragraphs, however modification of the models and of the subsoils have then been performed in order to study different cases. The surrounding soil was considered in almost all the cases clayey, in order to have conservative results (a sandy soil drains quickly and thus represents a much smaller problem of water flow handling for a road).

MODEL 1: highly trafficked motorway

Characteristics:

- Thickness asphalt (surface + base): 300 mm
- Thickness unbound subbase: 250 – 300 mm
- Draining pipe: at 1150 mm depth (500 mm from the bottom of the subbase)
- Road surface slope: 1 %
- Subsoil: clay

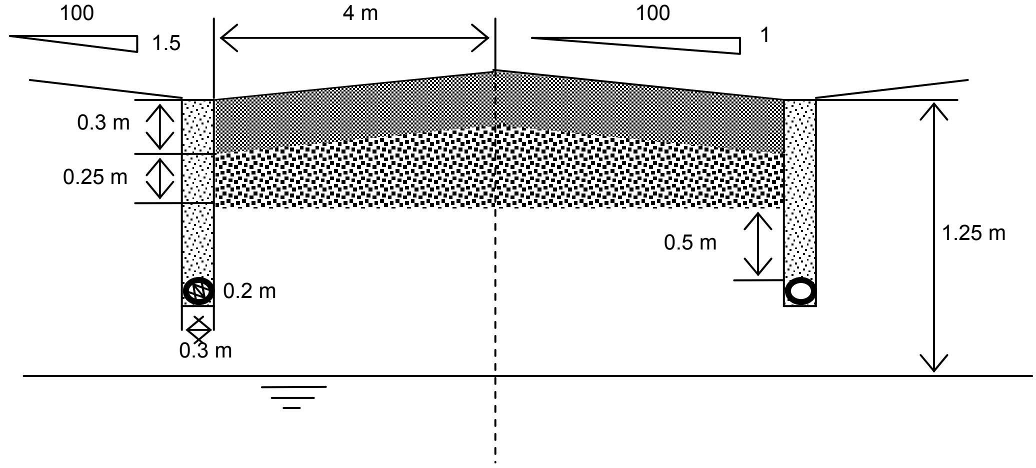


Figure 1: schematic of the high-volume traffic road simulated.

MODEL 2: porous asphalt road

Characteristics:

- Thickness surface porous asphalt: 50 mm
- Thickness asphaltic base: 250 mm
- Thickness unbound subbase: 250 – 310 mm
- Draining pipe: on the surface
- Road surface slope: 1.5 %
- Subsoil: clay

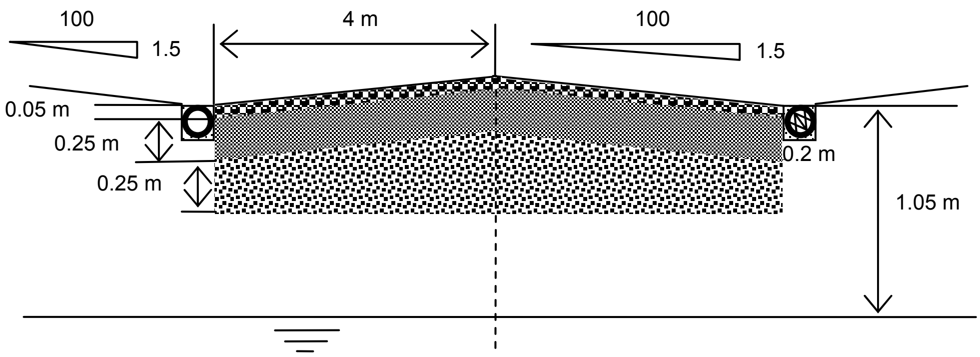


Figure 2: schematic of the porous road simulated.

MODEL 3: secondary Nordic road

Characteristics:

- Thickness asphalt: 50 mm
- Thickness unbound subbase: 250 mm
- Draining pipe: on the surface
- Road surface slope: none
- Subsoil: clay

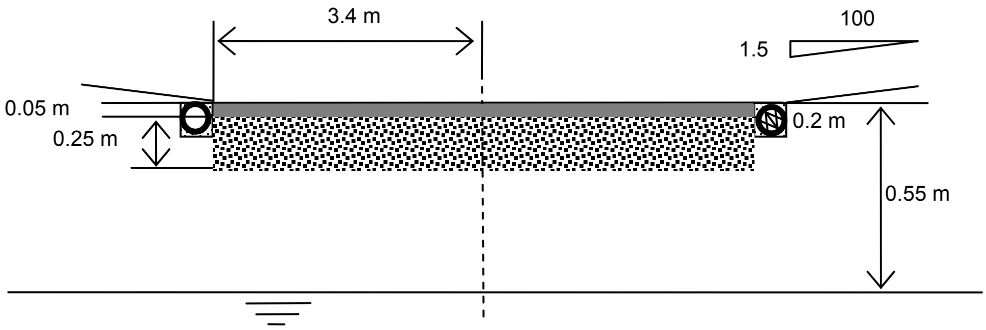


Figure 3: schematic of the secondary Nordic road simulated.

MODEL 4: heavily cracked road

Simulated as if all the rainfall infiltrates and reaches the subbase instantly = no asphaltic surface.

Characteristics:

- Thickness unbound subbase: 250 mm
- Draining pipe: at 1150 mm depth (500 mm from the bottom of the subbase)
- Road surface slope: none
- Subsoil: clay

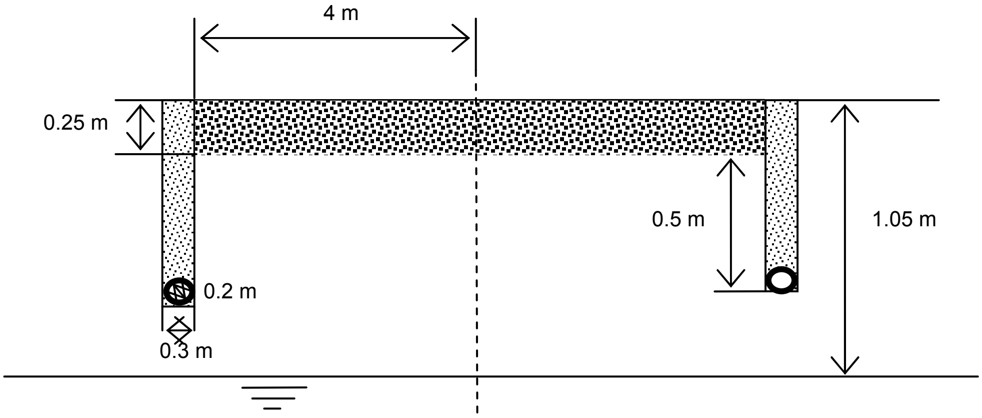


Figure 4: schematic of a heavily cracked road simulated.

2.3 Modelling of the rainfall patterns

The typical rainfall patterns in Europe were firstly studied; the mean yearly amount of rainfall was taken from the graphs produced by Makkonen (see Figure 5) and from the internet (http://www.skyscrapercity.com, http://www.climatetemp.info/ and http://www.lenntech.com/calculators/rain/rainfall-precipitation.htm). It was decided to consider an average yearly rainfall of 800 mm/year.

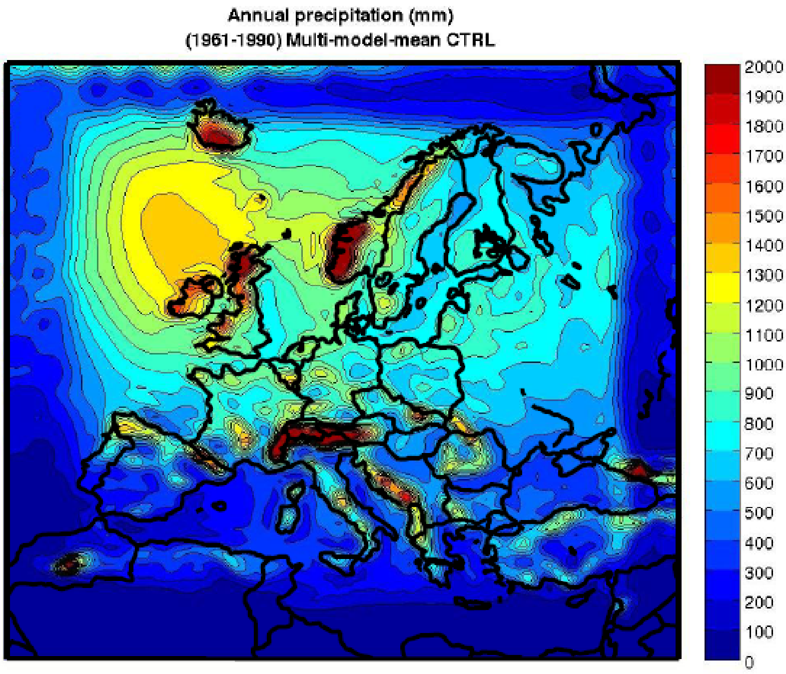


Fig. 5: annual precipitation in Europe in the period between 1961 and 1990.

In order to calculate its distribution, the average number of days per year with more than 0.1 mm of rainfall was taken for each country from http://www.climatetemp.info/, and a mean European value of 170.8 days of rain per year was found. This corresponds to the 46.8% of the year, and it means that it rains every 2.13 days, or 184601 seconds. Considering a rainfall of 800 mm/year, it means that, on average, 4.68 mm of rain fall each time it rains.

The aim of the first simulations was to see how the designed roads respond to different rainfall intensities. Therefore, the models were run simulating a rainfall of 4.68 mm each 2.13 days, in the first case falling within 1 hour (corresponding to 0.0013 mm/sec), and in a second case falling within 6 hours (0.0002 mm/sec) (see figure xx).

It should be considered that rainfall intensity is classified as (http://en.wikipedia.org/wiki/Rain):

- Light rain, when the precipitation rate is < 2.5 mm/hour
- Moderate rain, when the precipitation rate is between 2.5 mm and 10 mm/hour
- Heavy rain, when the precipitation rate is between 10 mm and 50 mm/hour
- Violent rain, when the precipitation rate is > 50 mm/hour.

Therefore, the first case can be considered a moderate rain, while the second case is a light rain.

An extreme case was also studied, simulating rainfalls that were double the amount of rain. The pattern was thus of 0.0026 mm/sec rainfalls for the duration of 1 hour, but every 4.3 days. The rainfall was doubled but the period of dry weather was maintained of 2.13 days in the case of the Nordic secondary road, as the prediction is that the North Europe will be the most affected by the increase of rain.

The last rainfall pattern modelled was characterised by a total rainfall amount of 1000 mm/year, thus 200 mm/year (25%) more than the average rainfall at present. Also, more extreme rainfalls were simulated considering long periods of dry weather (15 days) alternated to 1 hour rainfalls.

Finally, also high water table was simulated as it will be more probable in the future.

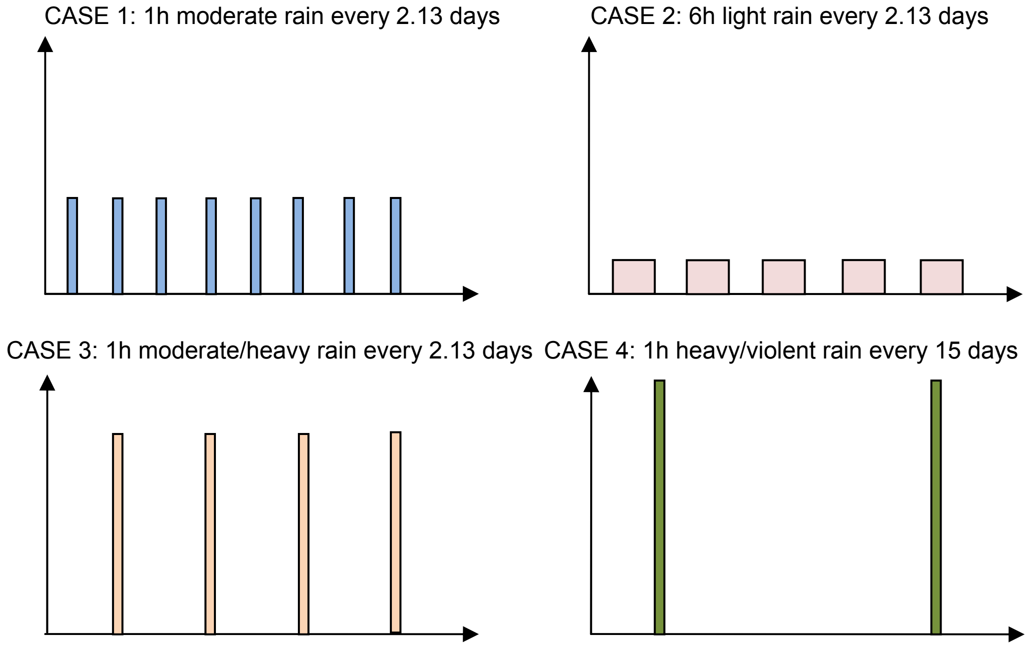


Figure 6: main rainfall patterns modelled.

3 Results

3.1 *Model 1: high volume traffic road*

The subgrade was considered clay, as this is the material that creates more problems. As the asphalt is considered impermeable, the asphaltic surface and base were put as no—flow areas. The rainfall that could not infiltrate in this area, i.e. the runoff water, was simulated as extra rainfall falling above the lateral drain. The results are shown in the next figures.

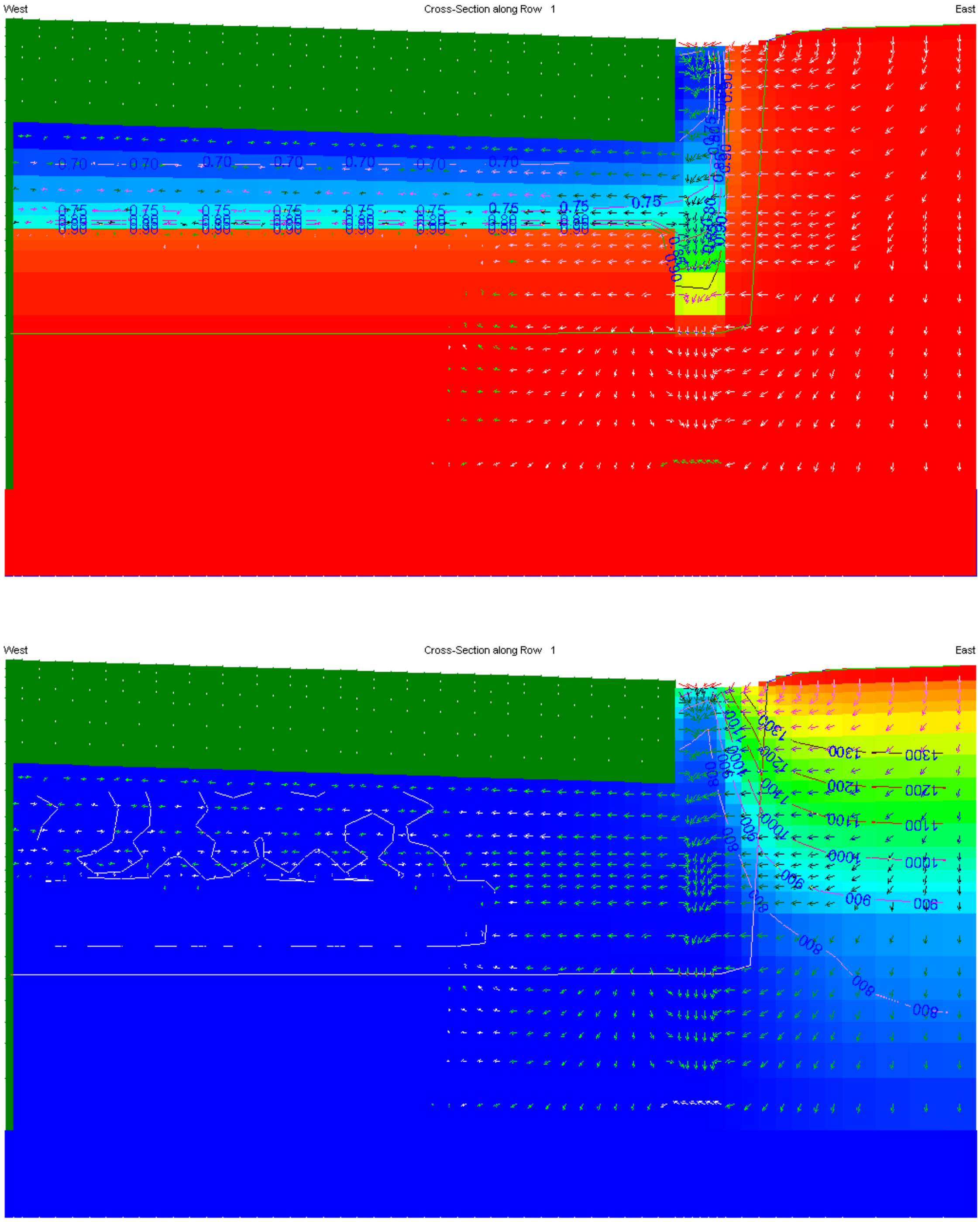


Figure 7: saturation level and head after rainfall, rainfall pattern 1.

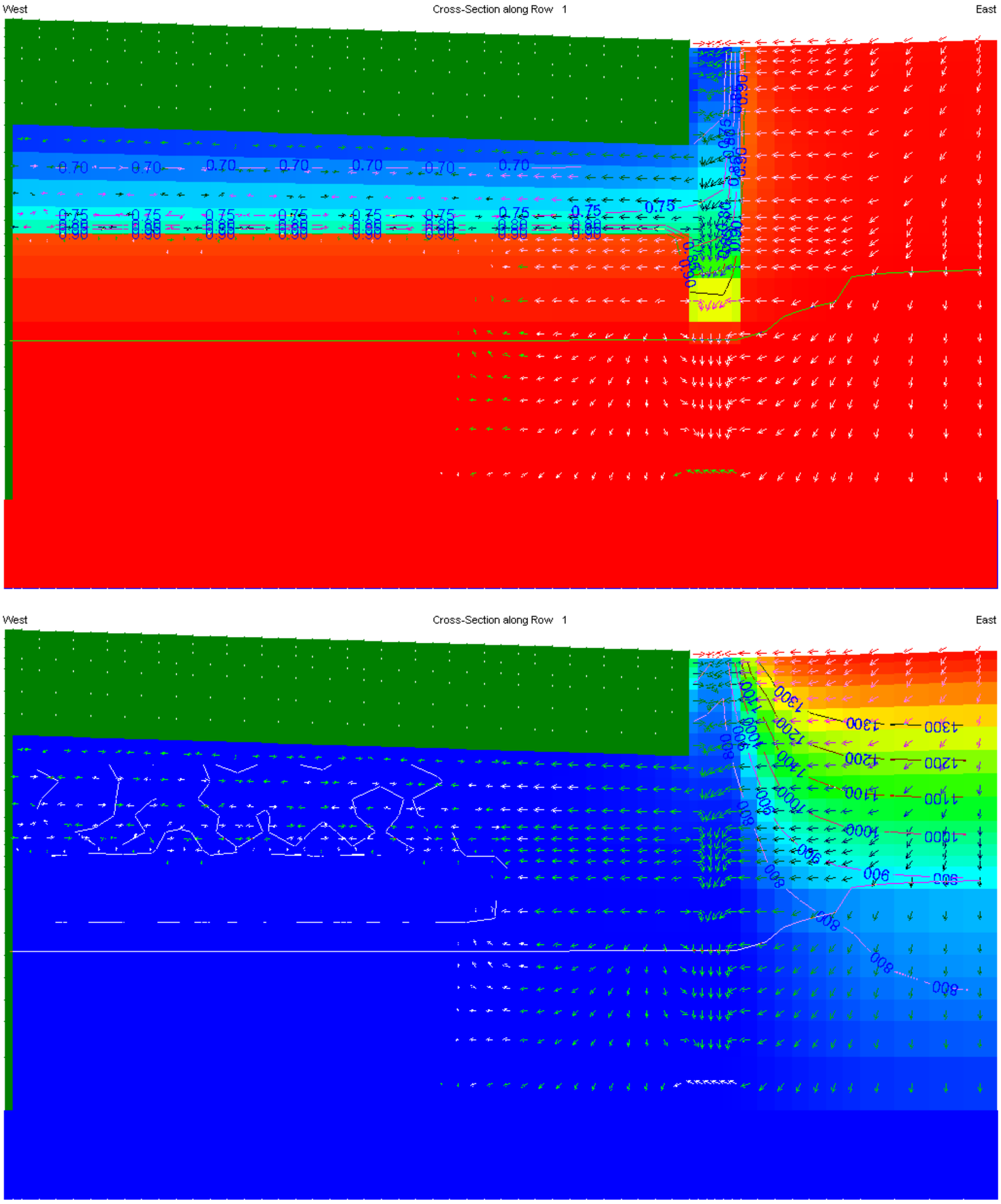


Figure 8: saturation level and head after dry period, rainfall pattern 1.

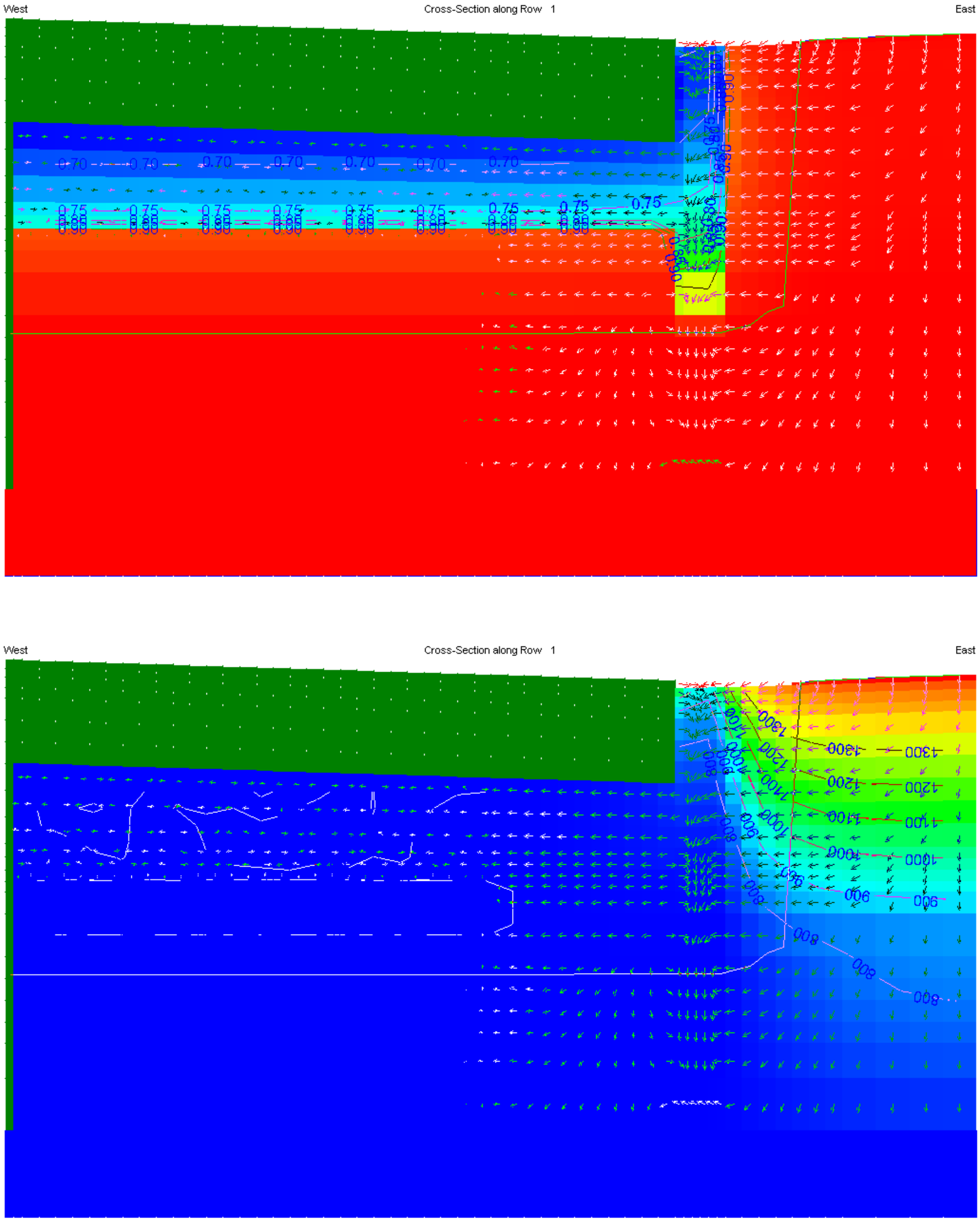
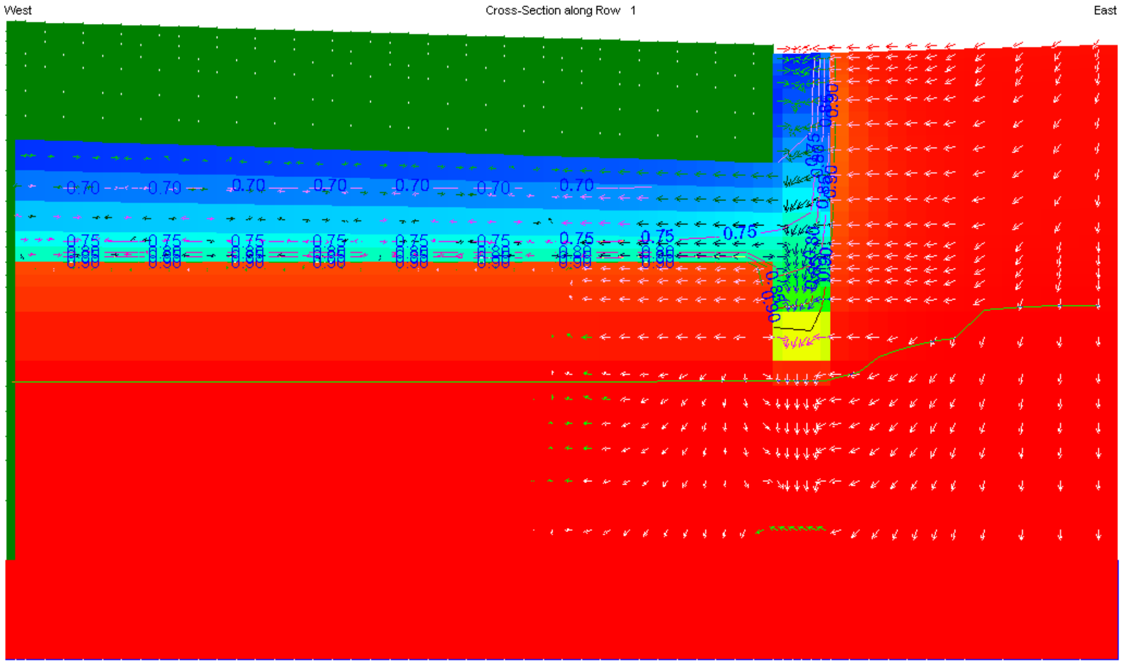


Figure 9: saturation level and head after rainfall, rainfall pattern 2.



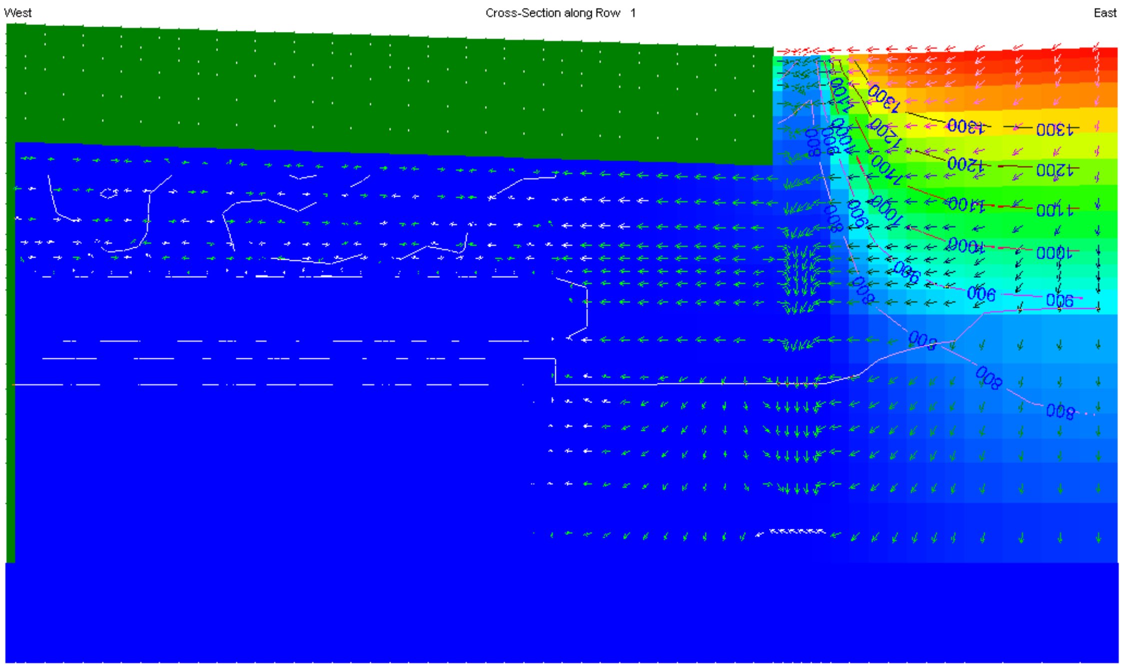


Figure 10: saturation level and head after dry period, rainfall pattern 2.

In these two cases, not much difference can be seen for the subbase; in both cases, it performs well, as saturation never increases too much, not even when the clay around is completely saturated and a rather high flow of water goes from the clay into the lateral drain and then infiltrates in the subbase.

The importance of applying, around the lateral drain, a geotextile able to leave water pass through but to limit the fine material intermixing with the lateral draining aggregate can be seen in the next simulation (figures 11 and 12). Here the draining aggregate on the side was substituted with the same aggregate that forms the subbase, i.e. an aggregate with a rather large grading curve, thus reduced hydraulic conductivity and porosity.

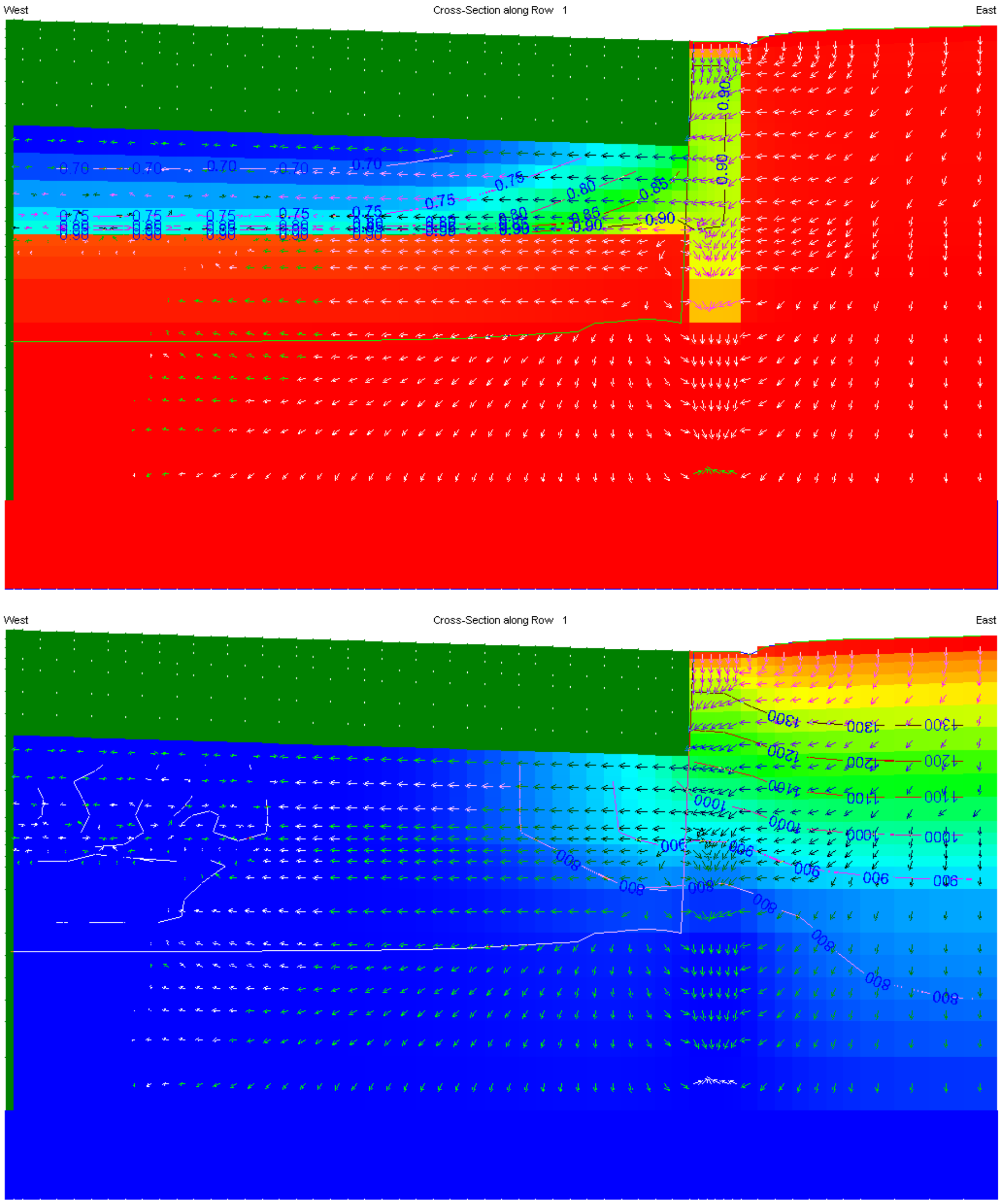


Figure 11: saturation level and heads, after rainfall, of a road where the draining materials has mixed with finer soil.

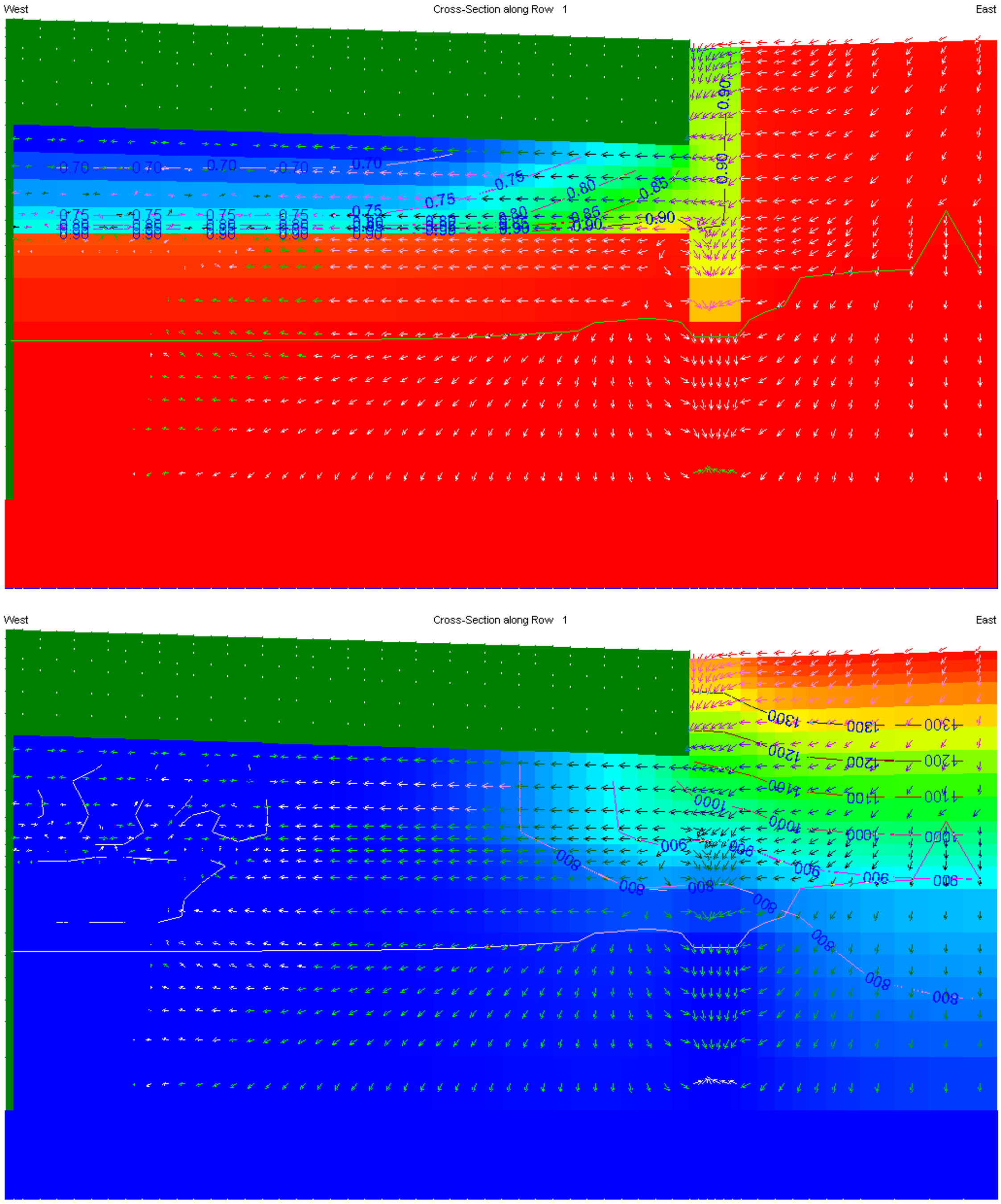


Figure 12: saturation level and heads, after dry weather, of a road where the draining materials has mixed with finer soil.

It can be seen that now the saturation of the subbase closer to the side of the road has increased, and remains higher even after a period of dry weather.

Also the simulation of the rainfall pattern n. 4 seems to show a subbase that keeps an acceptable level of saturation (figures 13 and 14).

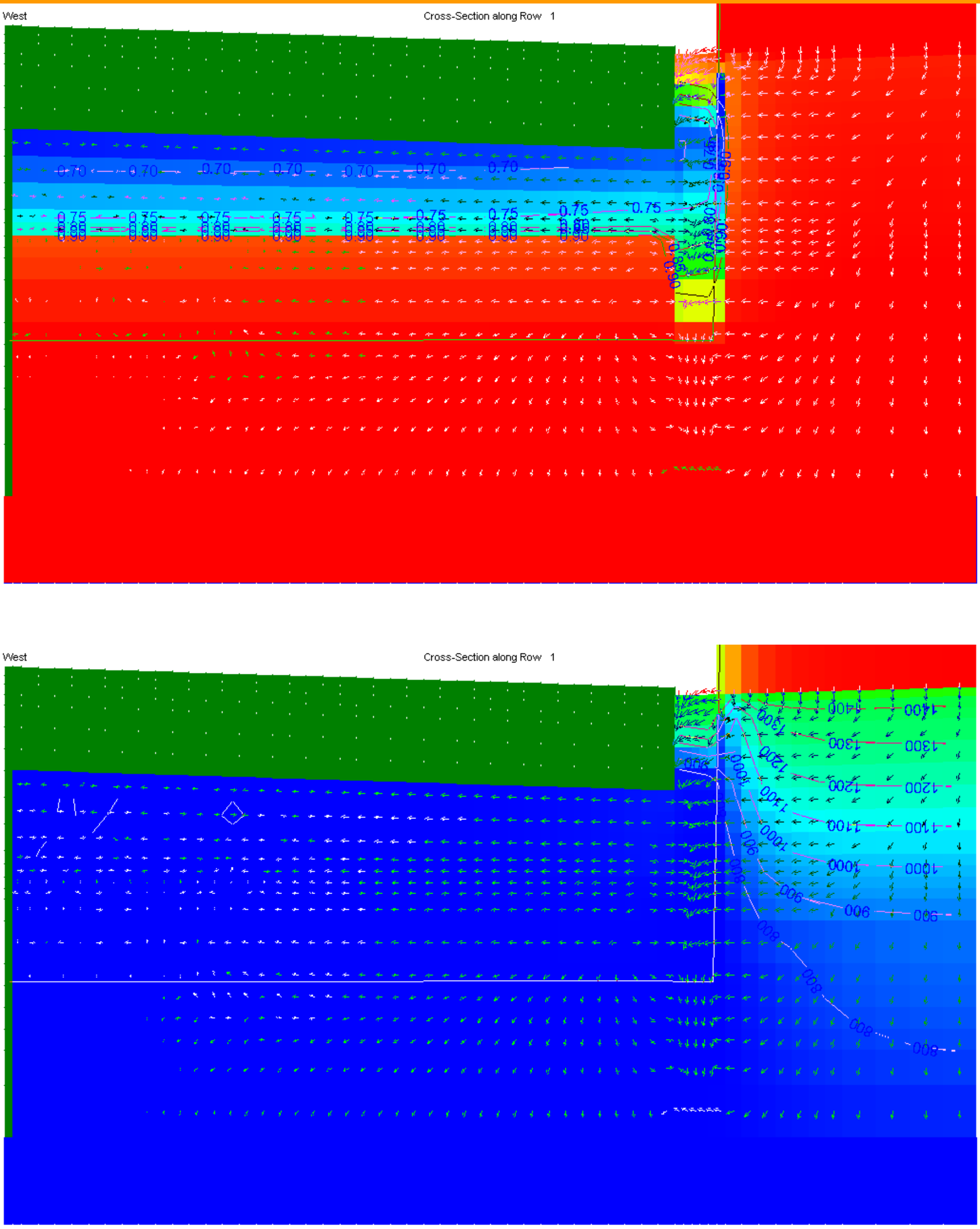


Figure 13: saturation level and head after rain, rainfall pattern 4.

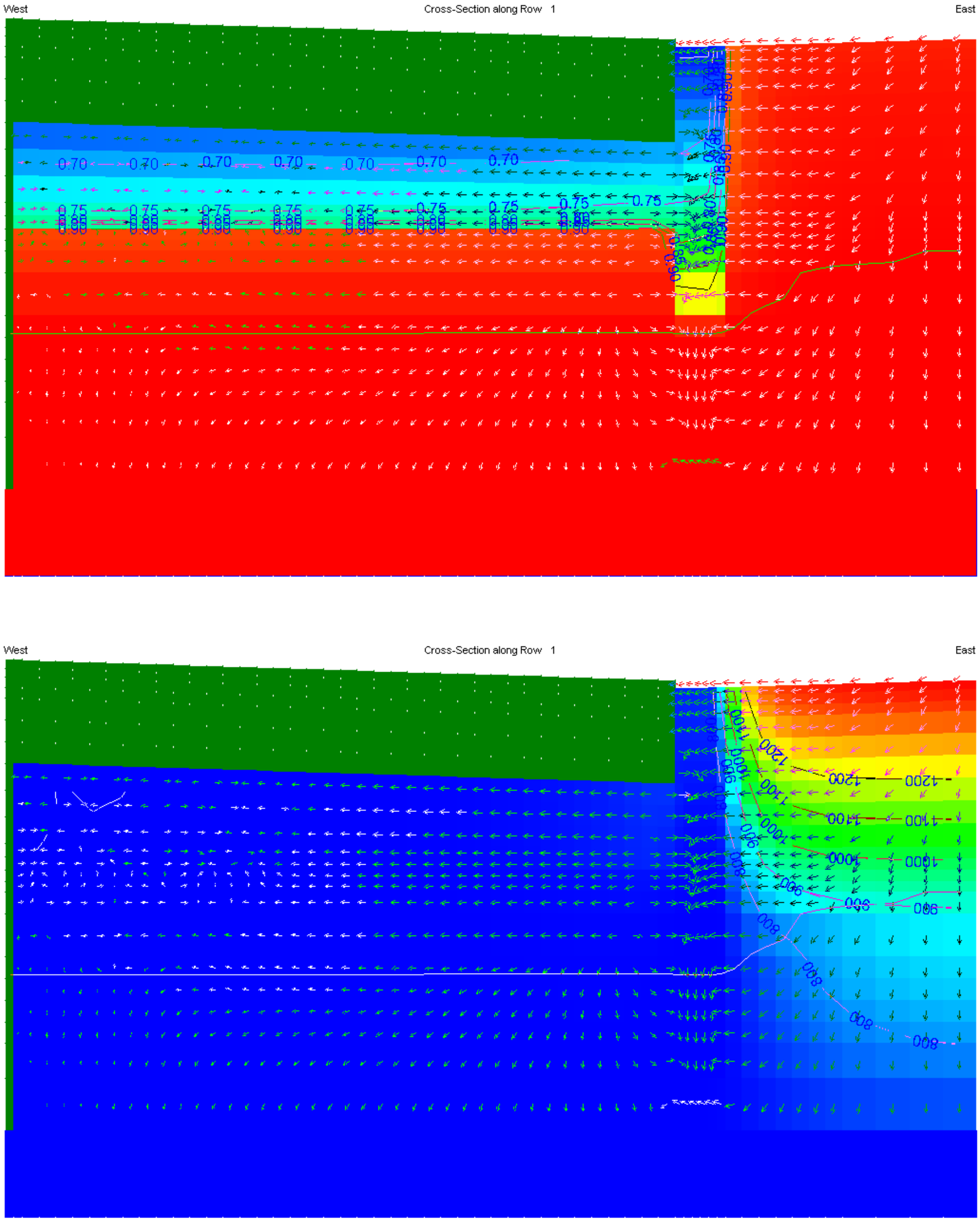


Figure 14: saturation level and head after dry period, rainfall pattern 4.

However, it must be considered that the program badly deals with the runoff, and in this case the runoff from the soil around seems to be not negligible (see high levels of water above lateral surface), and this water, infiltrating into the lateral drainage, is likely to increase the saturation of both the lateral draining material ad the subbase. Therefore, a surface lateral drain was added. The results are shown in figure 15.

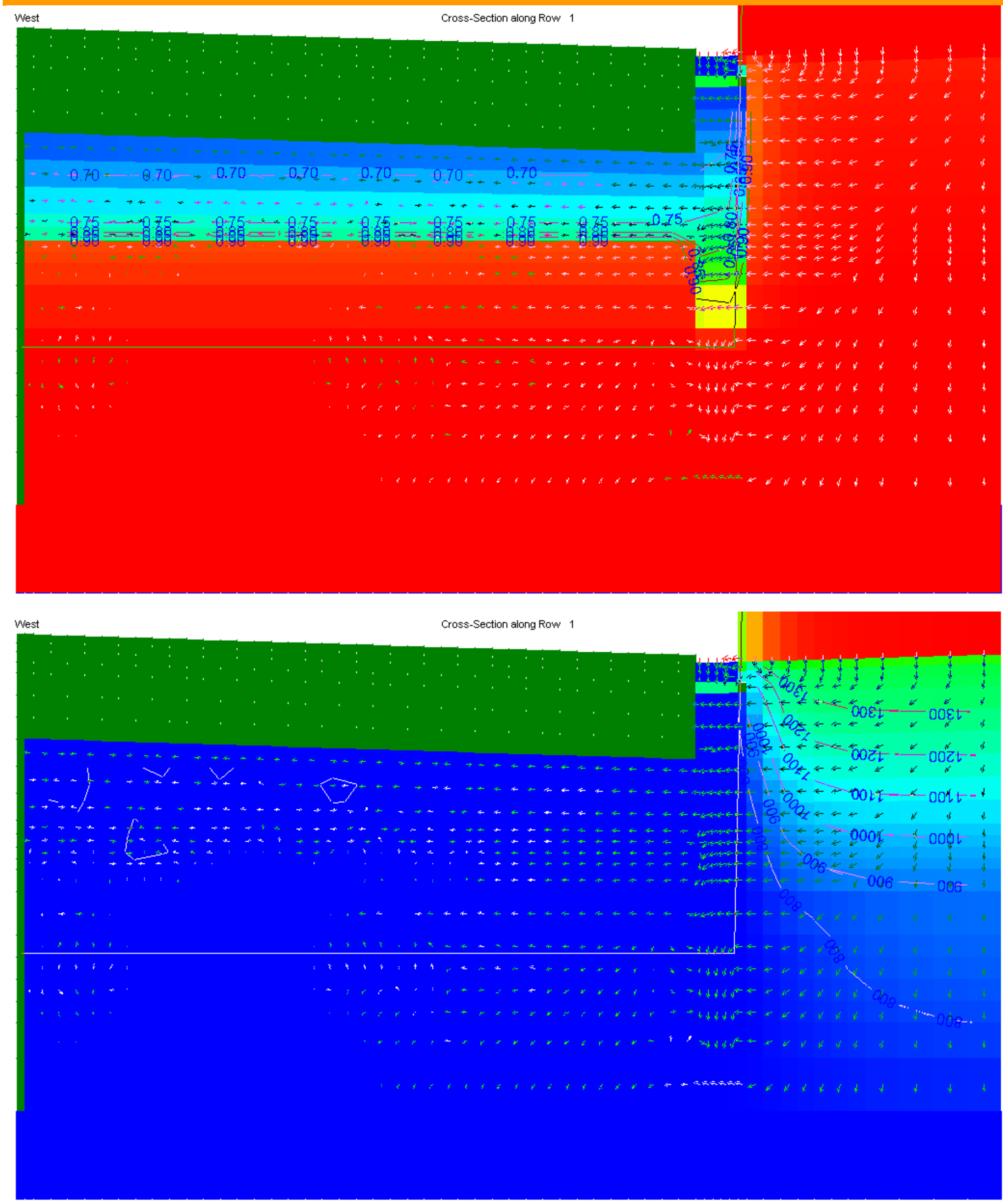


Figure 15: saturation level and head after rain, rainfall pattern 4, where a surface drain is added.

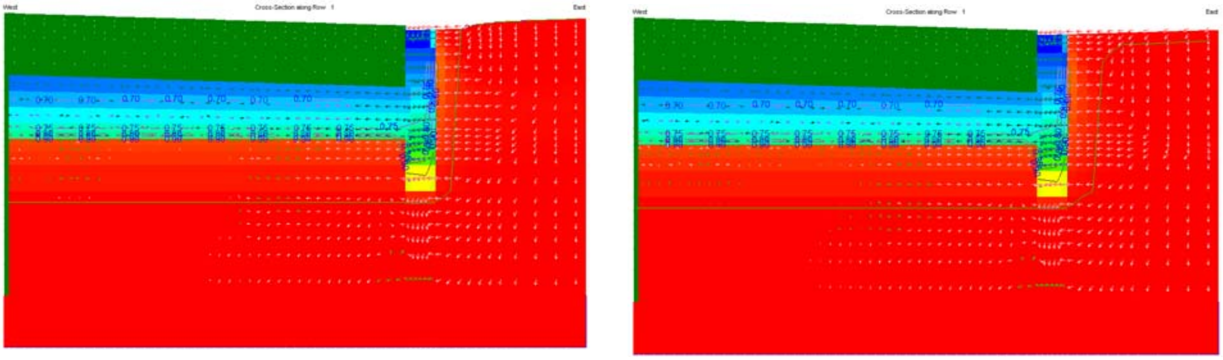
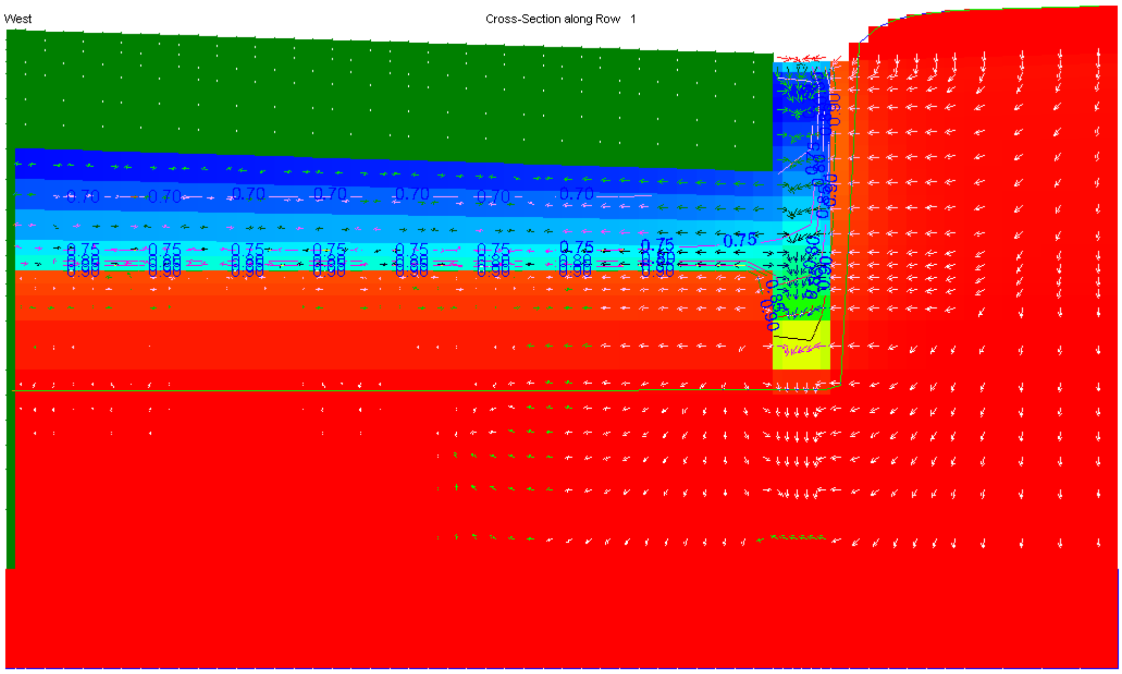


Figure 16: saturation level about 25 hours and 50 hours after rain, rainfall pattern 4, (surface drain added).

In this case, the runoff water from the top does not infiltrate and thus the lateral draining layer allows the flow of only the water that infiltrates into the clayey soil. After less than 2 days, the situation is almost normal (figure 16).

This result shows the importance of the presence of a surface drain to sustain the high levels of runoff water that can be expected as the precipitation tends to increase.

A similar situation, although less marked, was observed when simulating the rainfall pattern n. 3: again, even if there seems to be no problem for the subbase (figure 17 and 18), a much higher runoff into the later drain must be considered, and therefore a surface lateral drain (figure 19) is added.



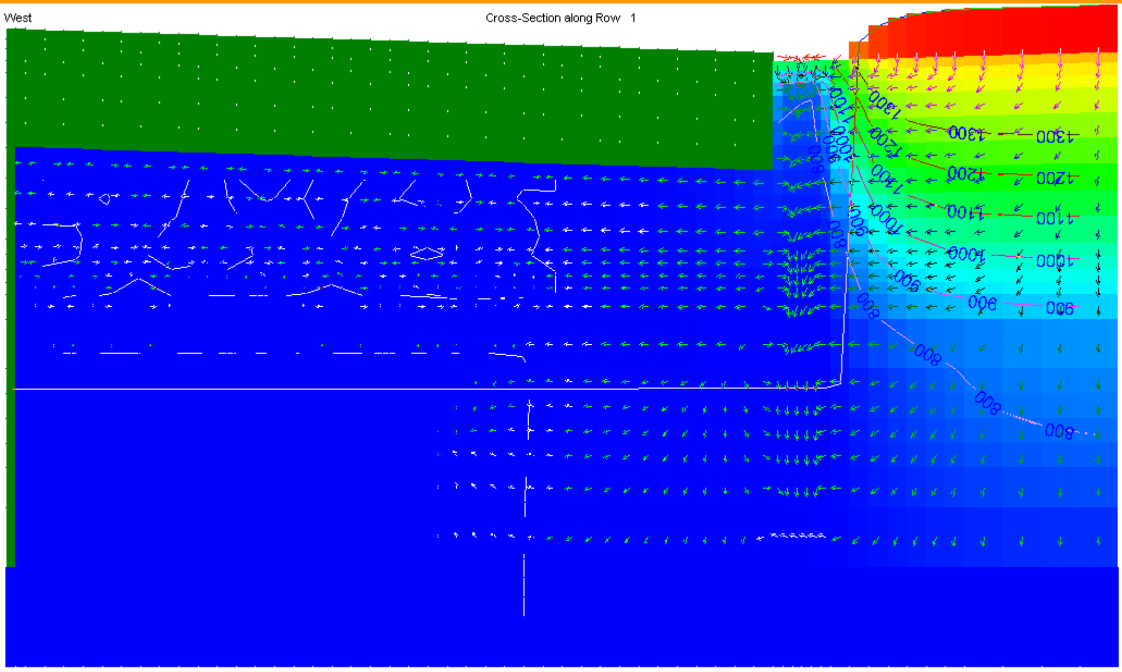
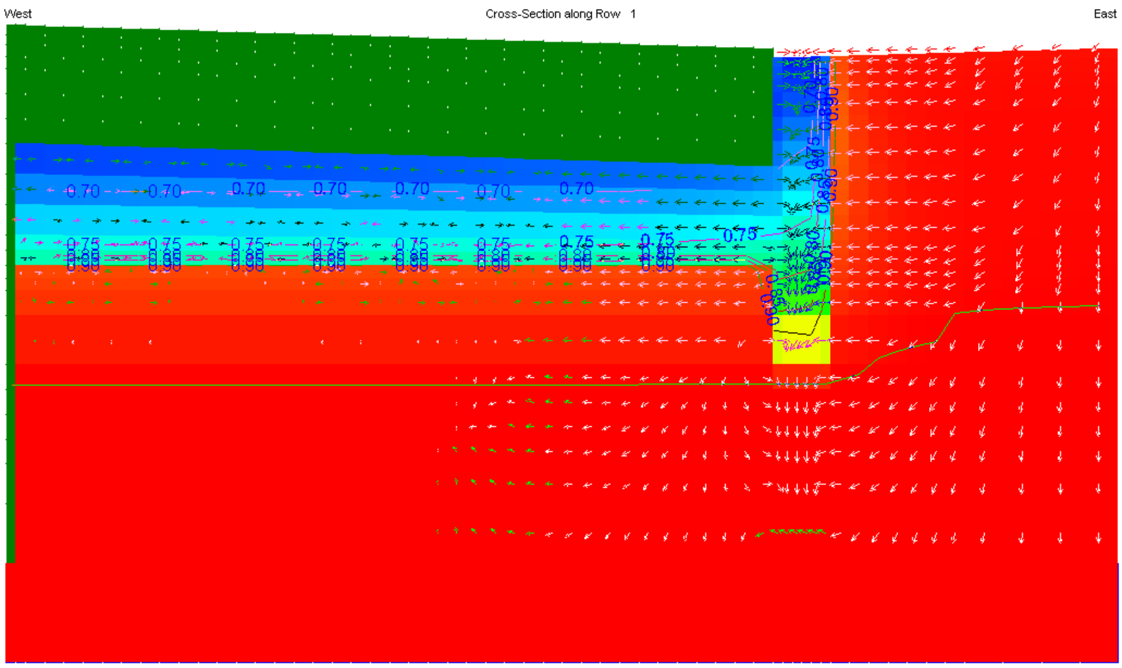


Figure 17: saturation level and head after rain, rainfall pattern 3.



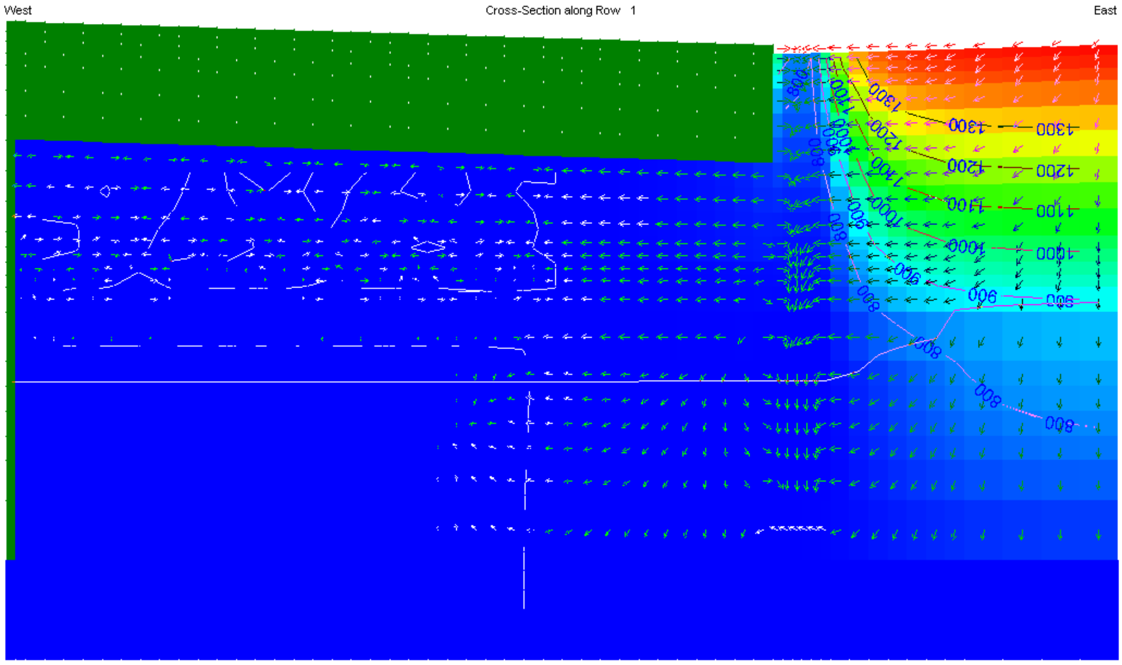


Figure 18: saturation level and head after dry period, rainfall pattern 3.

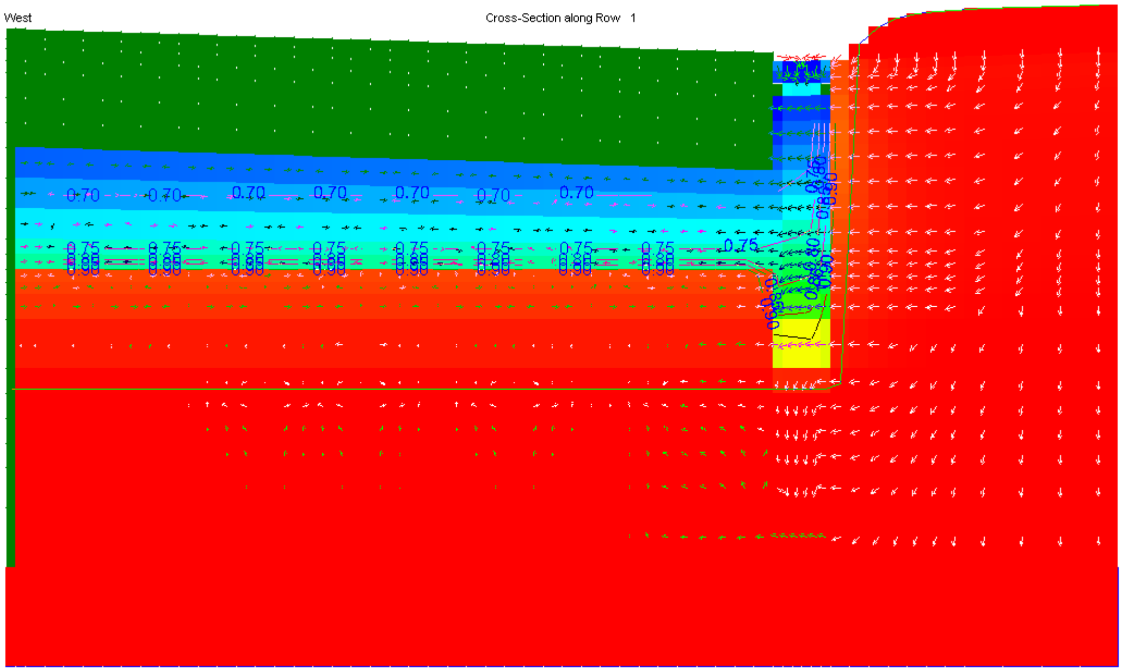
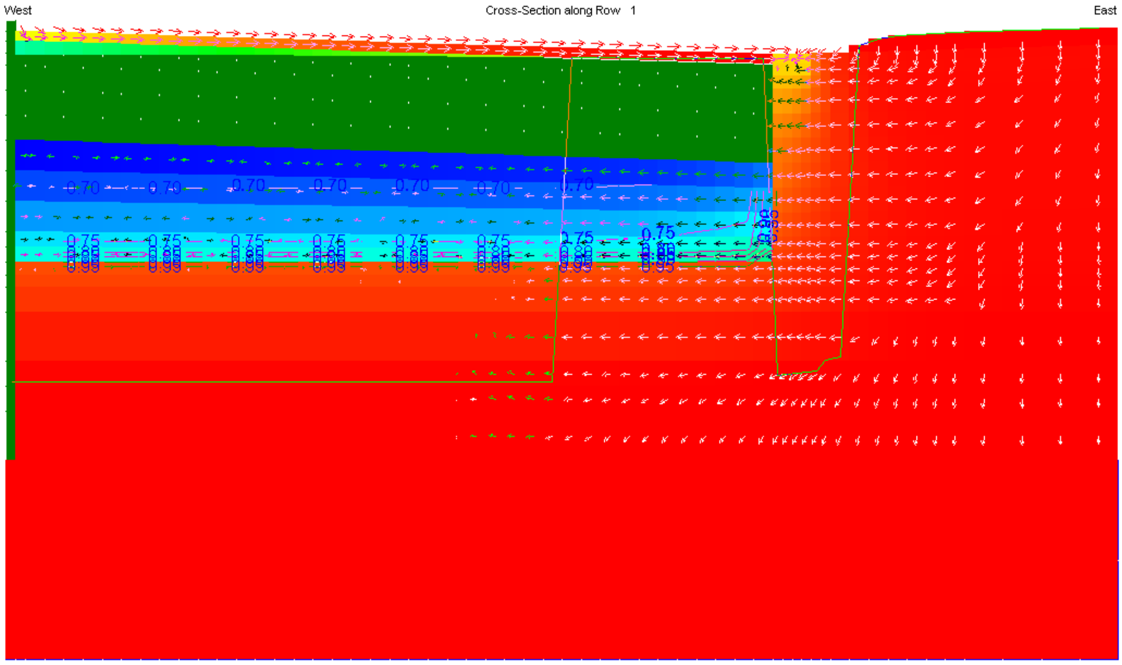


Figure 19: saturation level after rain, rainfall pattern 3, where a surface drain is added.

3.2 *Model 2: Porous asphalt road*

As for the high volume traffic roads, porous asphalt seems to perform well with different rainfall patterns (figures 20 to 23). Water does not seem to accumulate on the top of the road surface, and it maintains itself below saturation level.



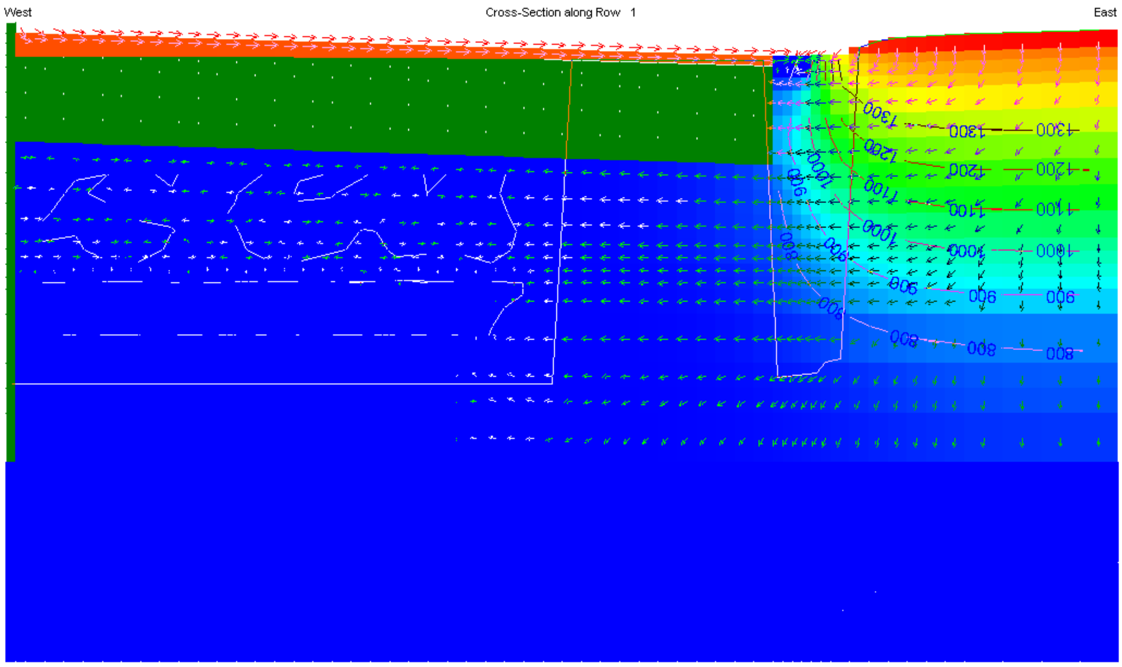
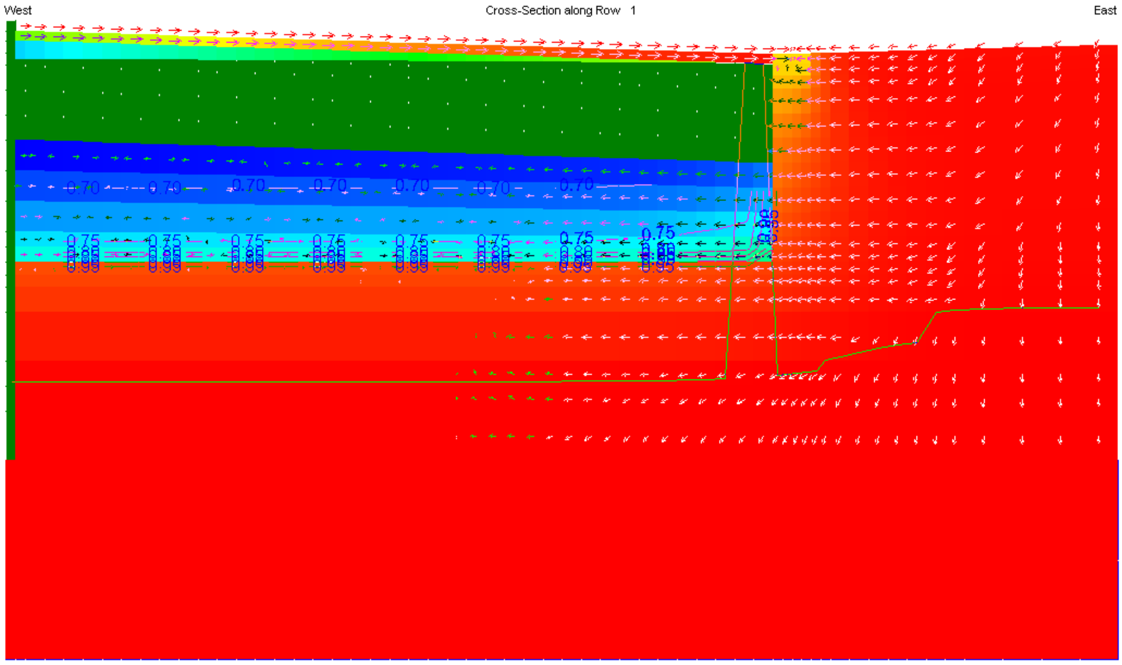


Figure 20: saturation level and head after rain, rainfall pattern 1.



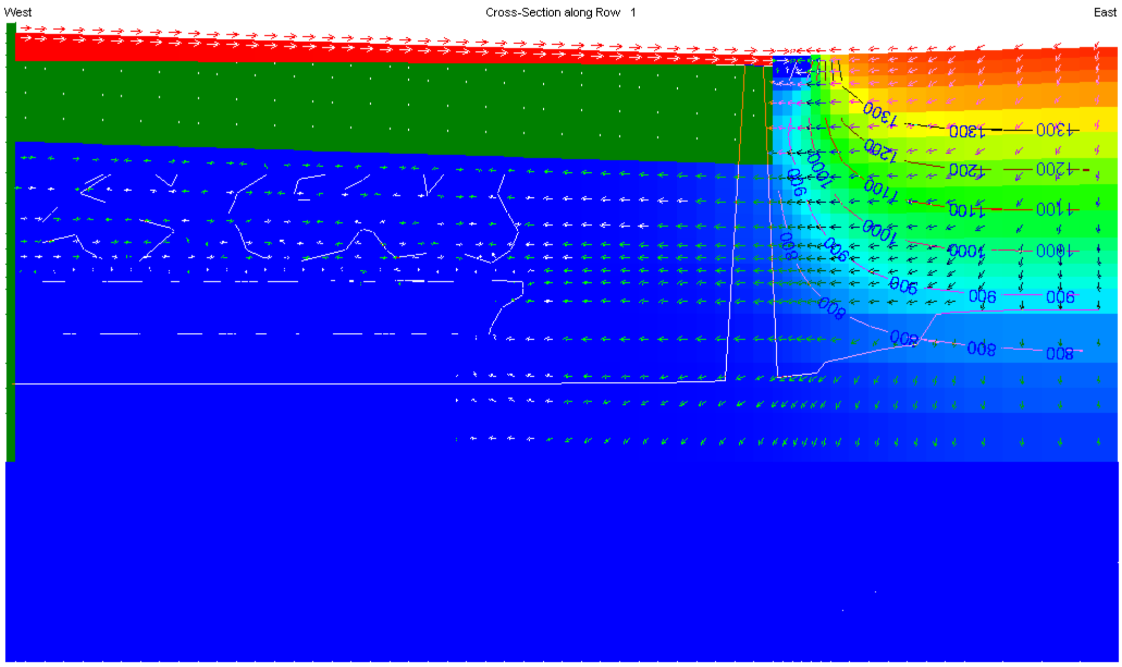


Figure 21: saturation level and head after dry period, rainfall pattern 1.

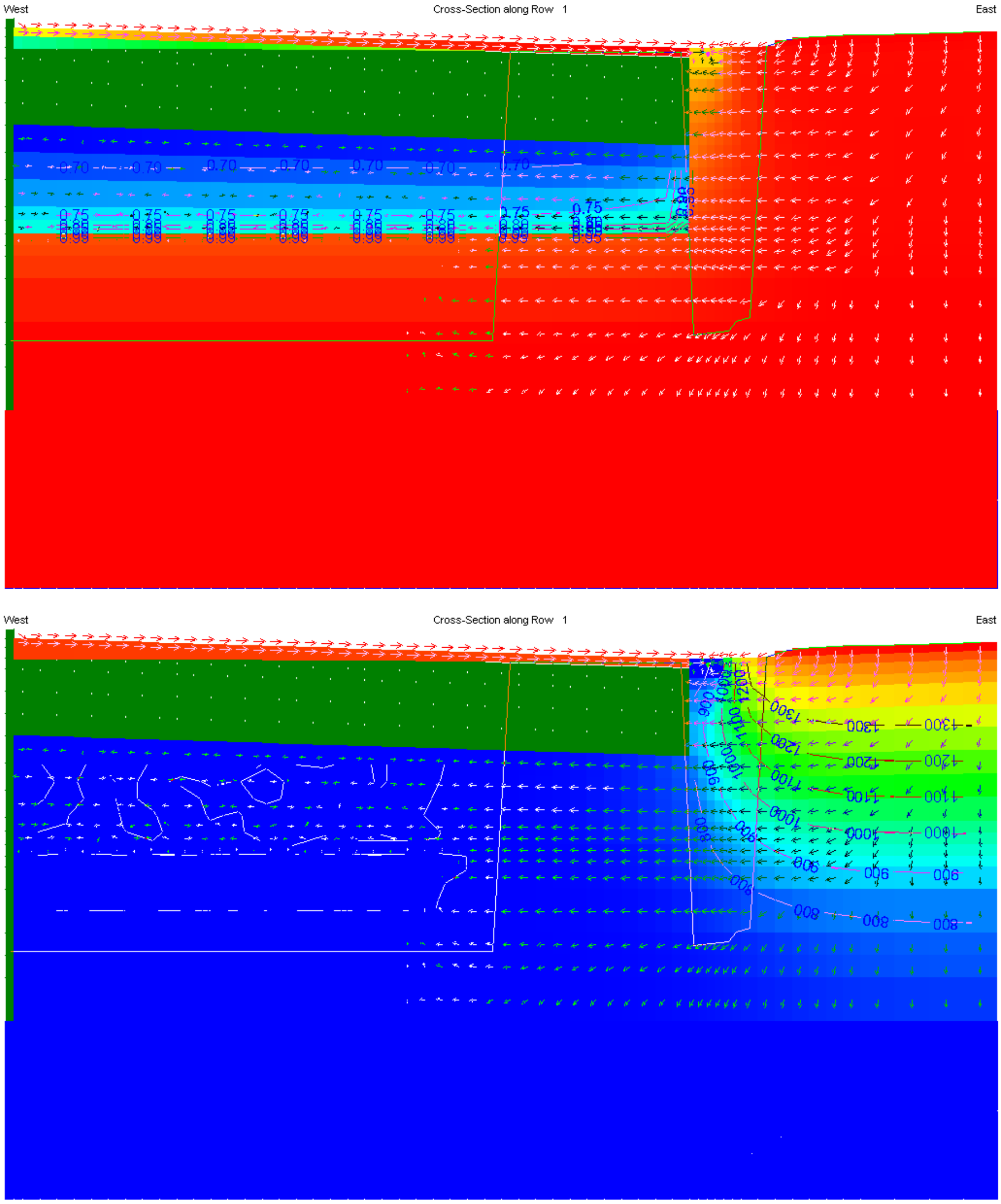


Figure 22: saturation level and head after rain, rainfall pattern 2.

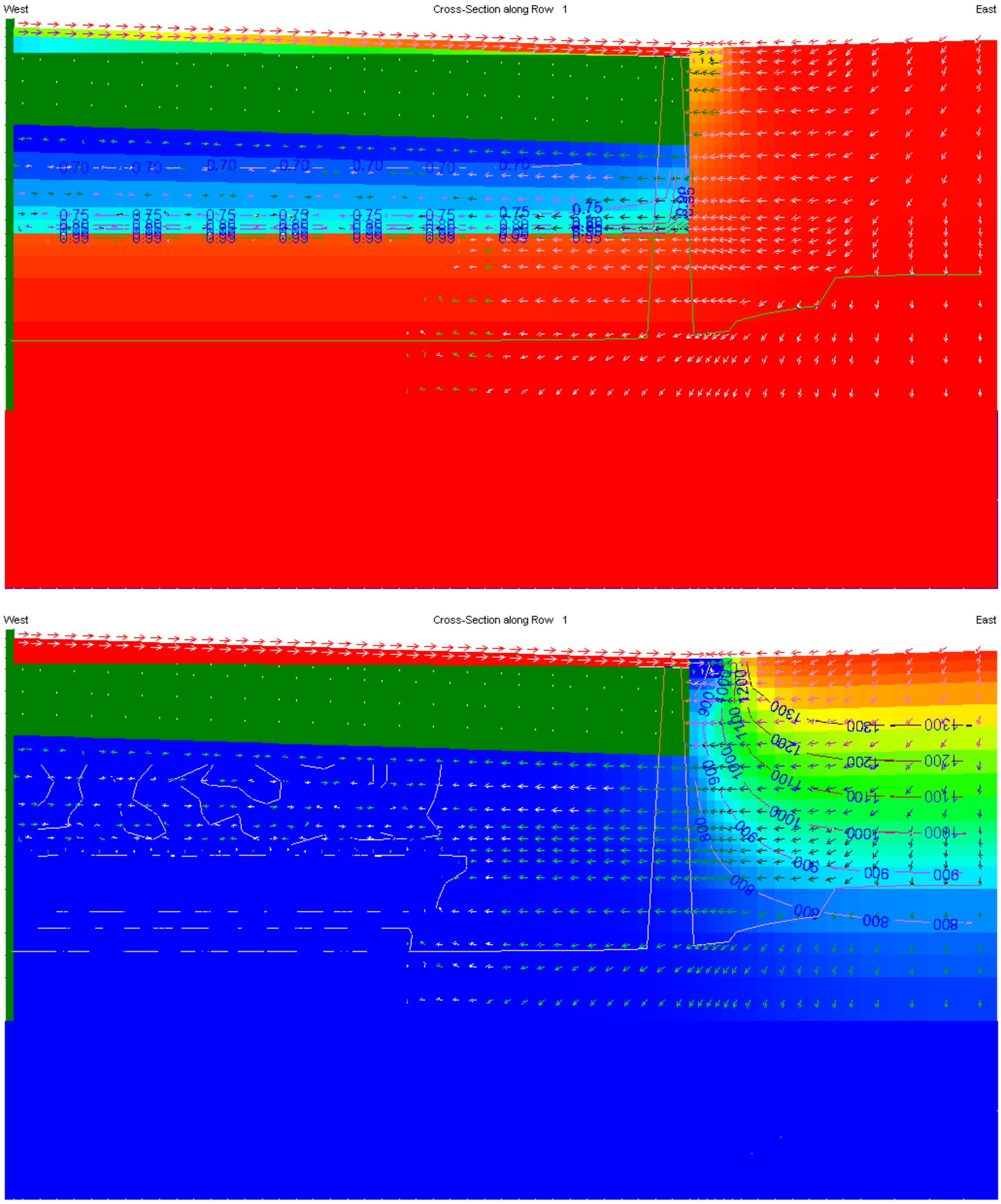


Figure 23: saturation level and head after dry period, rainfall pattern 2.

A more intense rainfall pattern (case 3, figure 24) shows only a slight increase of saturation level in the porous asphaltic layer on the sides of the road, but saturation does not reach the surface, while the subbase does not show any remarkable increase in saturation level.

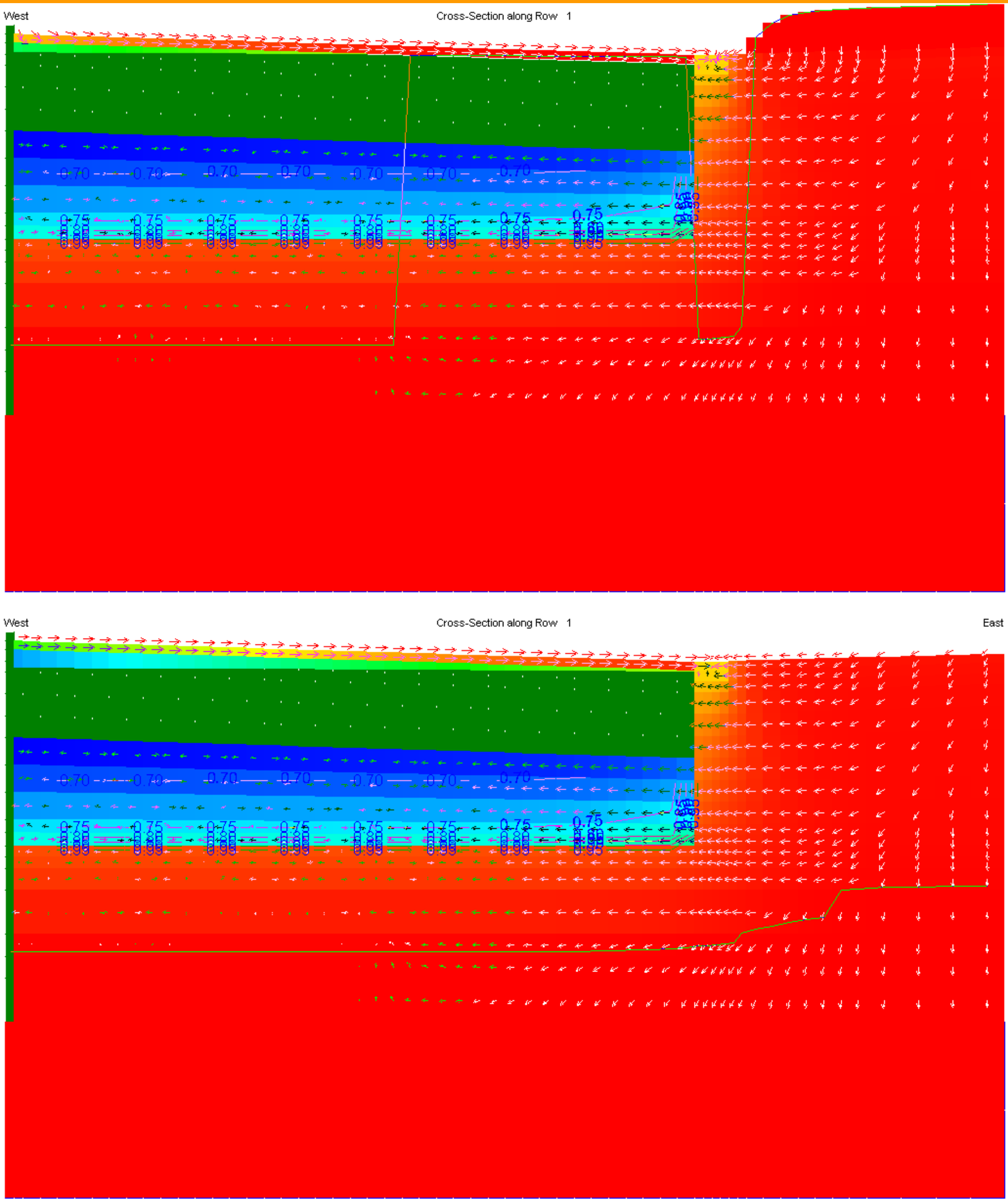


Figure 24: saturation level and head after rainfall and after dry period, rainfall pattern 3.

It should be noted that, in the case of porous asphalt, the presence of a subsurface drainage system below the level of the subbase does not seem to be necessary, however, as it can be seen in figure 25, its presence would help keeping the aggregate drier.

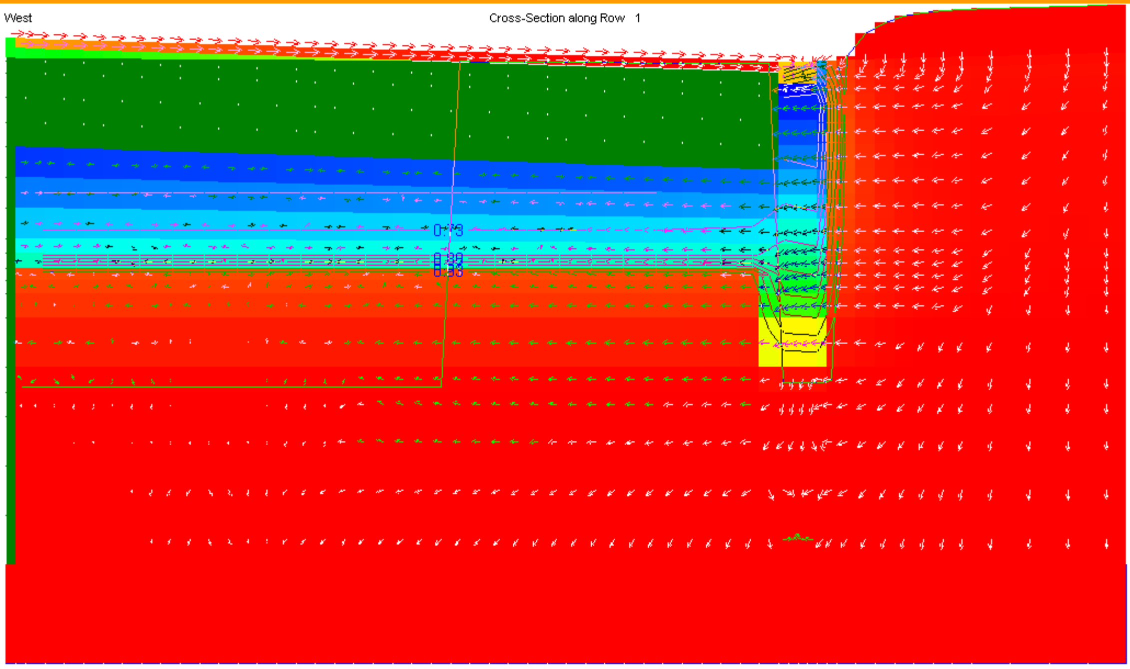
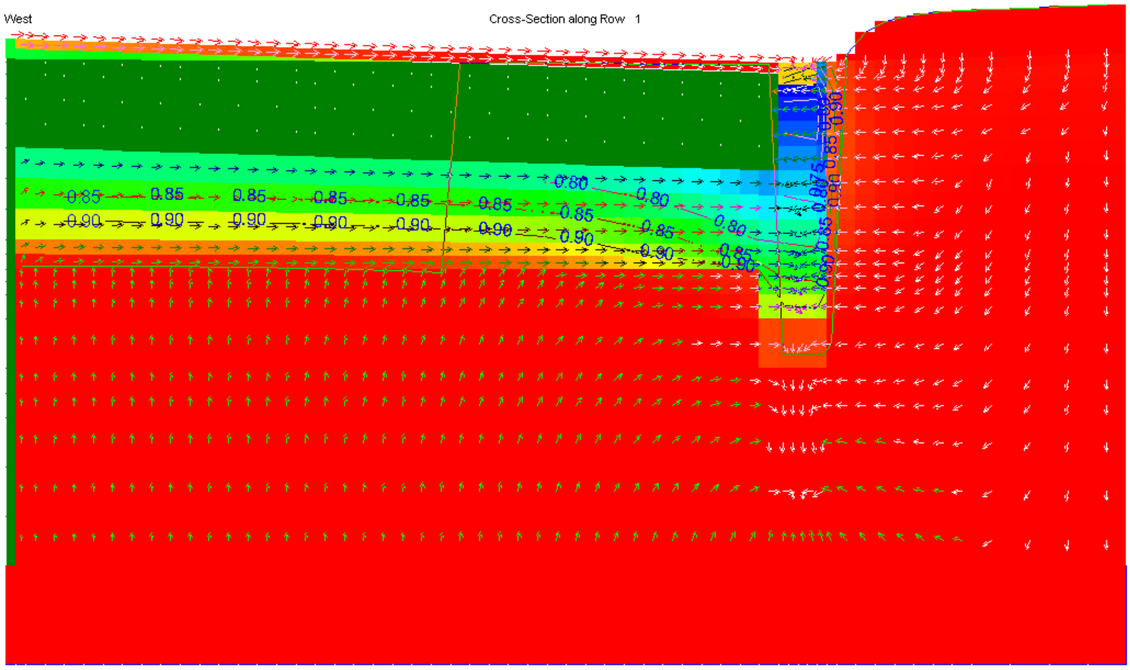


Figure 25: saturation level after rain for case 3, with a subsurface drainage system added.

The problem of a high level of saturation in the subbase appears in presence of a high water table, as it can be seen in figure 26 and 27. In this case, independently on the amount of rain falling, the saturation of the subbase is rather high. However, the subbase works as a barrier, not allowing water to reach the asphalt treated base.



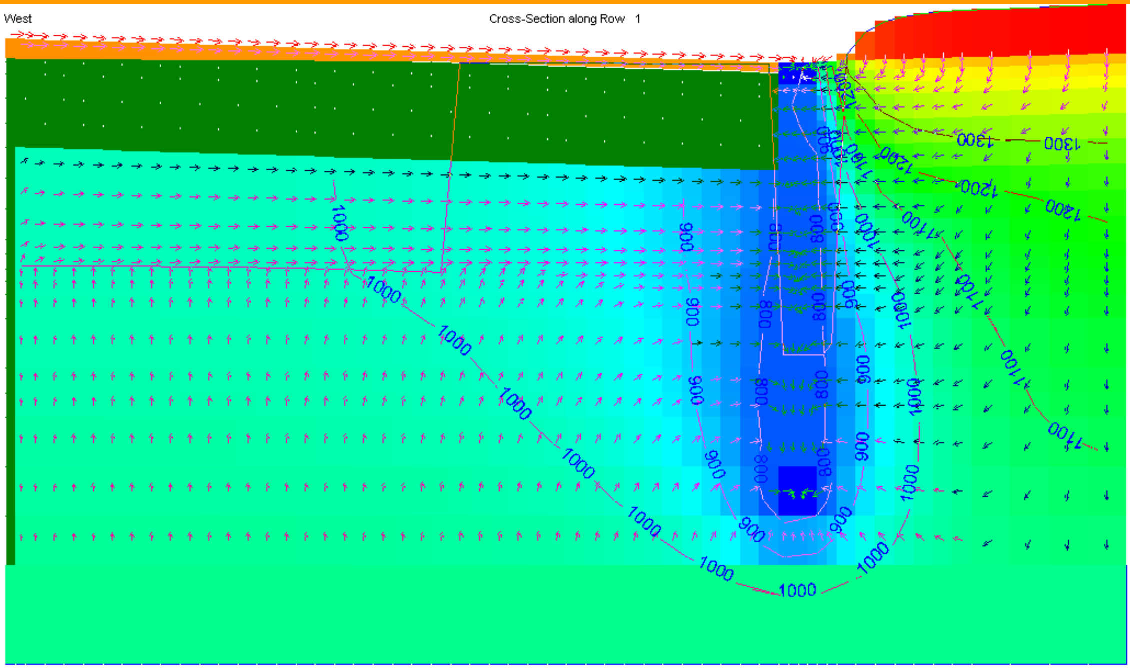
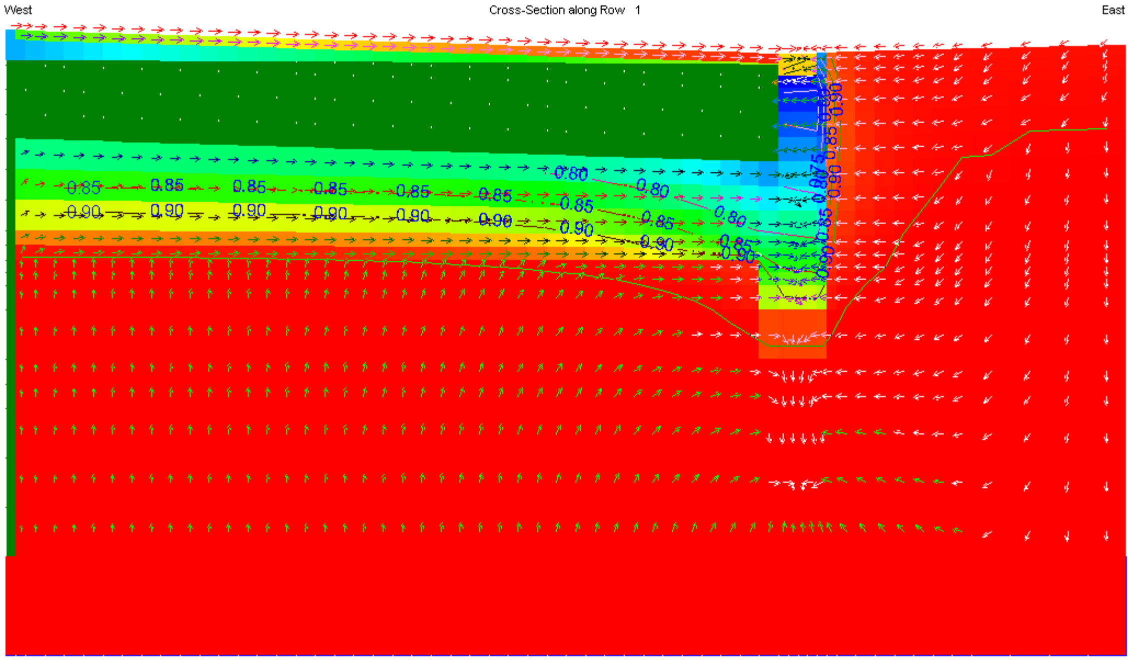


Figure 26: saturation level after rainfall in presence of a high watertable (case 3).



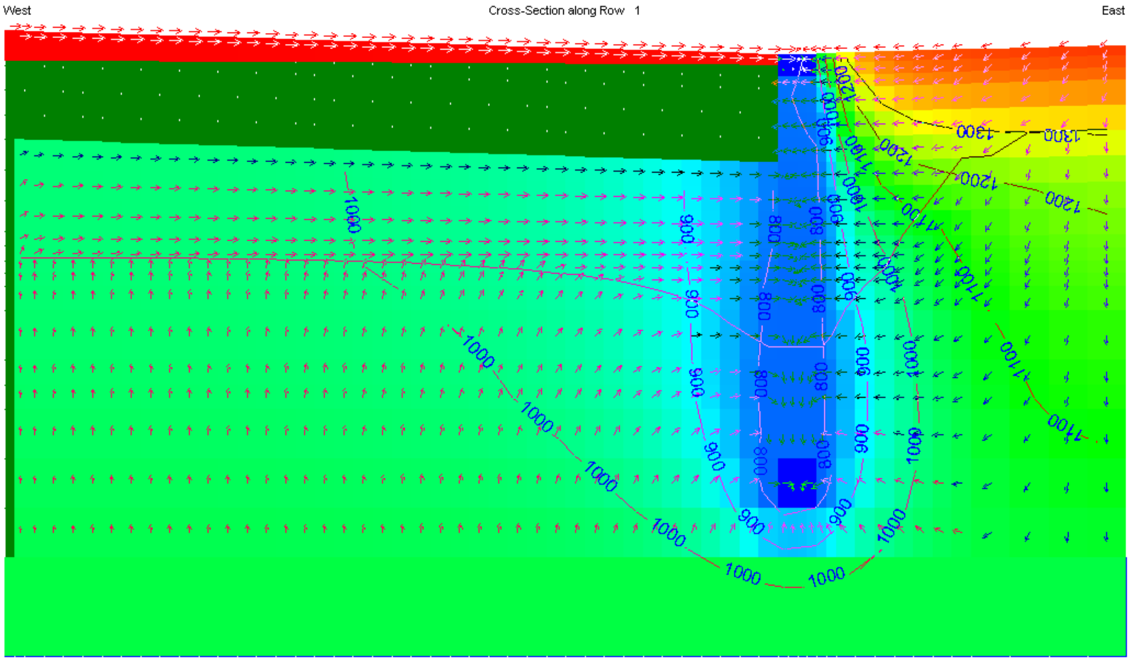


Figure 27: saturation level after a dry period in presence of a high watertable (case 3).

In this case, a solution that is commonly taken is to put a layer of draining aggregate between the subbase and the subgrade. This layer is tipically 100 to 150 mm thick (Watmove, 2008) and its bed must have a cross-fall of between 2% to 4% inclination, starting 1.0 meter away from the paved area. This situation has been simulated, considering an inclination of 3% (see scheme in figure 28). The results are shown in figure 29 and 30. It can be noticed that the results are quite good, although sometimes they might not be enough.

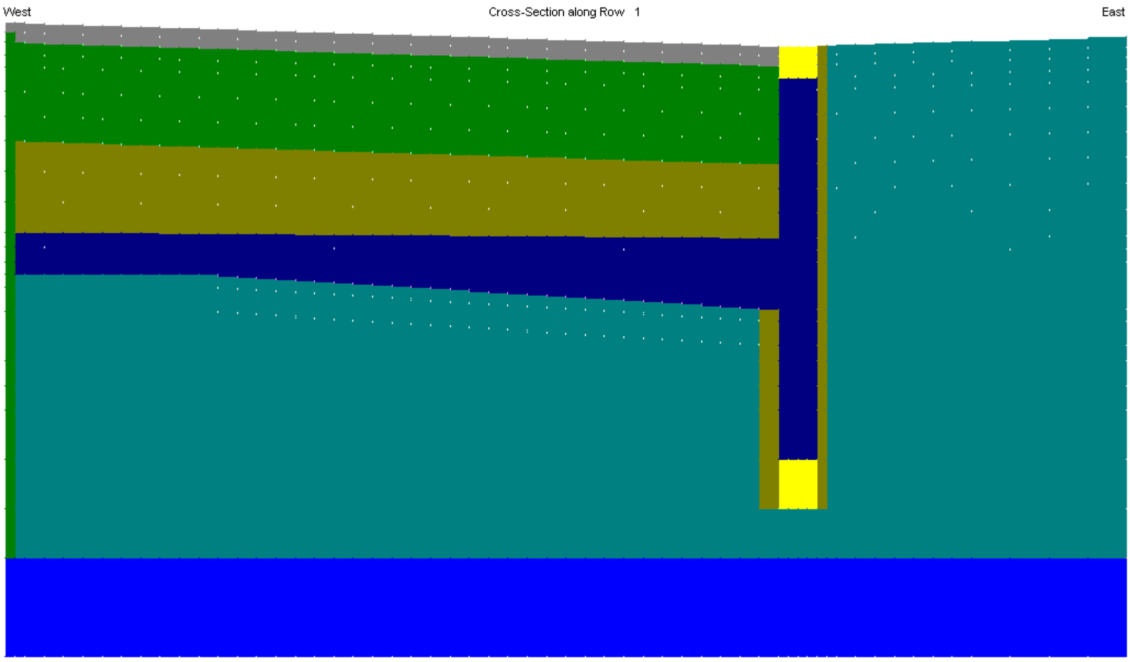


Figure 28: schematic of the model.

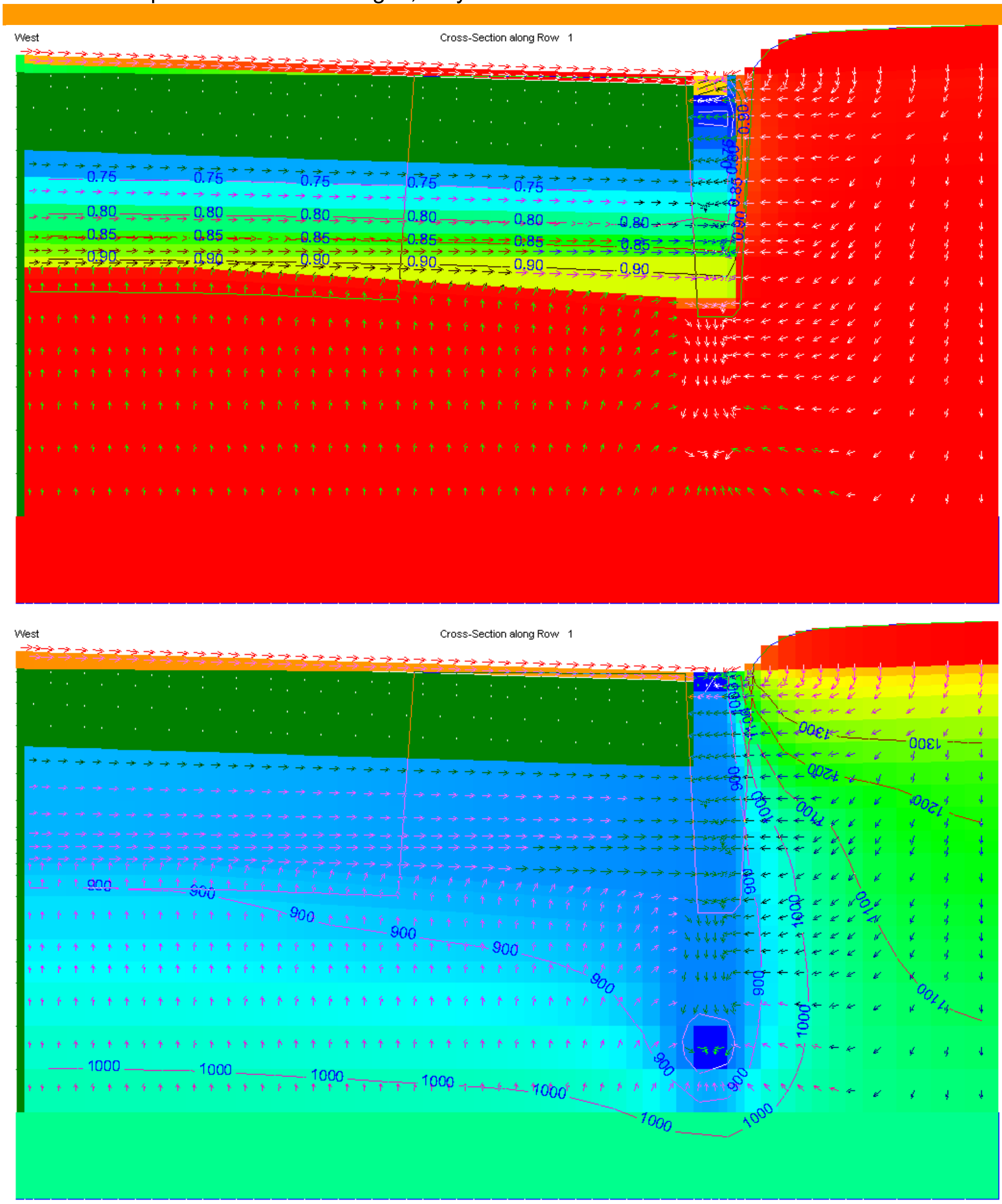


Figure 29: saturation level and head after rain (case 3), drainage layer between subbase and subgrade.

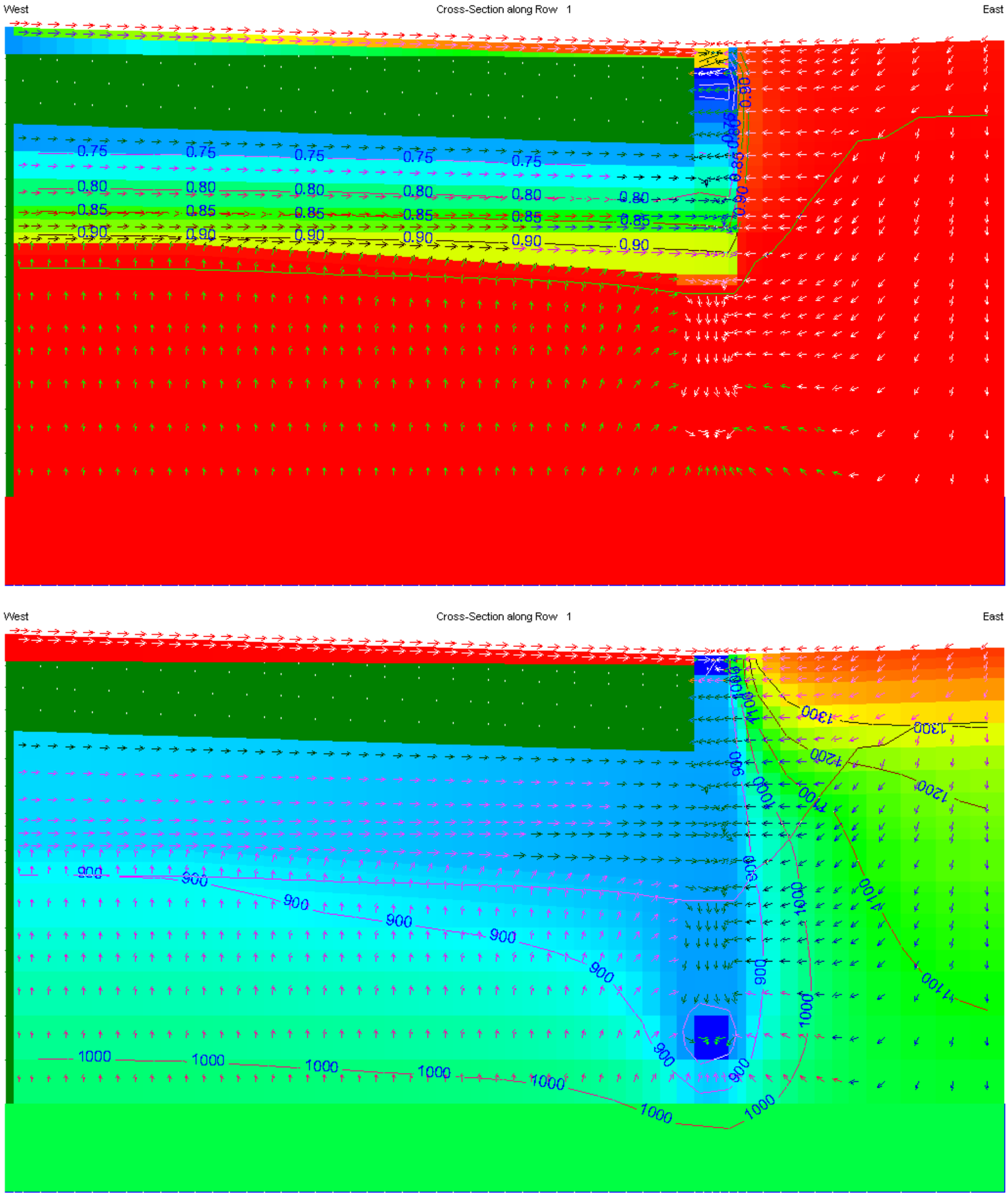


Figure 30: saturation level and head after dry period (case 3), drainage layer between subbase and subgrade.

Alternatively, in order to contrast the effect of high watertable levels on the subbase, the presence of a geotextile that works as an impermeable barrier can be very helpful: a geotextile put between the subgrade and the subbase does not allow water to infiltrate into the subbase, thus keeping its saturation level low (figure 31). The resulting saturation of the subbase is now much lower.

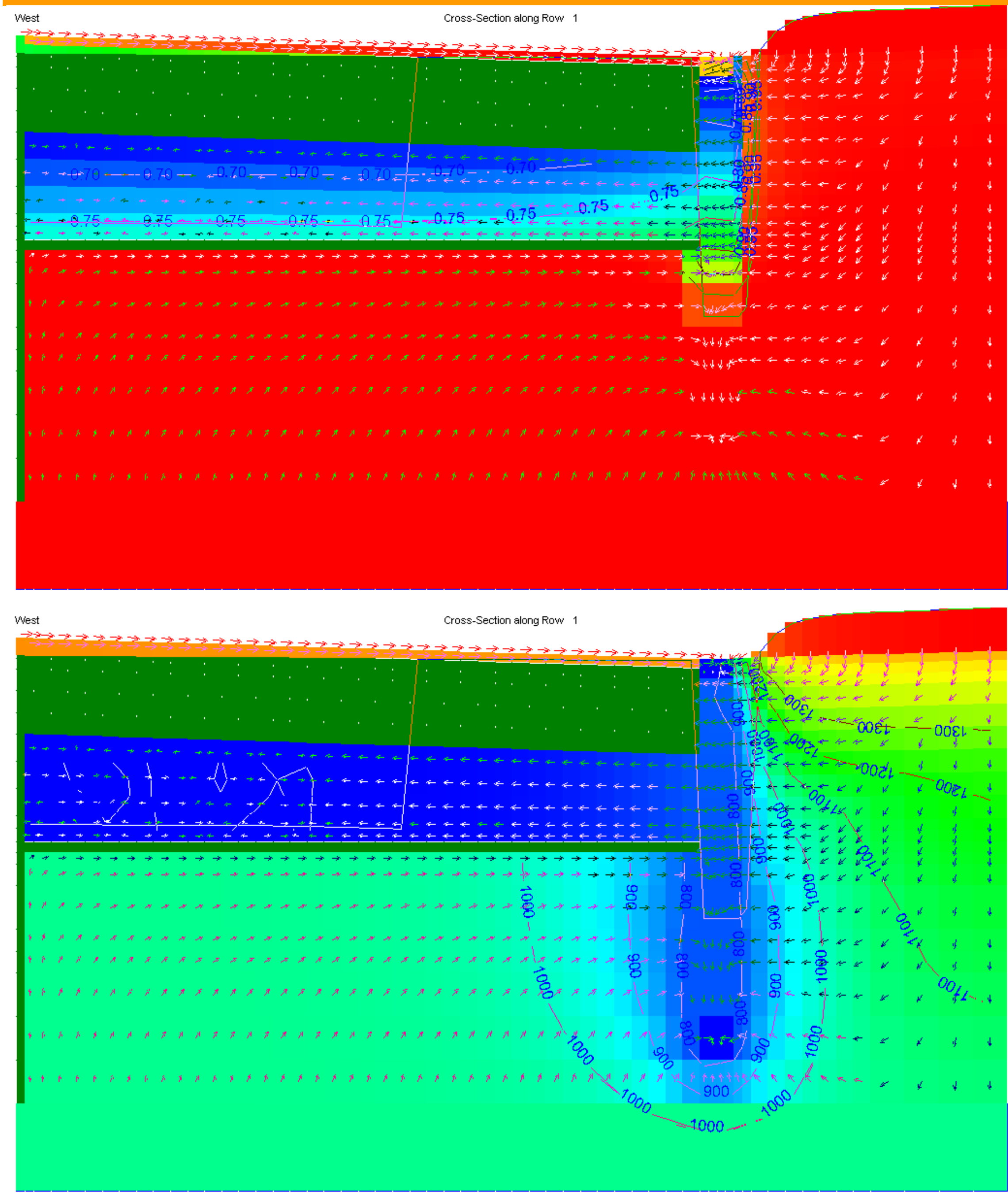


Figure 31: saturation level after a rainfall in presence of a high watertable and of an impermeable geotextile between subbase and subgrade (case 3).

However, such a structure might create problems to the subgrade in case it is clay with very low permeability (as the simulated case). In this case, water cannot escape from the subgrade, with the consequent risk of having high water pressures accumulated beneath the geotextile (see the graph of the heads in figure 31). In this case, a high drainage layer can be put below the geotextile to take the water from the clay and direct it into the draining pipe (see figure 32).

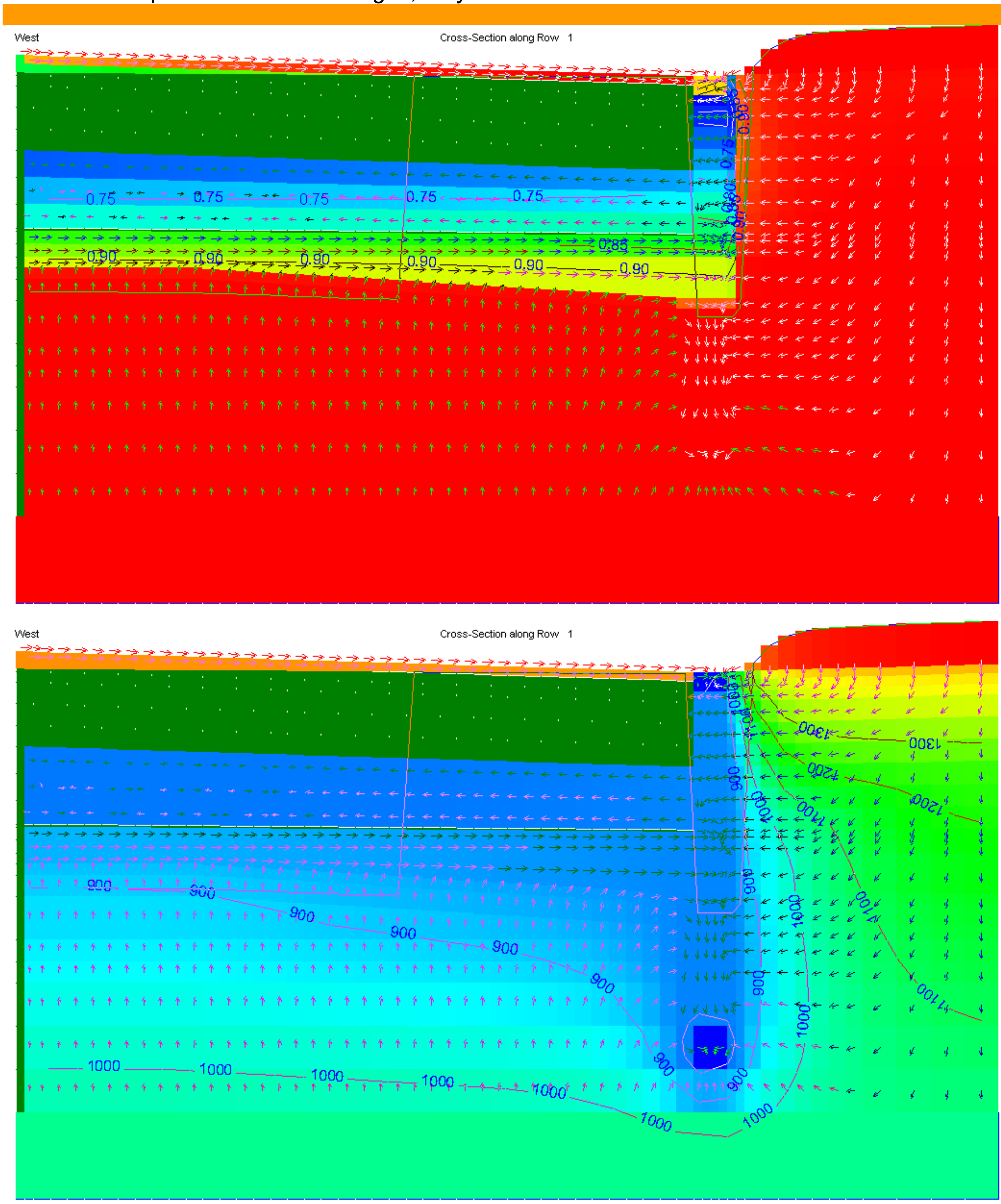


Figure 32: saturation level and head in the case of a high water table, considering a structure with both a geotextile to stop water from infiltrating into the subbase and a draining layer between the subbase and the clay to avoid water pressures accumulation.

An extreme case such as that represented by rainfall pattern n.4 creates serious problems even to porous asphalt (figure 33 and 34). In fact, the road surface is flooded. However, in this case, the presence of a subsurface drainage system does not help, nor does a large surface drainage (figure 35). This result does not mean that the porous asphalt does not work properly: on the contrary, it can help prevent road flooding. The reason why this problem did not show up for the high volume trafficked road is because it was not possible to simulate correctly the runoff water. What this result tells us is that, in case of extreme rainfalls, the risk of flooding cannot be always prevented.

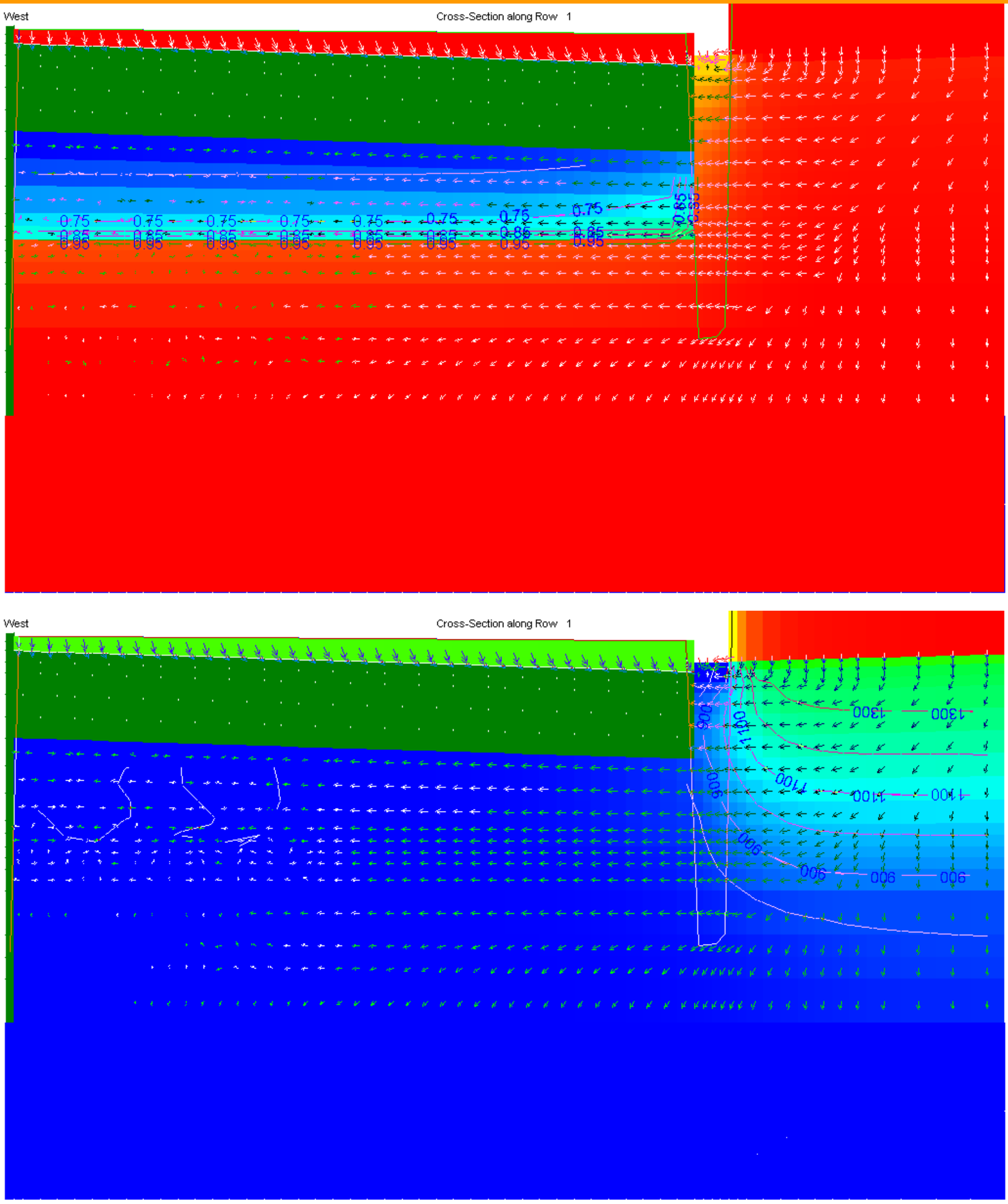


Figure 33: saturation level and head after rain, rainfall pattern 4.

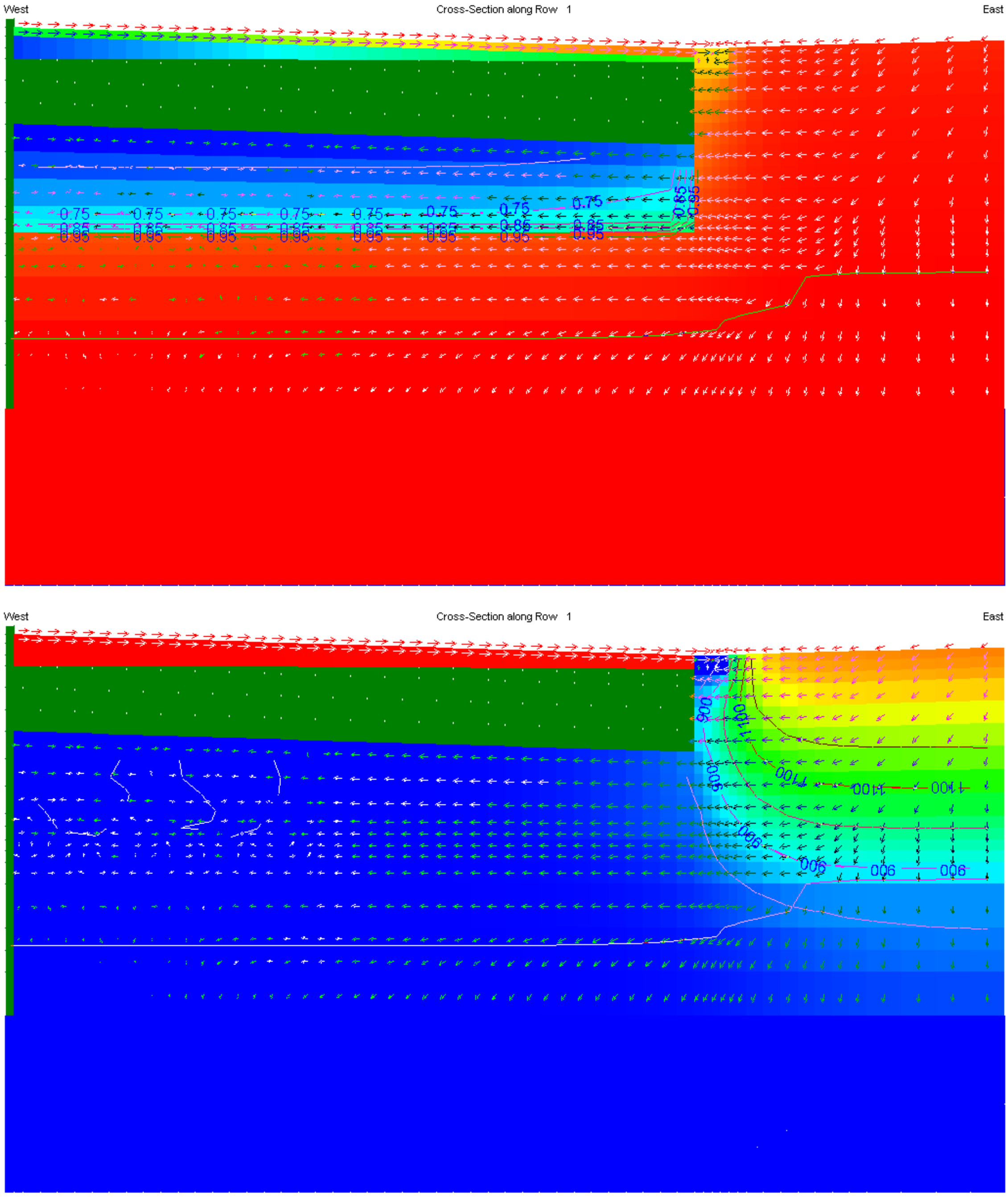


Figure 34: saturation level and head after a dry period, rainfall pattern 4.

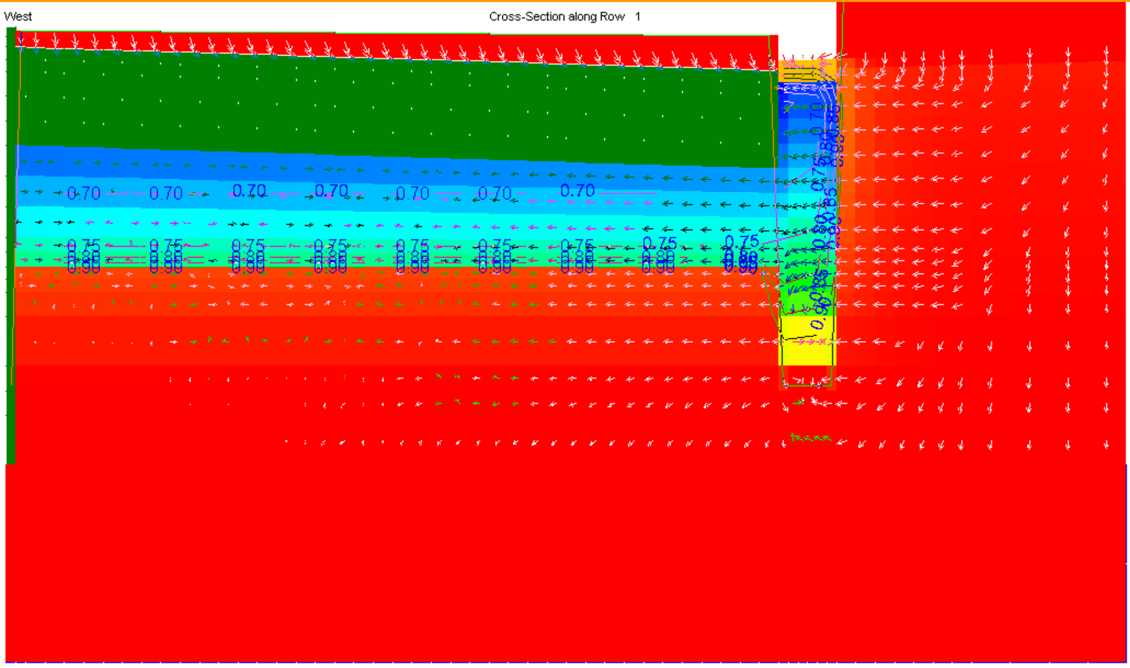
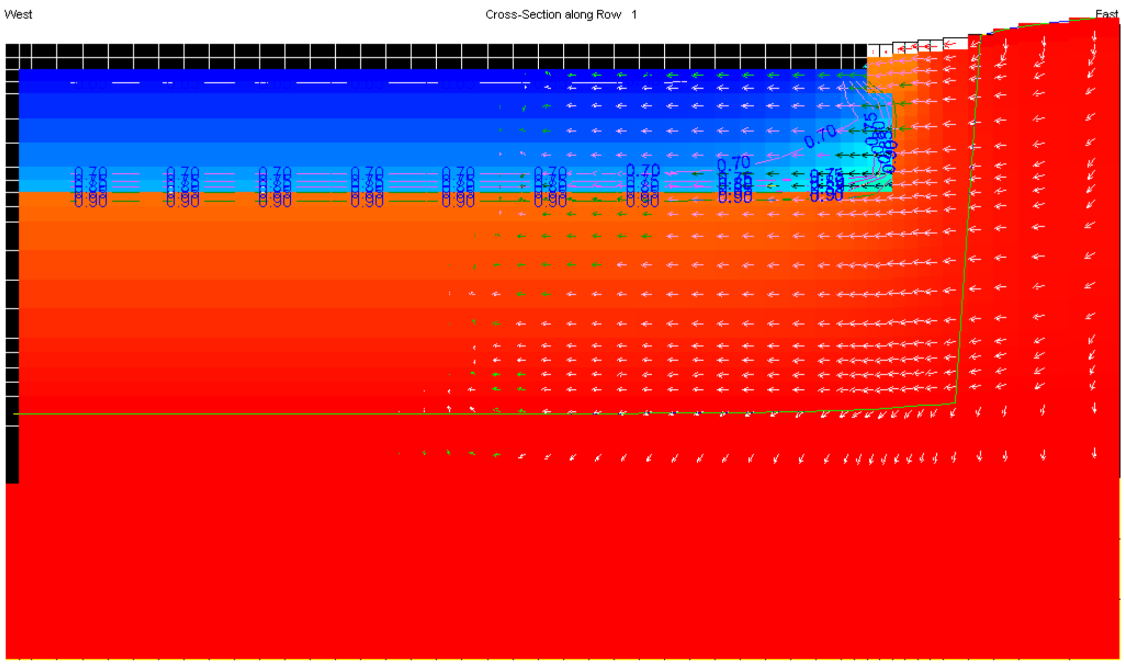


Figure 35: saturation level after rain, rainfall pattern 4, in presence of a subsurface drainage system and a larger surface drain.

3.3 Model 3: Nordic secondary road

As it can be seen in figure 36, also a typical Northern European secondary road does not seem to be affected by a change in intensity and duration, within certain limits, if the total amount of rain is the same. In fact, the subbase saturation does not seem to be strongly affected.



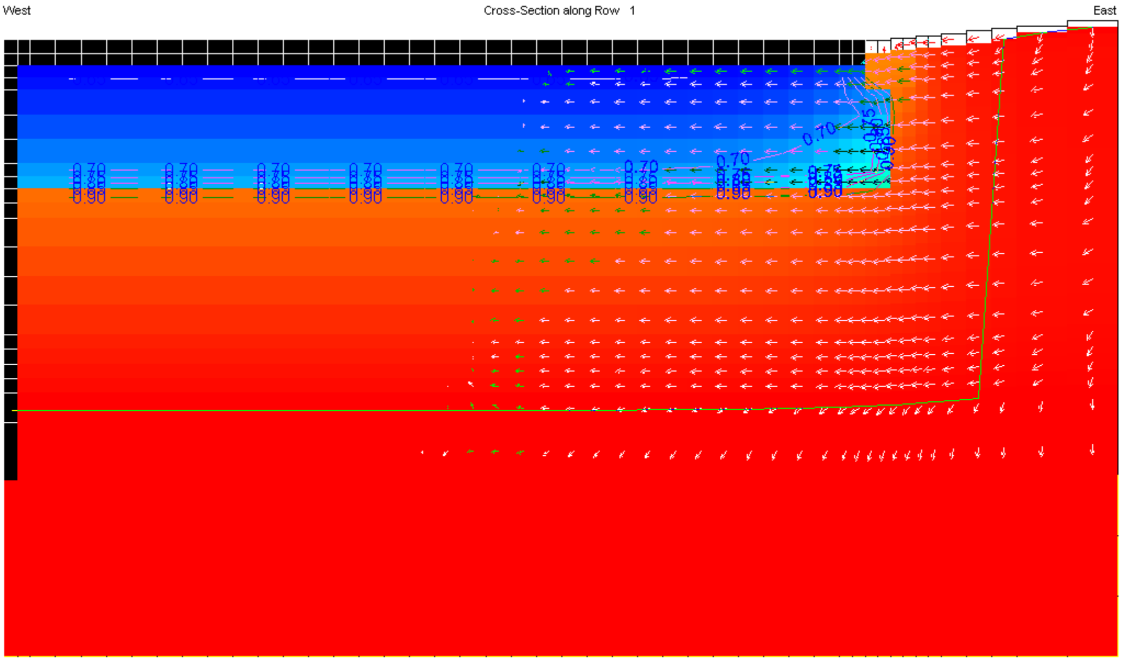


Figure 36: saturation level after a rainfall of high intensity but short duration (case 1) and after a rain of low intensity and long duration (case 2).

The subbase saturation does not seem to be affected either if not only the intensity is higher, but also the total amount of rain increases, as it is likely to happen in the northern countries (see figure 37).

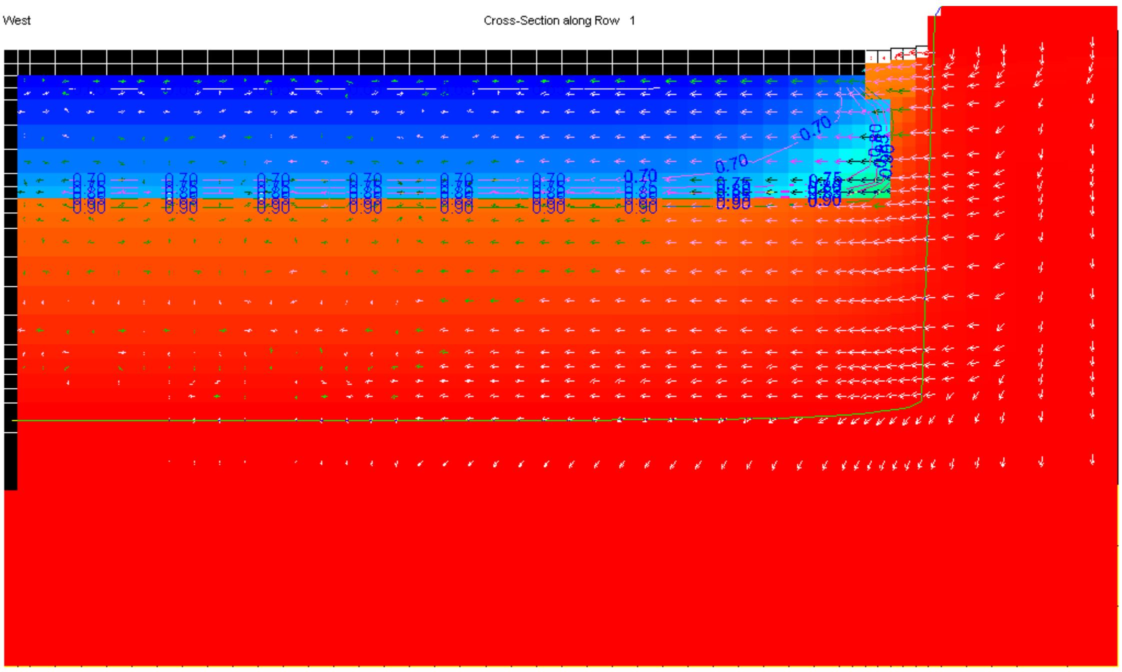


Figure 37: saturation level after 1 hour of heavy rainfall (case 3, but considering shorter “not-rain” intervals).

However, as in the previous simulations, also in this case it seems that the path of the water that does not infiltrate into the clay but rather runs off the surface cannot be simulated properly. Therefore, it is probable that the amount of water that ends up in the subbase is higher than that shown in figure 37. This fact is even more obvious in case of extreme rainfalls such as those simulated in case 4 (figure 38).

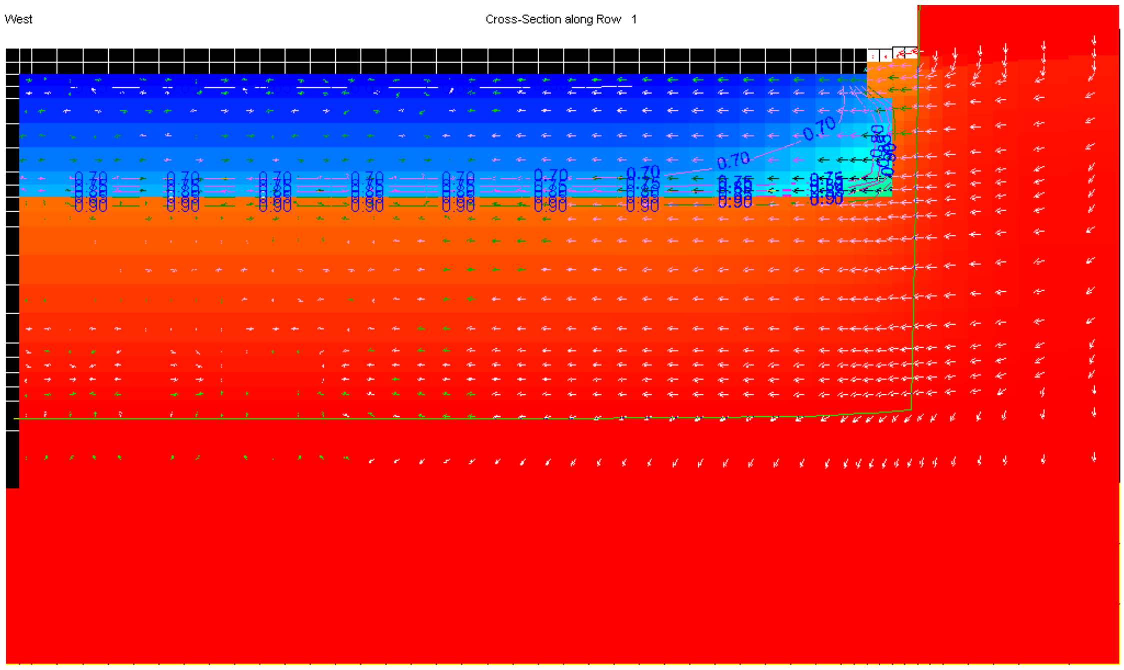


Figure 38: saturation level after 1 hour of very heavy rainfall (case 4).

In these cases, the presence of a thicker unbound subbase (0.6 m) as that shown in figures 39 and 40 can be of help. However, the simulations do not seem to show any substantial contribution, but viceversa, the presence of a thicker subbase layer seems to increase the flow of water beneath the road surface.

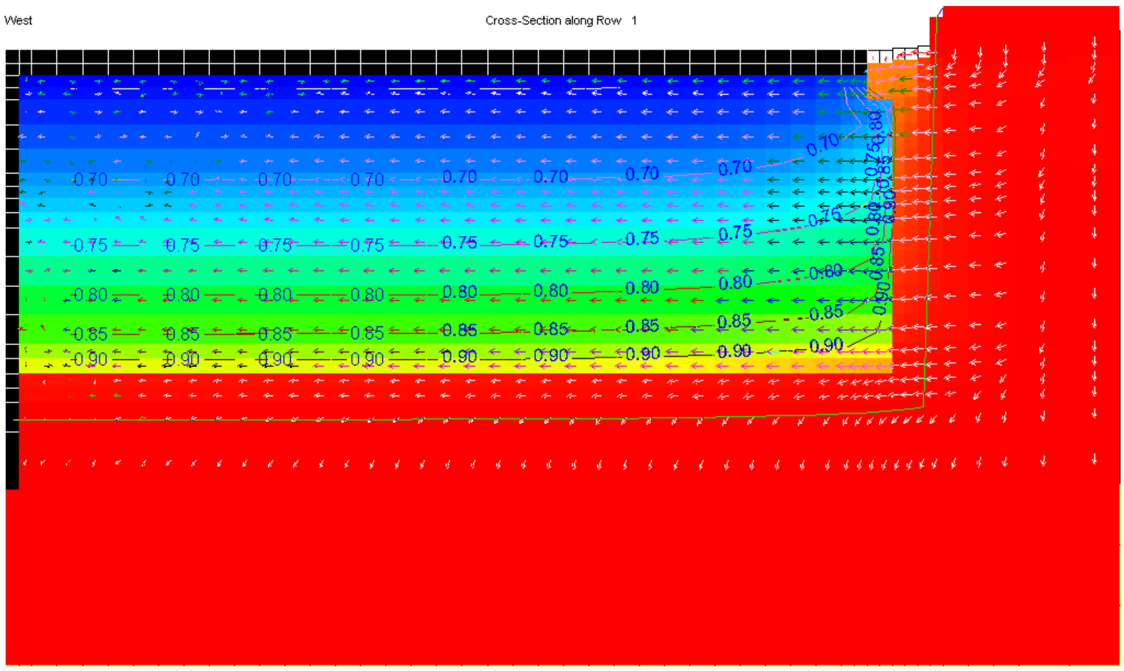


Figure 39: saturation level after a dry period (rainfall pattern n. 3).

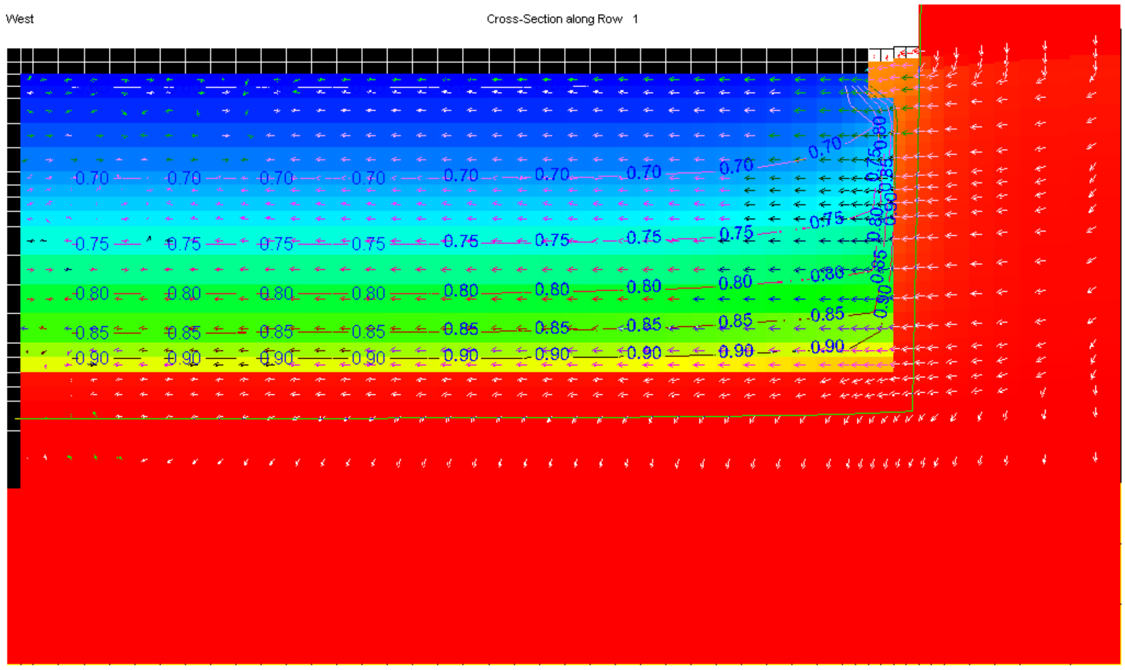


Figure 40: saturation level after rain (rainfall pattern n. 3).

The presence of an impermeable geotextile on the side of the subbase can help blocking the flow of water from the surrounding soil, as it can be seen in figure 41.

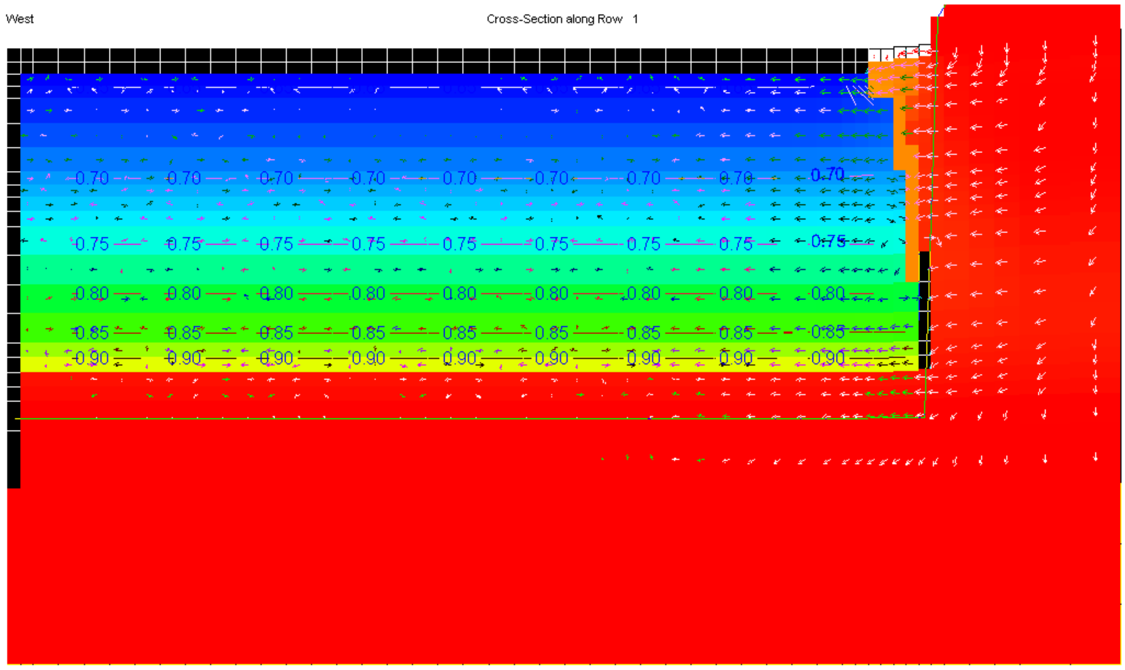


Figure 41: the same model shown in figure 39, but with the addition of a lateral impermeable geotextile.

It should be noted that, generally, in presence of a soil that drains more than a clay does, the problem of a high level of saturation in the subbase is less relevant, as it can be seen in figure 42.

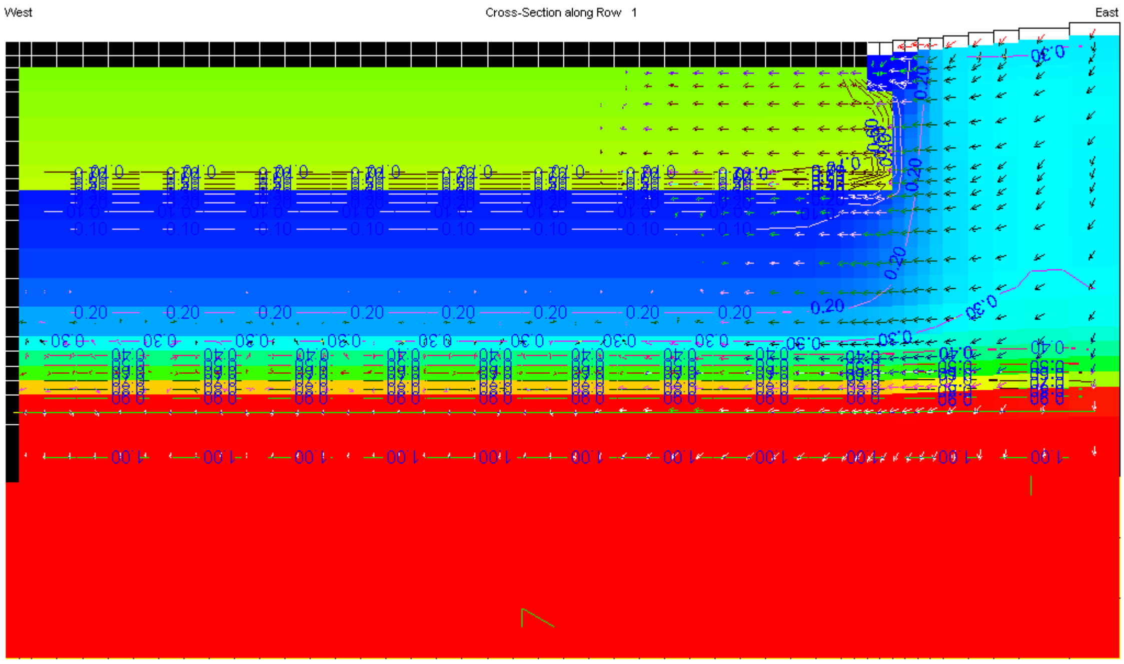


Figure 42: saturation level after rainfall (case 1), sandy soil.

3.4 Model 4: Heavily cracked road

Due to difficulties in simulating a heavily fractured asphalt surface properly, all rainfall was assumed to penetrate directly into the pavement structure. This simplification however allows a conservative estimate of the real situation. In this case, no surface drain is present as the simulation involves only subsurface layers.

Also in this case, the presence of a low permeability soil surrounding the structure can be considerably more harmful than a high permeability soil (figure 43).

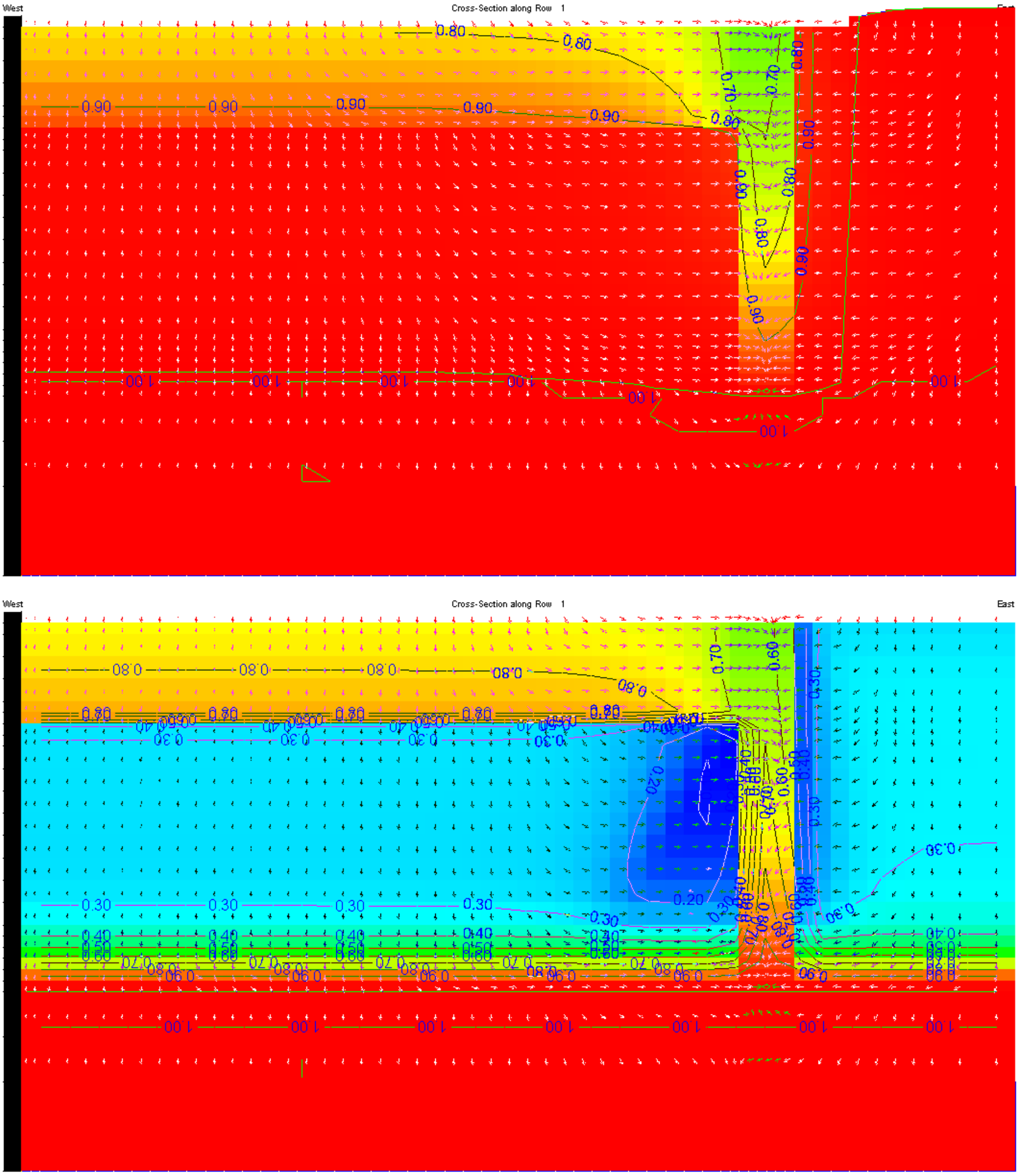


Figure 43: comparison between the saturation levels of a subbase surrounded by clay and by sand (rainfall pattern 1, after rain).

Comparing the results after a light, long lasting rainfall (case 2, figure 44) with a moderate, short rainfall (case 1, figure 43), it can be seen that, in any case, a cracked surface is an issue for the stability of the subbase, as its water content increases to dangerous levels.

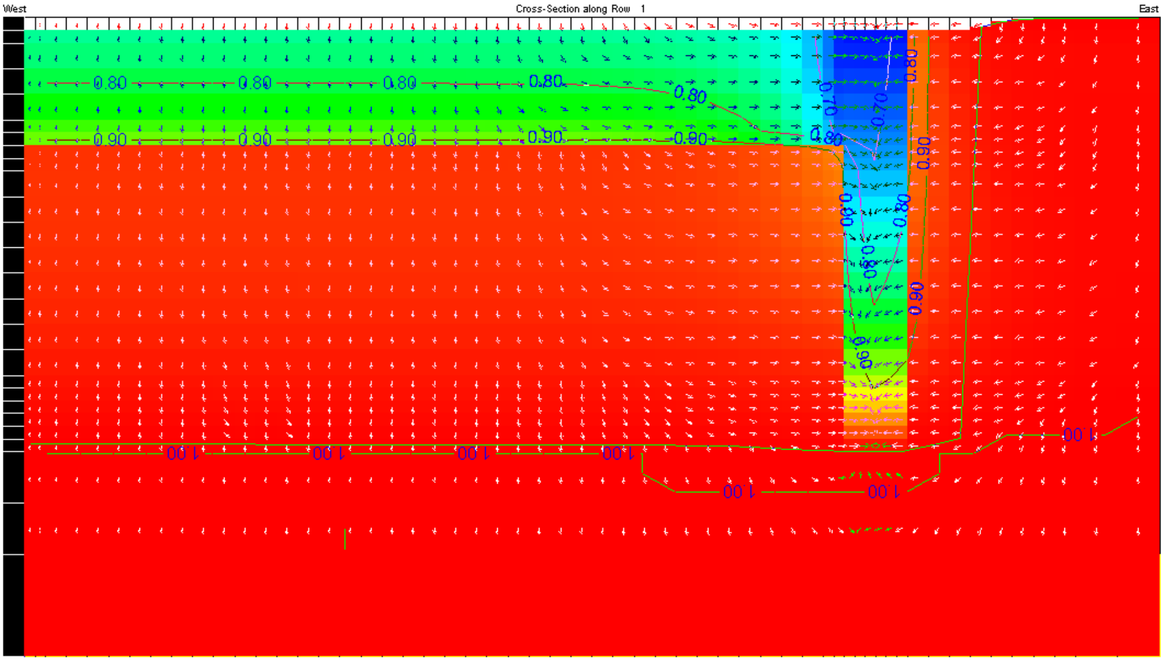
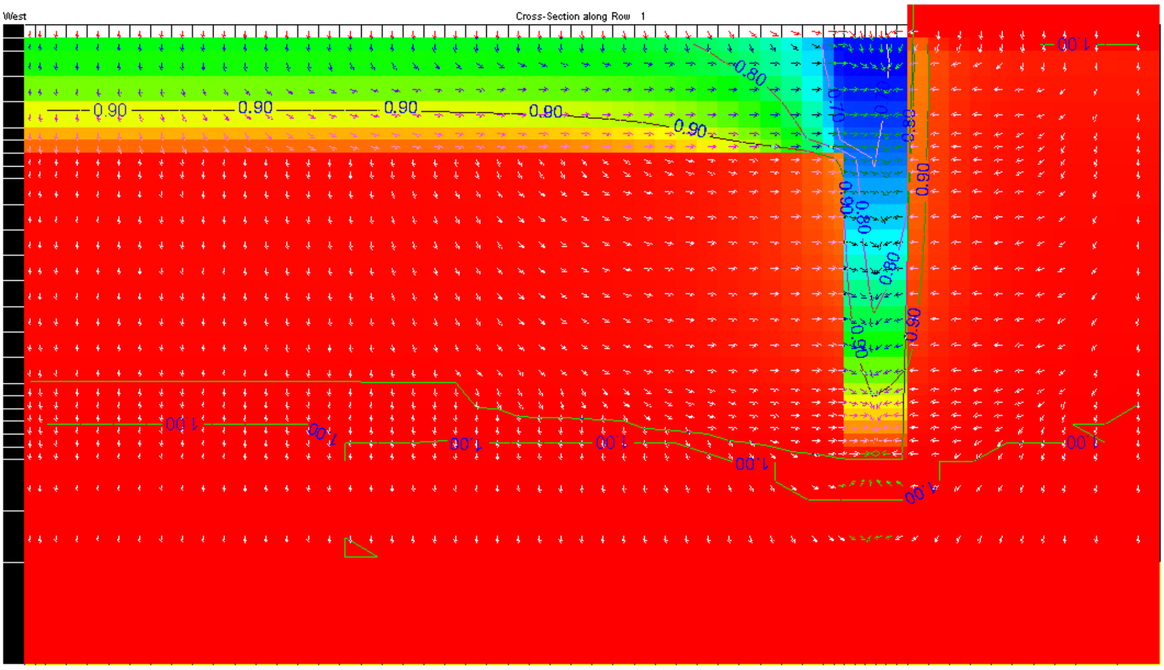


Figure 44: saturation level after a 6 hour light rain period (case 2).

The situation gets even worse in case of heavy rainfall periods (figure 45). The simulation of such events shows that the subbase is almost completely always above 80% saturation, and again, it is likely to be even higher due to the large amount of runoff water that cannot be simulated properly. It should be noted that the model shows that the high saturation level does not decrease appreciably even after a dry period of 15 days (figure 46), probably due to the runoff water that slowly infiltrates. The reality might be different though.



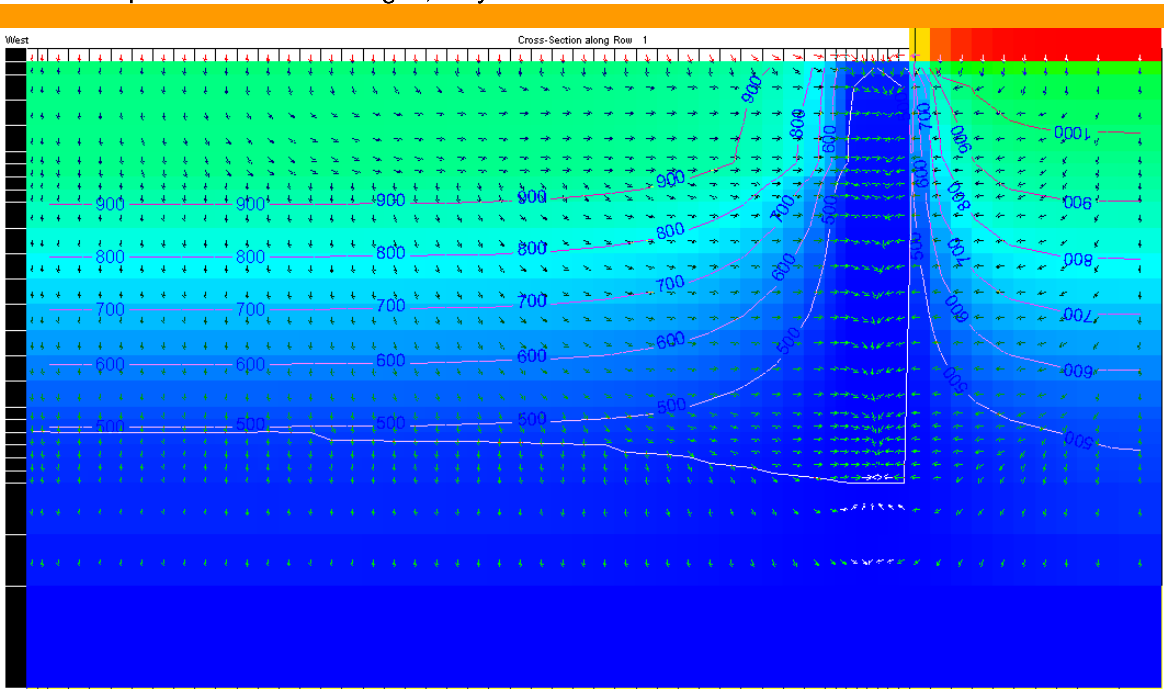
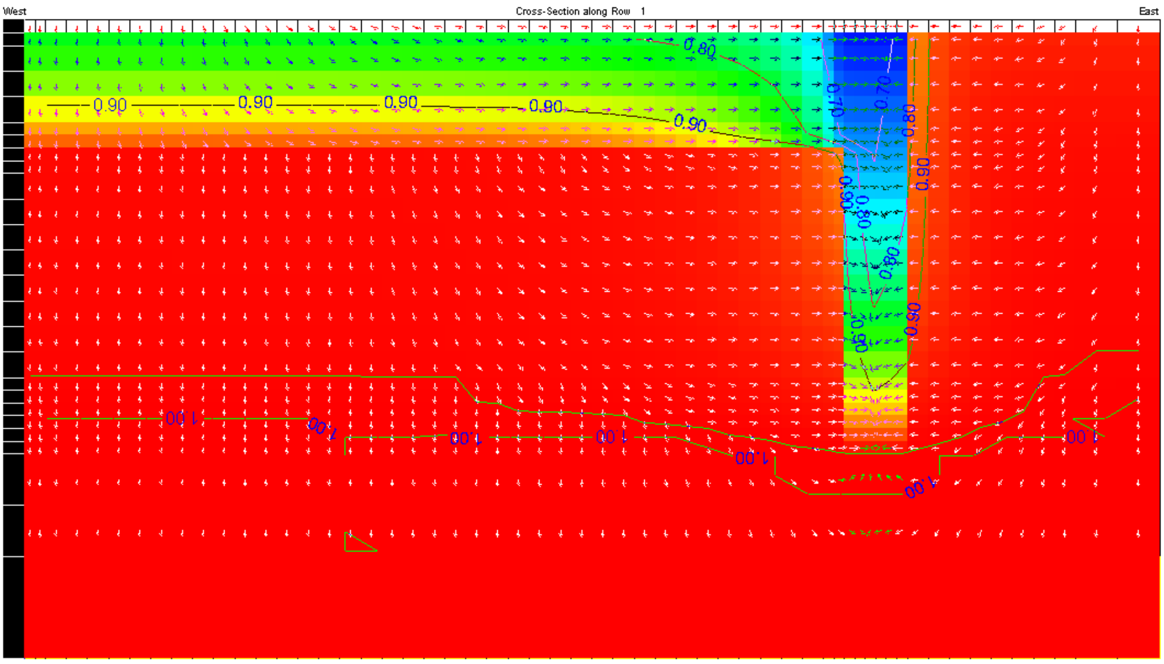


Figure 45: saturation level and head after rain, rainfall pattern 4.



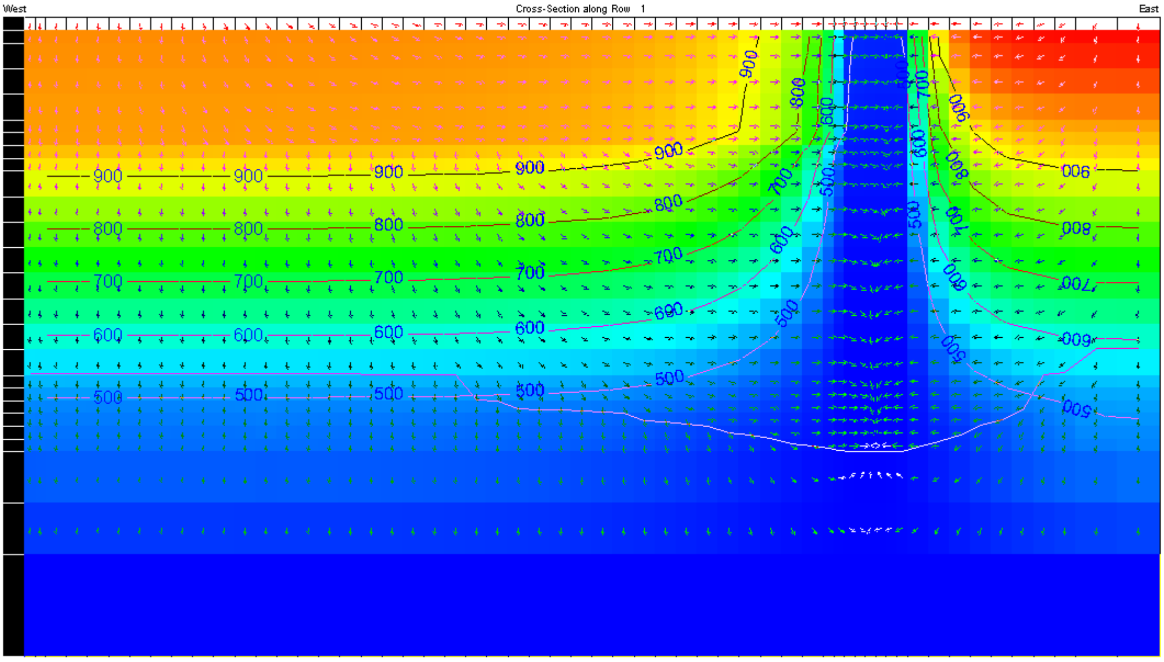
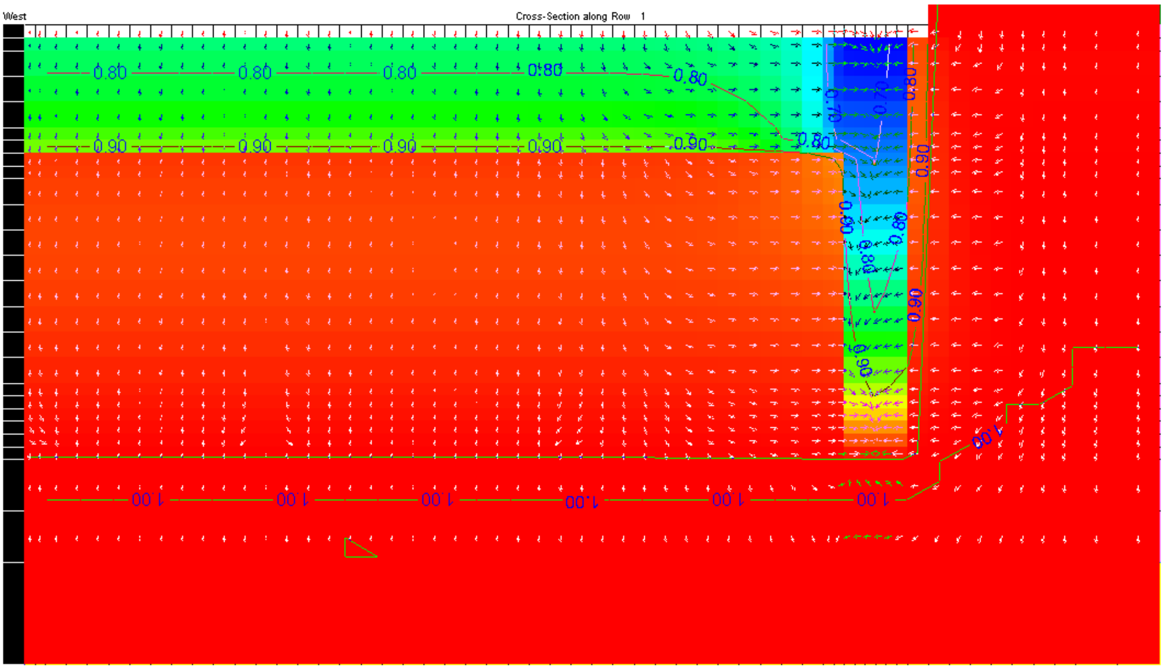


Figure 46: saturation level and head after a dry period, rainfall pattern 4.

A moderate/heavy rain of 0.0026 mm/sec every 2.13 days was finally simulated. This model reflects the rainfall and rainfall intensity increases that can be expected in the future. The results (figure 47) show that, even if the situation is not as critical as in the extreme case shown in figure 45 (case 4), however the saturation is still between 80% and 90% in the greatest part of the subbase.



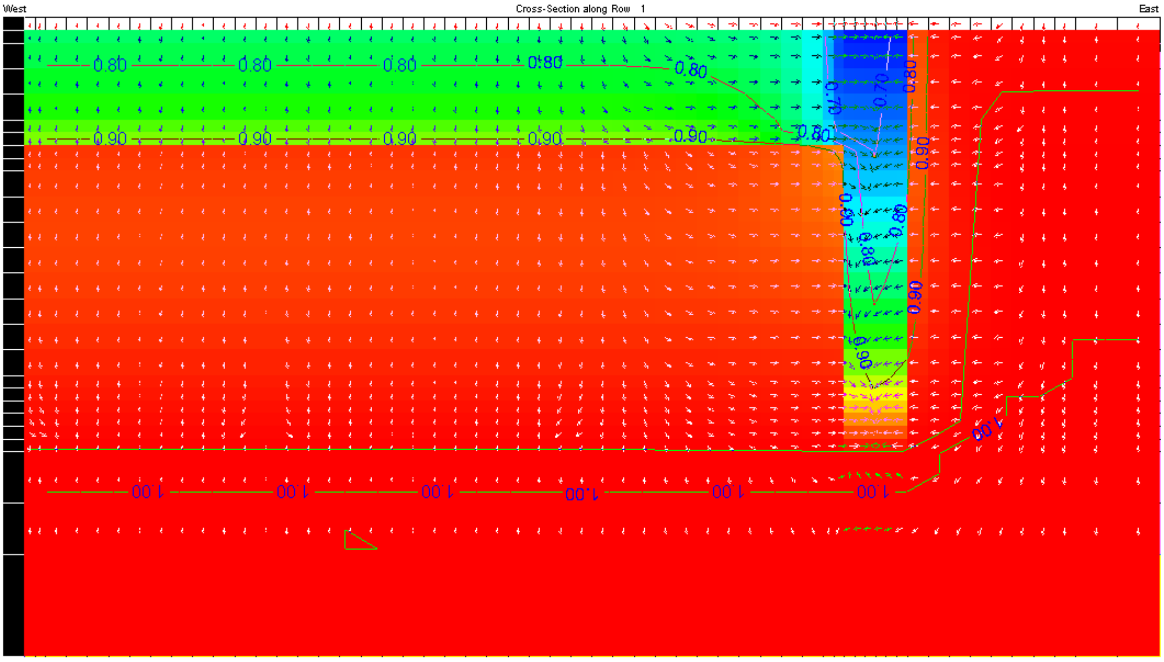


Figure 47: saturation level after rainfall and after dry period (moderate/heavy rain within short periods of time).

An inclined subbase bed aimed at helping the outflow of the water towards the lateral drainage was simulated (scheme shown in figure 48). The inclination is of 1% in correspondence to the centre of the road, and increases to 3% towards the sides. The results show that there is a slight improvement (figure 49), thus the cross-fall inclination can help, but, as saturation is still too high, it cannot be considered as only precaution to be taken.

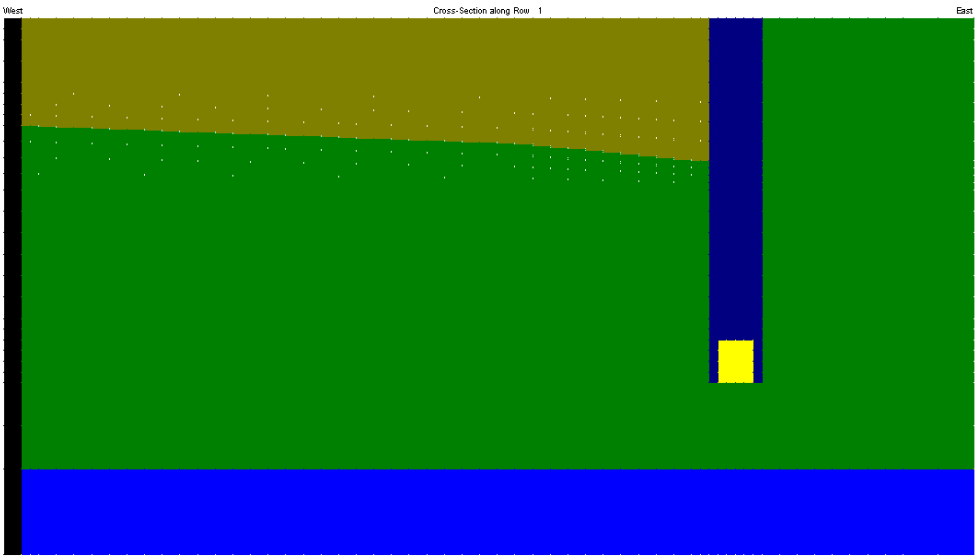


Figure 48: schematic of the inclined subbase bed.

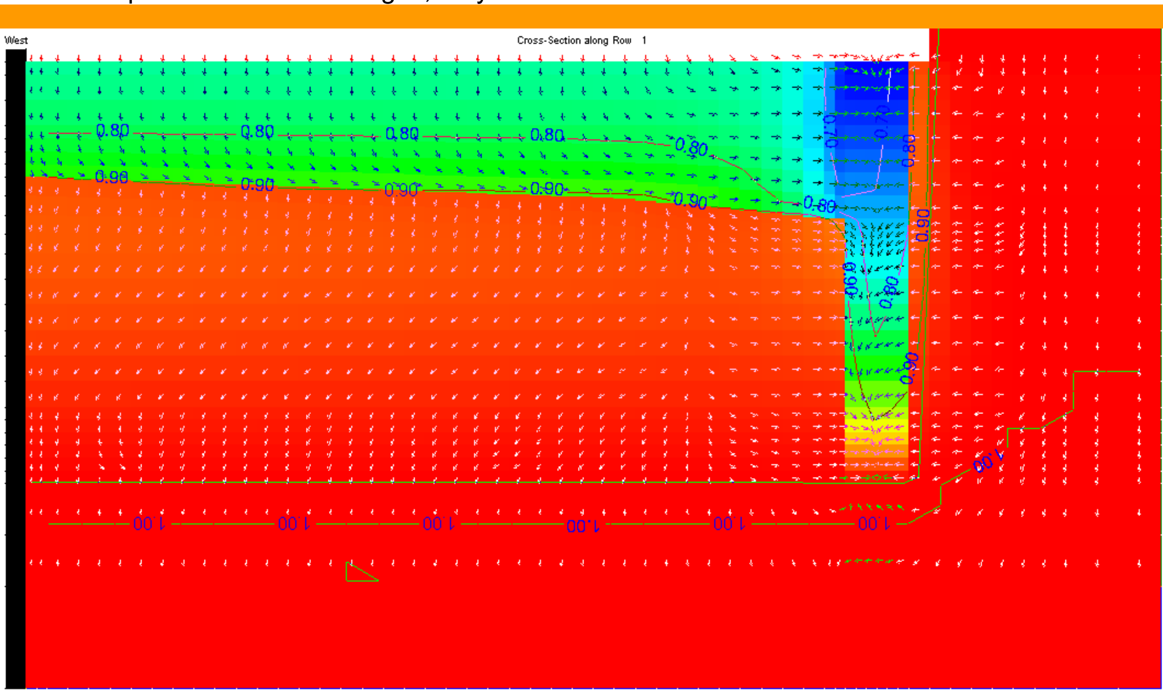


Figure 49: saturation level after rainfall (moderate/heavy rain within short periods of time), inclined subbase bed.

Finally, a model that considers a thicker subbase layer was created. The rainfall pattern was kept as in the previous model – 0.0026 mm/sec every 2.13 days. As it can be seen from figure 50, in this case a thicker layer can be of help (even if, also in this case, a remarkable difference cannot be observed). The possibility of a thick subbase coupled with an inclined bed might help in a more efficient manner.

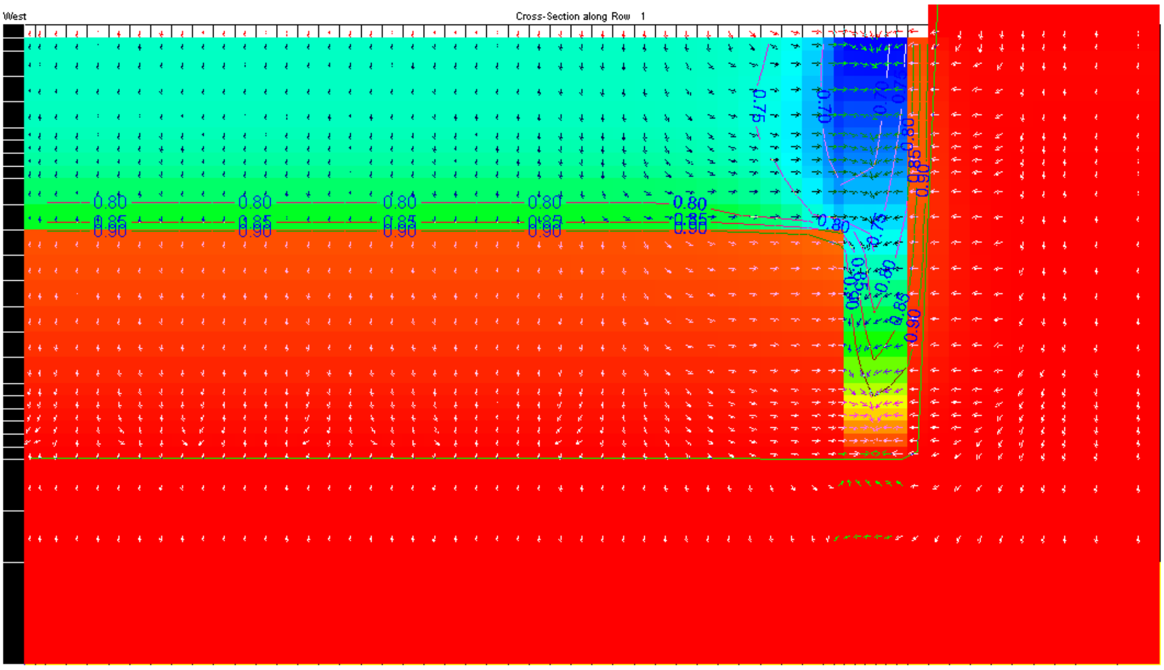


Figure 50: saturation level after rainfall (moderate/heavy rain within short periods of time), thicker subbase.

4 Conclusions

The simulations performed show that, in general, a relatively small change in rainfall pattern, i.e. average intensity and duration, not accompanied by increase in yearly amount of rainfall water, does not seem to affect sensibly the saturation level of the road structure. More extreme intensities or large changes in rainfall quantity can instead be an issue, as subbase saturation increases to dangerous levels. As it can be expected, clayey soils are the most problematic. Essential to maintain low saturation levels on the pavement structure is often the presence of a proper lateral subsurface drainage. This is constituted by a pipe at a level below the bed of the subbase, where water can be collected, and by a draining aggregate that allows water to be conveyed from the soil on the surface and around the subbase into the pipe. The importance of applying, around the lateral drain, a geotextile able to leave water pass through but to limit fine material from intermixing with the lateral draining aggregate was shown through the simulations.

A well constructed, high volume traffic road with a surface that does not show cracks, can handle quite well changes in rainfall intensity and quantity. This stresses the importance of taking action promptly as soon as damage appears on the surface, or even before. The simulations show that the presence of a surface lateral drain, however, is going to be more and more important as the rainfall events are likely to be more extreme and thus a greater amount of runoff water needs to be conveyed and removed from the road surface to avoid flooding.

Also porous asphalt seems to perform well even in presence of intense rainfall patterns: only a slight increase of saturation level in the porous asphaltic layer on the sides of the road can be observed, but saturation does not reach the surface, while the subbase does not show any remarkable increase in saturation level. Therefore, it seems to be a better option to help prevent road flooding. In the case of porous asphalt, the presence of a subsurface drainage system below the level of the subbase does not seem to be very important, although its presence does help keep the aggregate slightly drier.

An issue that is likely to become more important in the future is the presence of a high watertable below the road structure; in this case, the saturation of the subbase can reach levels that can decrease considerably the strength of the aggregate. When the watertable is shallow, the saturation of the subbase is rather high, independently on the amount of rain falling. In these cases, an impermeable geotextile placed between the subbase and the subgrade, coupled with a draining layer to let water flow from the subgrade into the draining pipe, seems to give very good results. Also the presence of a draining layer, with an inclined bed, between subbase and subgrade does help, however the results are less remarkable.

As for the previous cases, also a secondary Nordic road does not seem to be particularly affected by medium-small changes in rainfall intensity, nor by changes in rainfall total quantity on a year. Again, it's the extreme cases that make a large difference. In these cases, a high level of saturation can be reached by the subbase. The thickness of the subbase layer does not seem to improve the situation though: even a thick layer can reach relatively high saturation levels; viceversa, the presence of a thicker subbase tends to increase the flow of water beneath the road surface. Only the presence of an impermeable geotextile on the side of the subbase can help blocking the flow of water from the surrounding soil.

A cracked pavement surface is an issue for the stability of the subbase independently of the rainfall intensity, as its water content increases in any cases to dangerous levels, and the situation gets obviously worse in extreme cases such as heavy rainfalls. An inclined subbase bed aimed at helping the outflow of the water towards the lateral drainage brings a slight improvement, but, as saturation is still too high, it cannot be considered as the only precaution to be taken. Also a thicker layer seems to bring some benefit, but again the difference is not very significant. Therefore, the coupling of a thick subbase with an inclined bed might be more efficient.

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