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IT IS WARMER, BUT ARE OUR ROAD EMBANKMENTS STILL SAFE?

Extreme events and climate change

Climate changes predictions for the Netherlands indicate increased frequency or intensity of extreme events and changes on precipitation and temperature [1]. Rain and extreme rain conditions will increase in winter while extreme rain will become more intense in the summer, with heavier hail and thunderstorm. The temperature keeps increasing, i.e. milder winters and hotter summers will happen more frequently. There will be more often dry periods, also in combination with changes in rain and evaporation. This will lead to an increase of potential evaporation, which depends on temperature and solar radiation.

A report from the Royal Netherlands Meteorological Institute, KNMI, published in 2014, [1] gives the likely changes in the climate of the Netherlands around 2050 and 2085 compared to the climate in the period 1981-2010. The report translates the research results on the global climate in the Intergovernmental Panel on Climate Change IPCC report of 2013 to the Netherlands. Four scenarios describe the likely changes in the climate of the Netherlands. The scenarios differ in the extent to which the global temperature increases ("Moderate" and "Warm") and the possible change in the air circulation pattern ("Low value" and "High Value"), as shown in Figure 1.

The increasing temperature, mean amount of precipitation, drought events and increasing intense precipitation are the major climatic changes that are likely to affect the stability of geotechnical infrastructures. The main climate-change-driven processes will be the generation of soil drying, the reduction in soil suctions, soil desiccation, soil erosion, flooding and hydro-mechanical failure [2].

Effect on road embankments

Extreme climatic events (e.g. rain and drought) can lead to instability of road embankments. Rainfall induced slope failure is governed by the hydro-mechanical behaviour of the slope, external loads and environmental (weather) conditions. Infiltration of water influences predominantly this process, causing a change in the effective stresses in the slope [3]. The interdependent in·uence of weather conditions, soil permeability and surface vegetation dominates the pore water pressure regime within embankments. The dominant type and timing of embankment failure is influenced by the material composition and the difference in construction of highway and railway embankments.

Soil matric suction, which affects both the permeability of the soil and its shear strength, plays an important role in the slope failure process. Modelling the unsaturated zone, through the correct determination of saturated hydraulic conductivity and soil-water retention curve, is of main importance [4]. Above certain rainfall intensity, no more infiltration into the soil happens and only surface runoff increases.

Not only rainfall, but also drought can weaken embankments and lead to their instability. Extreme drought conditions impose thermo-hydro-mechanical weakening mechanisms to slopes. These mechanisms include the following: influence on soil strength, desiccation cracking and soil softening, land erosion and subsidence, and soil organic carbon decomposition [5]. An overall increase in temperature and prolonged periods of drought can cause long-term soil drying. High temperatures during dry seasons can lower the water table to considerable depth in the soil profile. The unsaturated area dries out due to evaporation and plant transpiration, volume

Figure 1 – Collapse of a road embankment after heavy rain along the highway A74 near Venlo, the Netherlands. Photo by Fer Traugott [10].

SUMMARY

Extreme weather events such as long and/or intensive rainfall can lead to instability of natural and man-made slopes. In the Netherlands, the changing climate will possibly impose increased frequency or intensity of such extreme weather events. These will likely influence the state of existing and mostly aging transport embankments that were not designed with climate change aspects in mind. Therefore, there is a need to better understand how these embankments will perform under climate change scenarios and if necessary, devise plans for adapting them to new climatic conditions. We provide a method to estimate the effect of climate change on geotechnical stability of road embankments. A series of fully coupled hydro-mechanical analyses under unsaturated condition are carried out on a typical road embankment. A selection of probable climate scenarios for the next 70 years is applied to the calculations in terms of rainfall intensity and duration. The results compare the current climate based on historical data with the climate scenario around 2085, as reported from the Royal Netherlands Meteorological Institute, KNMI. The authors also looked at how the development of soil desiccation cracks, after prolonged periods of drought, effect the stability of the road embankment.

change/shrinkage occurs as its water content decreases. Due to volume shrinkage and increase of suction, the tensile stresses in the dehydrated soil increases and when it exceeds the tensile strength of the material, shrinkage cracks initiate.

As rainwater infiltrates less easily into the dehydrated soil, shrinkage continues, and cracks grow deeper. The process stops when the soil reaches its shrinkage limit and the void ratio remains constant with reduction in moisture content [6]. The initiation and propagation of cracks due to shrinkage depend on several factors, such as initial water content, mineral composition, clay content and plasticity index, layer thickness and size, surface vegetation cover, cyclic change of the climate [7]. Soil mechanical and hydraulic characteristics are significantly modified by the presence of desiccation cracks. The hydraulic conductivity increases, sometimes as large as three orders of magnitude. Water infiltration into open cracks can occur more rapidly, pore pressures increase and the effective stress and corresponding soil strength decreases [8]. Moreover, the sliding surface follows the path of least resistance. If an open crack, which has no shearing resistance, is located near the most likely sliding surface (without cracking), the sliding surface can follow the crack and lead to failure.

Numerical simulations

This work focuses on short and long duration rainfall events with high and low intensity, respectively. To that end, a series of fully coupled hydro-mechanical analyses under unsaturated condition are carried out on a typical road embankment using the Finite Element package, PLAXIS 2D, version 2017 [8]. The model uses a 4 m high embankment with a slope of 1:3, as shown in figure 2. The core material consists of sand, covered by a 30 cm top layer. The road, consisting of impermeable crushed asphalt, lies on top of a permeable granular road base, both having thickness of 30 cm. An FE mesh consisting of six-noded triangular elements is employed to discretize the soil material. The mesh is refined close to the boundaries of the slope. The analysis uses the Mohr-Coulomb material model. To obtain a representative case, data obtained from practice have been used. The hydraulic properties of the soil are described with Soil-Water Characteristic Curve (SWCC) and Hydraulic Conductivity Function (HCF). The left and right boundaries of the domain enable movement in the vertical direction and restrict movement in the horizontal direction, while the bottom boundary is fixed. For hydraulic boundary conditions, the lateral and the bottom boundaries are set as closed, while rainfall boundary is assigned to the top boundaries of the model.

A selection of probable climate scenarios for the next 70 years is applied to the calculations in terms of rainfall intensity and duration. The current study considers rainfall duration and intensities for the winter and summer months, comparing the current climate based on historical data with the WH scenario around 2085, as given by [7]. Here only the results for the summer scenarios are presented. The simulation for the summer considers the effect of extreme precipitation events. Scenario WH around 2085 exhibits a decrease of mean amount of precipitation but an increase of extreme rain

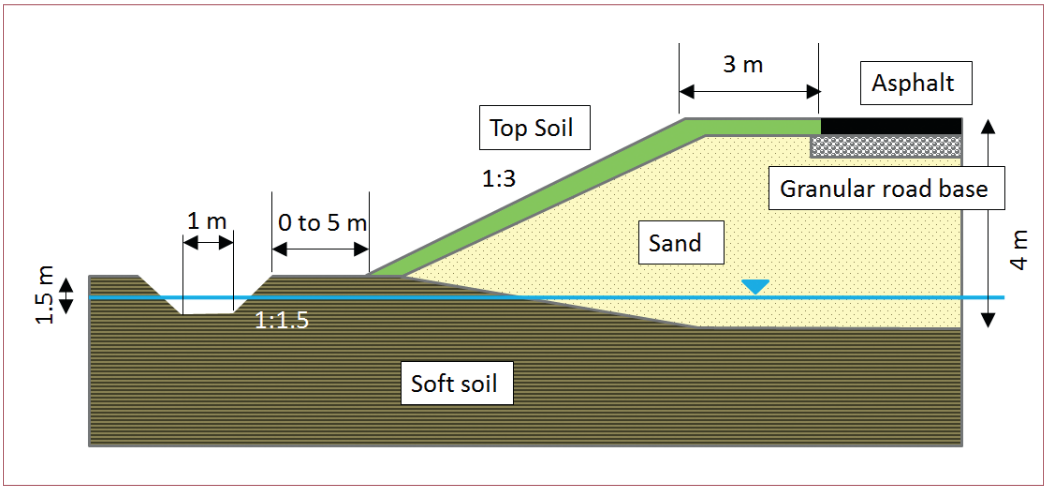

Figure 2a – Geometry of the road embankment (top) and FE mesh (bottom) used in the analysis.

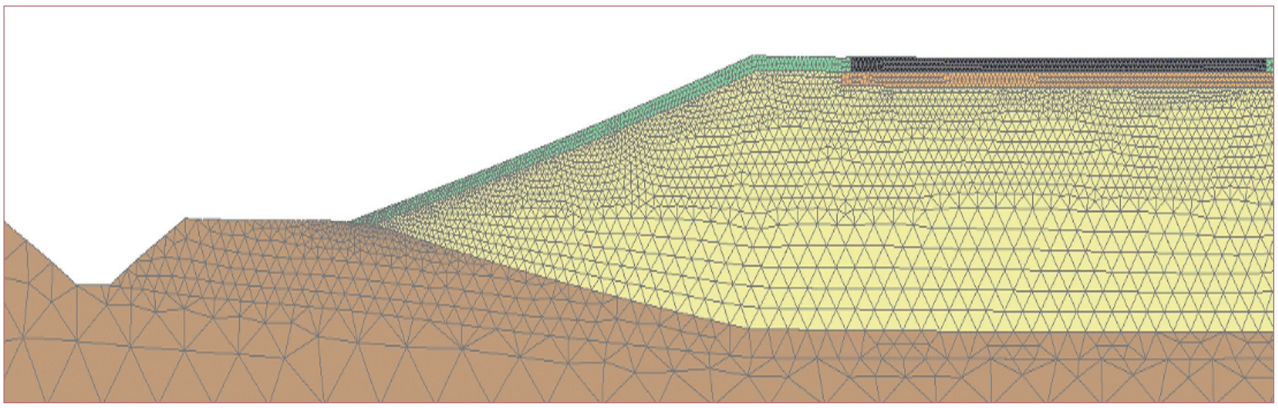

Figure 2b – Results in terms of safety factor for the summer scenarios. Results are given with and without desiccation cracks, for three scenarios: no rain, current climate scenario and climate scenario around 2085.

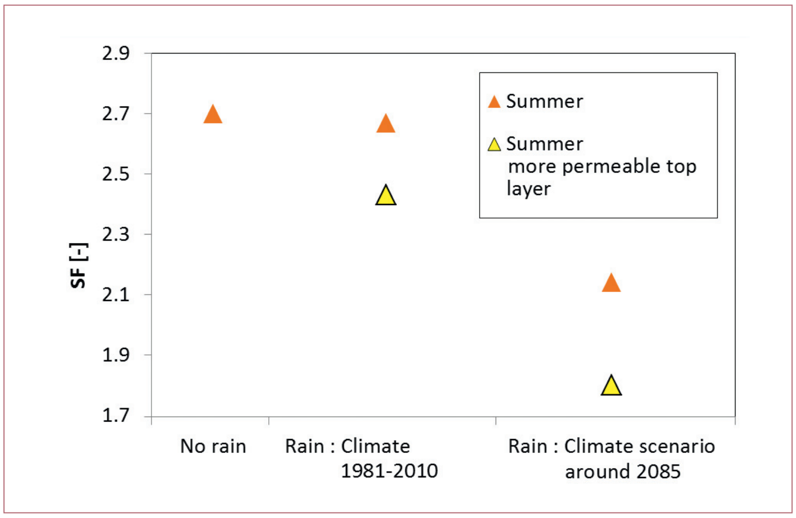

Table 1 - Rainfall duration and intensity for summer considered in the analyses for current climate and climate scenario around 2085.
The scenarios for summer consist of two phases: a longer duration rainfall event of 1 week, followed by an extreme precipitation event (2 hours).

Scenario	*Rainfall parameter*	*Phase 1* *longer duration rain*	*Phase 2* *extreme precipitation*
Summer	Duration	1 week	2 hours
[m/day]	Intensity – current	0.0078	1.54
	Intensity – WH 2085	0.0071	2.24

Figure 3 – Results in terms of safety factor for the summer scenarios. Results are given with and without desiccation cracks, for three scenarios: no rain, current climate scenario and climate scenario around 2085.

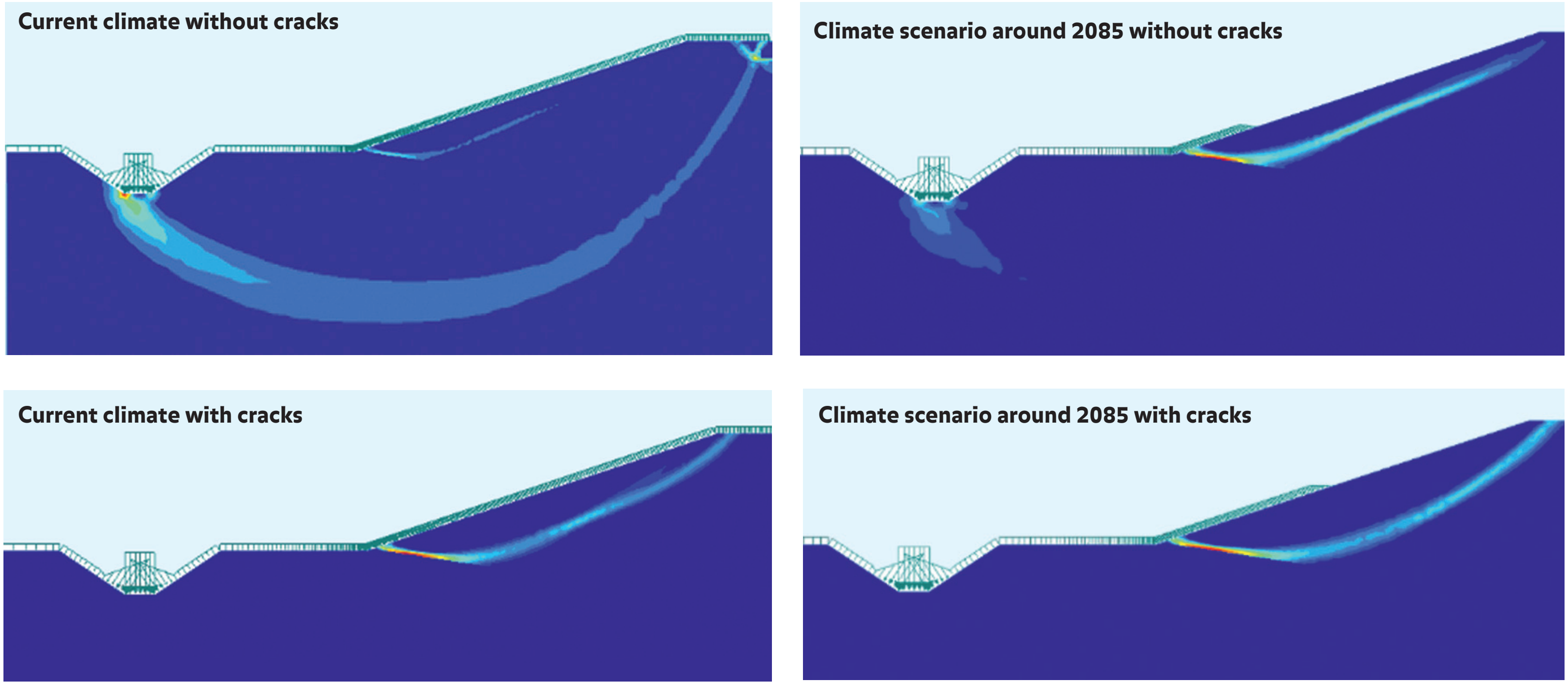

Figure 4 – Failure surfaces for the summer scenarios: current climate on the left and climate scenario around 2085 on the right. Results are given for the case without (above) and with cracks (below).

events [1]. The simulations apply a week of mean intensity rain followed by two hours of intense rainfall to the model. Average quantity of rainfall per summer corresponds to 224 mm in the reference period 1981-2010 with a year to year variation of 113 mm. The amount of infiltration, applied for a week for the reference scenario is equal 0.0078 m/day, considering the upper bound of the variation and 43 days of rains. The climate change values for the climate around 2085 present a decrease of 23% according to scenario WH for 2085, a natural variation averaged over 30 years of 15%, a year-to-year variation increase of 2.3% and a decrease of rainy days of 5%. By combining these values as described by KNMI, rainfall intensity of 0.0071 m/day is applied to the future scenario for a week of rain. After that, two hours of intense precipitation are applied to the model, with values corresponding to 1.54 m/day and 2.24 m/day for the current and future scenarios respectively, according to a return time of 1000 years.

As according to design requirements, the calculation considers a traffic load equal to 20 kPa over the whole roadway [9]. The factor of safety is then calculated by means of a phi-c reduction procedure.

Figure 3 shows the safety factor, which is calculated through shear strength reduction method, for the summer scenario. The safety factor decreases in the future scenario. It is equal to 2.70 in case of no rain and for the current climate, while it decreases to 2.1 for the climate around 2085. It implies that climate change has effect for stability, reducing the safety factor by 22%.

According to KNMI scenarios for future climate, temperature will also increase. Increase in temperature and prolonged periods of drought can cause long-term soil drying. The effect of soil desiccation with largest impact on the stability of geotechnical infrastructure is the development of dessication cracks. The presence of desiccation cracks in soil significantly modifies its mechanical and hydraulic characteristics. In order to account for this effect, a second calculation considers a top layer with a hydraulic conductivity one order of magnitude larger and soil water characteristic curve and hydraulic conductivity function of a medium type soil, as given by the Plaxis database. The resulting safety factor for the climate scenario around 2085 is equal to 1.80 (Figure 3). Similarly, soil desiccation cracking is simulated for the current scenario, leading to a safety factor equal to 2.40.

The failure surface, for future climate scenario both in the case of presence or absence of cracks, starts from the top of the slope and it ends at its toe (Figure 4). However the presence of cracks reduces the safety factor by 33% compared to the case without precipitation. Desiccation cracking facilitates the infiltration of water, leading to significant decreases in the effective stress and corresponding soil strength.

It should be noted that also calculations for the winter scenarios have been carried out. The safety factor decreases slightly when rainfall is applied to the model, while climate change doesn't contribute to its reduction.

Conclusions

A method to estimate the effect of climate change on geotechnical stability of road embankments has been presented. It is suggested to include the effect of climate change when designing and assessing the safety of road embankments. After definiting the critical cross section and determining the hydraulic and mechanical properties, climate scenarios should be chosen as suggested by national or local climate centers.

The results of the calculations indicate that the criticality of the extreme events for geotechnical stability strongly depends on the hydraulic properties of the top layer. Due to drought, desiccation cracking can decrease the hydraulic conductivity of the top soil; if then a longer period of rain happens, less run off occurs and more water infiltrates. When periods of drought are followed by low-intensity precipitation of long duration and sequentially by an extreme rainfall event, the stability may critically decrease. Higher temperature and prolonged periods of drought do also increase soil suction. Depending on the hydraulic conductivity of the material, the reduction of hydraulic conductivity with higher suction reduces the infiltration of water. In this case, extreme events could instead lead to erosion of the slope of the embankments. Contributions of climate changes on crack development and erosion are therefore critical and, for this reason, they are currently under study.

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