CONFERENCE

Resilient strategies to combat hydrogeological instability - 2nd Edition

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asset

Ground Instabilities: Landslides

Slope stability evaluation and Case histories from North Macedonia

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OUTLINE

- Introduction
- Database of Landslides in R.N. Macedonia
- Ground Instabilities in R.N. Macedonia
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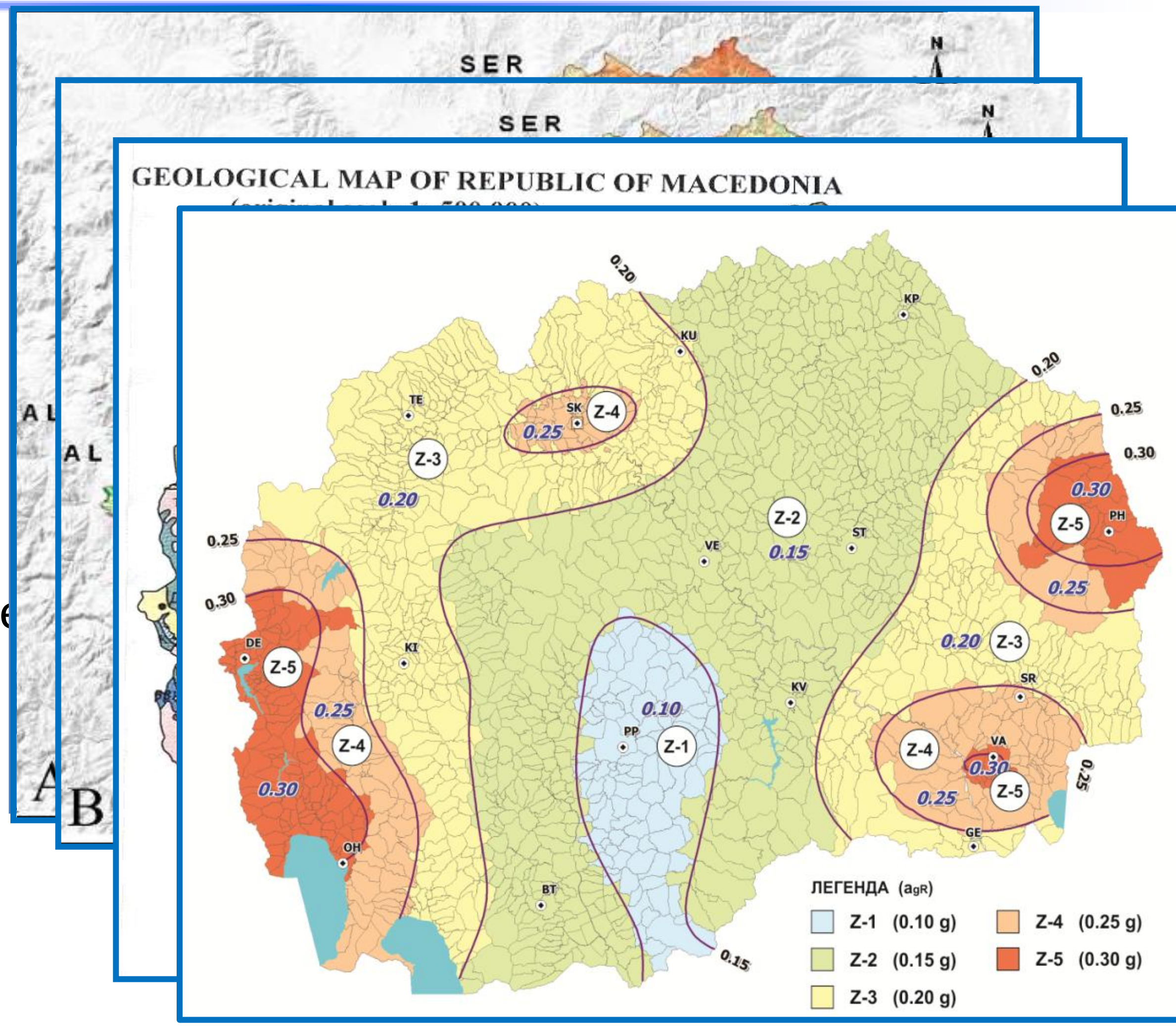
  - Part 2: Construction of new Highway on Corridor 8, Section Kicevo - Ohrid
  - Part 3. Exploitation of new Highway on Corridor 8, Section Miladinovci - Shtip
- Conclusions

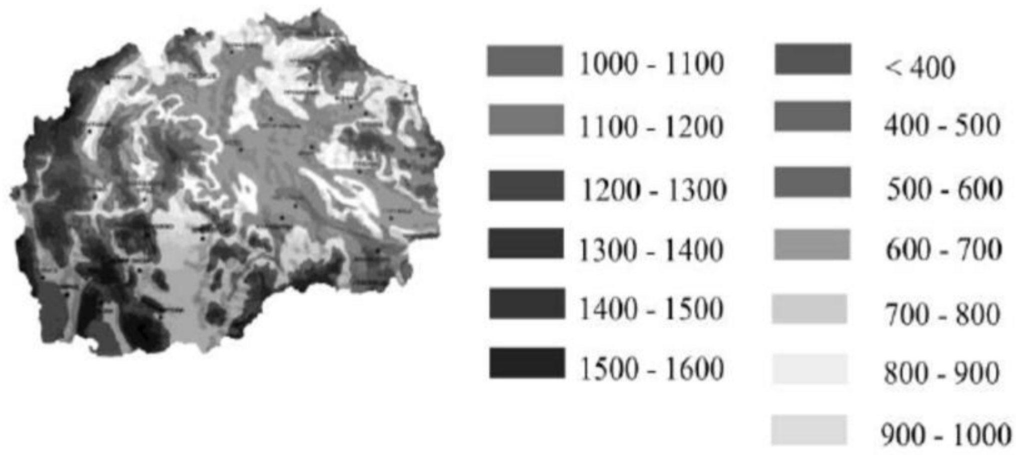
Introduction: Topography & Geology

- 79 % are hills and mountains with mean altitude of 832 m.
- Mean topographic slope 13.5° with 39.5 % of the area steeper than 15°.
- Mostly crystalline rocks (gneiss, mica-schist’s, othe schist’s), sandstones, lacustrine.
- Seismically active region with M 5.5-6

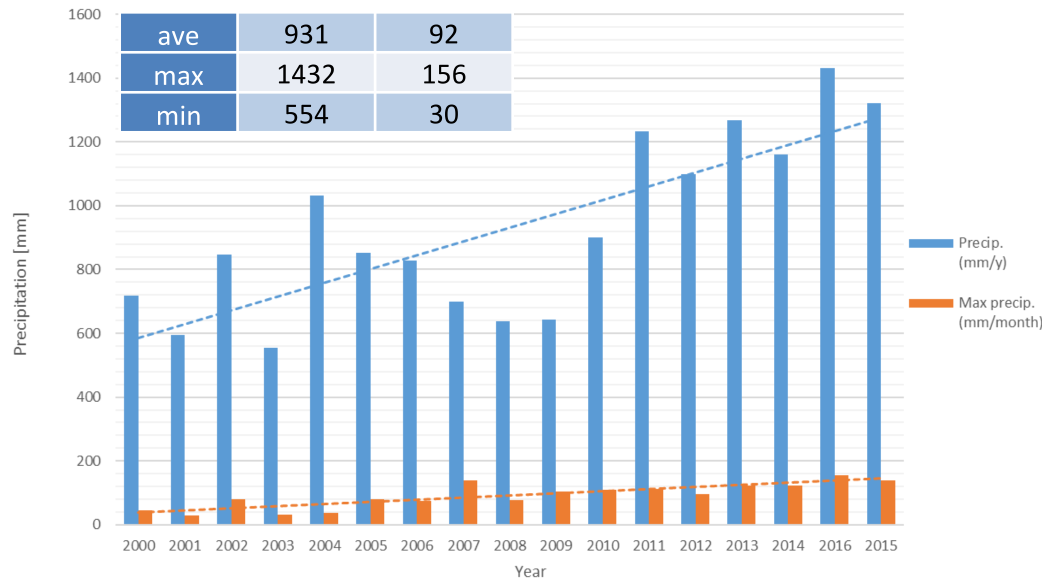


Introduction: Climate & Rainfall

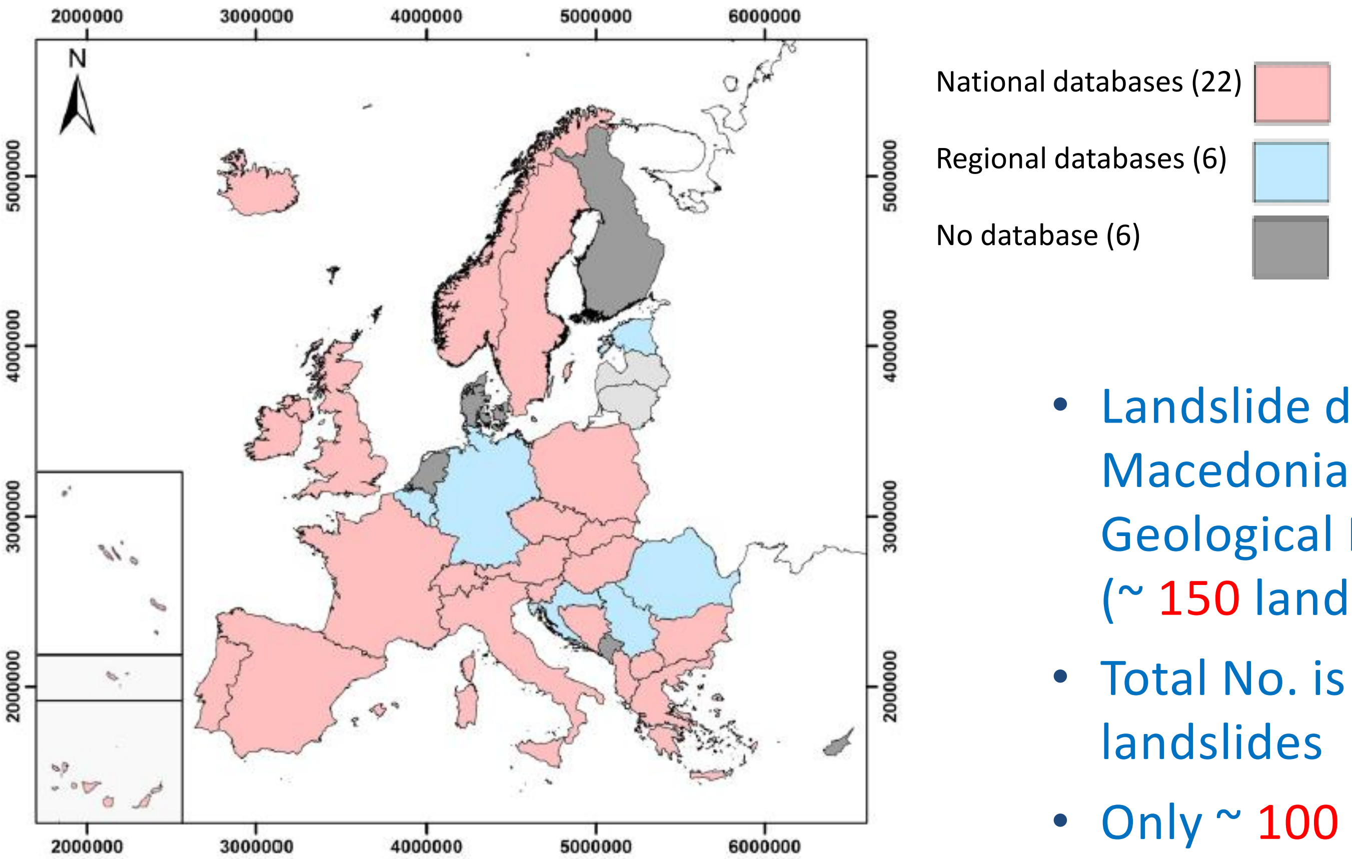
- Continental and Mediterranean climate
- Semi-arid with *short-wet periods* and unequal seasonal precipitation *(500-1500 mm/yr)*
- Rainfall season (October to March) with *excess runoff cause extreme raise of water in GWL.*
- *In the past two decade there is gradual increase in precipitation (mm/yr)*



Precipitation layout (mm) in the R. N. Macedonia



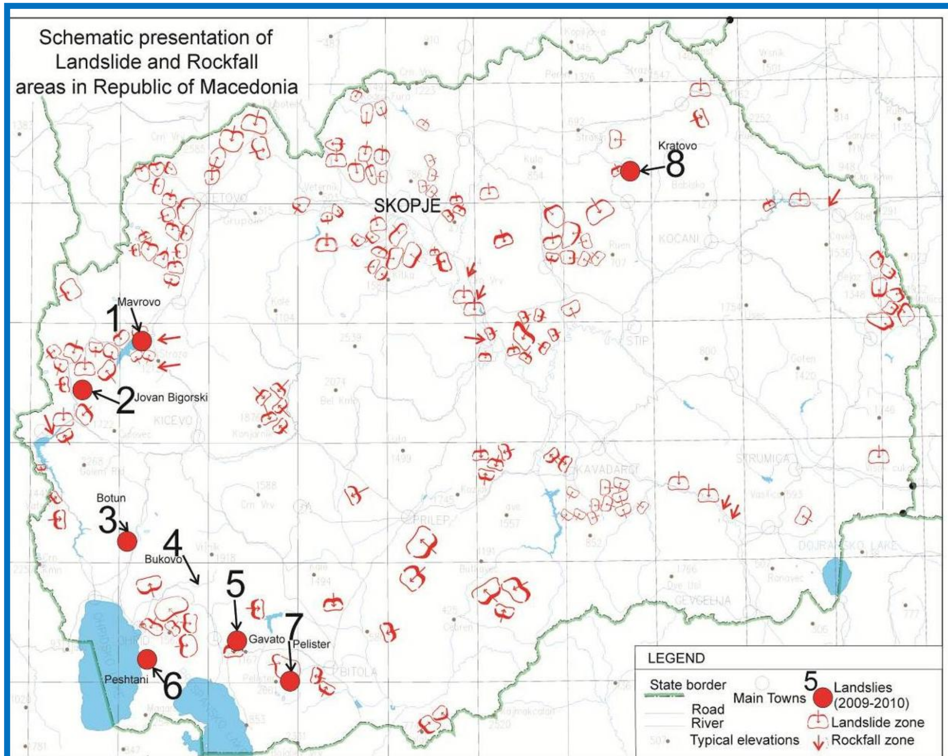
DATABASE OF LANDSLIDES

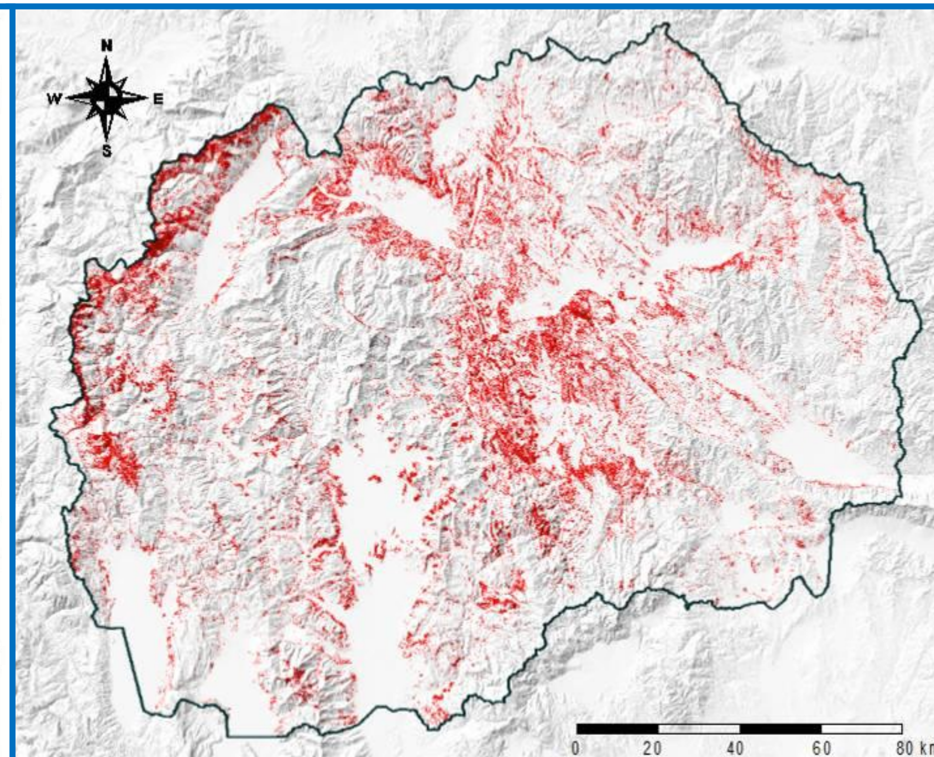


Source (M.V.D Eeckhaut, J. Hervás Institute for Environment and Sustainability, (JRC), European Commission, 21027 Ispra, Italy)

- Landslide database of N. Macedonia -Basic Geological Map from 1970 (~ 150 landslides mapped)
- Total No. is estimated > 300 landslides
- Only ~ 100 landslides are known and unregistered

DATABASE OF LANDSLIDES : GIS map of Landslide areas





Schematic map of Landslide and Rockfall areas in N. Macedonia

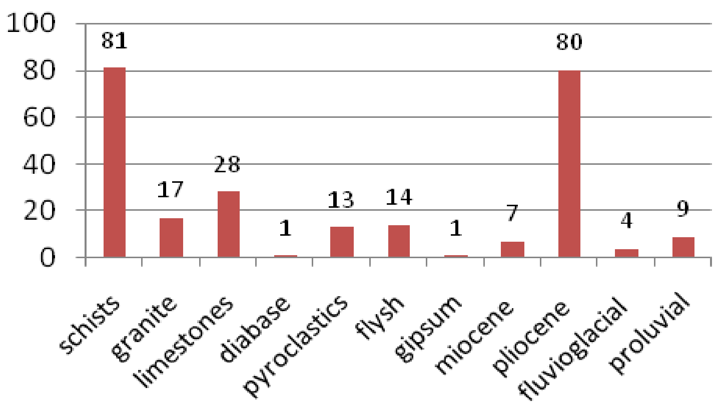
Ground instabilities: trans. and rot. landslides, rock falls, debris flows, excessive erosion.

Landslide development potential with SAGA cluster classification method

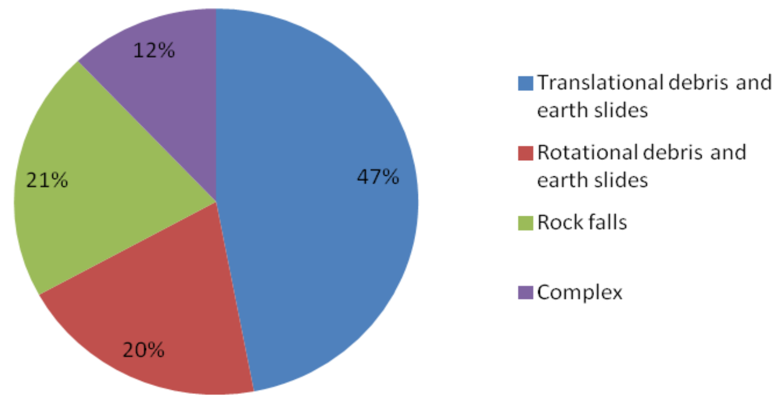
Landslide potential map which in using a GIS database is available (I. Peshevski)

DATABASE OF LANDSLIDES : Statistics

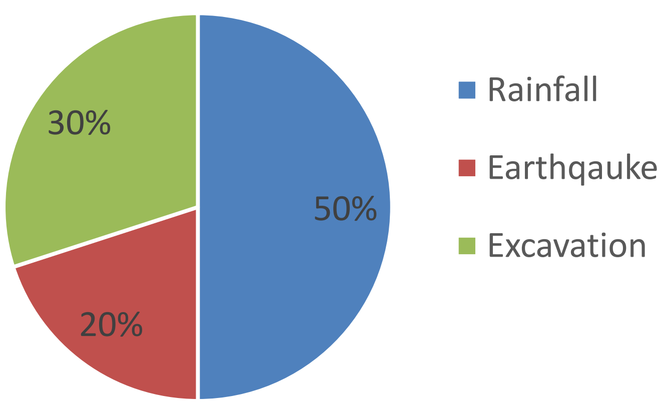
According to Geological conditions



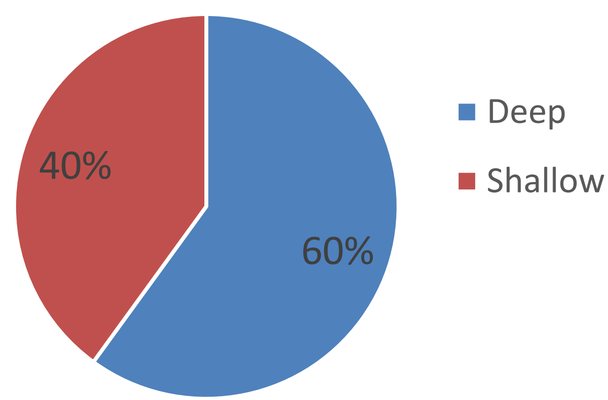
According to Landslide mechanism



According to Triggering mechanism



According to Landslide depth



Ground instabilities: 2010–2019

Mavrovi a.-Debar (snow avalanche),Feb. 2010

access road to monastery St.Petka - v.Orovnik, 2010

Landslide on regional road M-5 Resen-Bitola, Feb. 2010

Rockfall on regional road Mavrovi a-Debar, Feb.2013

Rockfall on railway Gostivar-Kichevo. March 2010

Rockfall on road Delcevo-Pehcevo, April 2013

road Mavrovi anovi-Debar, Feb.2013

Rockslip on the road Berovo-Strumica, March 2010

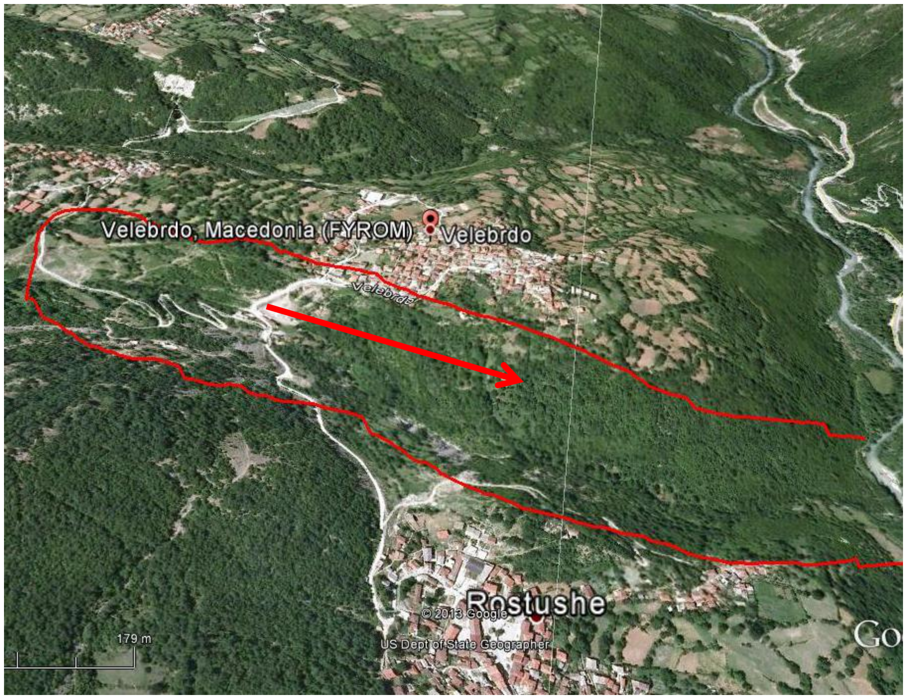
Landslide on highway Skopje-Bitola, Near v.Farish, 2013

highway E-75 (Katlanovo – Veles) Feb. 2013

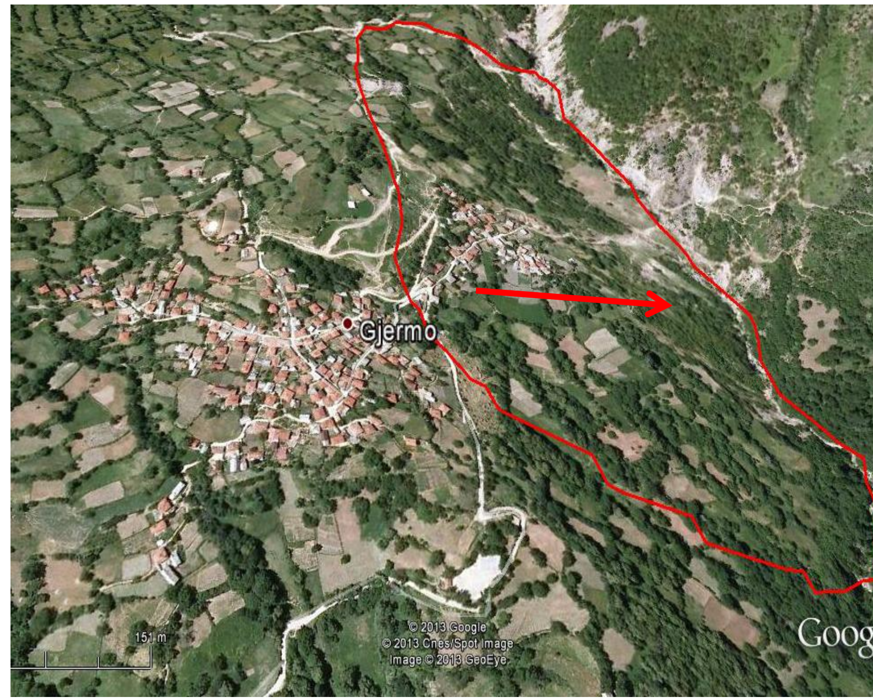
Rockfall on regional road Kochani-Delchevo, Nov. 2013

Ramina, urbaised hill in Veles

Part 1. Natural Landslides



"Velebrdo" landslide
last activation 2009 (500,000 m^2)



"Germo" landslide
last activation in 2000 (450,000 m^2)

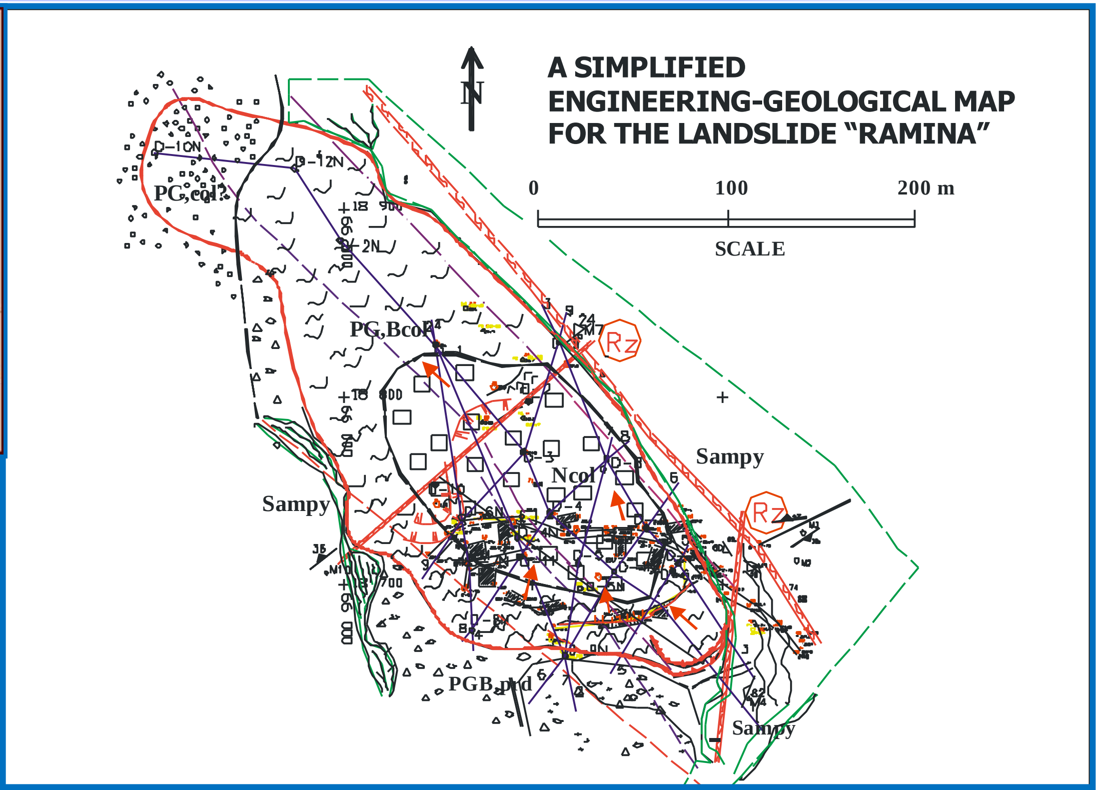
Case #1: Landslide “Ramina” : From Natural Hazard to Prevention (1963, 1999, 2002)

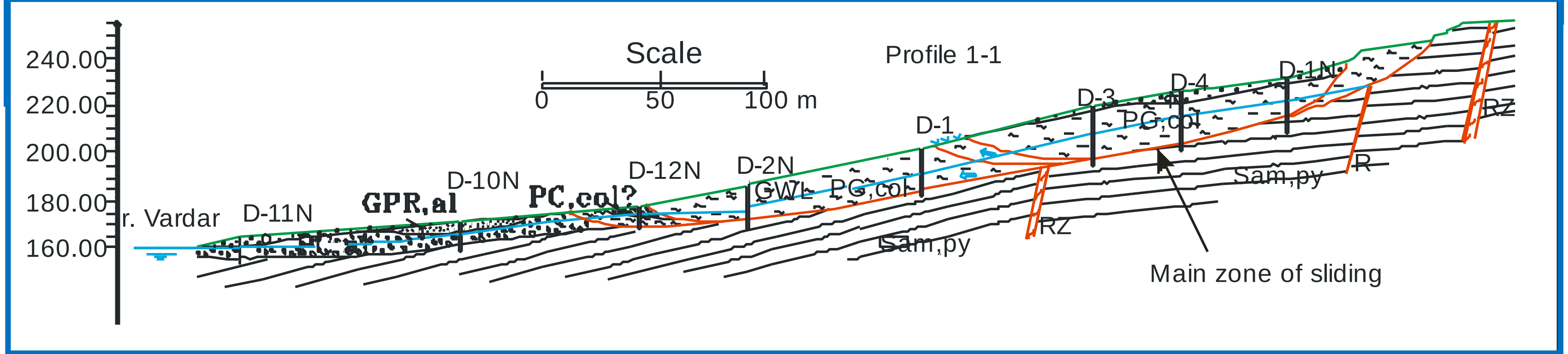





“Ramina” Landslide data

Length L = 500 m
Height H = 95 m
Width B = 80 – 110 m
Depth Dmax = 24 m
Area A = 37.600 m^2
Volume V = 475.200 m^3





FEM modelling aspects: M- model

- Fully coupled HM analysis

Deformation Eq. (Linear momentum balance)

$$\underline{\underline{L}}^T \left[\underline{\underline{M}} \left(\underline{\underline{L}}\, d\underline{u} \right) + S_e\, dp_w\, \underline{m} \right] + d(\rho \underline{g}) = \underline{0}$$

$$\boldsymbol{\sigma} = \boldsymbol{\sigma}' + \mathbf{m}\left(\chi p_w + (1-\chi) p_a \right)$$

$$\boldsymbol{\sigma} = \boldsymbol{\sigma}' + \mathbf{m}\left(S_e p_w \right)$$ (Bishop & Blight, 1963)

Continuity Eq. (Mass conservation)

$$\nabla^T \left[\rho_w \frac{k_{rel}}{\rho_w g} \underline{\underline{k}}^{sat} \left(\nabla p_w + \rho_w \underline{g} \right) \right] = -\frac{\partial}{\partial t}\left(\rho_w n S \right)$$

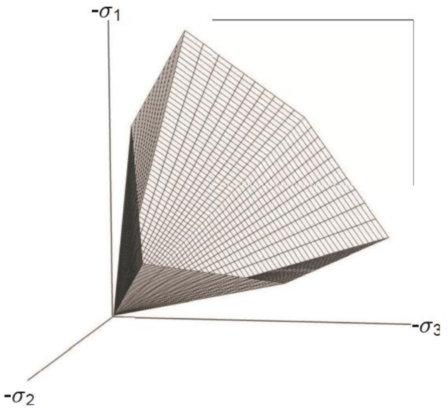
Fully coupled HM analysis (FE formulation)

$$\begin{bmatrix} \underline{\underline{K}} & \underline{\underline{Q}} \\ \underline{\underline{C}} & -\underline{\underline{S}} \end{bmatrix} \begin{bmatrix} \dfrac{d\underline{v}}{dt} \\ \dfrac{d\underline{p}_w}{dt} \end{bmatrix} = \begin{bmatrix} 0 & 0 \\ 0 & \underline{\underline{H}} \end{bmatrix} \begin{bmatrix} \underline{v} \\ \underline{p}_w \end{bmatrix} + \begin{bmatrix} \dfrac{d\underline{f}_u}{dt} \\ \underline{G} + \underline{q}_p \end{bmatrix}$$

- Mechanical conditions

  – *Elasto-plastic Mohr–Coulomb model*

Parameter / Soil material	Sandy-Clay
Unit weight γ (kN/m³)	20.14
Eff. friction angle φ’ (⁰)	23
Eff. Cohesion c’ (kPa)	12
Eff. Poisson’s ratio n’ (/)	0.32
Elastic modulus E’ (kPa)	10000



The Mohr-Coulomb yield surface in principal stress space

  – *Phi / c reduction*

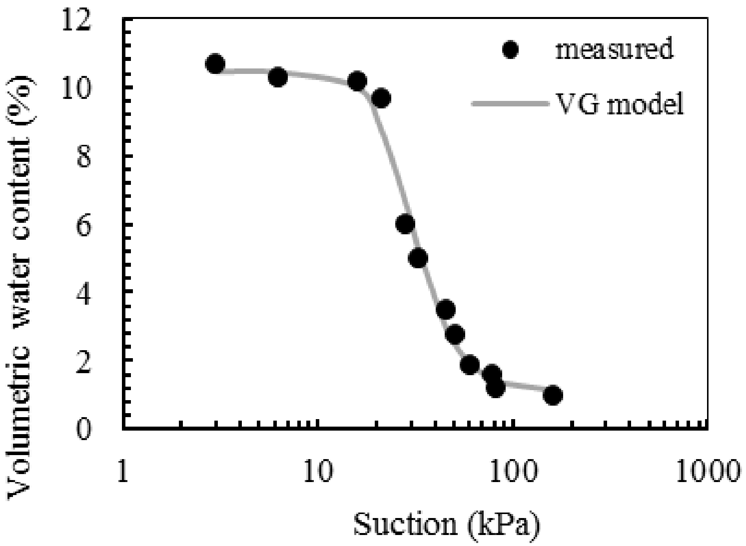
$$\Sigma Msf = \frac{\tan \varphi_{input}}{\tan \varphi_{reduced}} = \frac{c_{input}}{c_{reduced}} = \frac{s_{u,input}}{s_{u,reduced}} = \frac{Tensile\ strength_{input}}{Tensile\ strength_{reduced}}$$

FEM modelling aspects: H- model

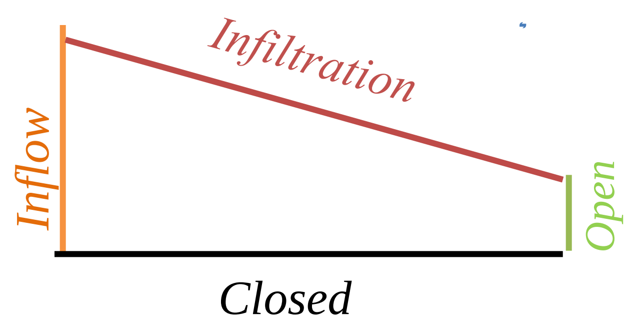
- Soil definition
  - *SWRC & van Genuchten model*

$$\theta = \theta_r + \frac{\theta_s - \theta_r}{[1 + |\alpha h|^n]^m}$$

Soil	k_{sat} (m/s)	θ_s (%)	θr (%)	(1/kPa)	n (-)
Sandy-Clay	*1E-6*	*38.70*	*10.45*	*0.35*	*4.17*

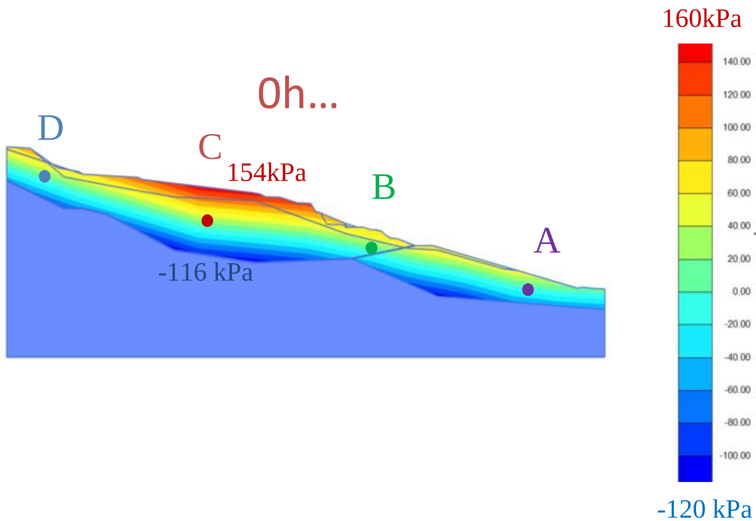


- Model Bc's
  - *Upper (Left) boundary = Inflow*
  - *Lower (Right) boundary = Open*
  - *Surface (Top) boundary = Infiltration*
  - *Bottom boundary = Closed*



- Loading and other effects
  - *Projected rainfall - Constant intensity of 5mm/h*
  - *GW Inflow – 0.5 m^3/h*
  - *Infiltration with 2mm/h runoff water*
  - *No vegetation or root systems are modelled*
  - *No evapo-transpiration effects are modelled*

Analysis results: PWP (0-24h)



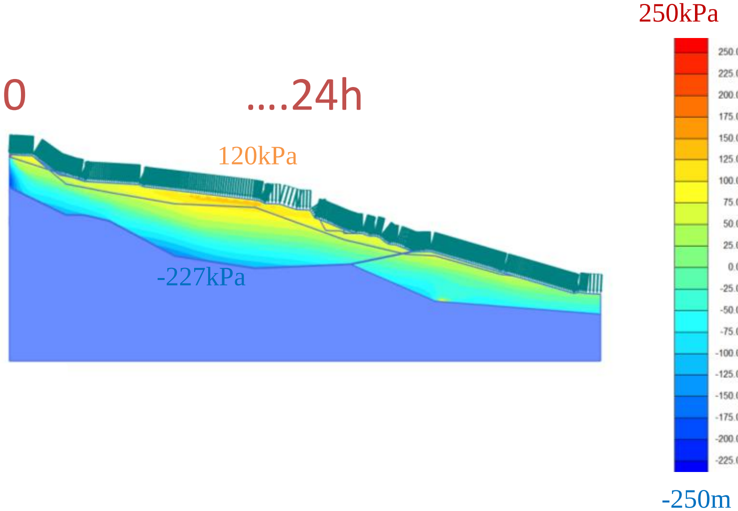
2...4...8...12...16...20

max PWP ↑ x 100%

-116kPa <...> -227kPa

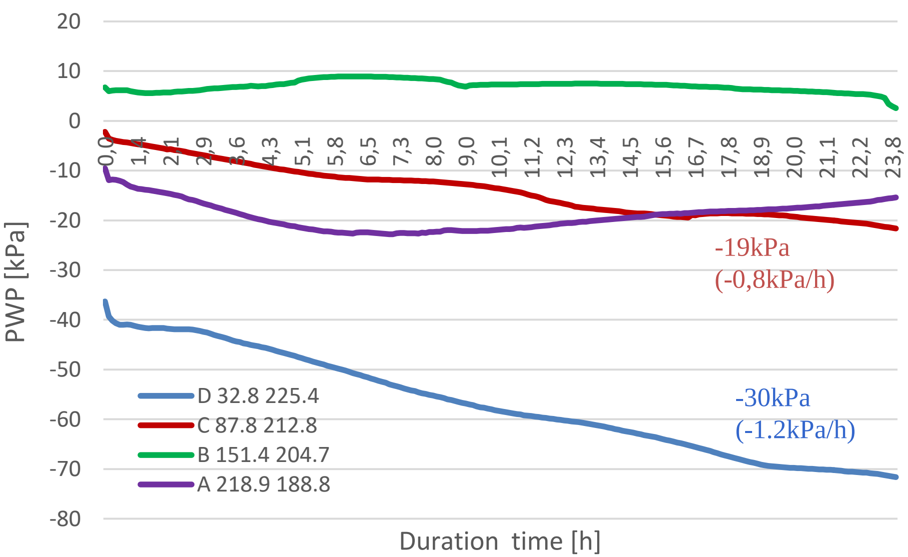
max Suction ↓ 33%

160kPa <...> 120kPa

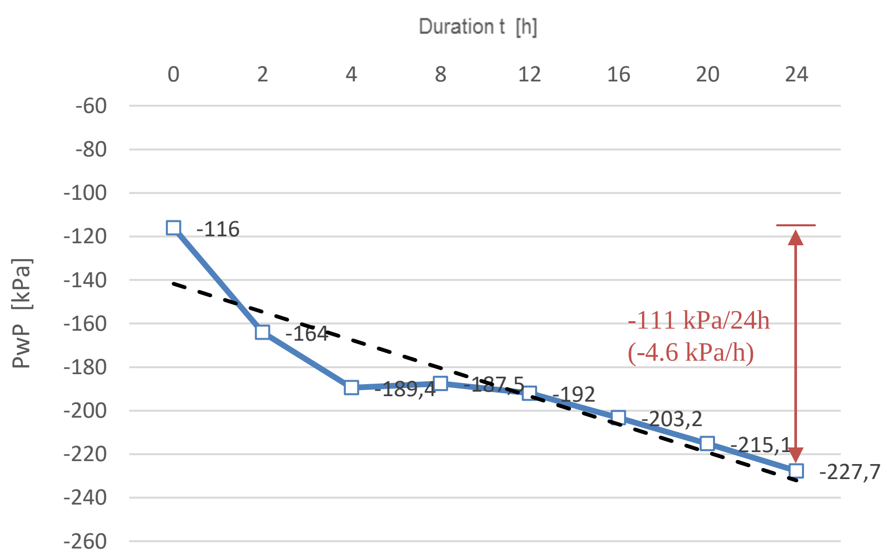


PWP diagrams

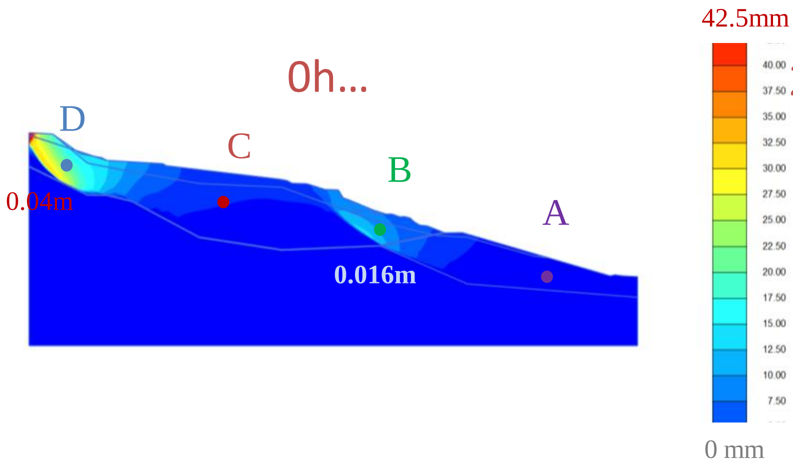
PWP at points A, B, C, D



max PWP value



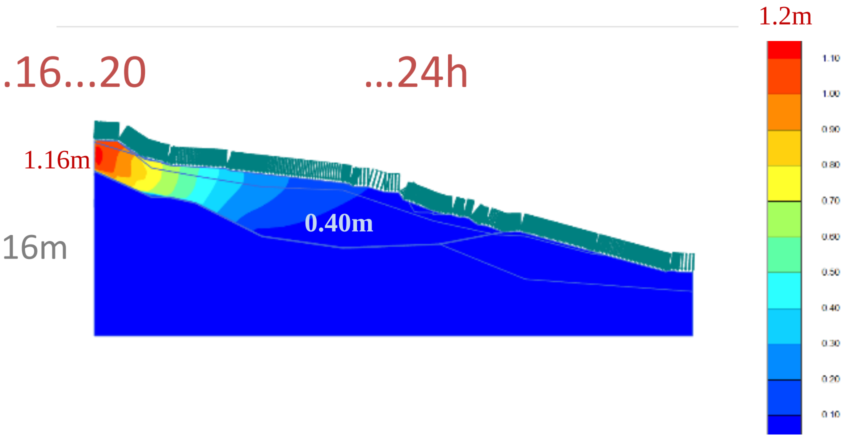
Analysis results: Slope displ. (0-24h)



2…4…8…12…16…20

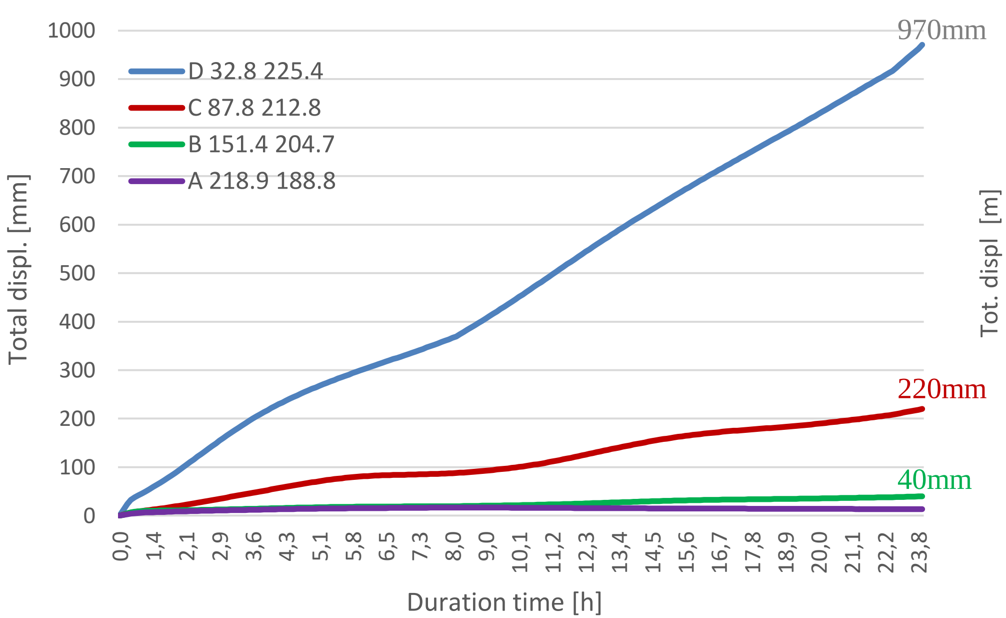
max U_tot

0.045 m <…> 1.16m

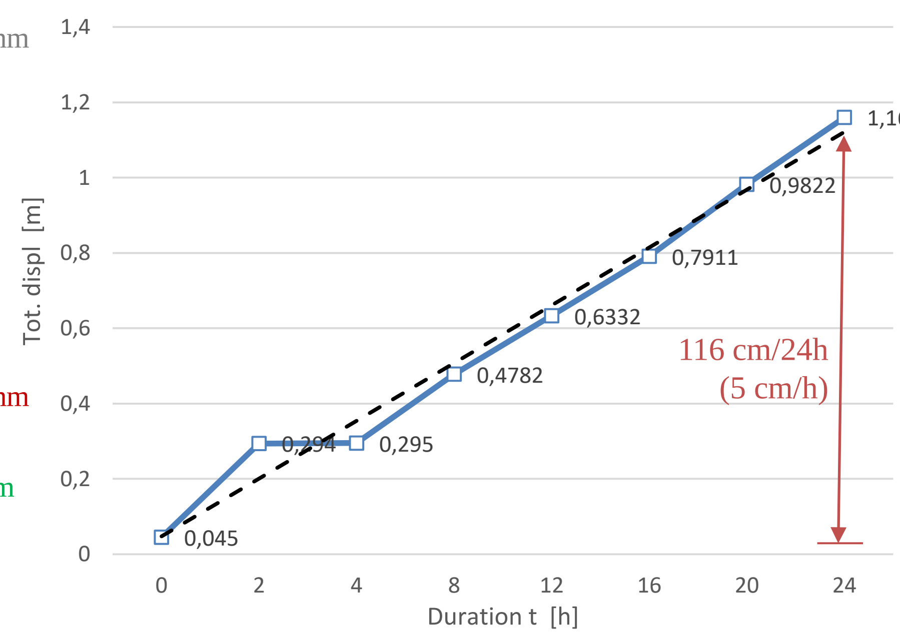


U_tot diagram

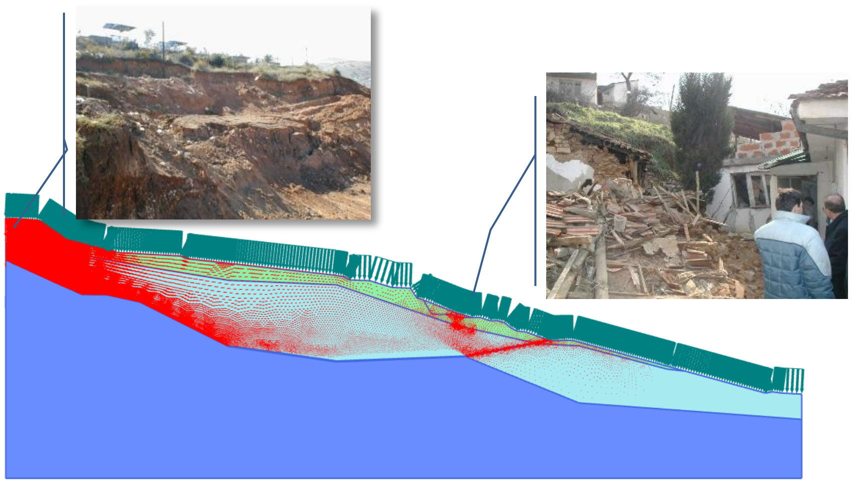
U_tot at points A, B, C, D



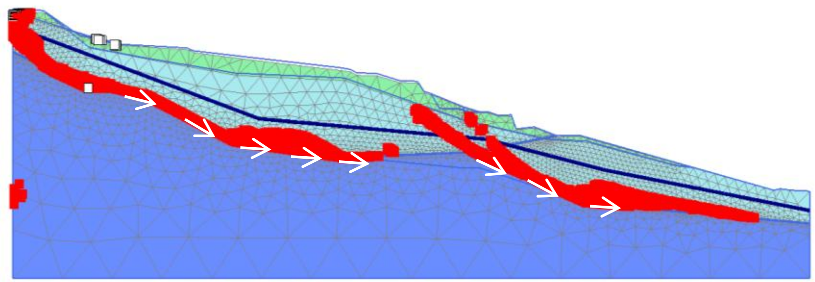
max U_tot value



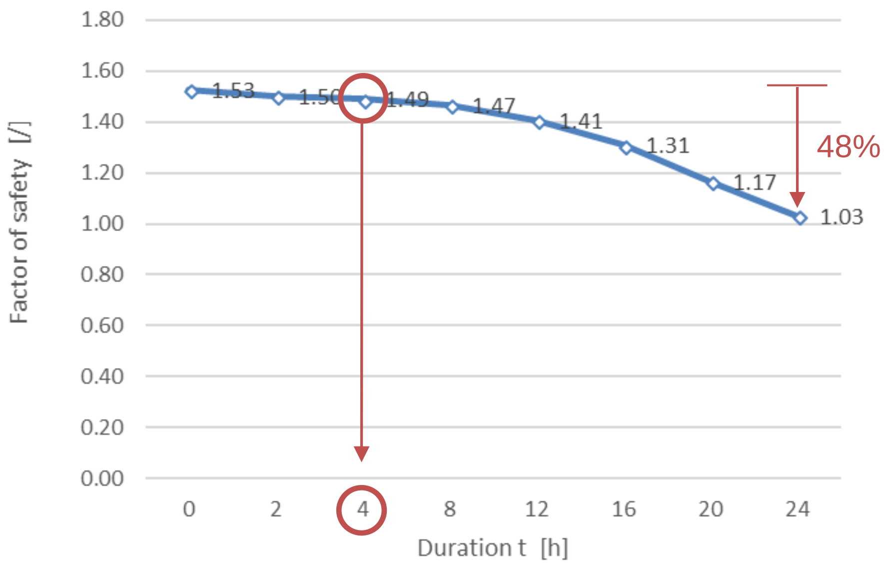
Data analysis of the 24h rainfall effects

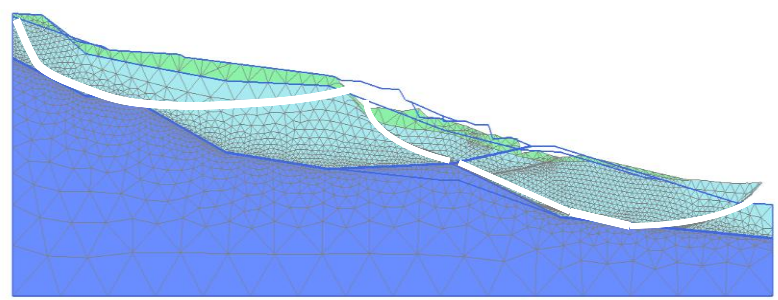


max U_{tot}= 1.16m



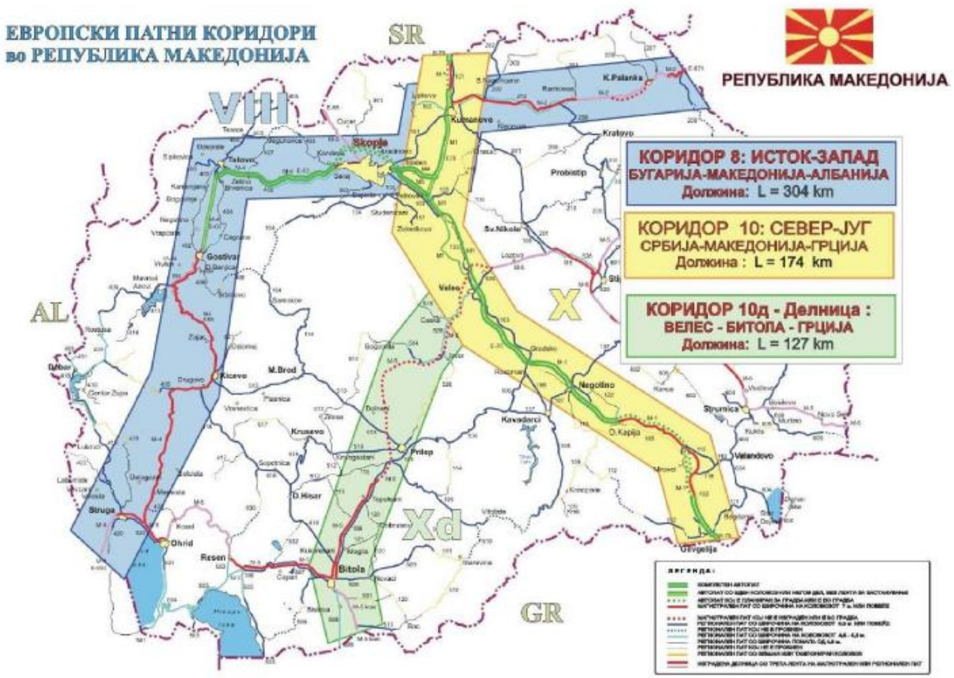
Raise in PWP (raise in shear str.)> Plastic zone



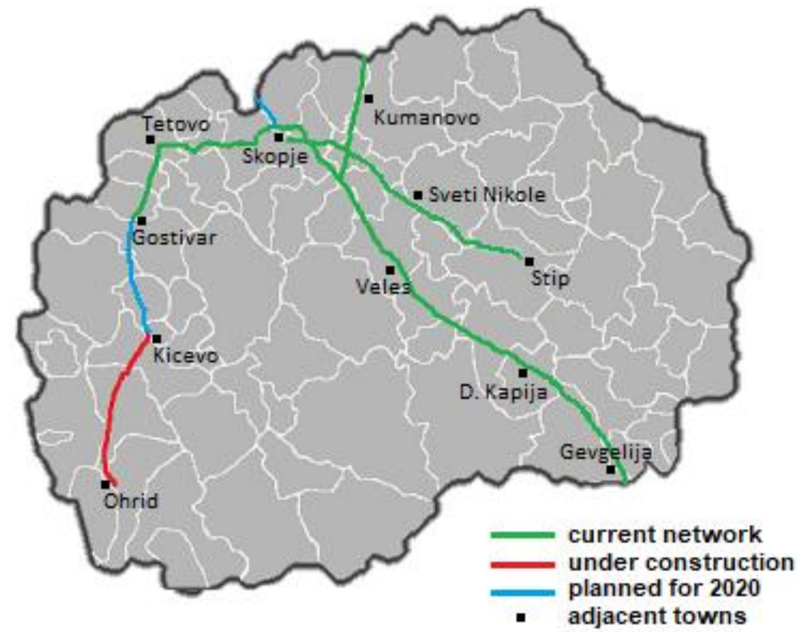


FoS = 1.03

Part 2. Stability of rengineered slopes for infrastructure

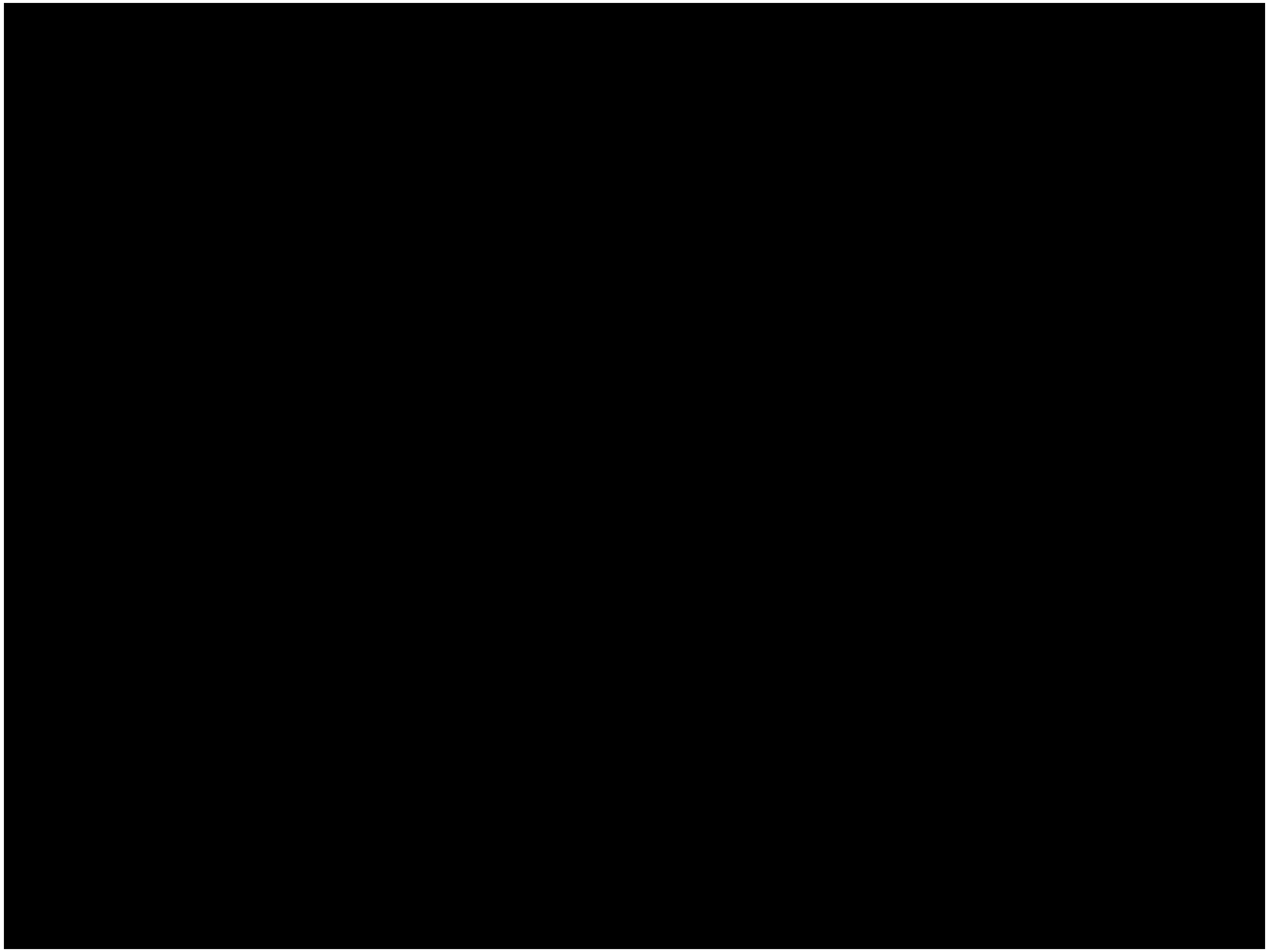


European corridors in North Macedonia



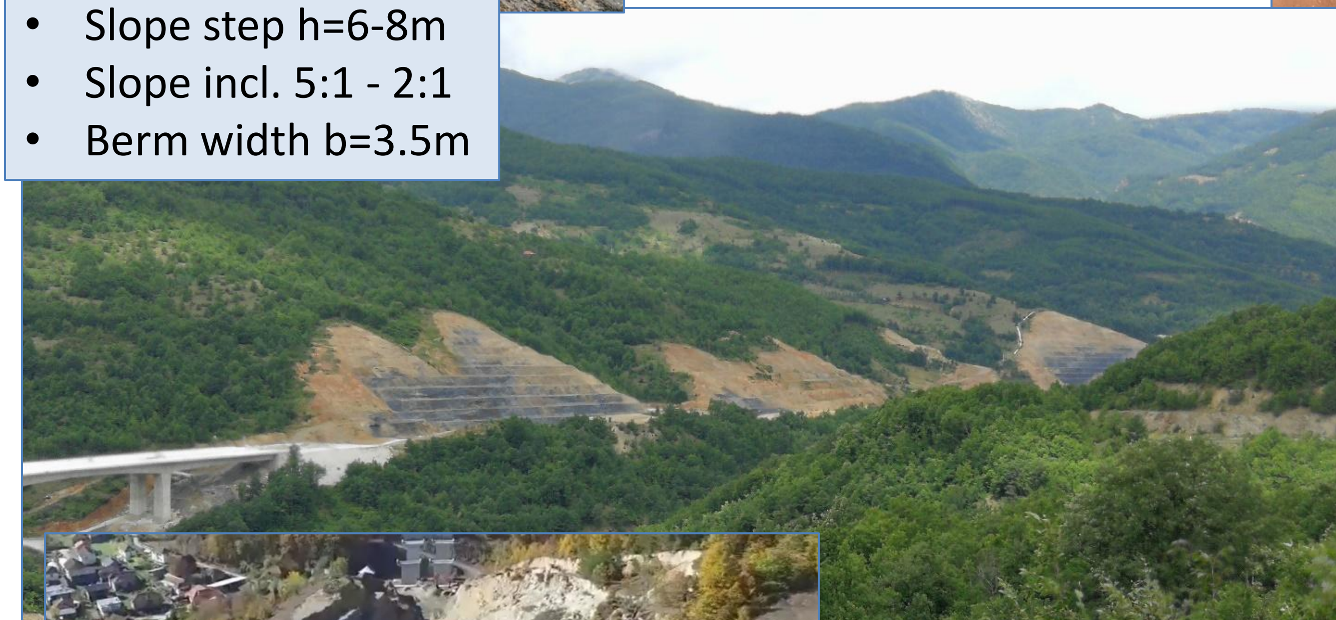
Planned and executed routes

Case #2: Construction of new Highway on Corridor VIII, Route Kicevo - Ohrid (due 2019 - ext. 2022)



- 52 km
- 42 Slopes
- 18 Bridges
- 2 Tunnels
- 620 mil. Euros
- Deadline 2019 (ext.2021)

- Slope H=20-75 m
- Slope step h=6-8m
- Slope incl. 5:1 - 2:1
- Berm width b=3.5m



around 9 mil. m^3 of excavation in decomposed conglomerates and fractured schist

Slope stability evaluation analyses

- FMEA (Failure Mode Effect Analysis) (Potential Landslides)
- LEM analysis
  - Deterministic
  - Probabilistic

OK !

(Variations in material properties)

- FEM analysis
  - Static (HM)
  - Seismic (PGa)
  - Flow-deformation (hydro-mech)

(Existing Landslides)

(Change in GW profile)

- RocPlane (Planar Wedge Stability Analysis)
- SWEDGE (Surface Wedge Stability Analysis)

OK !

FMEA (Failure Mode Effect Analysis)

- Risk analysis approach that detection potential failures
- Simple and widely applicable for the design
- Assess the structural risk and drawing conclusions for further remediation measures.
- Quantitative description of the failure model, which consists of three different dimensionless variables:

$$\mathbf{R = S \cdot O \cdot D}$$

- Where: Risk Priority Number (RPN), Consequence size (S-severity), Possibility of occurrence (O-occurrence), Possibility of event detection (D-detectability).

*Table 4. Ways to estimate the **Frequency of occurrence (O)***

Extent of investigations	
Nr	Oi
1	10
2	9
3	8
4	7
5	6
6	5
7	4
8	3
9	2
10	1

Structure condition	
description	Ok
failure above 75%	10
failure above 50%	9
partial failure	8
very large structural damage	7
large structural damage	6
medium structural damage	5
small structural damage	4
small damage	3
very small damage	2
no signs of deformation	1

Number of critical tests	
Nr	Oo
2	10
4	9
6	8
8	7
10	6
12	5
14	4
16	3
18	2
20	1

FS of the structure	
Fs	Ofs
1.10	10
1.26	9
1.41	8
1.57	7
1.72	6
1.88	5
2.03	4
2.19	3
2.34	2
2.5	1

$$\mathbf{O = c_1{*}O_i + c_2{*}O_k + c_3{*}O_o + c_4{*}O_{fs}}$$ (c_i – weight coefficients)

Table 5. Ranking of qualitative expression of ***failure probability (O)***

Probability of failure occurrence (O)	Probability of occurrence	Ranking
Very high: the failure is almost certain	>1 in 2	10
	1 in 3	9
High: repetition of failure over time	1 in 8	8
	1 in 20	7
Medium: Occasional failures	1 in 80	6
	1 in 400	5
	1 in 2000	4
Low: relatively low number of failures	1 in 15000	3
	1 in 150000	2
Rare: It is almost certain that there will be no failure	1 in 1500000	1

Table 6. Qualitative ranking of ***risk/hazard consequences (S)***

Effect	Effect severity (S)	Ranking
Dangerous without warning	Very severe consequences	10
Dangerous with a warning	Slightly lower consequences, compared to the previous degree	9
Very large	The road is inoperable and unsafe	8
Large	The road is inoperable with damages	7
Medium	The road is inoperable with less damage	6
Low	The road is inoperable without damage	5
Very low	The road is operable, but with considerable usage restrictions	4
Insignificant	The road is operable, but with some usage restrictions	3
Very insignificant	The road is operable, but with minor usage restrictions	2
No effects	No effects	1

Table 7. Qualitative ranking of ***risk detection probability (D)***

Detection	Detection probability	Ranking
Unobservable	Detection of possible reason of failure or subsequent failures is not possible	10
Very hard	Detection of possible reason of failure or subsequent failures is very hard	9
Hard	Detection of possible reason of failure or subsequent failures is hard	8
Very low	Detection of possible reason of failure or subsequent failures is very low	7
Low	Detection of possible reason of failure or subsequent failures is low	6
Medium	Detection of possible reason of failure or subsequent failures is medium	5
Above medium	Detection of possible reason of failure or subsequent failures is above medium	4
High	Detection of possible reason of failure is high	3
Very high	Detection of possible reason of failure is very high	2
Almost certain	Detection of possible reason of failure or subsequent failures is almost certain	1

Table 8. Typical FMEA application table

Structure	Type of risk	Explanation	Estimated frequency of occurrence (O)	Estimated importance of consequences (S)	Detection probability (D)	RPN (Risk Priority Number)	Recommended action + structural measures	After the measure (O)	After the measure (S)	After the measure (D)	Estimated RPN after the measure
Retaining structure, landslide, river area regulation, etc.											

Table 9. ***Priority risk levels by RPN*** *(Risk Priority Number)*

RPN (Risk Priority Number)	Measure
RPN<40	No measures required
RPN 40-100	Moderate measures required to reduce the risk
RPN>100	Special attention needed - high risk

Type of hazard	Explanation	Estimated frequency of occurrence (O)	Estimated importance – consequences (S)	Probability of detection (D)	RPN (Risk Priority Number)	Recommended action + structural measures	After the application of a measure (O)	After the application of a measure (S)	After the application of a measure (D)	Estimated RPN with application of a measure
Groundwater	In the site investigation stage, groundwater was not treated/detected as a particular problem. Starting the execution of the works reveals that it is one of the main conditional factors on this location and therefore a cause of major problems	9	8	7	504	Permanent control of the operation of the drainage, realization of additional hydro geological investigations and, if necessary, implementation of additional drainage measures for the site. Applies to all types of drainage activities in the wider surroundings of the M2 wall	9	4	2	72
Complex geotechnical composition of a terrain	The review of existing technical documentation reveals that relatively high values of geotechnical parameters have been adopted for part of the rock masses for certain chainages. It is unclear whether the GWL and seismic effect were taken into account in the analyzes	7	9	6	378	Implementation of deep geotechnical boreholes, verification of geotechnical parameters of the rock and repetition of additional stability/bearing capacity analysis. Force testing in anchors, additional tightening and preparation of Elaborate.	4	6	4	96
Groundwater level	Present in the drainage channels and during the dry period of the year. It is not yet clear from the technical documentation whether the water is of a permanent character and in what quantities it should be expected to exert a pressure on structures	4	8	3	96	Continuous monitoring with piezometers and performance on additional piezometers. Measurement of groundwater inflow into the drainage in the course of the year. If visual inspection detects a higher humidity, it is required to perform additional sub-horizontal drains and to appropriately conduct the water to existing drainage structures on the surface.	2	6	1	12
Possibility of a partial failure of retaining structures, depending on actual geotechnical conditions	Due to the possible reduced performance of all protection measures in relation to numerous construction factors related to local variations of geotechnical parameters	8	10	2	160	Control testing of materials according to EN regulations	4	10	2	80
						Regular maintenance of the equipment, calibration of devices, checking of stability of fixed markers outside the unstable zone, providing access to all				

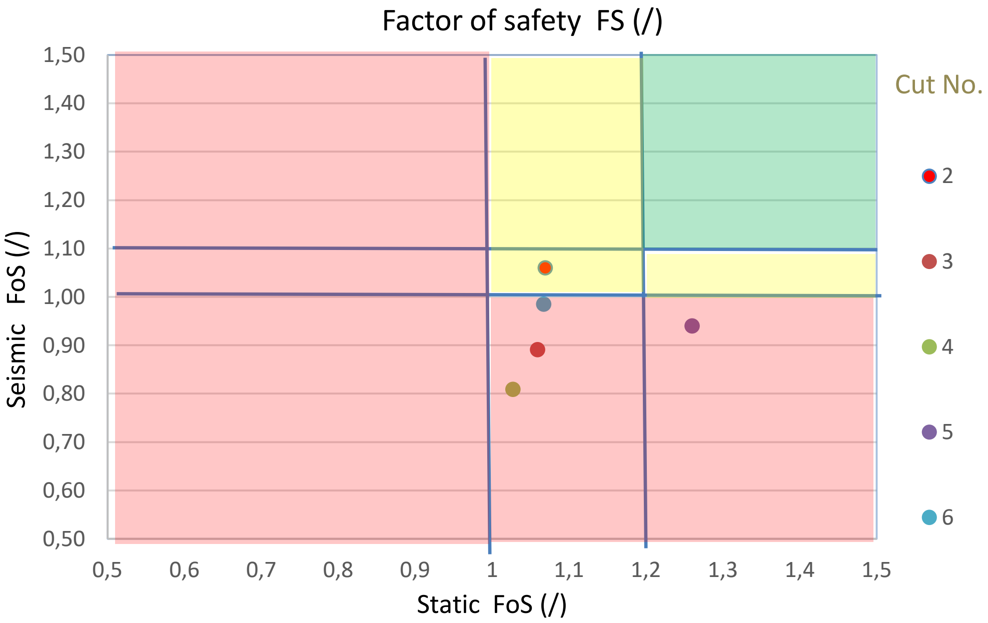
Evaluation of Slope stability using LEM

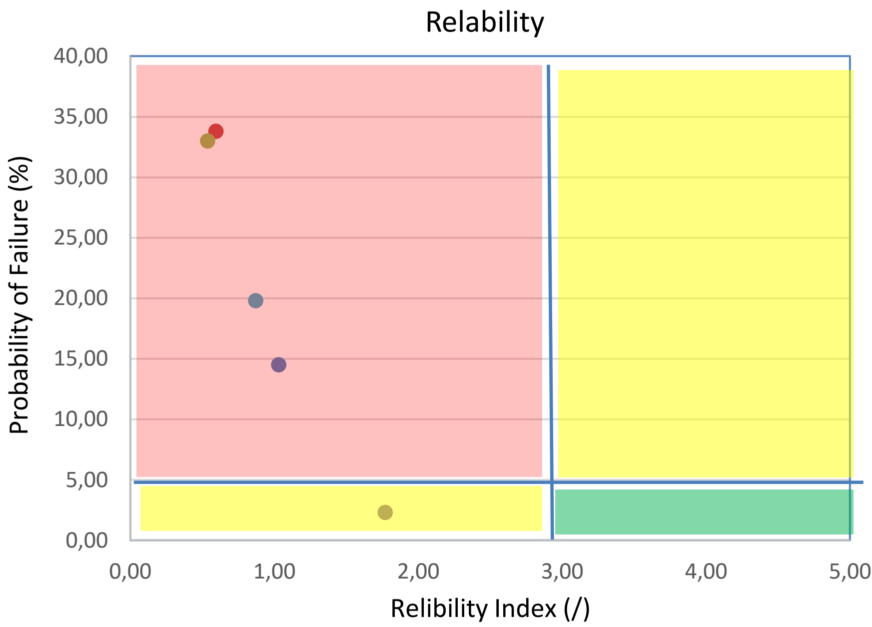
Safety factors for static and seismic loading

	Static FoS (/)		Seism. FoS (/)
Cut No.	Deterministic	Probabilistic	
2	1.065	1.069	1.060
3	1.023	1.059	0.891
4	1.025	1.027	0.809
5	1.140	1.260	0.940
Criteria	> 1.2	> 1.2	> 1.1

Probabilistic analysis parameters

Cut No.	Probability of failure PF (%)	Reliability index RI (/)
2	14.50	1.03
3	33.80	0.59
4	33.00	0.54
5	2.30	1.77
Criteria	5 <	> 3





Estimation of Safety

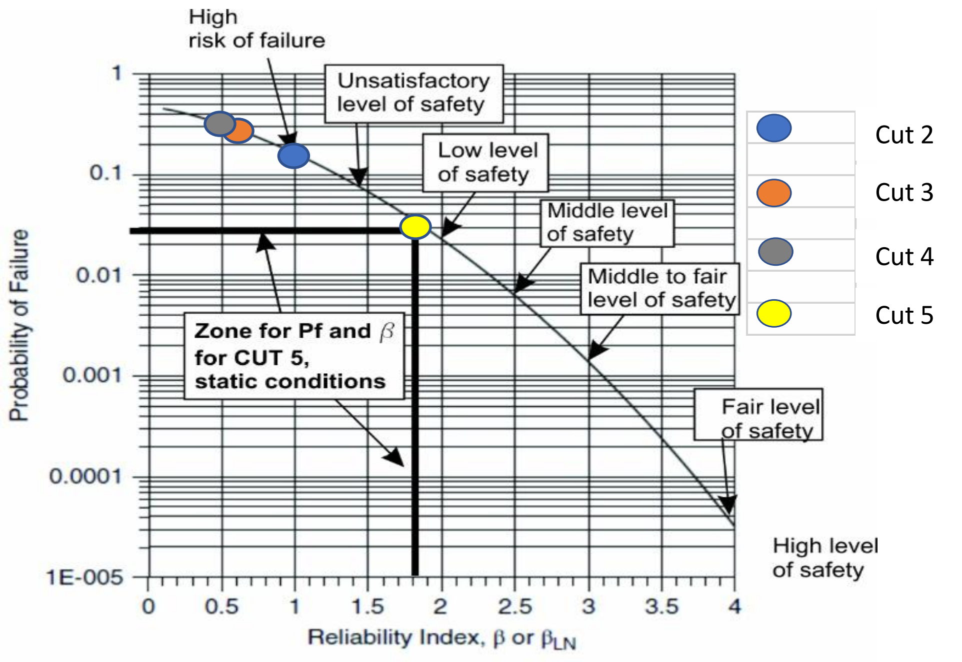


Diagram of Reliability index vs. Probability of failure *(Duncan J.M., Wright S.J., Brandon L.T., 2014)*

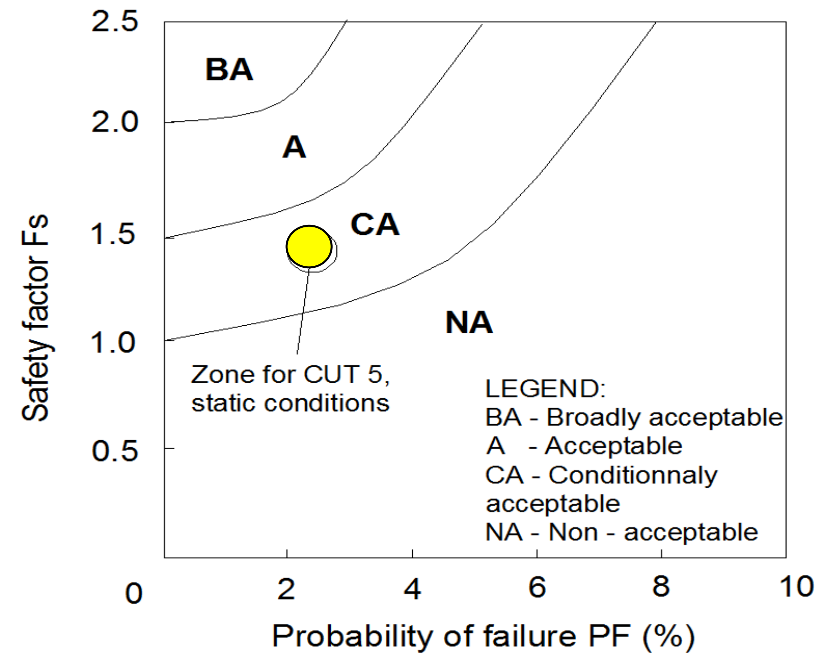


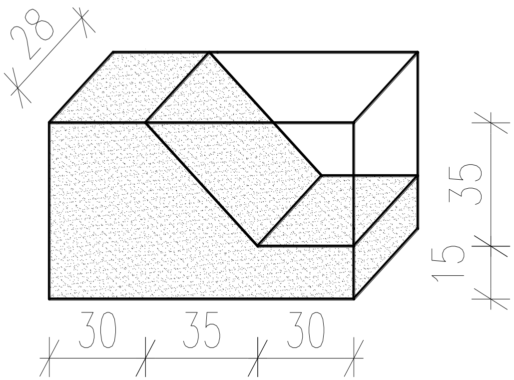
Diagram of Probability of failure vs. Factor of safety for the Cut No. 5 *(Peshevski et al., 2018)*

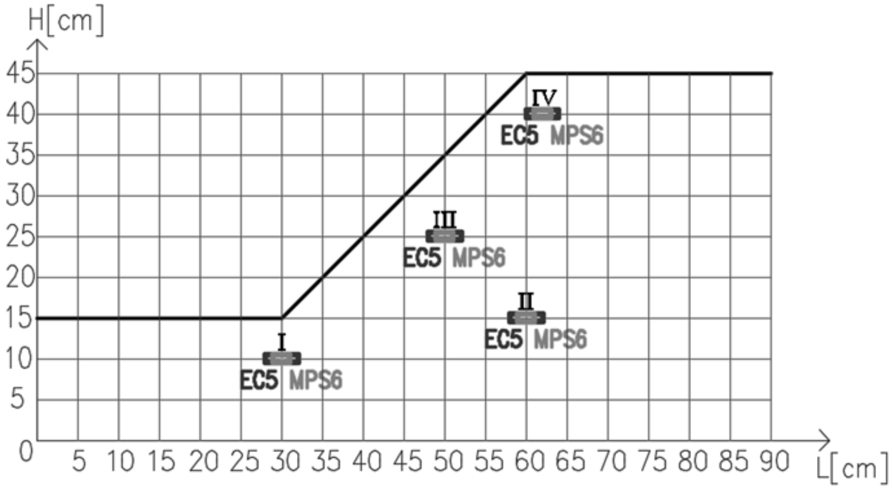
Part 3. Research study on Erosion and Infiltration

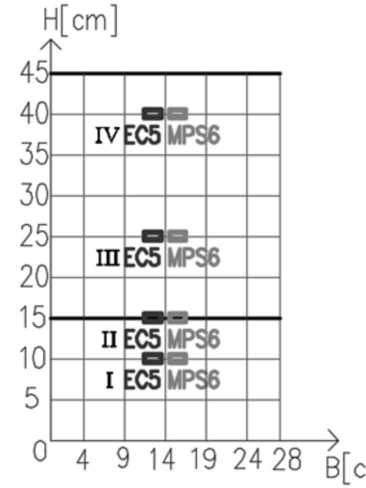
Corridor VIII - Highway route Miladinovci- Stip (2019)

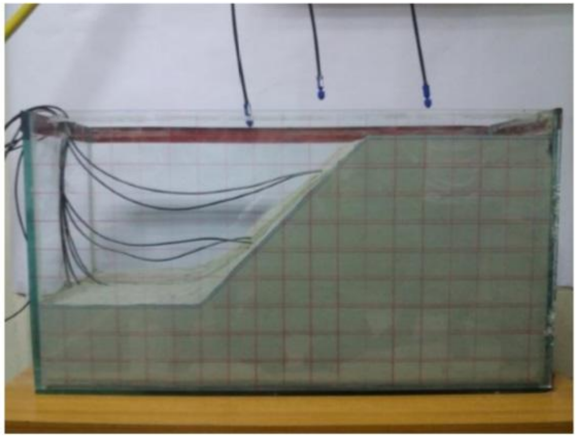
Experimental tests

Small-scale physical model









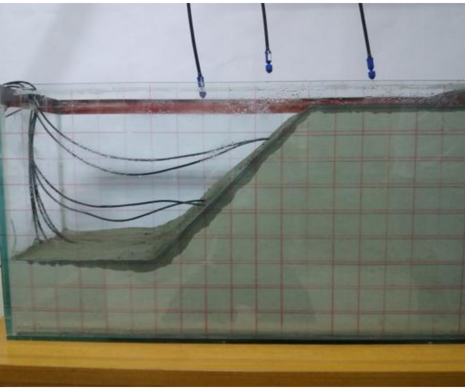
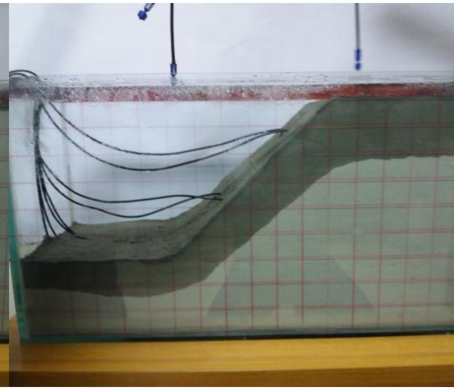
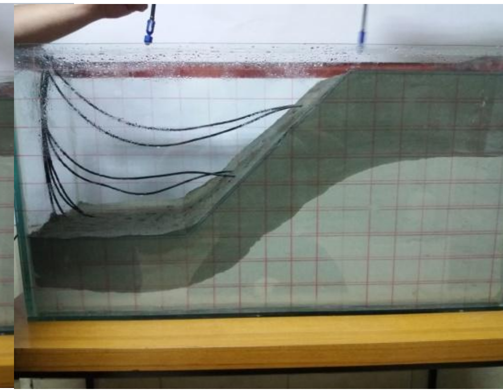
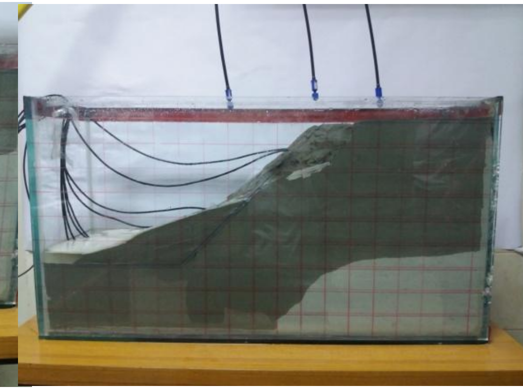
EC-5 VWC

MPS-6 Suction

Experimental tests

Erosion simulation model

Extreme rainfall (28mm/h) on Slope inclination 1:1

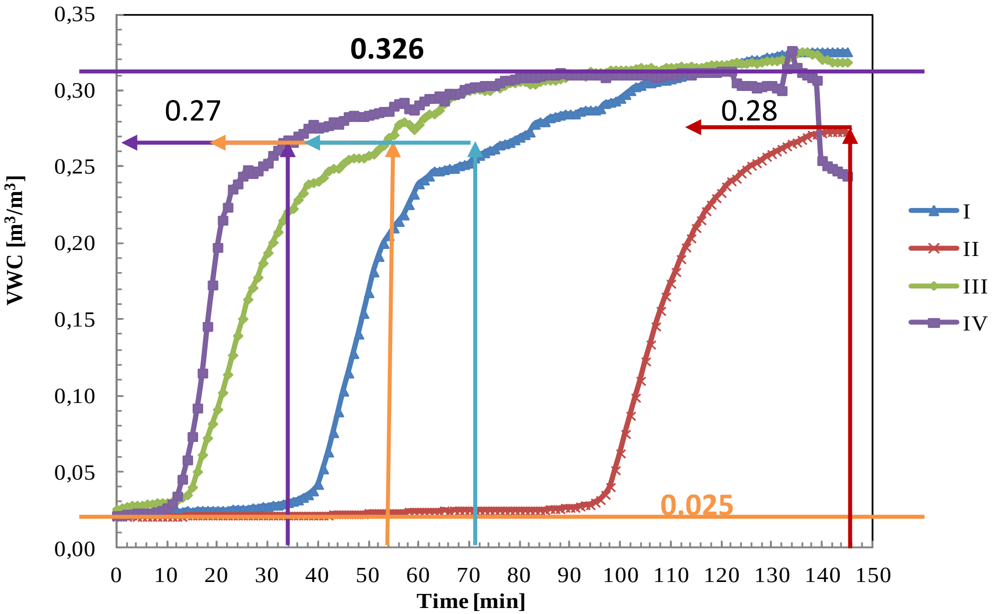
after 30 min. after 100 min. after 120 min. after 135 min.




Experimental tests

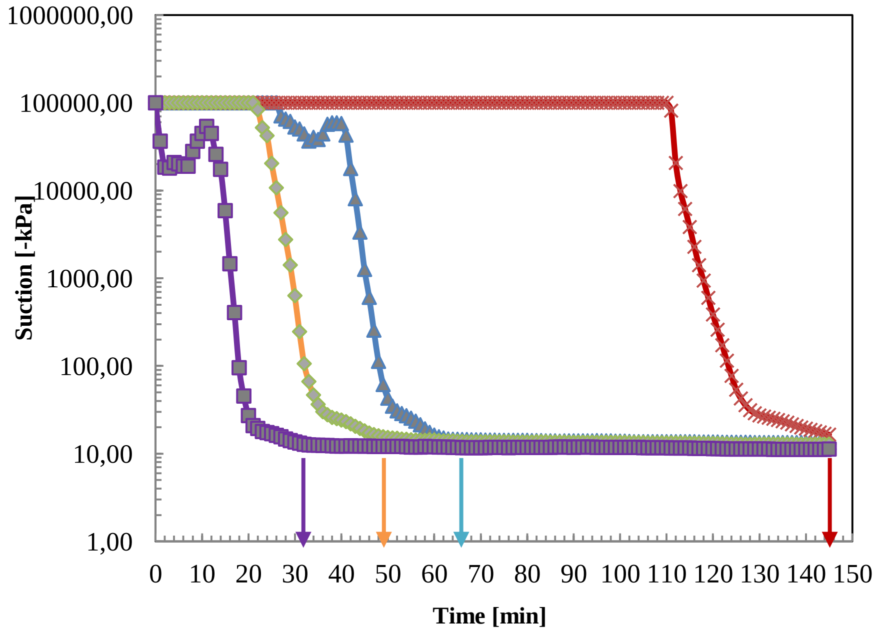
Results:

Volume Water Content



Sensor	VWC [m³/m³]	Time [min]	Suction [kPa]
I	0.326	134	10
II	0.273	141	10
III	0.326	136	10
IV	0.313	120	10

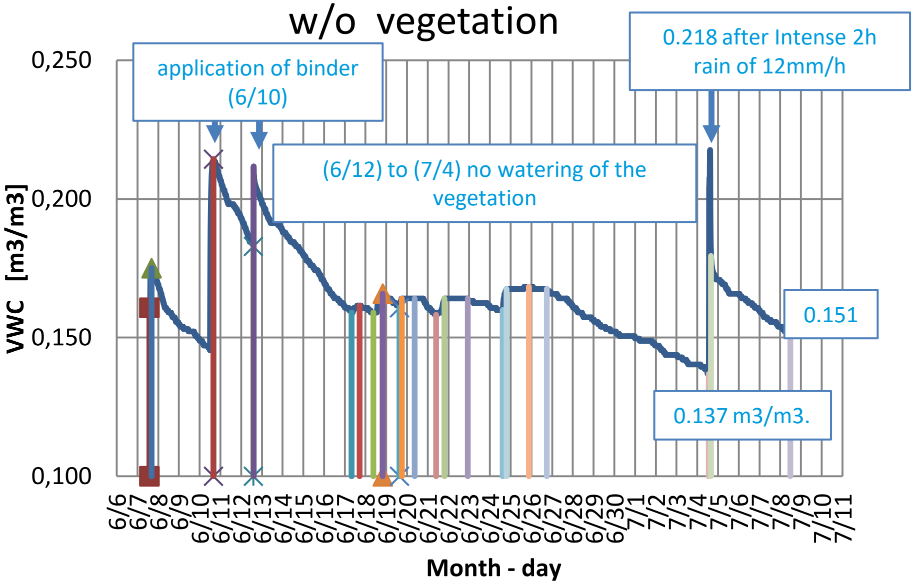
Suction

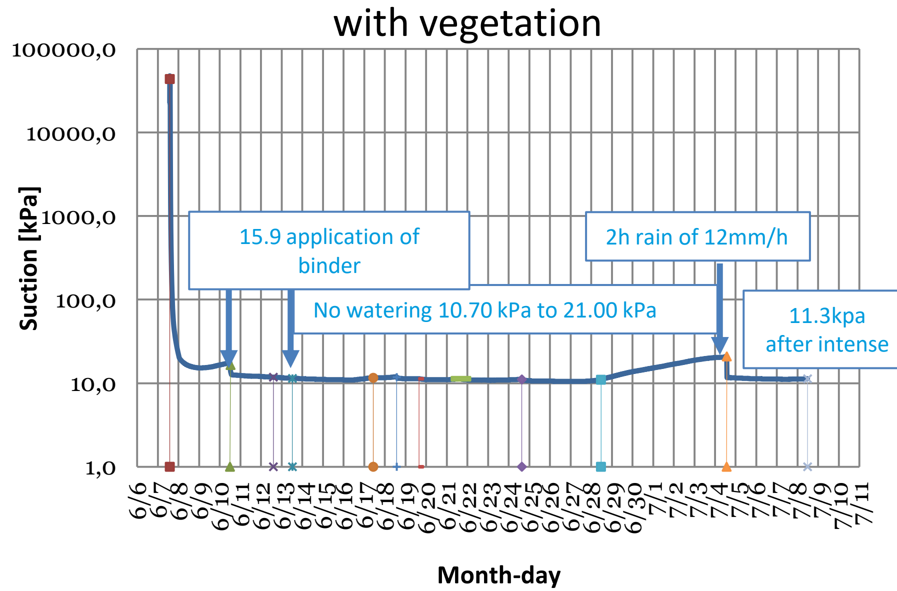


Sensor	Suction [kPa]	Time [min]	VWC [m³/m³]
I	10	145	0.28
II	10	70	0.27
III	10	50	0.27
IV	10	33	0.27

Experimental tests

Erosion & infiltration control with polymer and vegetation





Conclusions

- Climate changes in particular increase in **rainfall can have significant impact on slope stability**
- **Intense rainfall can affect even the stability on engineered slopes** triggering shallow sliding systems
- The study aims to quantitatively **assess the influence of intensity, frequency and duration of the rainfall on slope stability**
- The study underlines the importance of **slope stability check on intensive rainfall (10 -20 mm/h) with longer duration**
- The use of **biopolymers has shown positive effect reducing the hydraulic conductivity, thus an increase in erosion resistance** of soils
- **Serviceability analyses is advised to evaluate the risk with projected rainfall** intensity, duration and probability of occurrence