Slope stability analysis: different approaches for different landslides

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There are many problems related to LANDSLIDES.

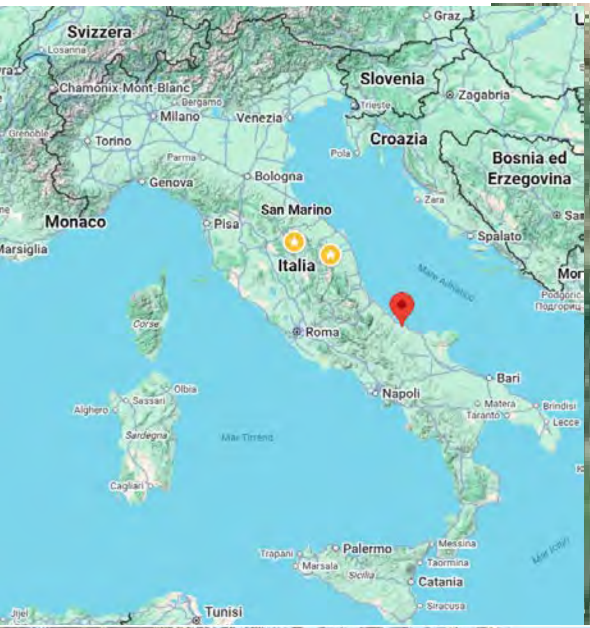
Before going in depth, it is necessary to focus our attention on a basic issue:

Which is the main OBJECTIVE of my analysis?

Why I have to study this problem?

The answer to these questions determines the APPROACH and the METHODS!

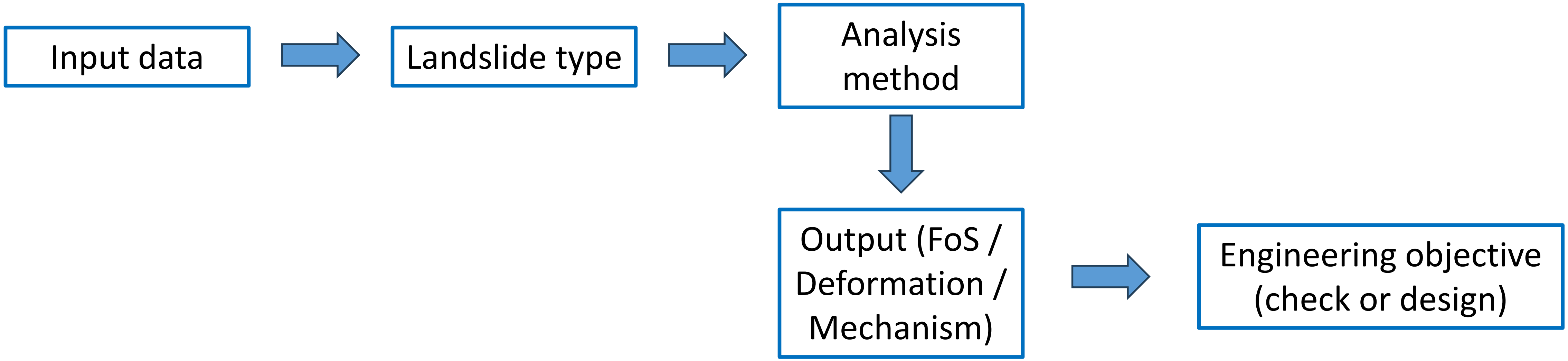
An example from Italy: Petacciato landslide → Which is the main OBJECTIVE?



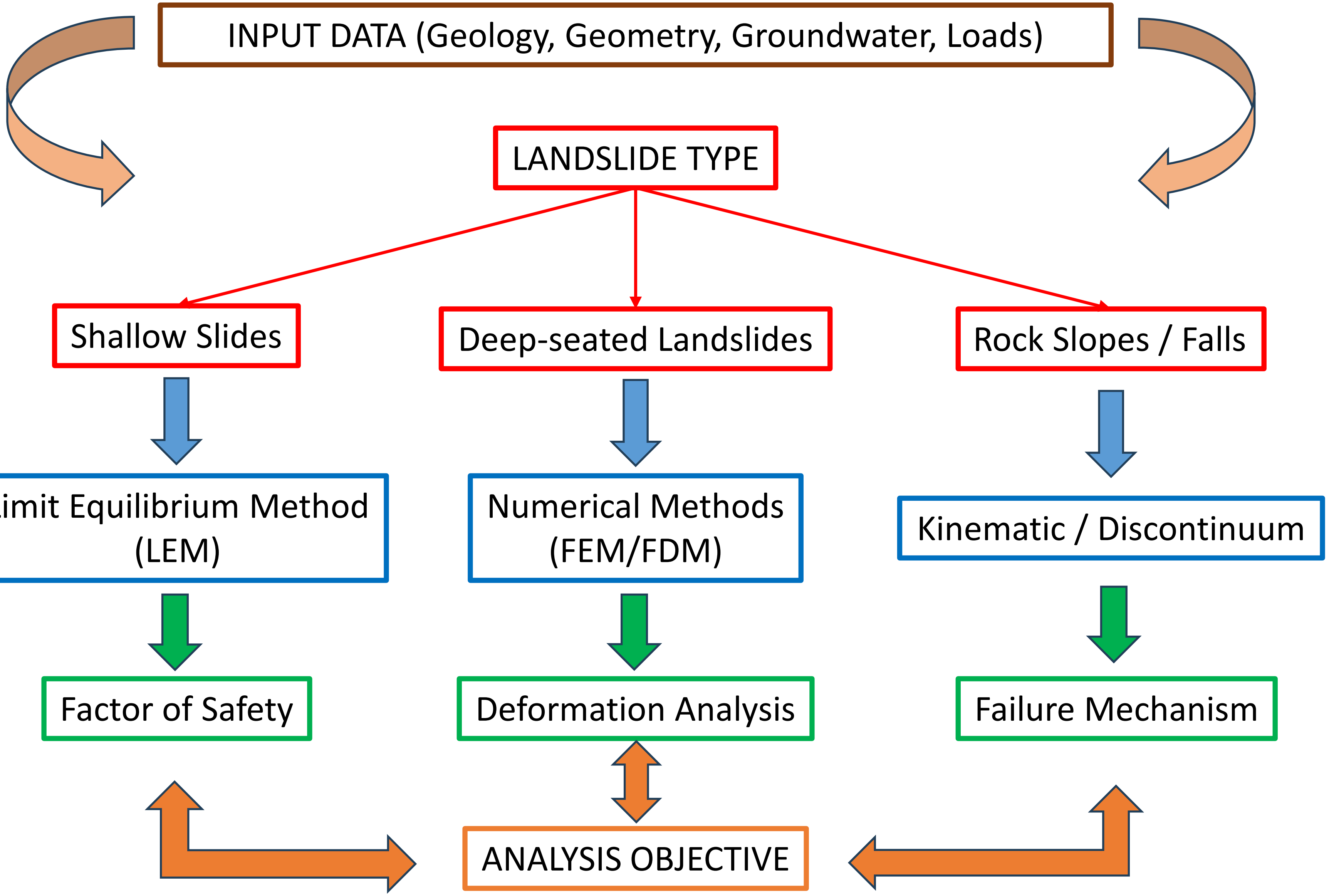
An example from Kenya → Which is the main OBJECTIVE?


Heavy rains on November 1, 2025, triggered a massive landslide in Elgeyo Marakwet County's Marakwet East constituency, killing 21 people and leaving over 30 missing in areas like Chesongoch and Moror Village.

Different landslide types require different analysis methods, depending on the objective: from simple stability checks to detailed design and deformation analysis.

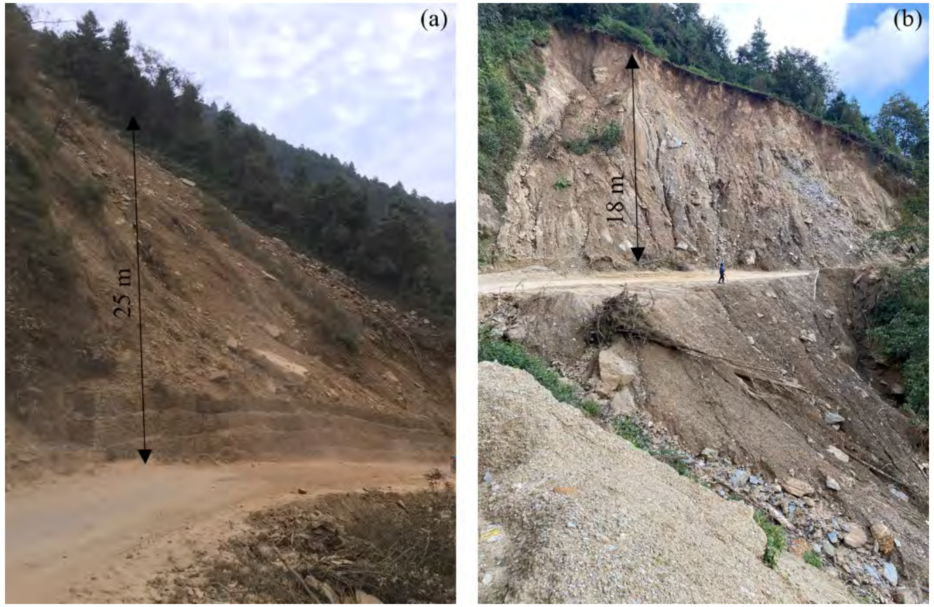


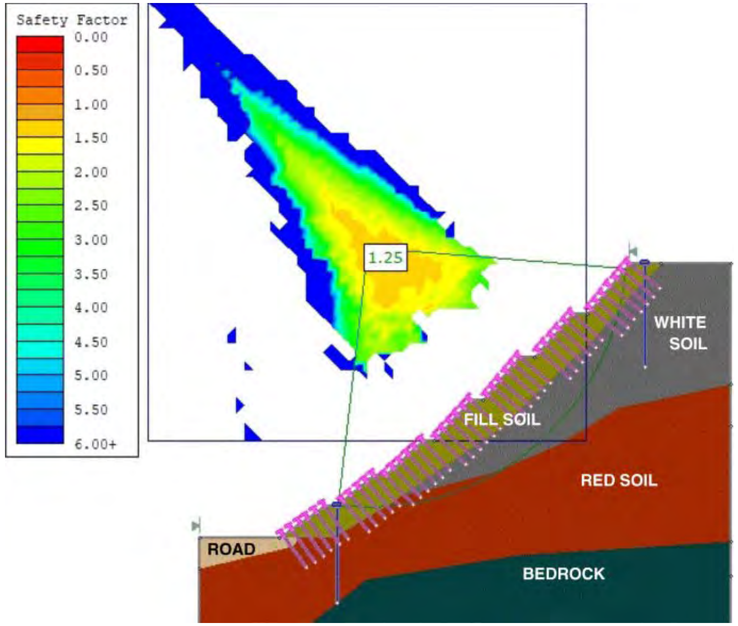
Slope Stability Analysis Framework



If the objective is stabilizing a road cut slope, we need:

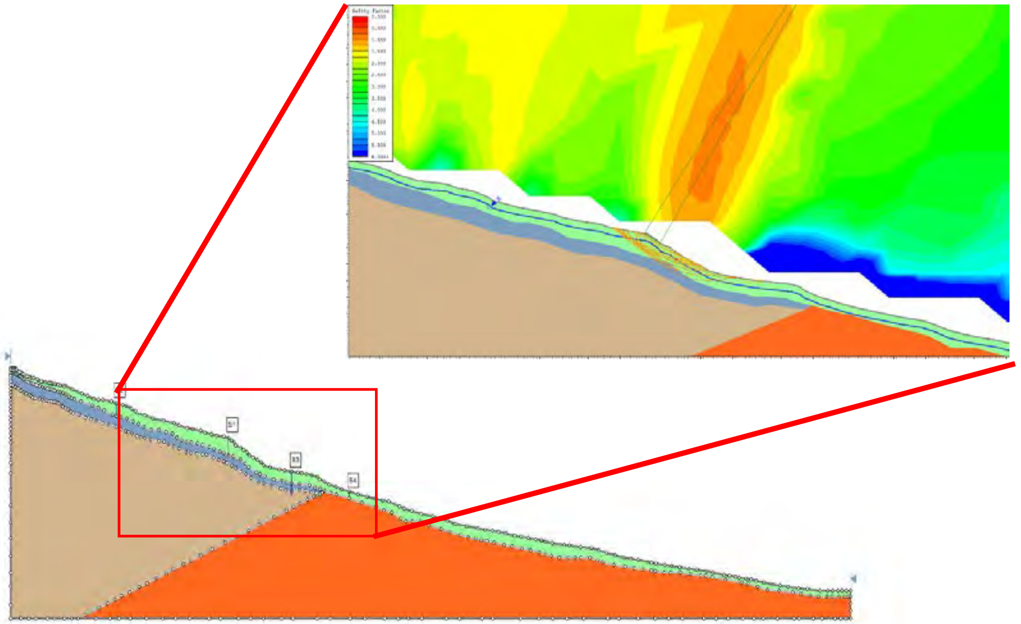
- Detailed field survey (geometry)
- Deep field (geotechnical) investigations
- Field tests
- Laboratory tests
- Numerical modeling at slope scale





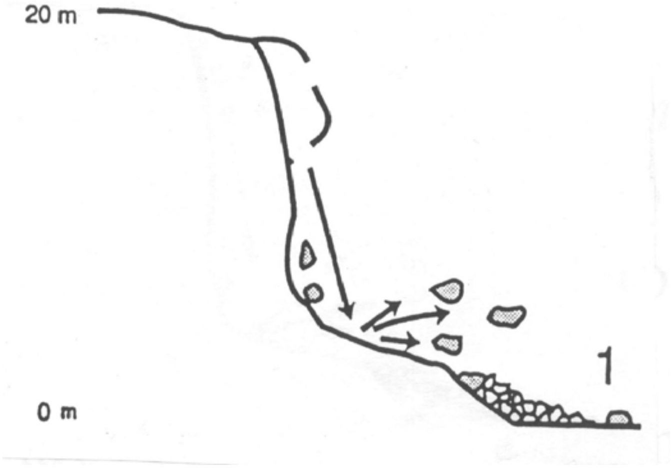
If the objective is analizing a natural slope, we need:

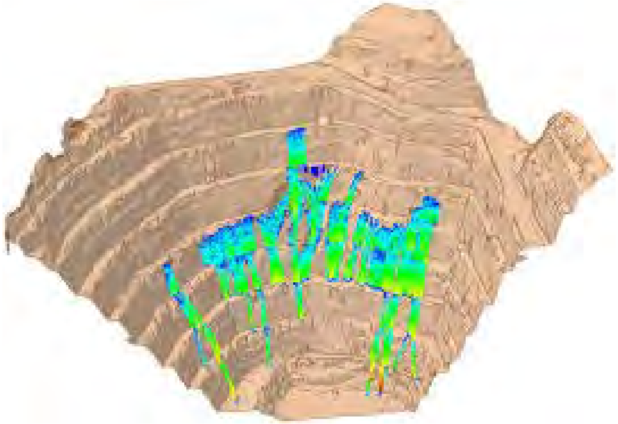
- Detailed field survey (geometry)
- Deep field (geotechnical) investigations
- Field tests
- Laboratory tests
- Numerical modeling at slope scale



If the objective is protecting a road or an infrastructure, we need:

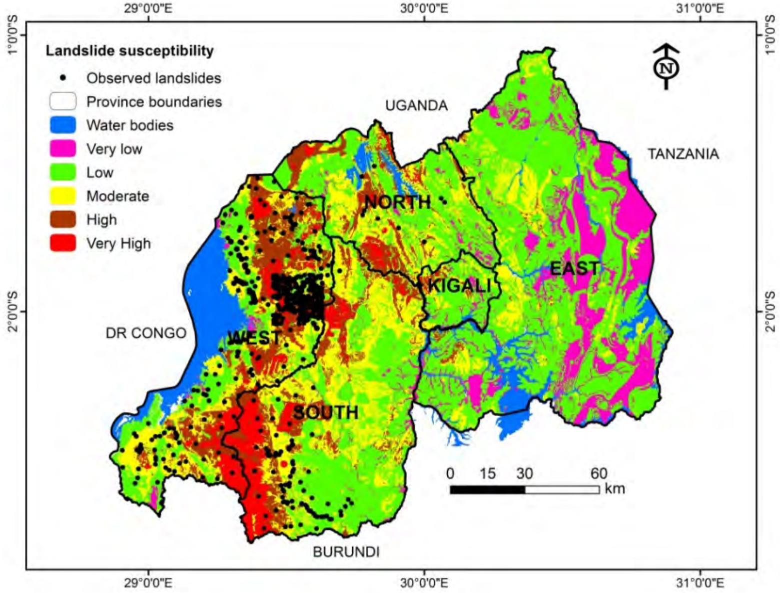
- Detailed field survey (geometry)
- Deep field (geotechnical) investigations
- Field tests
- Laboratory tests
- Numerical modeling at slope scale

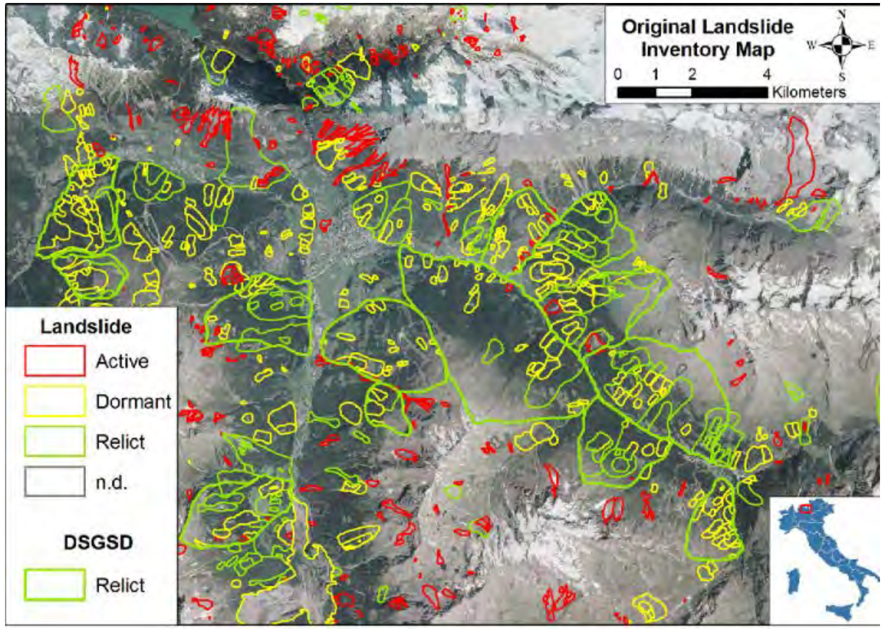




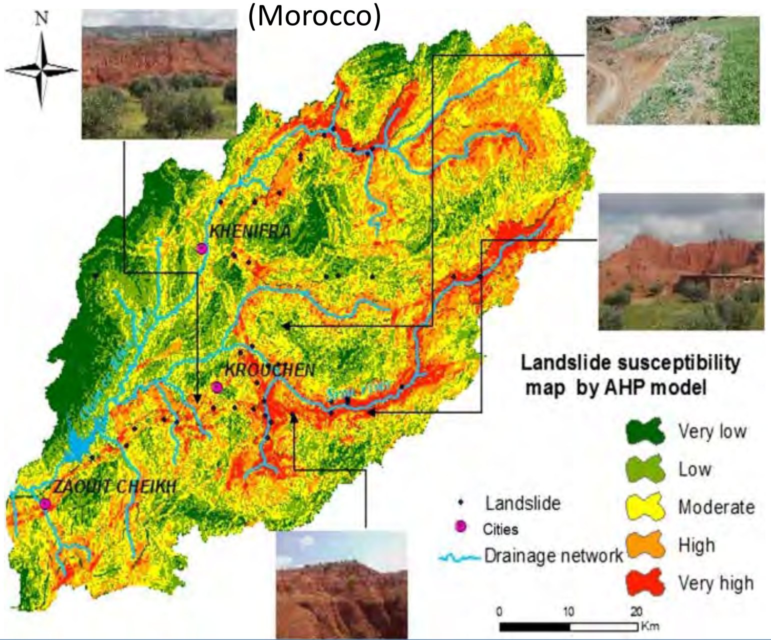
If the objective is mapping potentially unstable areas, we need:

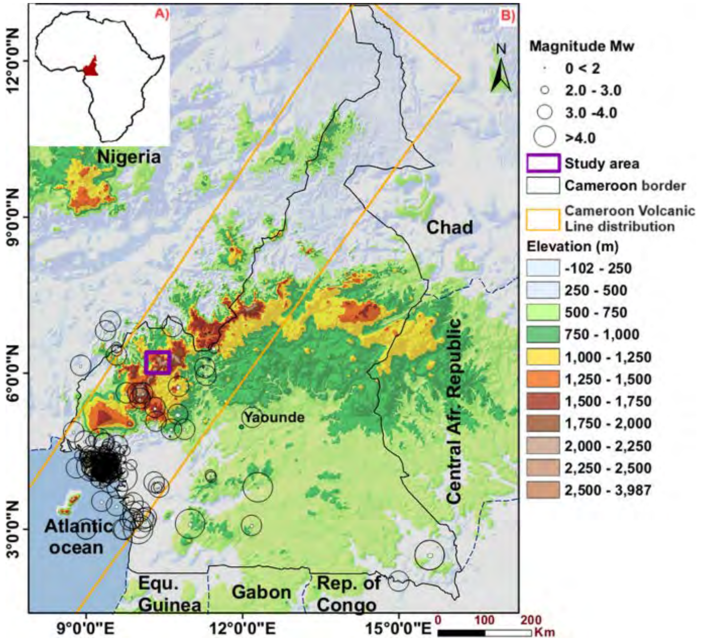
- Field survey + aerial/satellite photos
- Inventory map
- Field (geotechnical) investigations
- Good basic datasets
- Numerical modeling at regional scale





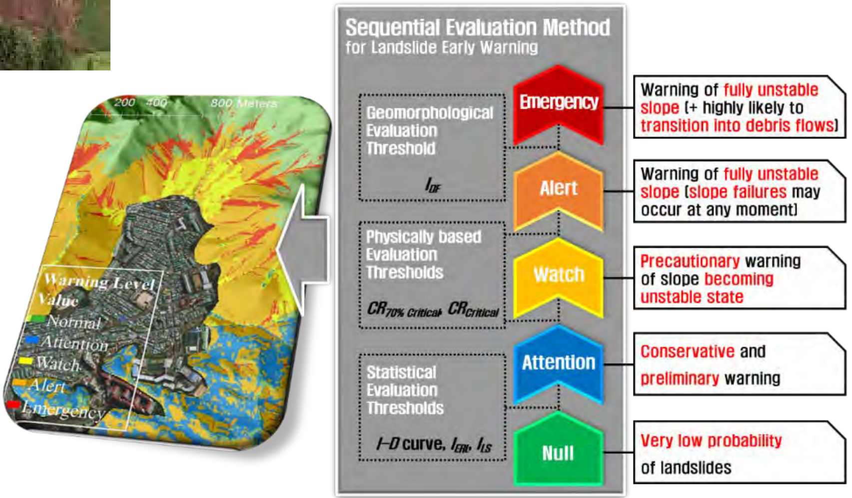
(Morocco)

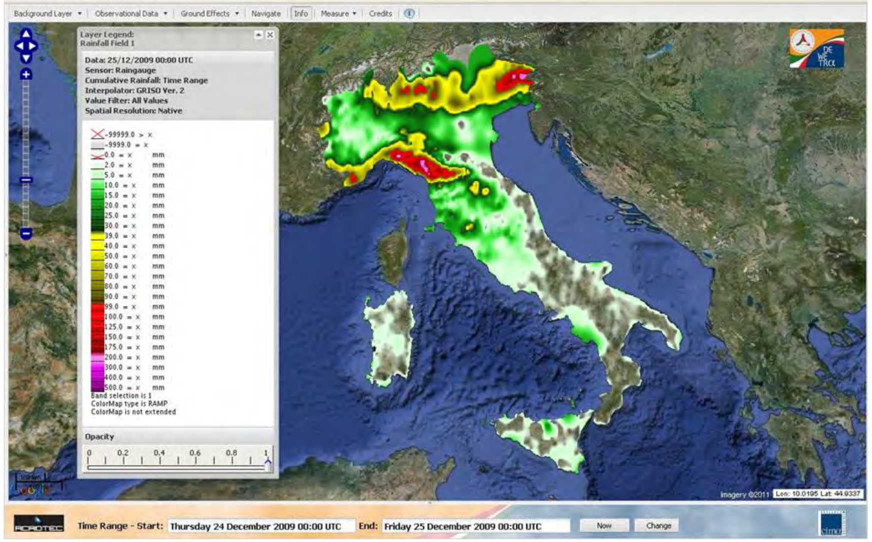




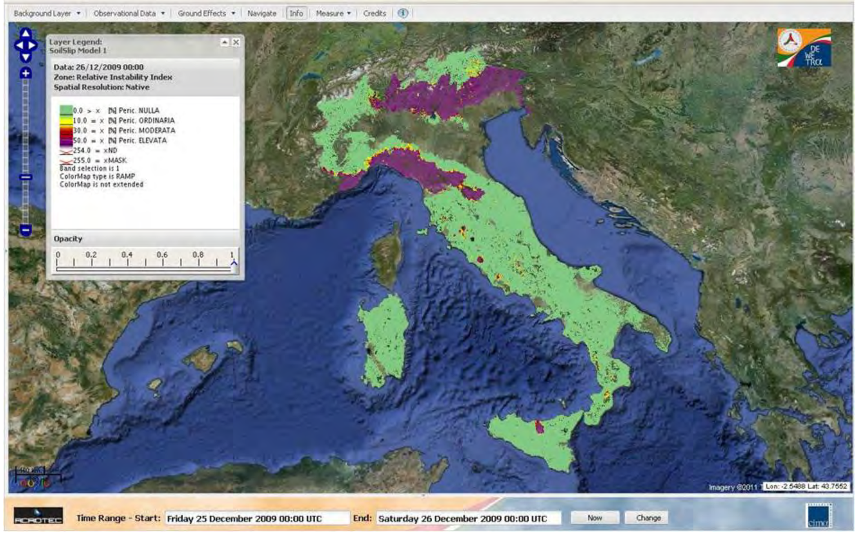
If the objective is an early warning system…

- Field (geotechnical) investigations
- Good basic datasets
- Forecasted rainfalls
- Numerical modeling at regional scale





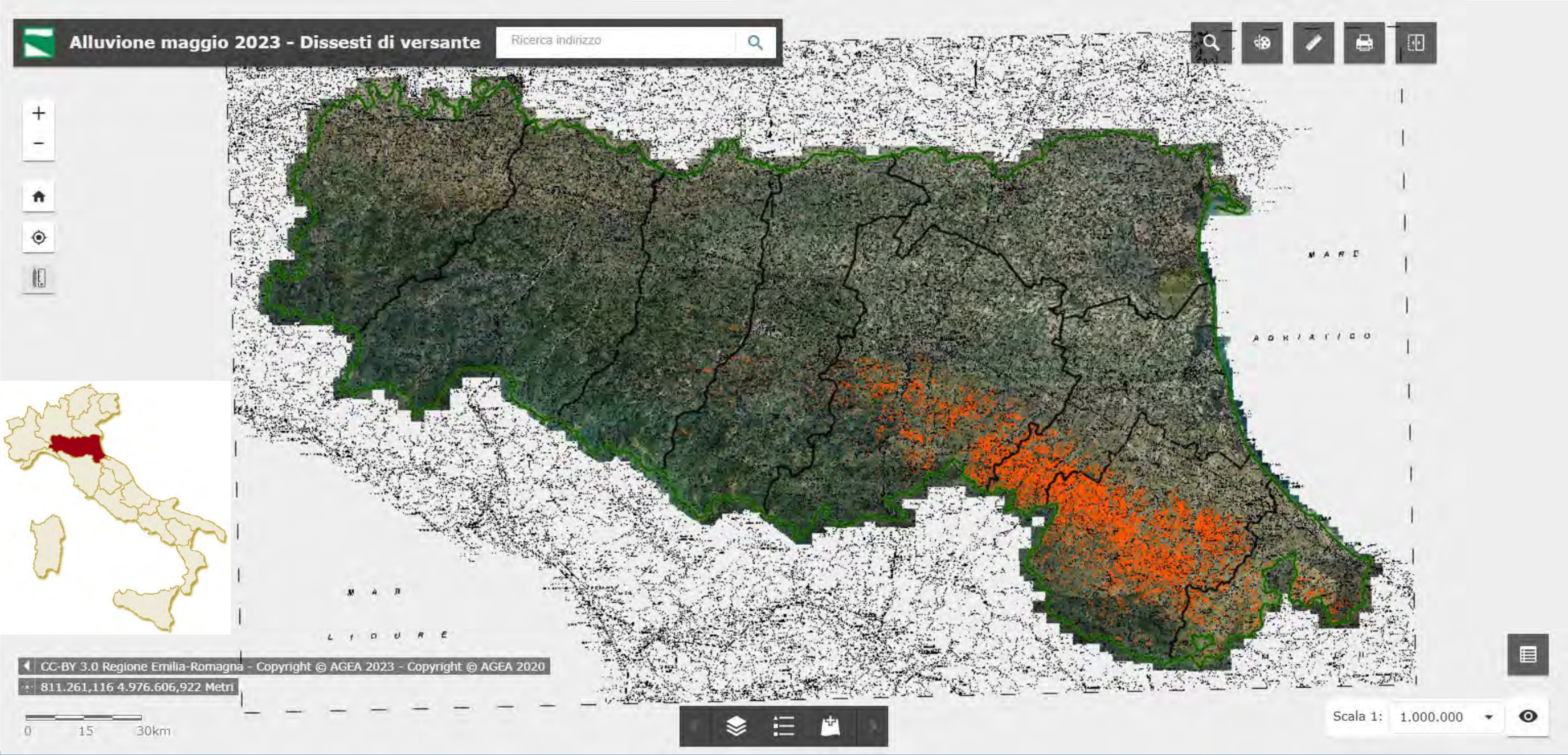
Rainfall map



Map of instability index

An example from Emilia Romagna Region…

Emilia Romagna Region, May 2023, more than 80,000 landslides…



Emilia Romagna, May 2023, more than 80,000 landslides…

Which is the objective of the regional administration?

Some problems…

…sometimes, we have results of models but NOT results of field surveys

Some questions…

What do we *really* know about the *real* phenomena?

Can we improve hour knowledge?

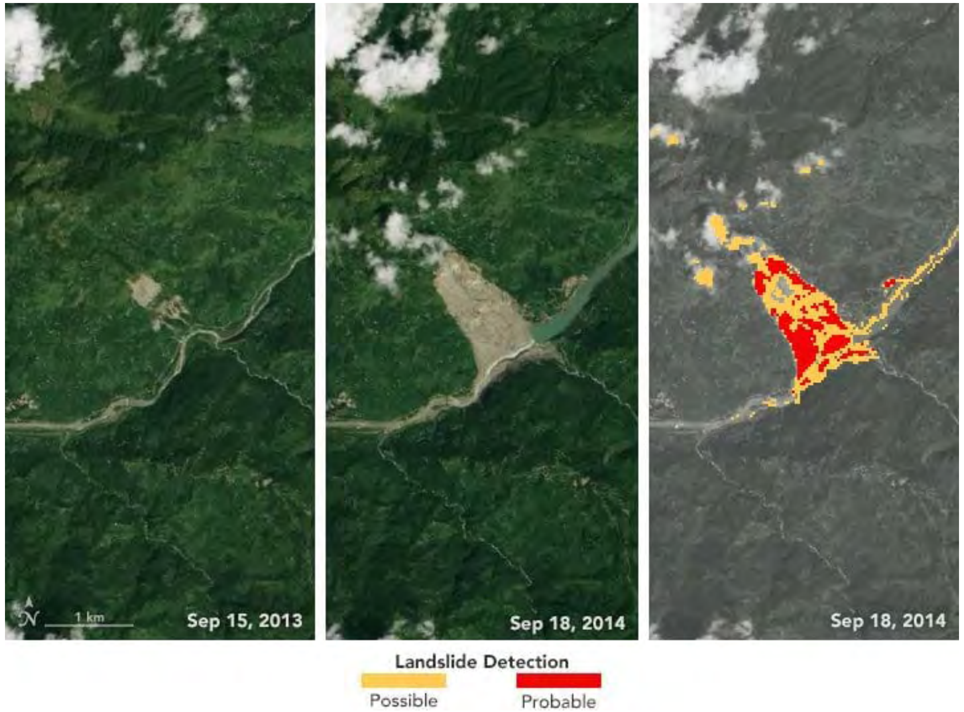
How?

Different investigation methods…

FIELD SURVEY

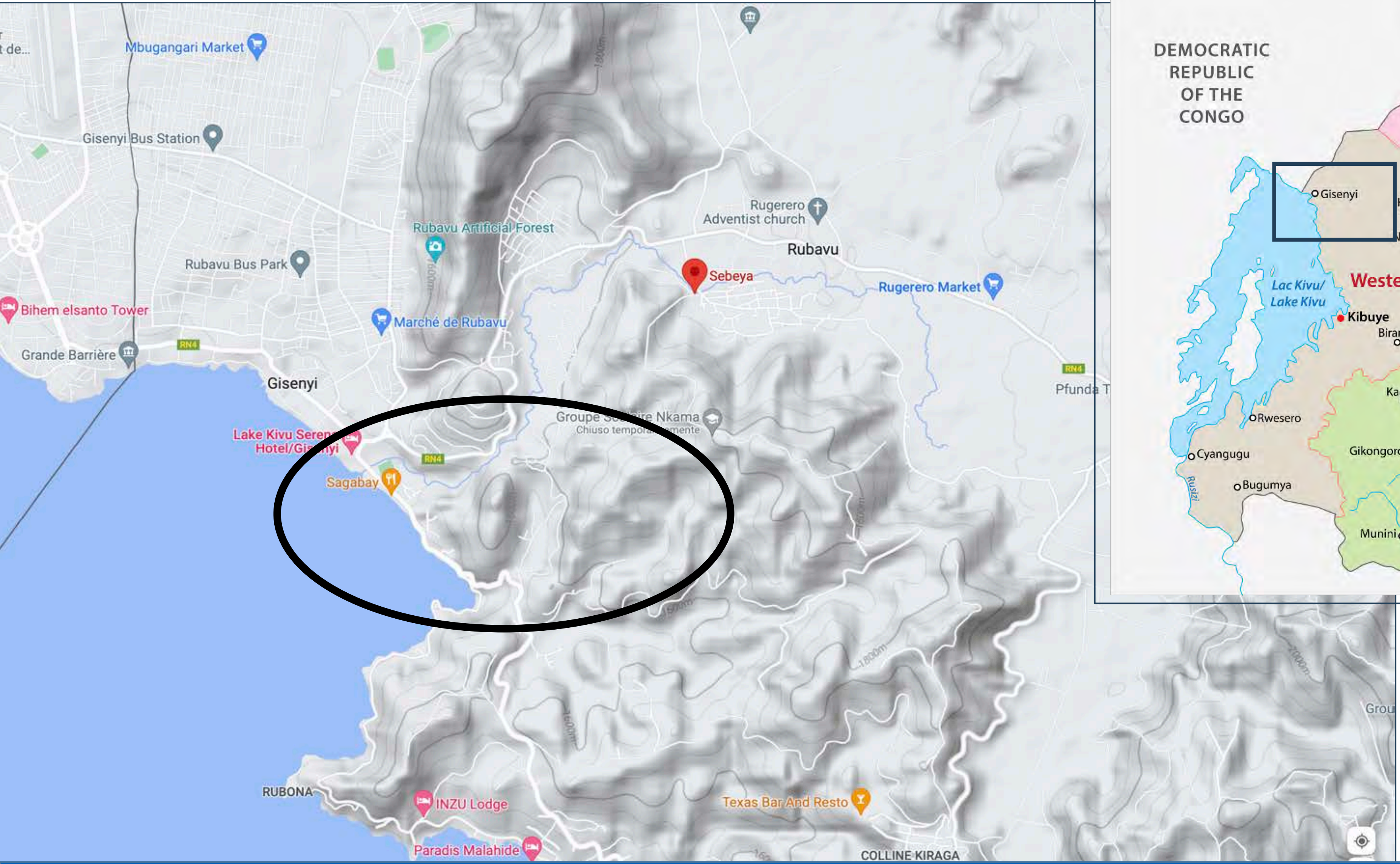
AERIAL PHOTOS

SATELLITE IMAGES



Rwanda rainfall event 2/3 May 2023: landslides and floods

Area



Sebeya Cathment

PLANETSCOPE : 3.01m/px

Landslides

Length: 280m
Area: 0.031 Km^2

Pre-Event (10/04/2023)

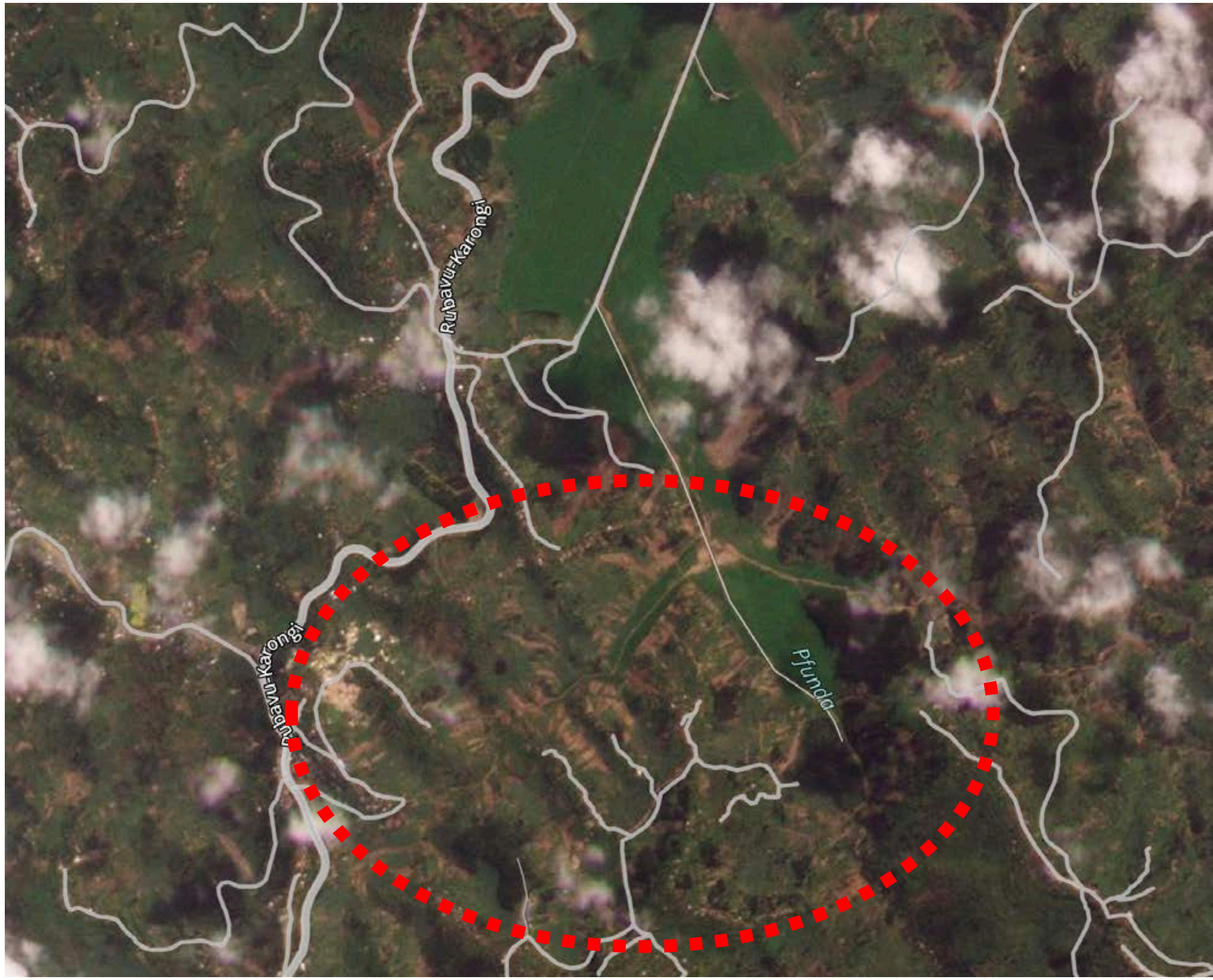
Post-Event (20/05/2023)

PLANETSCOPE : 3.01m/px

Landslides

Pre-Event (10/04/2023)

Post-Event (20/05/2023)



PLANETSCOPE : 3.01m/px

Landslides

Pre-Event (10/04/23)

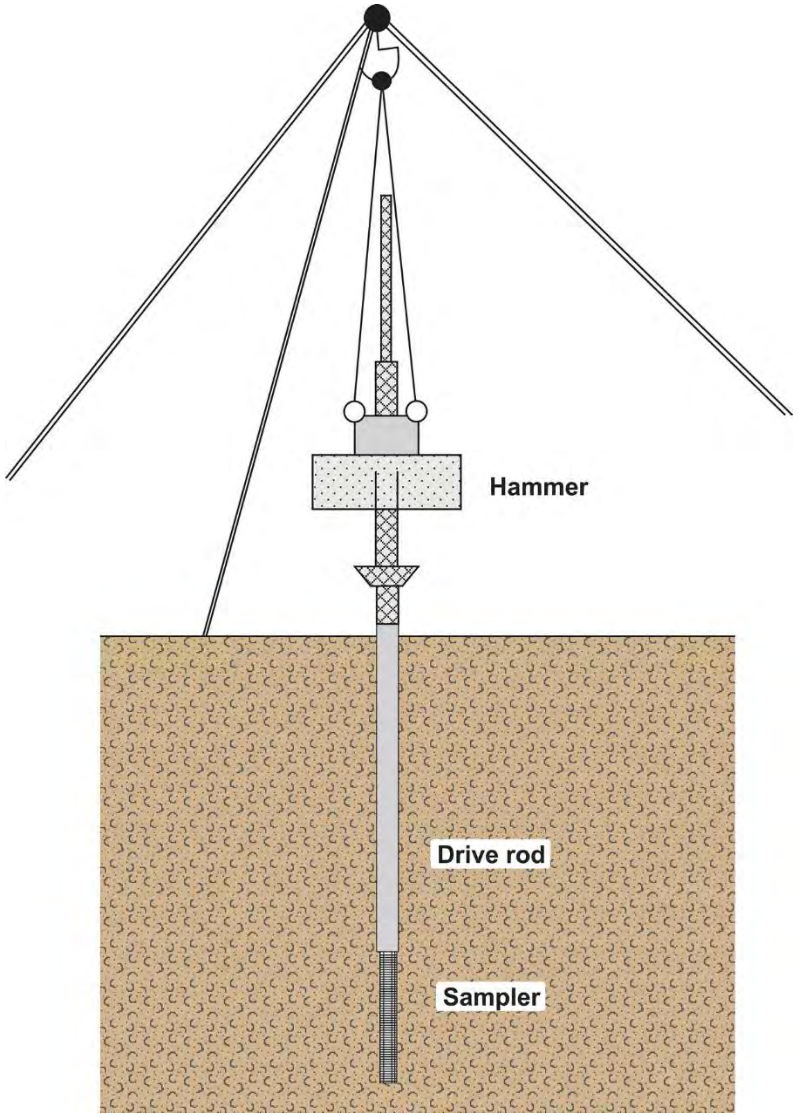
Post-Event (20/05/23)

First goal: ***INVENTORY MAP***

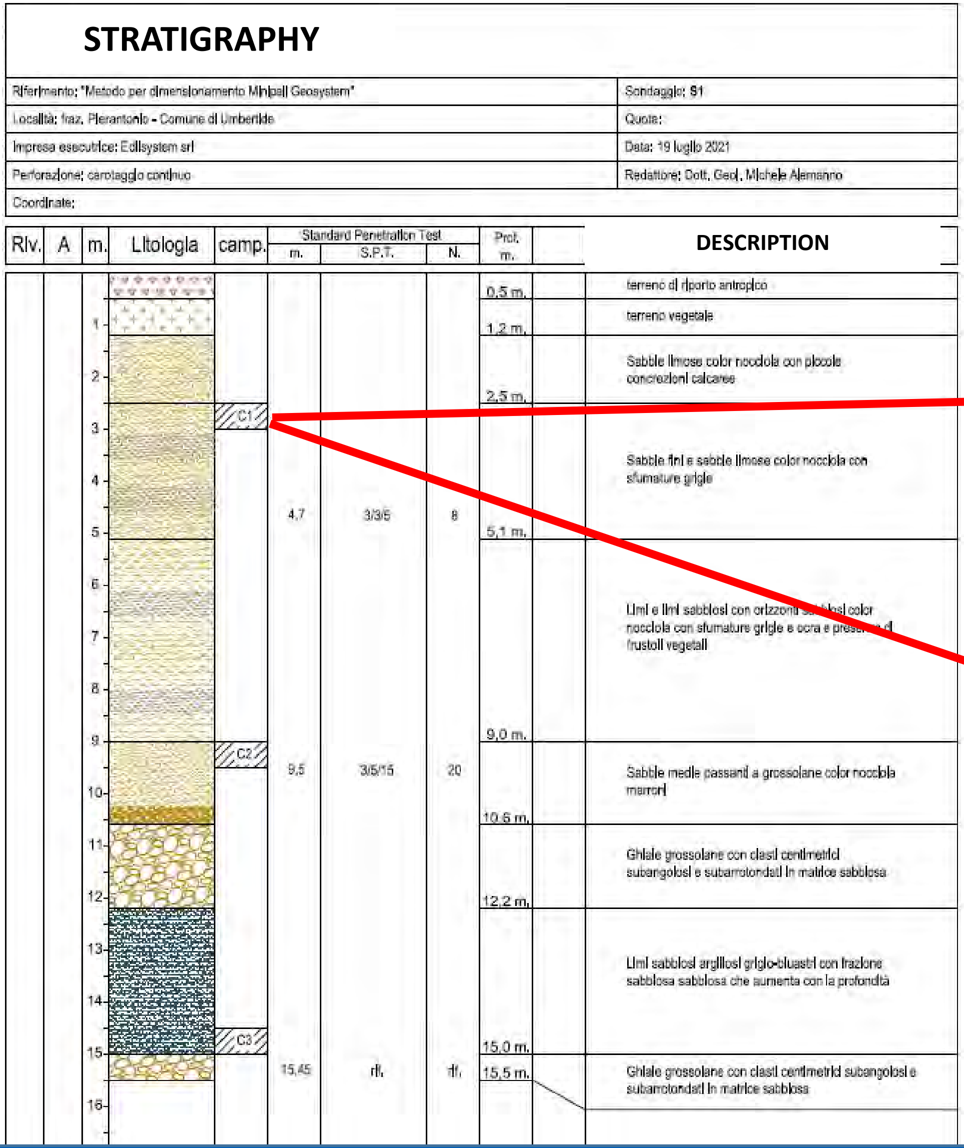
Second goal: ***DATA COLLECTION = SOIL CHARACTERIZATION***

Soil samples for lab analyses

Geotechnical drilling and sampling



Geotechnical drilling and sampling



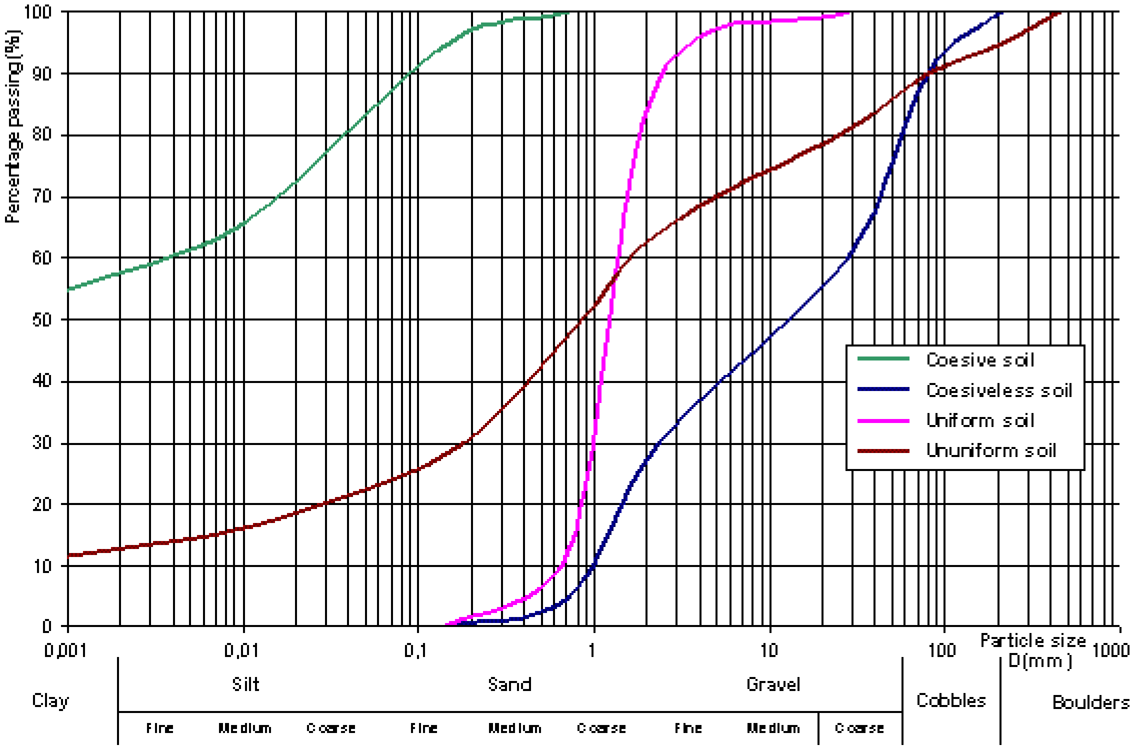
STRATIGRAPHY

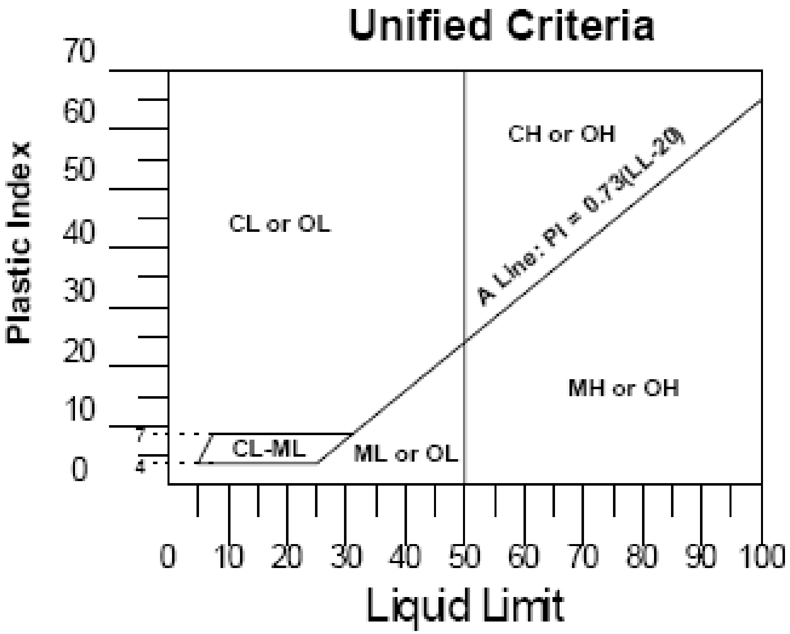
Riferimento: "Metodo per dimensionamento Minipali Geosystem"	Sondaggio: S1
Località: fraz. Pierantonio - Comune di Umbertide	Quota:
Impresa esecutrice: Edilsystem srl	Data: 19 luglio 2021
Perforazione: carotaggio continuo	Redattore: Dott. Geol. Michele Alemanno
Coordinate:	

Riv.	A	m.	Litologia	camp.	Standard Penetration Test m.	S.P.T.	N.	Prof. m.	DESCRIPTION
								0,5 m.	terreno di riporto antropico
		1						1,2 m.	terreno vegetale
		2						2,5 m.	Sabbie limose color nocciola con piccole concrezioni calcaree
		3, 4, 5		C1	4,7	3/3/5	8	5,1 m.	Sabbie fini e sabbie limose color nocciola con sfumature grigie
		6, 7, 8, 9						9,0 m.	Limi e limi sabbiosi con orizzonti [illegible] color nocciola con sfumature grigie e ocra e presenza [illegible] frustoli vegetali
		10		C2	9,5	3/5/15	20	10,6 m.	Sabbie medie passanti a grossolane color nocciola marroni
		11, 12						12,2 m.	Ghiaie grossolane con clasti centimetrici subangolosi e subarrotondati in matrice sabbiosa
		13, 14		C3				15,0 m.	Limi sabbiosi argillosi grigio-bluastri con frazione sabbiosa sabbiosa che aumenta con la profondità
		15, 16			15,45	rif.	rif.	15,5 m.	Ghiaie grossolane con clasti centimetrici subangolosi e subarrotondati in matrice sabbiosa

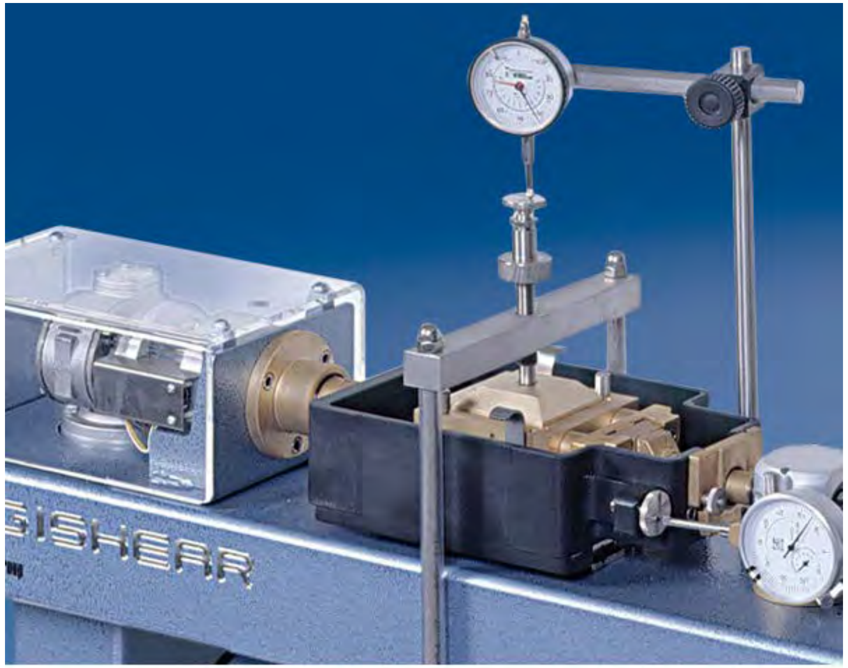
Soil classification in the lab

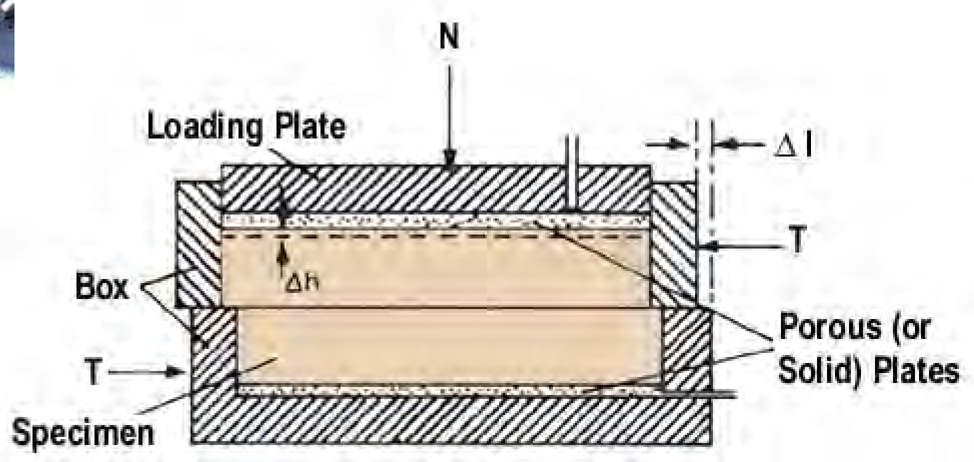
GRAIN SIZE DISTRIBUTION CURVE



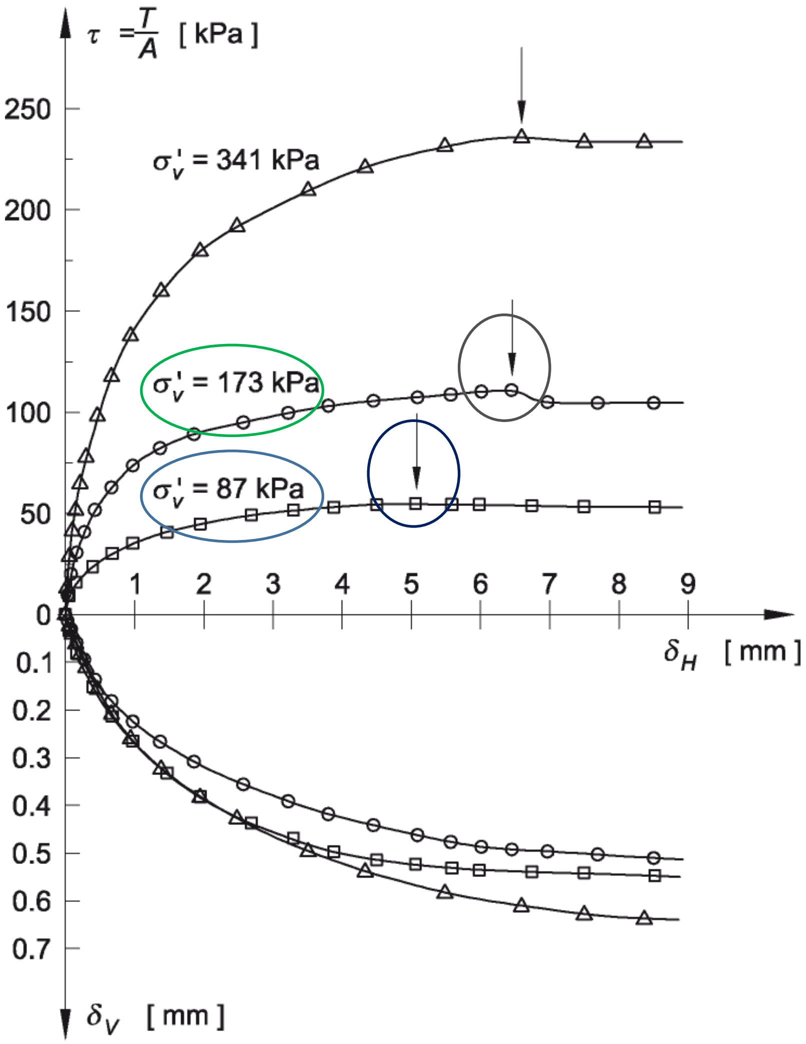


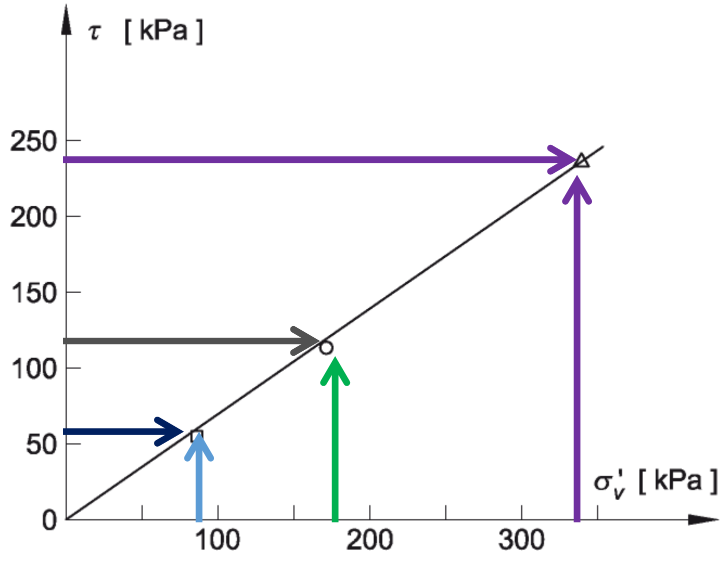
The shear box for DIRECT SHEAR TEST





Direct shear test





MODENA CLAY

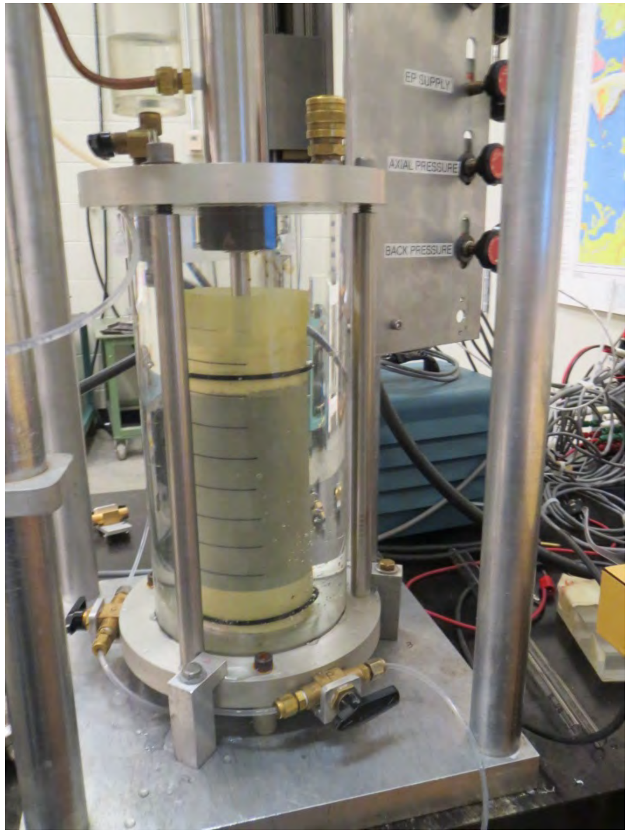
Prof. 8.36 m

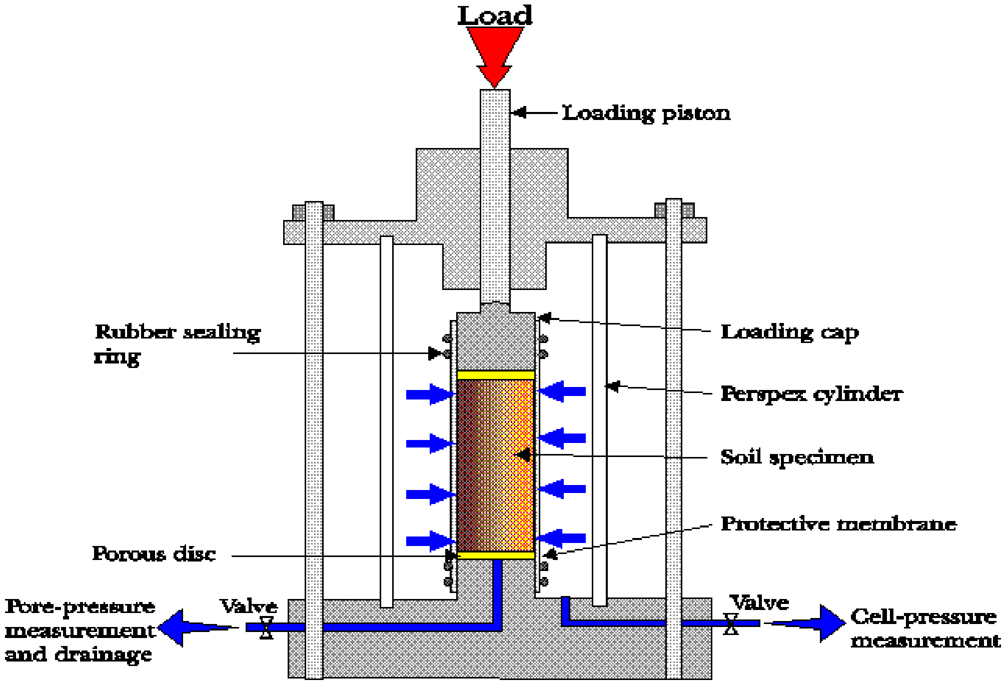
W_L = 36.3 [%] PI = 13.2 [%]

G_s = 2.739 [-] CF = 27.0 [%]

$v = \frac{\delta_H}{t}$ = 0.006 [mm/min]

Triaxial tests



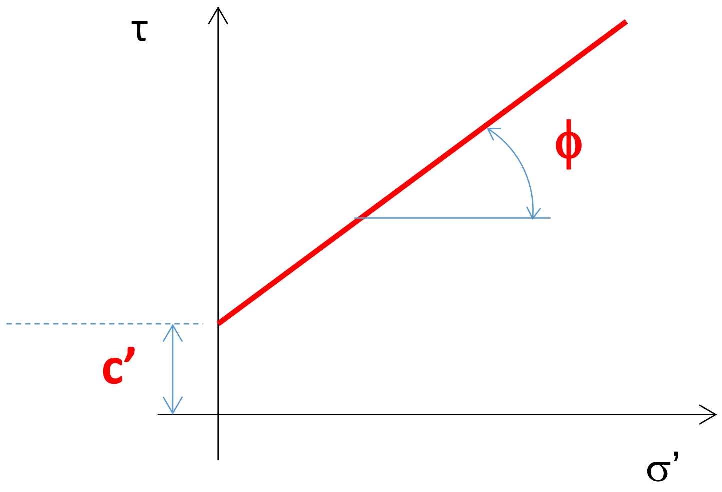


Triaxial apparatus

Mohr-Coulomb shear strength parameters

The shear strength of soils (and rocks) is expressed by two mechanical parameters coming from the Mohr-Coulomb criterion:

ϕ = friction angle + c' = effective cohesion



$$\tau_f = \tan\phi \cdot \sigma' + c'$$

ϕ and c' are also called **shear strength parameters of soils**

Landslide inventory (+ MAP):

- Date (day/month/year)
- Position (on the map)
- Shape (edge as polygon on the map)/2D profile
- Type
- Type of material (rock of soil)
- New or re-activated
- Triggering factors
- Land use
- Damage
- Photo

Data collection:

✓ Soil/rock samples

✓ Lab tests for classification and mechanical characterization

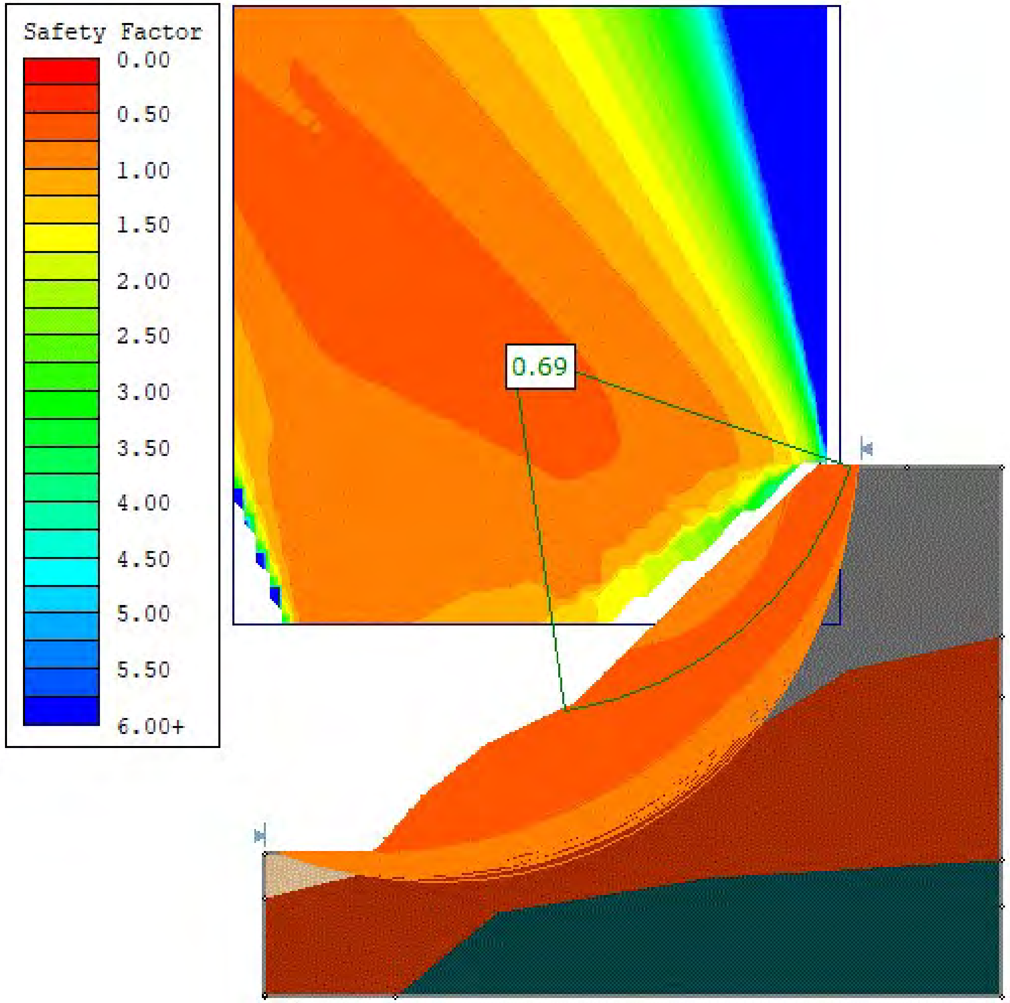
SINGLE SLOPE SCALE

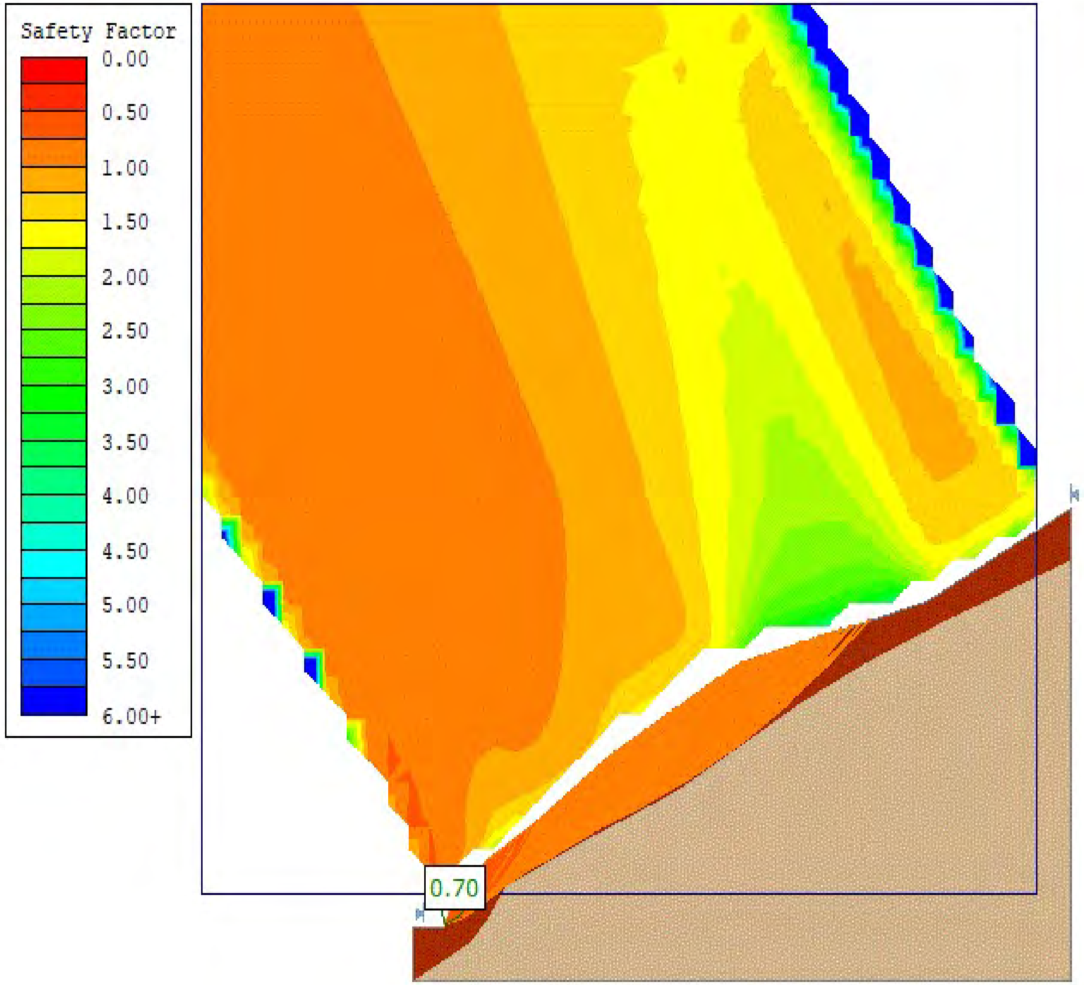
LEM

LARGE SCALE (Village, District, Catchment, Region, Country)

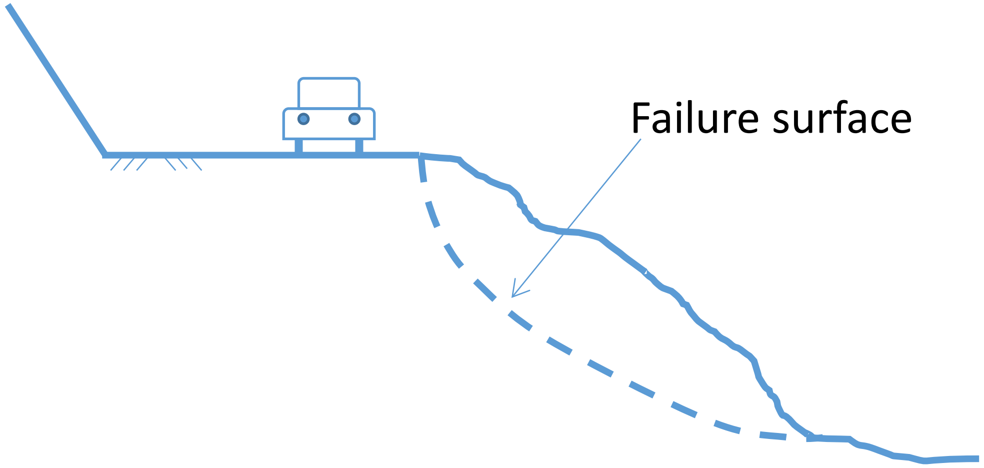
SLOPE ANALYSIS AT SINGLE SLOPE SCALE

SLOPE ANALYSIS AT SINGLE SLOPE SCALE



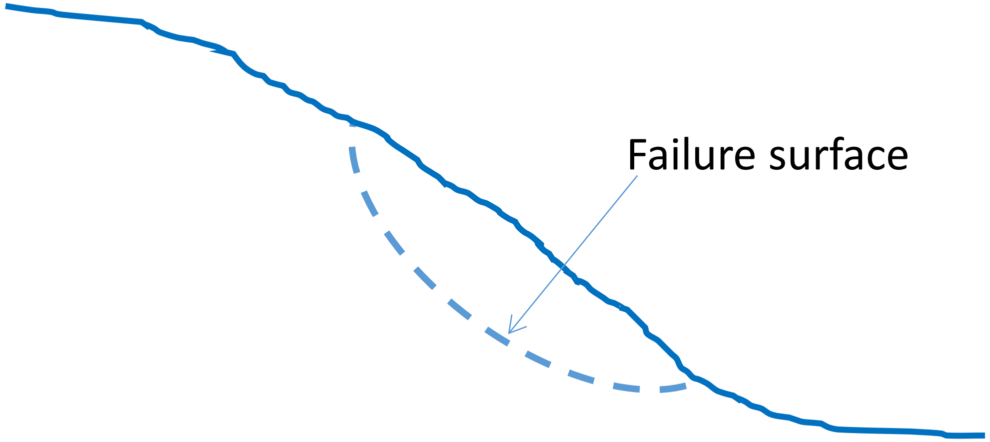


Slope stability: some examples



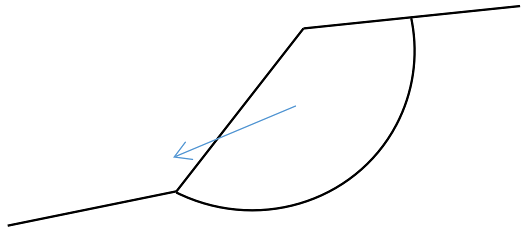
Natural or artificially constructed slopes may be stable at the moment, but they might lose their stability and cause collapse.
When it happens, the collapse can be sudden and catastrophic .

Slope stability: some examples

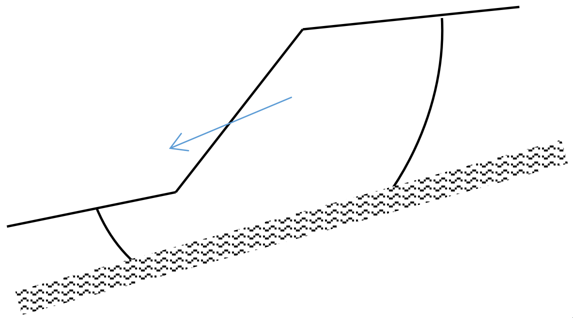


Slope stability

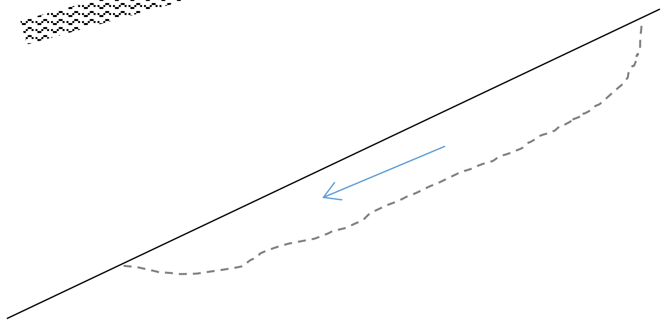
Several failure modes:



Rotational failure



Rotational-planar failure



Translational failure

Safety factor of a slope

Definition of «Safety factor» *or* «Factor of safety»

$$F_s = \frac{Stabilizing\ actions}{Destabilizing\ actions}$$

> 1 Stability

= 1 Limit of equilibrium

< 1 Instability

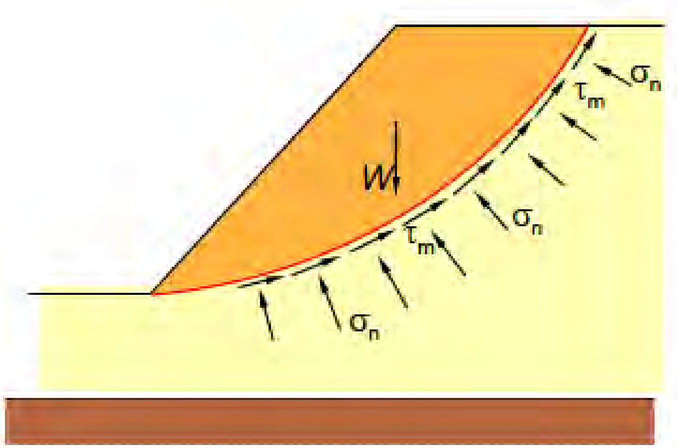
Stabilizing actions

↓

Soil shear strength → $\tau_f = c' + (\sigma_n - u) \cdot tan\phi'$

↓

$$F_s = \frac{\tau_f}{\tau_m}$$

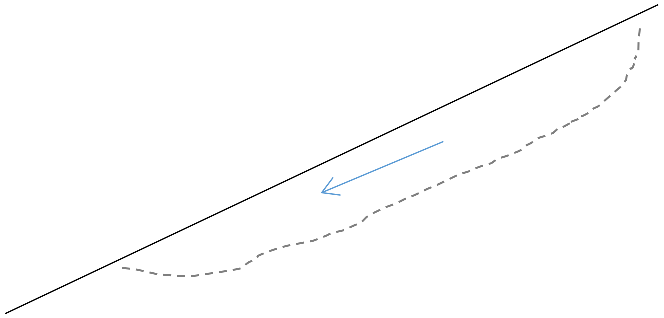


Limit Equilibrium Method

Assumptions

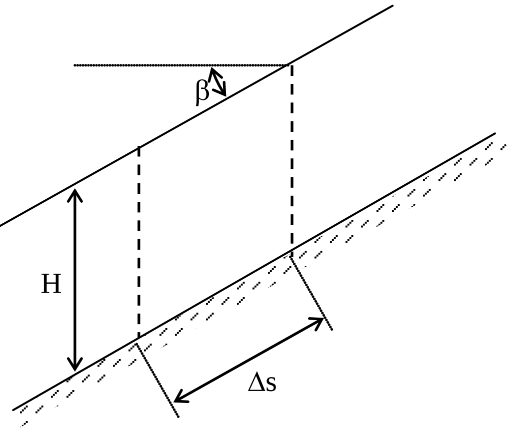
- The stress system is two-dimensional. Stresses in the third direction (perpendicular to the soil mass section) are assumed to be zero.
- The Mohr-Coulomb equation for shear strength is assumed to be valid, and the strength parameters ϕ' and c' are known in drained conditions (c_u is known in undrained conditions).
- Seepage conditions and water levels are known and pore water pressure can be calculated.
- Plastic failure conditions are assumed to be met along the critical/failure surface. In other words, shearing strains are large enough at all points of the critical surface to mobilize all available shear strength at the same time (rigid-plastic behavior).

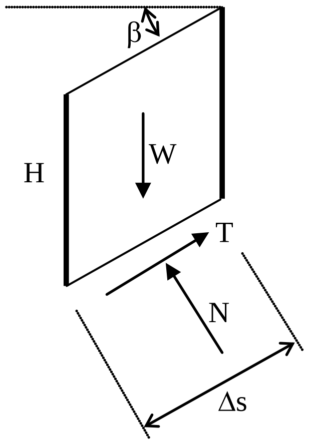
Slope stability: infinite slope (dry soil)



Translational failure

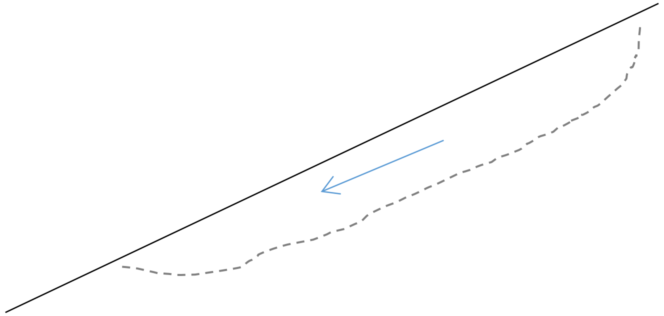
$\phi' \neq 0$ $c' = 0$ Dry soil





$$F_S = \frac{T_S}{T_D} = \frac{N \cdot tan\phi'}{W \cdot sin\beta} = \frac{W cos\beta \cdot tan\phi'}{W \cdot sin\beta} = \frac{tan\phi'}{tan\beta}$$

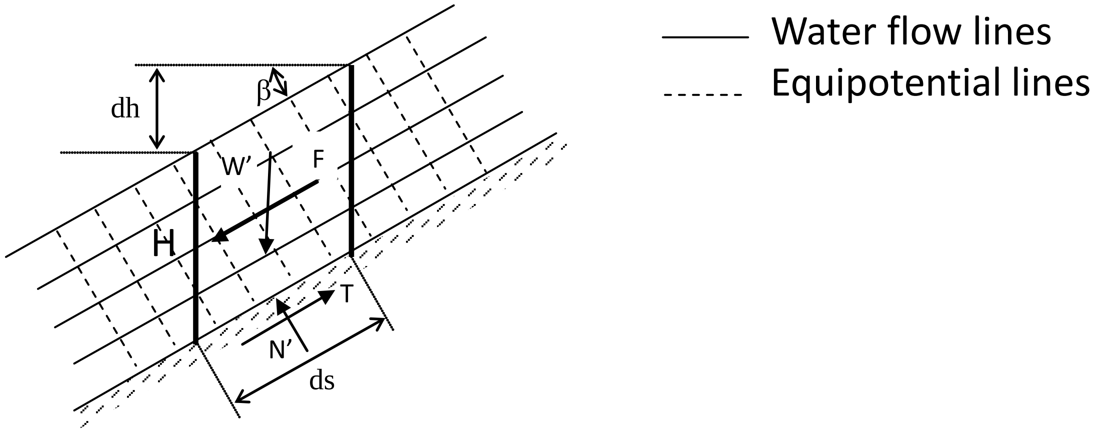
Slope stability: infinite slope (saturated soil with water table)



Translational failure

$\phi' \neq 0$ $c' = 0$

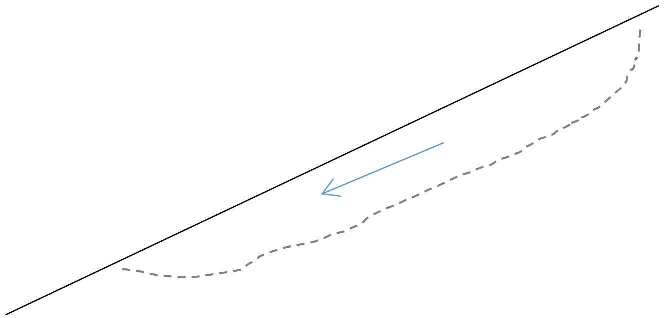
water table at slope surface

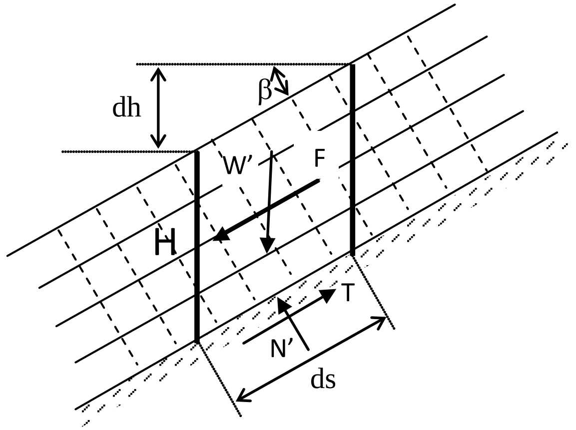


$$F_S = \frac{T_S}{T_D} = \frac{N' \cdot tan\phi'}{W' \cdot sin\beta + F'} = \frac{\gamma' H \cdot ds \cdot cos\beta \cdot cos\beta \cdot tan\phi'}{\gamma' H \cdot ds \cdot cos\beta \cdot sin\beta + \gamma_w H \cdot ds \cdot cos\beta \cdot sin\beta}$$

$$= \frac{\gamma'}{\gamma' + \gamma_w} \cdot \frac{tan\phi'}{tan\beta} = \frac{\gamma'}{\gamma_{sat}} \cdot \frac{tan\phi'}{tan\beta}$$

Slope stability: infinite slope (saturated soil with water table)





Translational failure

$\phi' \neq 0$ $c' \neq 0$

water table at slope surface

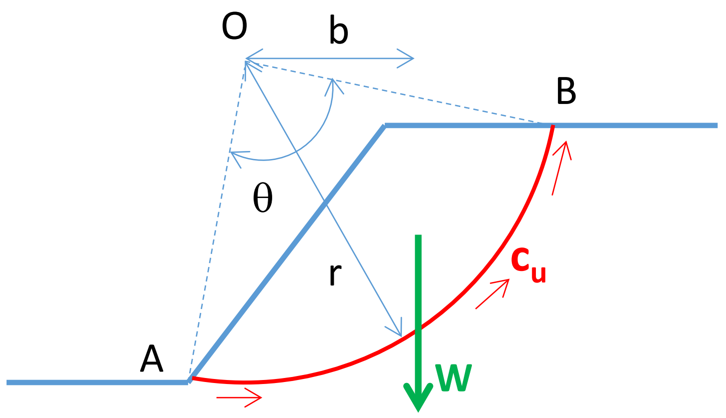
——— Water flow lines

- - - - - - Equipotential lines

$$F_S = \frac{T_S}{T_D} = \frac{N' \cdot tan\phi' + c' \cdot ds}{W' \cdot sin\beta + F'} = \frac{\gamma' H \cdot ds \cdot cos\beta \cdot cos\beta \cdot tan\phi' + c' \cdot ds}{\gamma' H \cdot ds \cdot cos\beta \cdot sin\beta + \gamma_w H \cdot ds \cdot cos\beta \cdot sin\beta}$$

$$= \frac{\gamma' H \cdot cos^2\beta \cdot tan\phi' + c'}{\gamma_{sat} H \cdot cos\beta \cdot sin\beta}$$

Slope stability: circular slip surface in undrained conditions



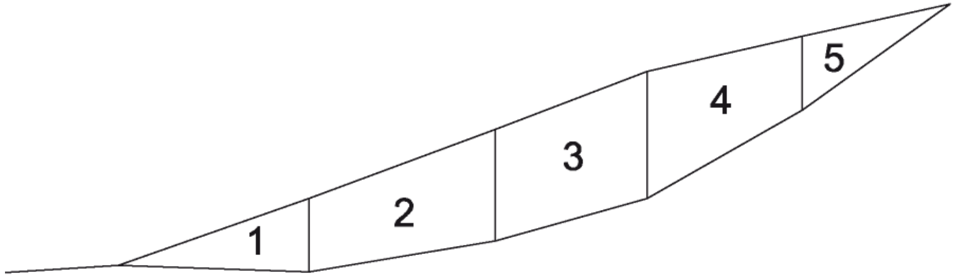
Rotational failure

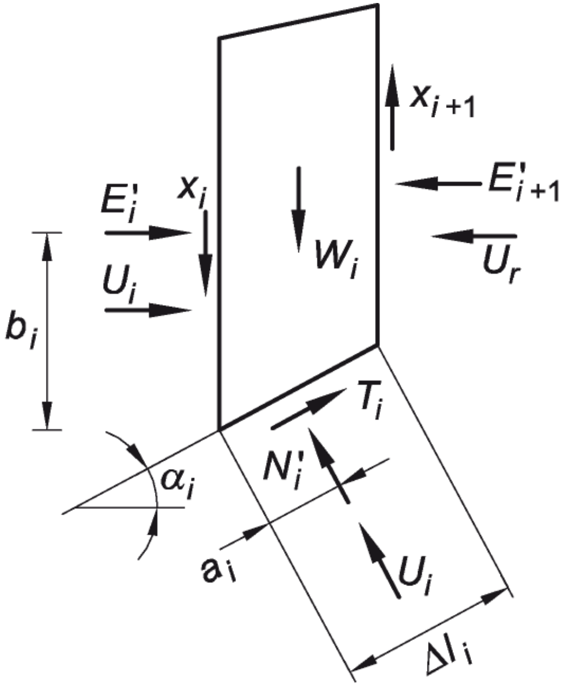
$c_u \neq 0$

Total stresses

$$F_S = \frac{M_S}{M_D} = \frac{c_u \cdot r \cdot l_{AB}}{W \cdot b} = \frac{c_u \cdot r \cdot r \cdot \frac{\vartheta \cdot \pi}{180°}}{W \cdot b}$$

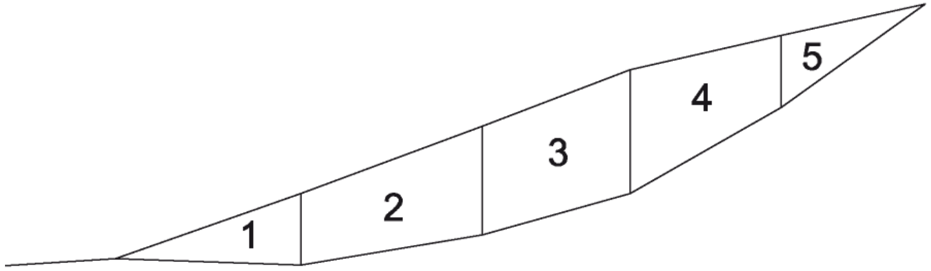
Slope stability: slice method

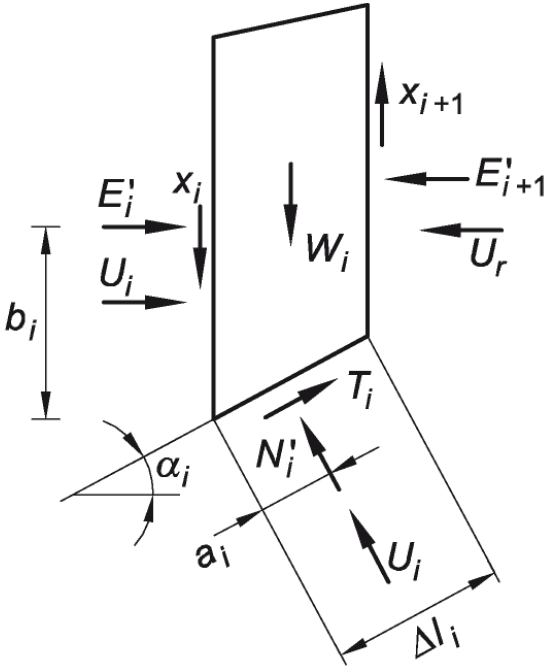




- The potentially unstable soil mass is divided into ***n* slices**;
- ***Slices*** interact with each other and are delimited by the potential failure surface at the bottom;
- The discretization makes it possible to treat each individual ***slice*** as a single, potentially unstable “rigid” block;
- Each ***slice*** is subject to external forces and also forces (x_i; E_i) acting at the interface between two slices.

Slope stability: slice method

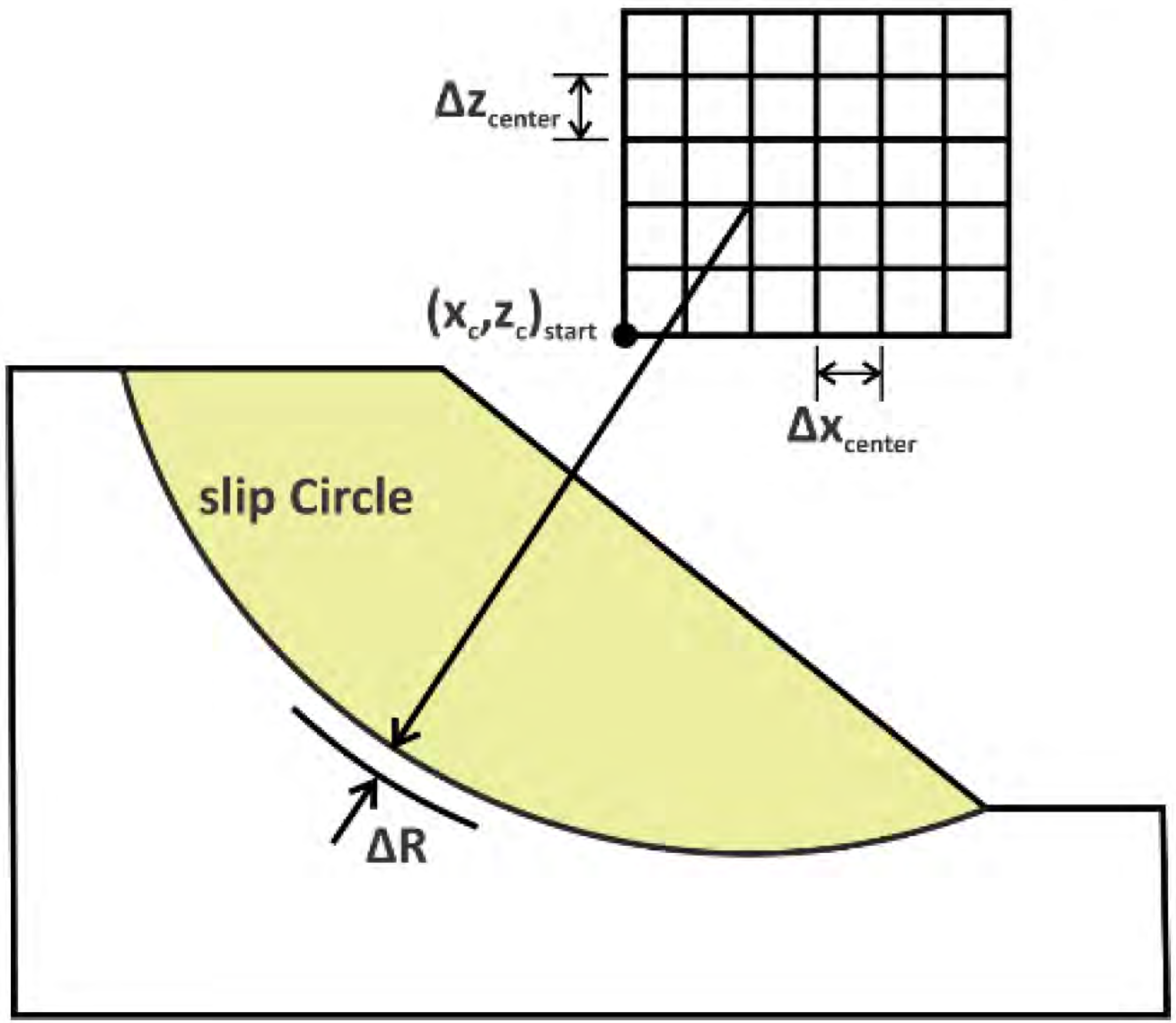




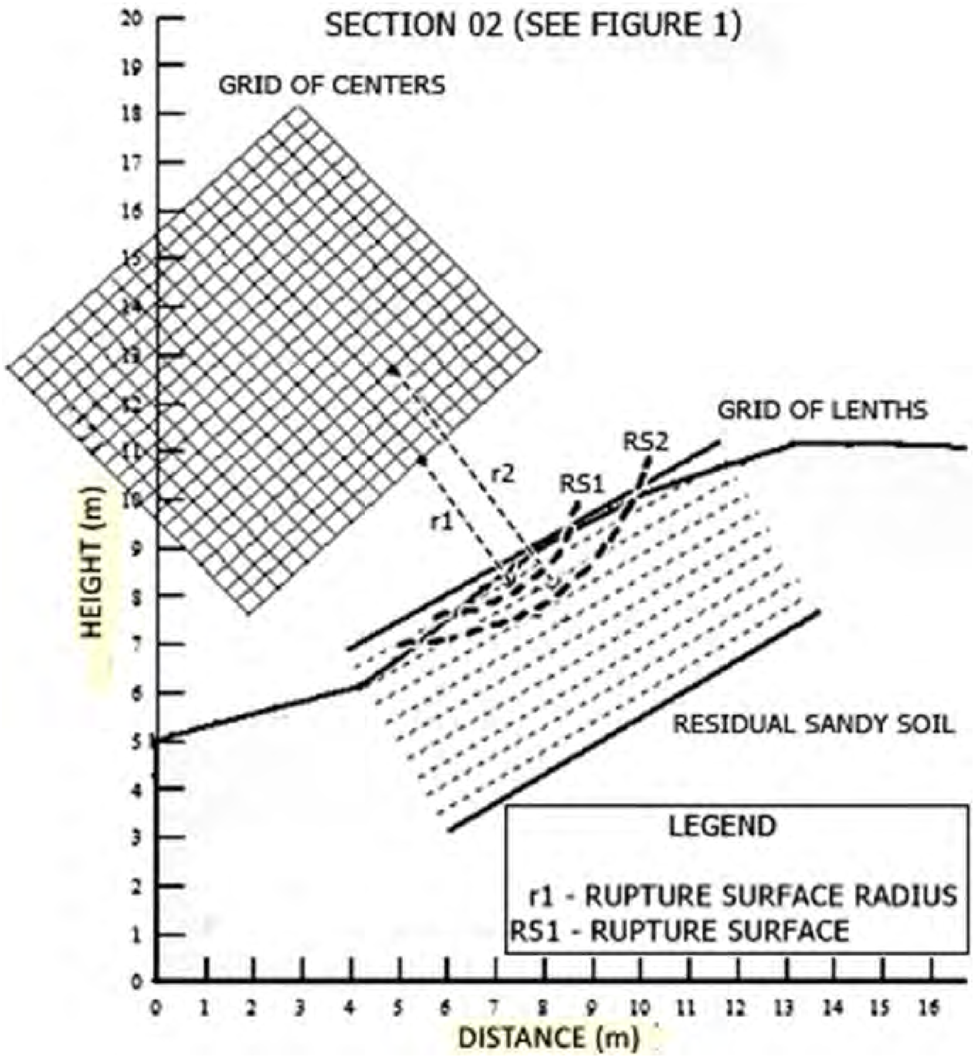
In addition to the interaction forces between slices, it is possible to take into account:

- different stratigraphic conditions in the subsurface;
- different ϕ' and c' values along the failure surface (as they relate to different segments);
- pore water pressures;
- variously distributed external forces;
- failure surfaces of any shape.

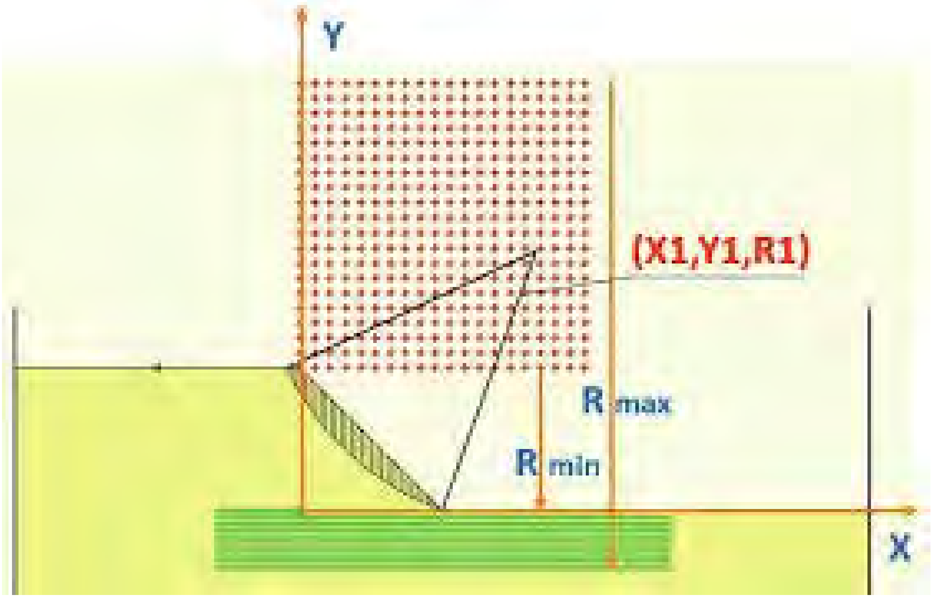
Slope stability: slice method

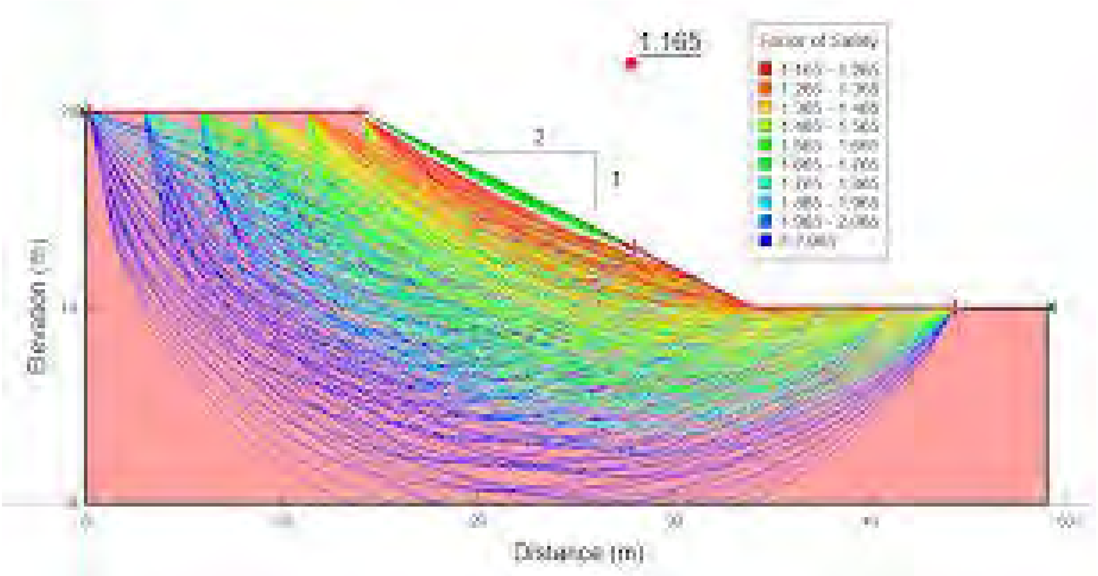


Slope stability: slice method

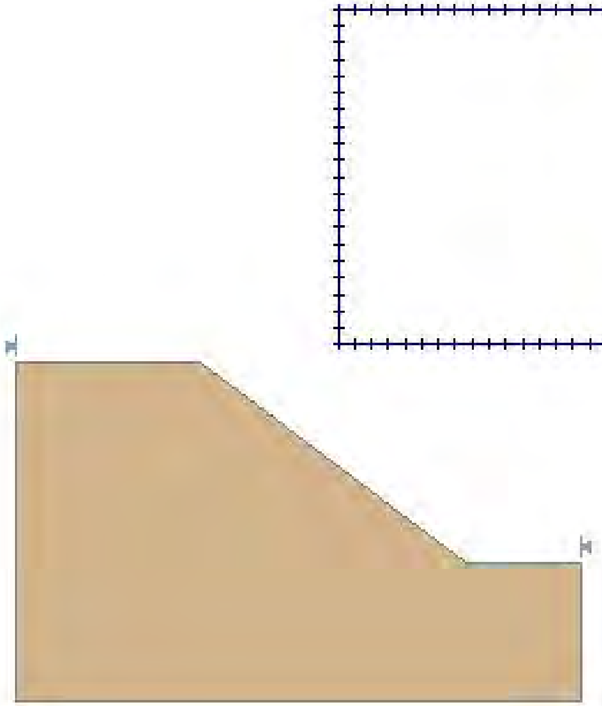


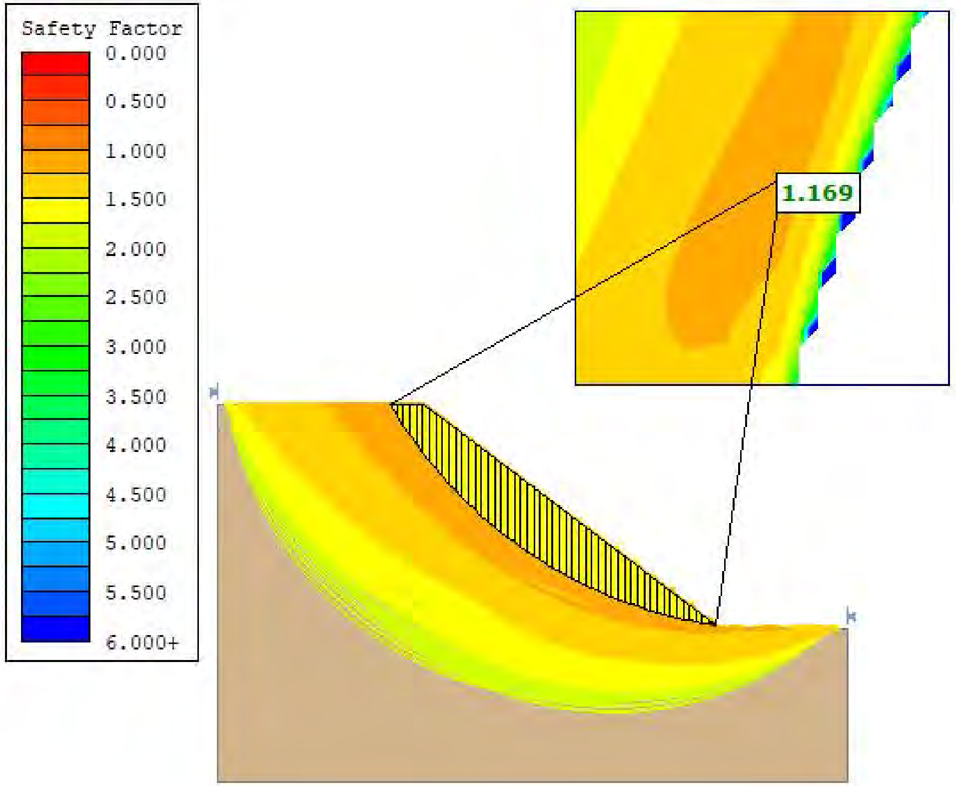
Slope stability: slice method





Slope stability: slice method



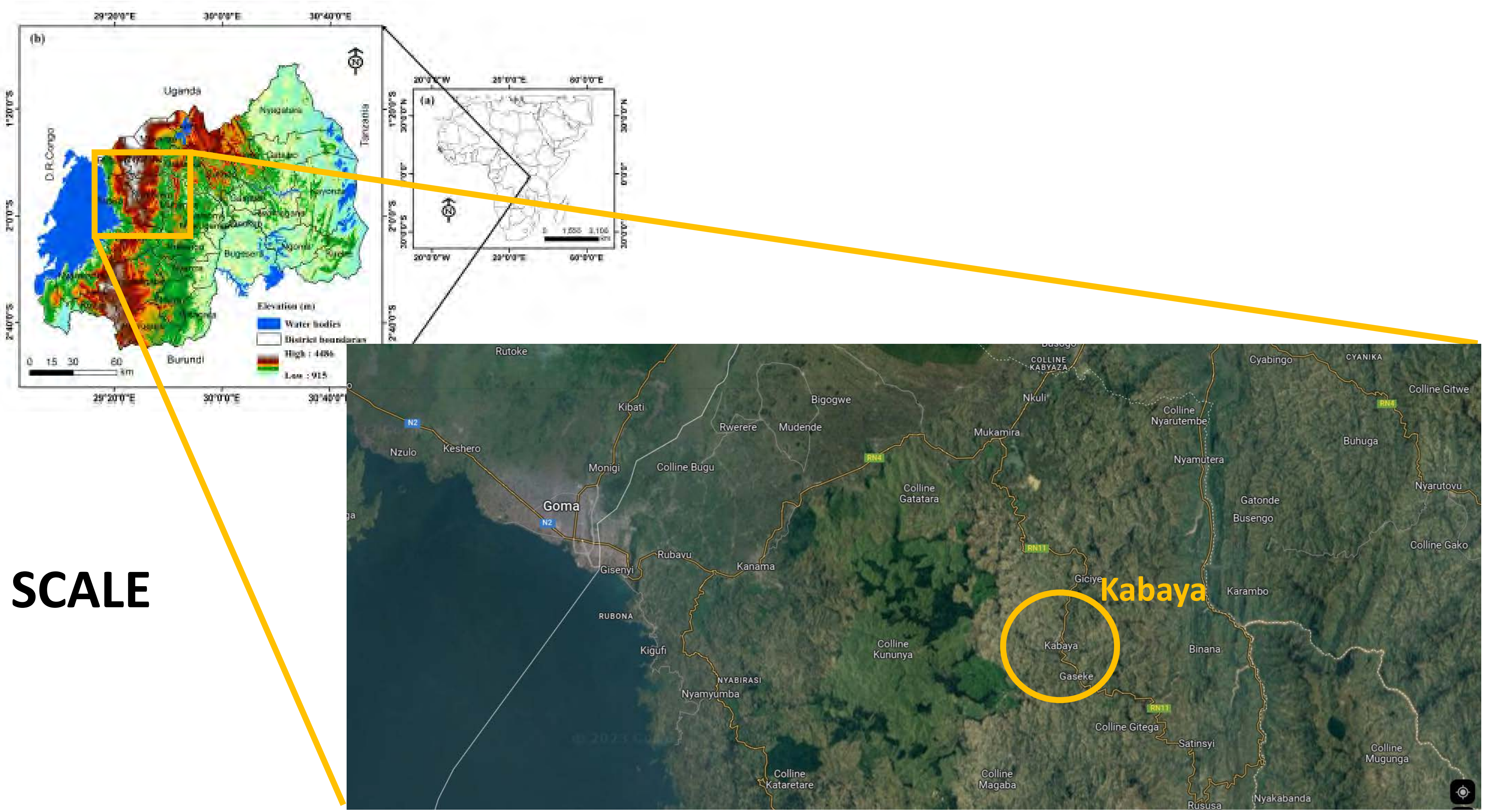


Free software

GeoWizard
Geo-Engineering Programs

HYRCAN 2.0
©2022 Roozbeh Geraili Mikola

Case studies in Rwanda: RN 11 Kabaya – Ngororero, May 2018

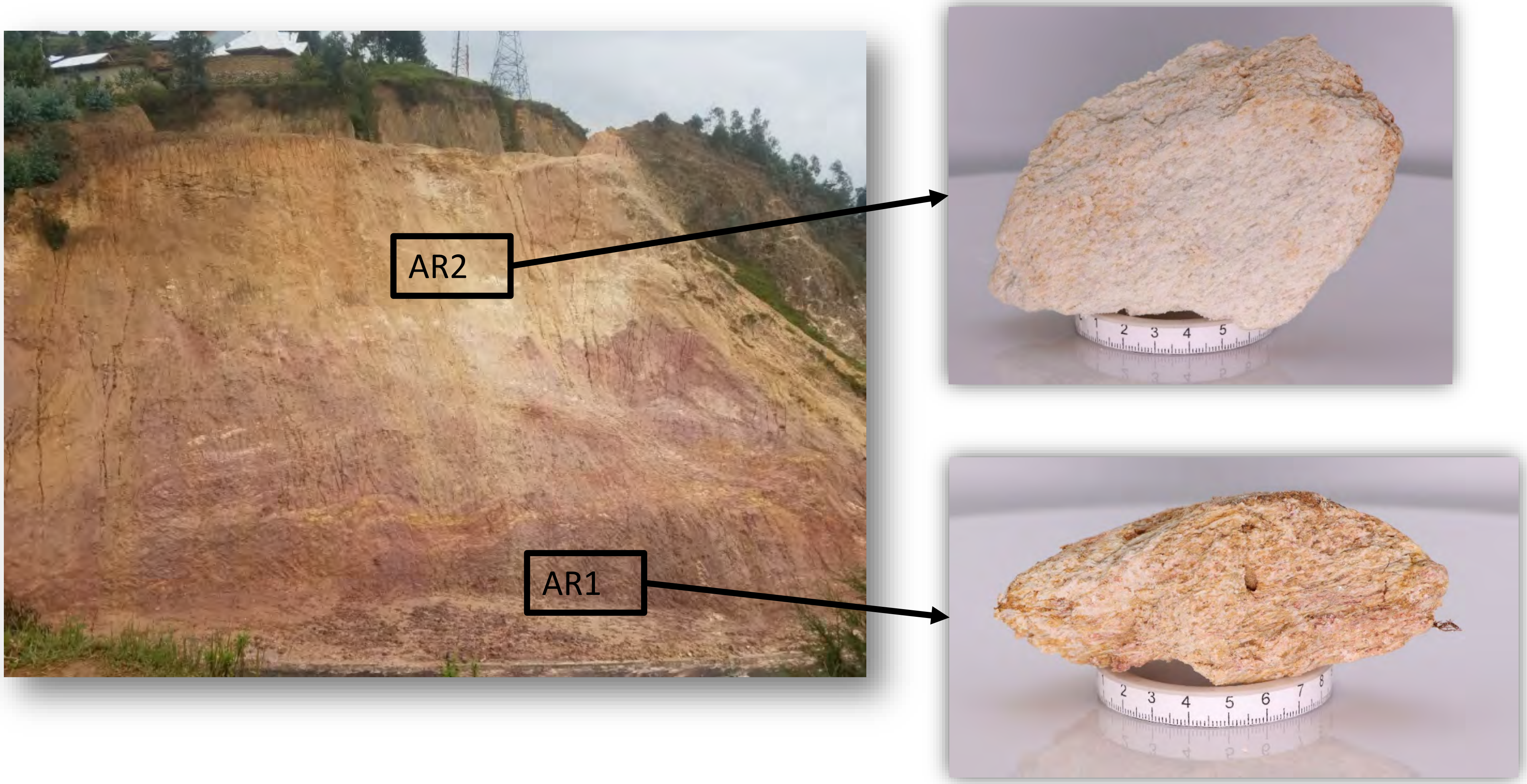


SLOPE SCALE

Case studies in Rwanda: RN 11 Kabaya – Ngororero, May 2018

Case studies in Rwanda: RN 11 Kabaya – Ngororero, May 2018

Collection of 2 soil samples

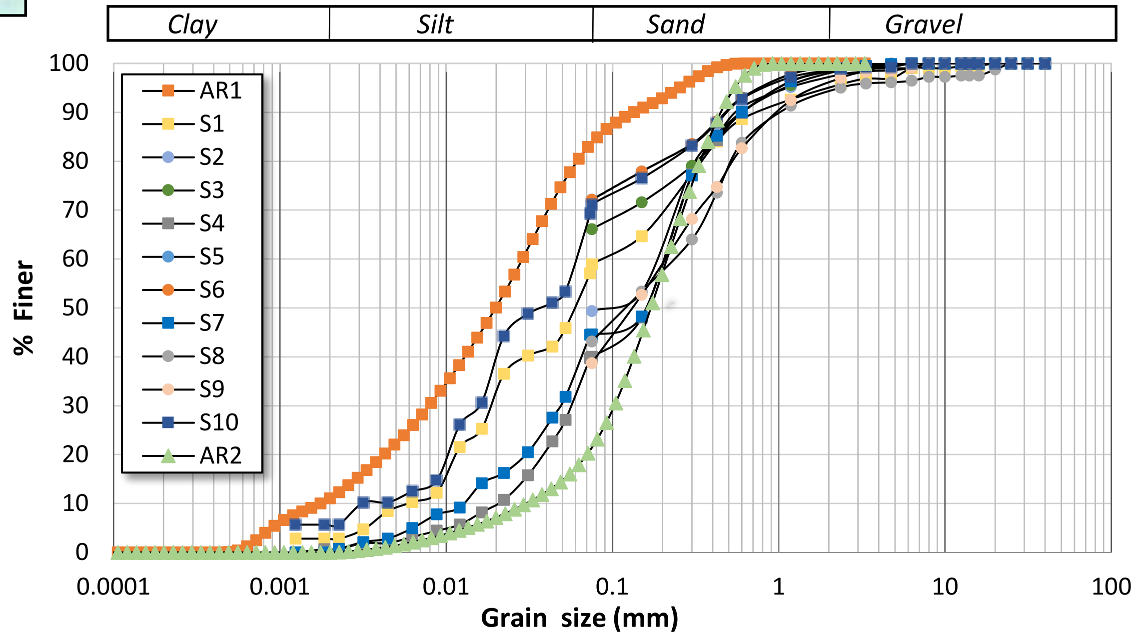


Case studies in Rwanda: RN 11 Kabaya – Ngororero, May 2018

Sedimentation

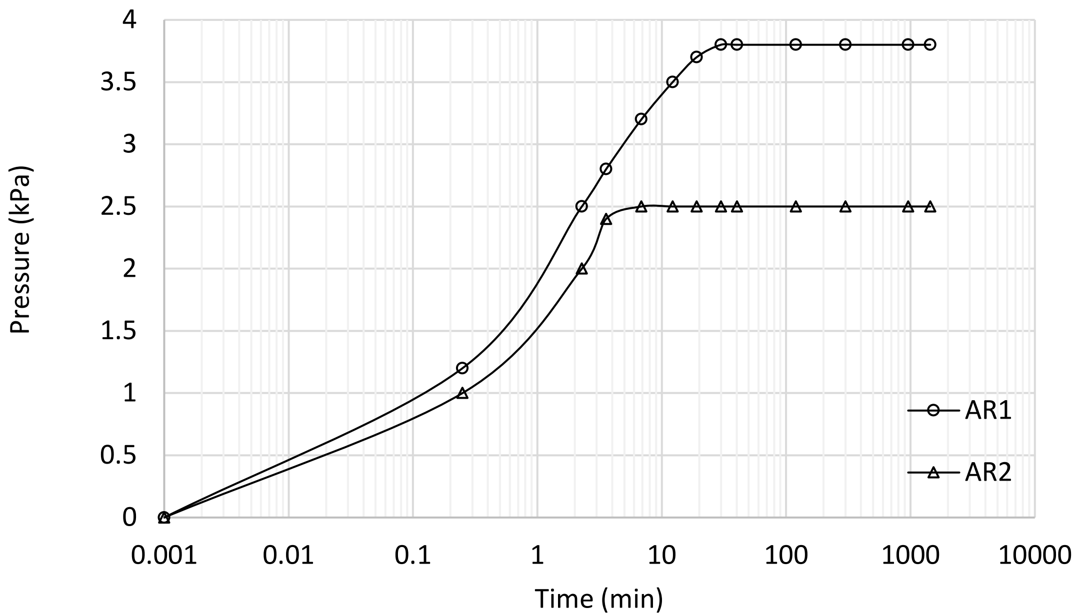
Sieving

Laser optical granulometer



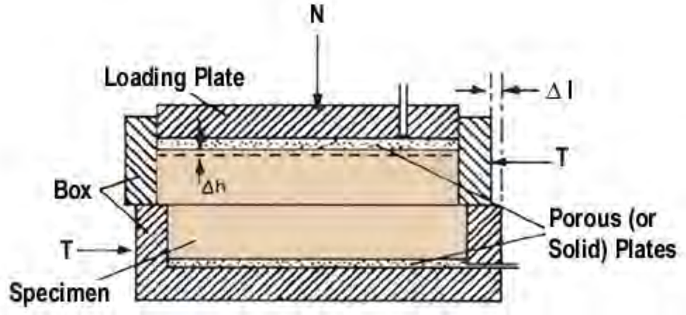
Case studies in Rwanda: RN 11 Kabaya – Ngororero, May 2018

Swelling tests to determine the swelling pressure, by using the oedometer and the constant volume method (Method C) based on ASTM D4546-21

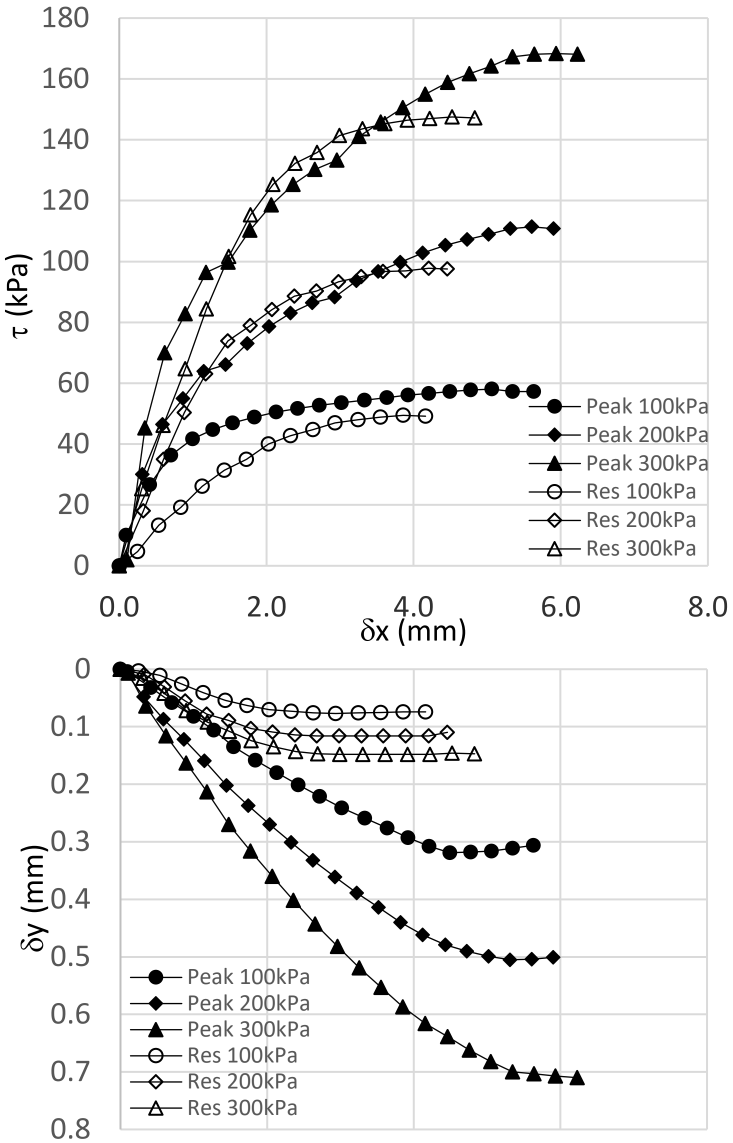


Case studies in Rwanda: RN 11 Kabaya – Ngororero, May 2018

Direct shear test: mechanichal characterization of soil (AR1)

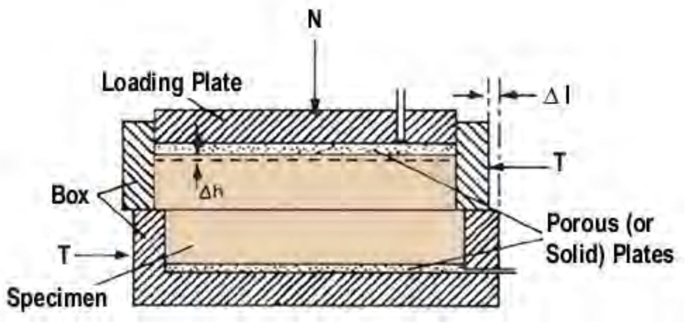


$$\tau_f = \tan\phi \cdot \sigma' + c'$$

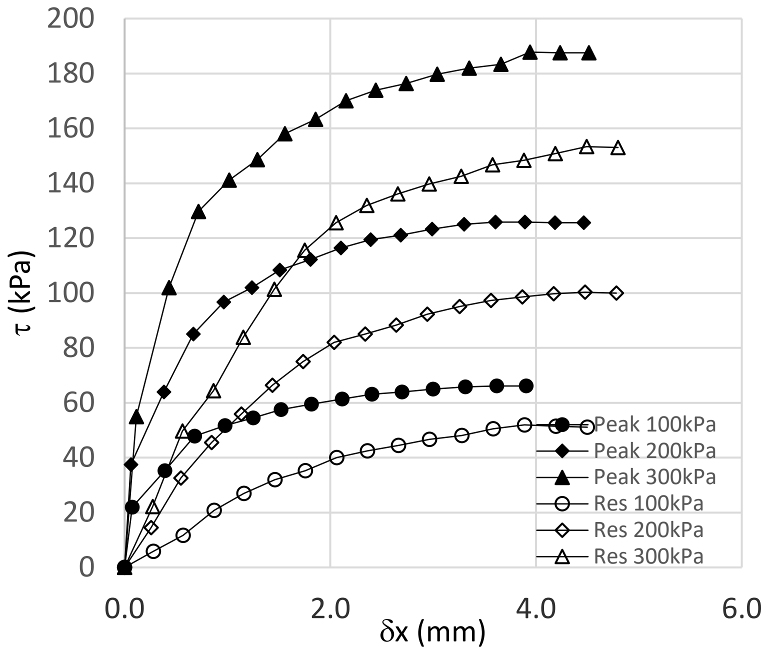


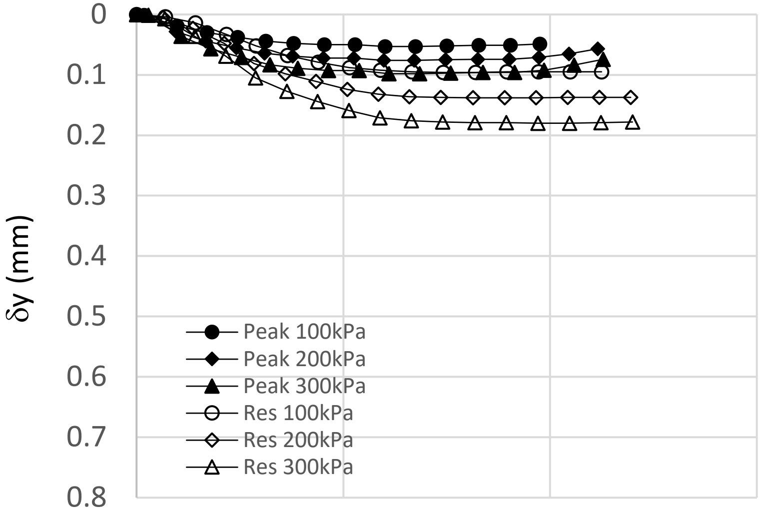
Case studies in Rwanda: RN 11 Kabaya – Ngororero, May 2018

Direct shear test: mechanichal characterization of soil (AR2)



$$\tau_f = \tan\phi \cdot \sigma' + c'$$

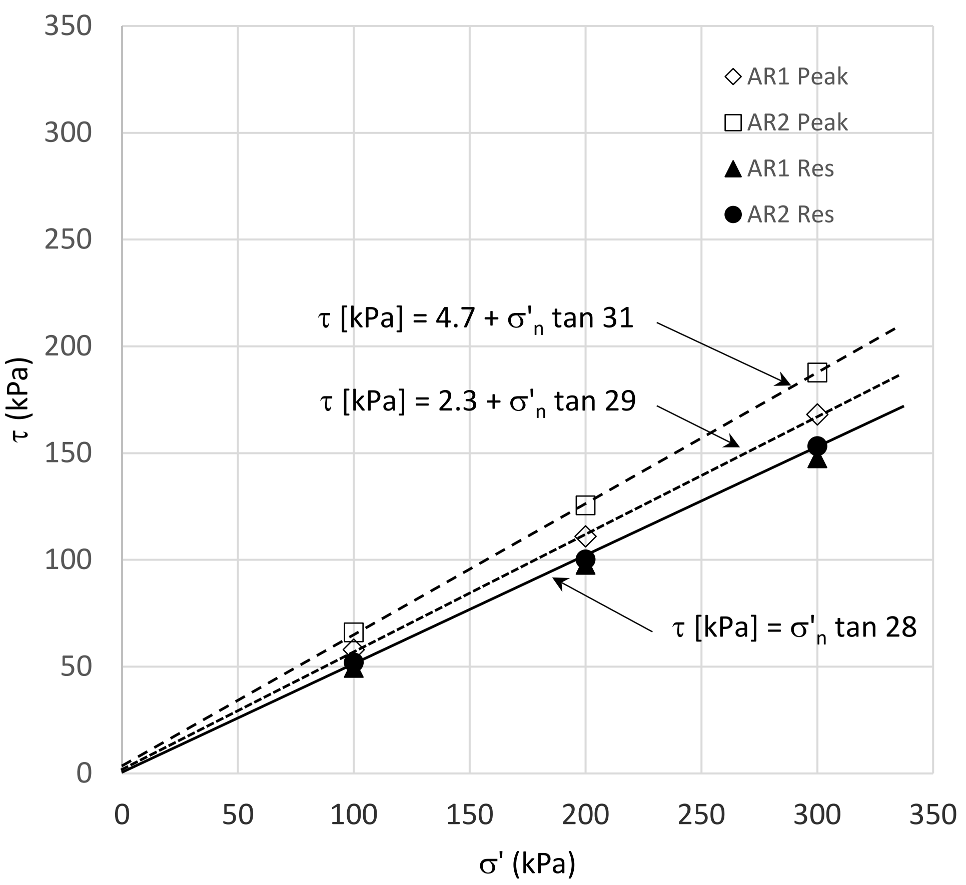




Case studies in Rwanda: RN 11 Kabaya – Ngororero, May 2018

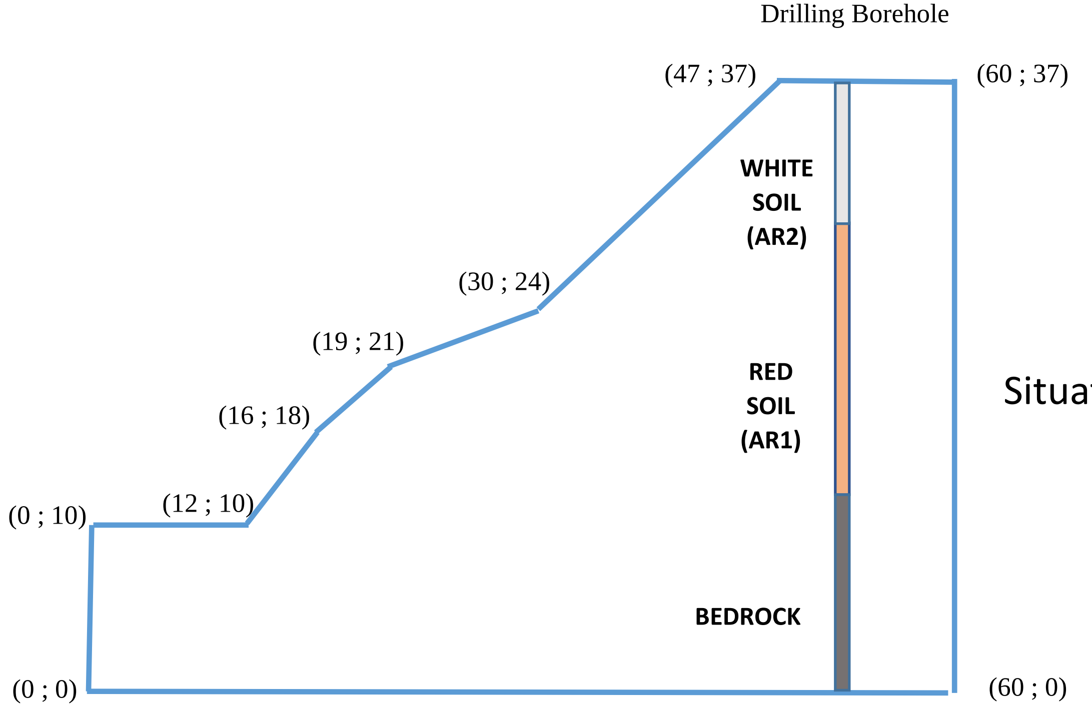
Mohr-Coulomb shear strength criterion

$$\tau_f = \tan\phi \cdot \sigma' + c'$$



Case studies in Rwanda: RN 11 Kabaya – Ngororero, May 2018

Material	Top (m)	Bottom (m)	Unit weight (kN/m³)	Effective cohesion c' (kPa)	Shear strength angle ϕ' (degree)
"White" soil (AR2)	0	8	17	4.7	31
"Red" soil (AR1)	8	26	18	2.3	29
Bedrock	26	37	23	50	35



Situation before failure

Profile coordinates

x	y
0	0
0	10
12	10
16	18
19	21
30	24
47	37
60	37
60	0
0	0

Case studies in Rwanda: RN 11 Kabaya – Ngororero, May 2018

Material	Top (m)	Bottom (m)	Unit weight (kN/m³)	Effective cohesion c' (kPa)	Shear strength angle ϕ' (degree)
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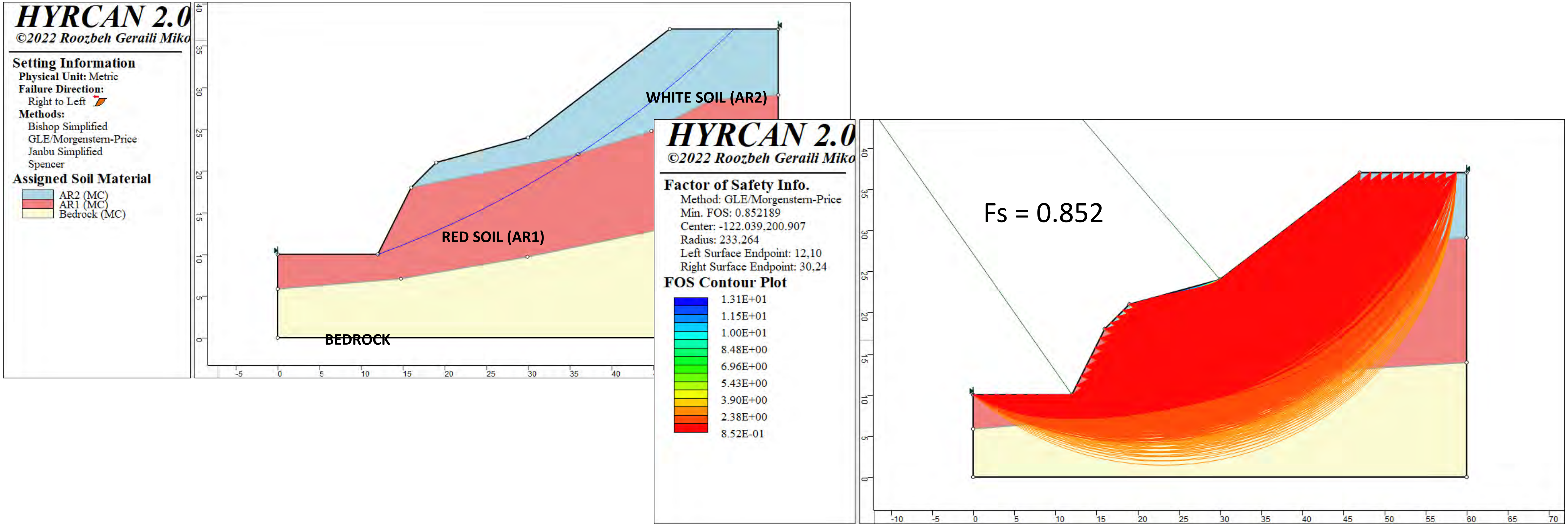
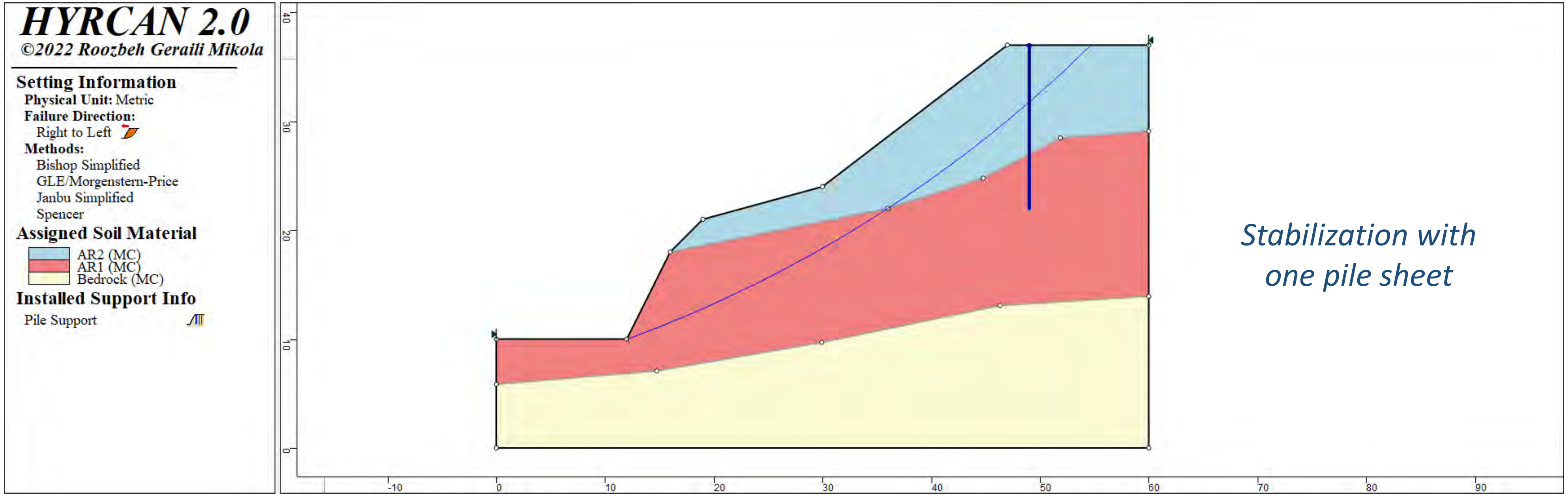
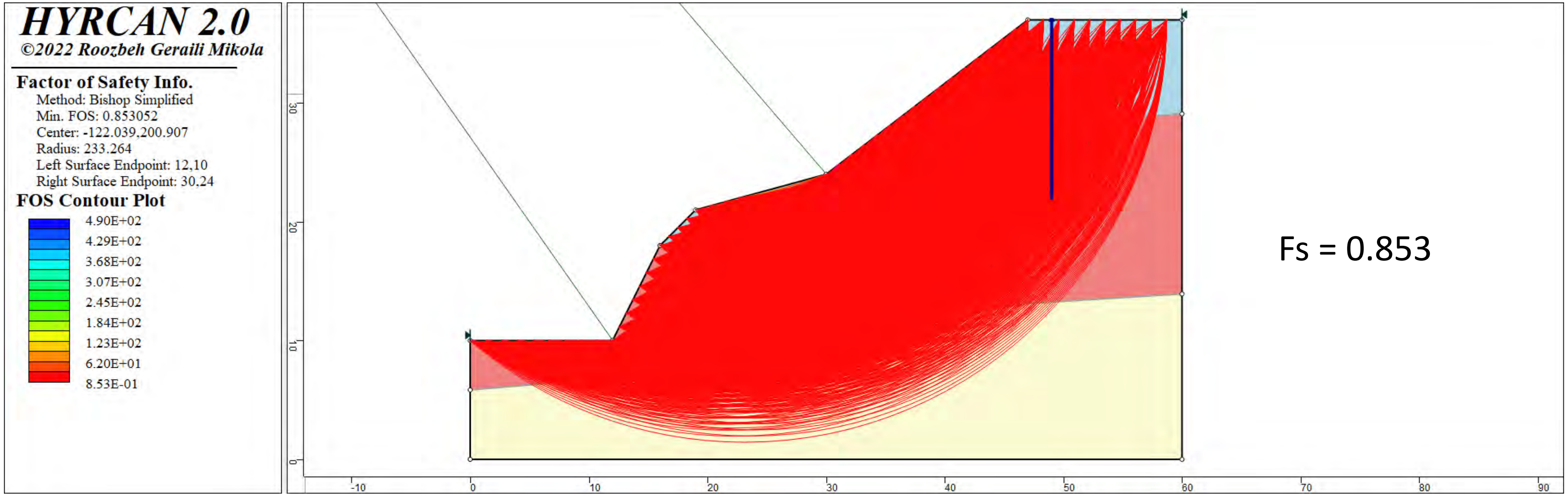


Case studies in Rwanda: RN 11 Kabaya – Ngororero, May 2018

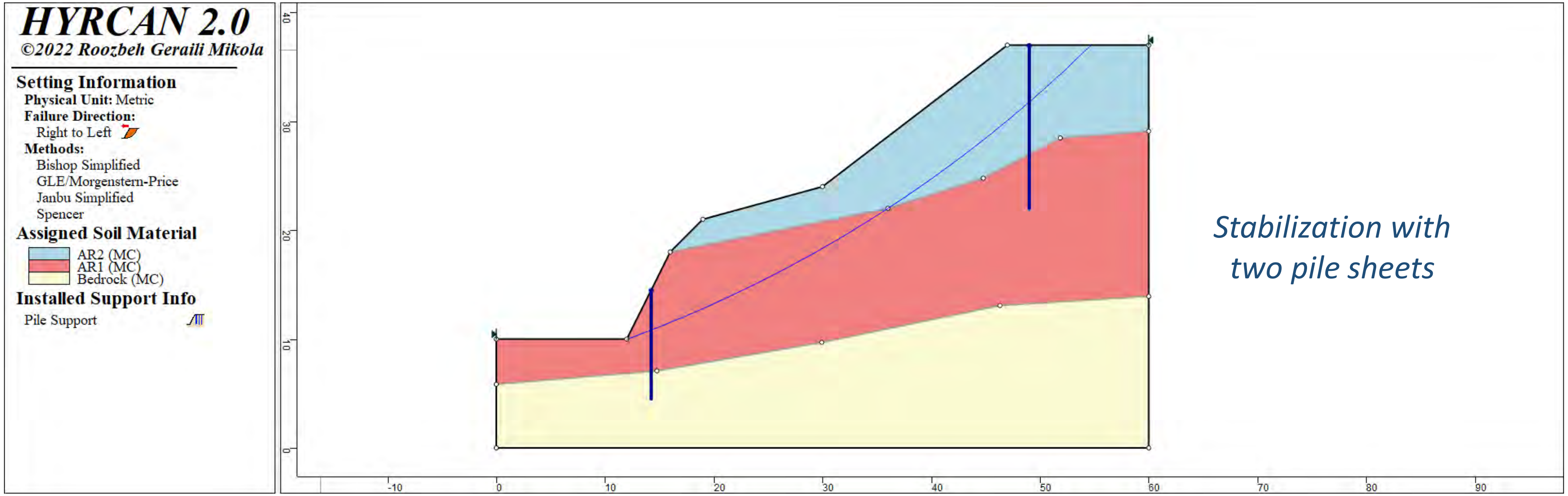


Stabilization with one pile sheet

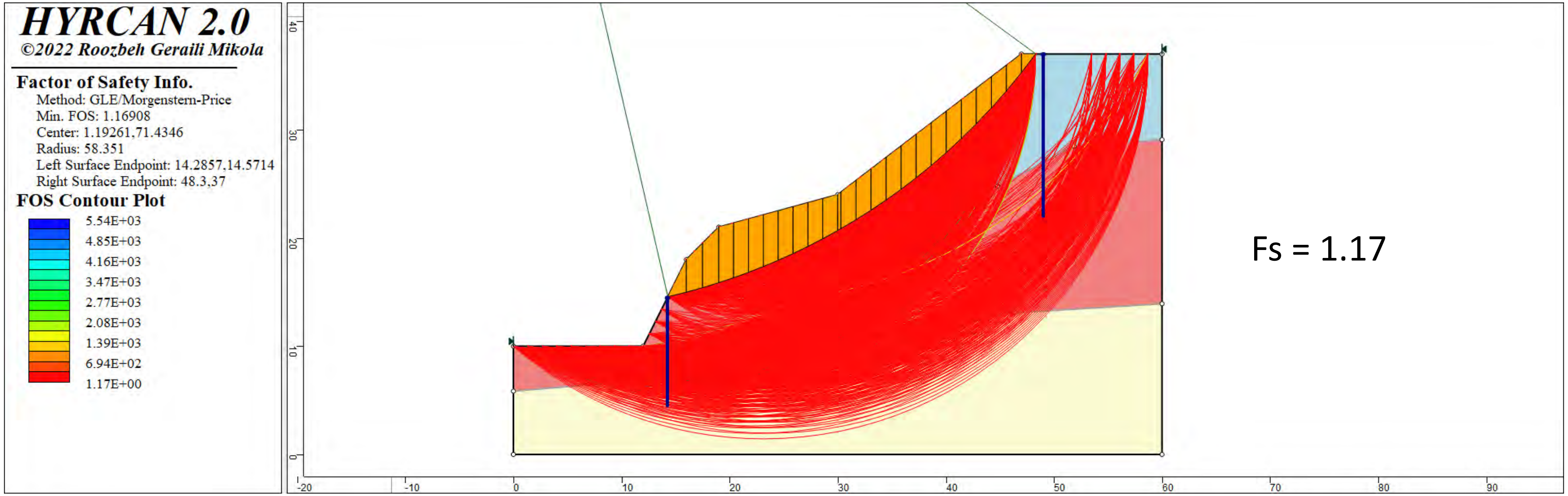


Fs = 0.853

Case studies in Rwanda: RN 11 Kabaya – Ngororero, May 2018



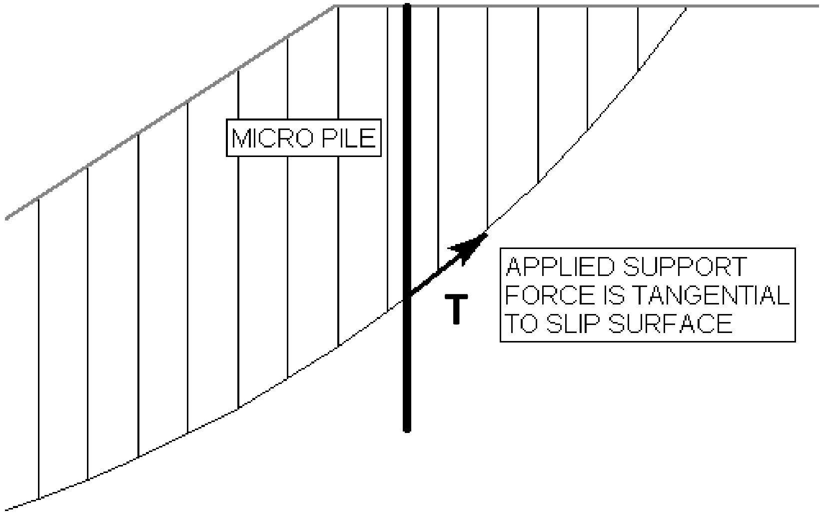
Stabilization with two pile sheets

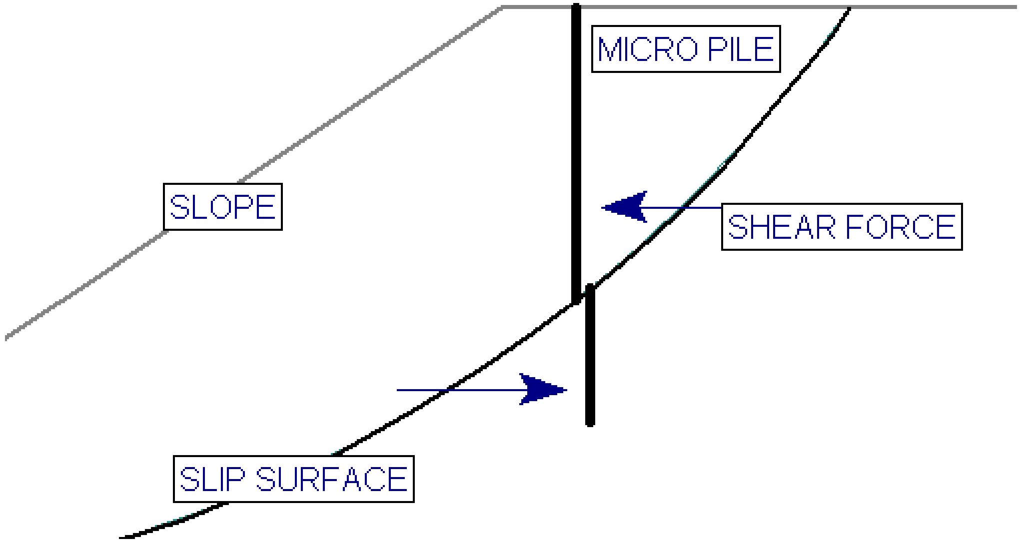


Fs = 1.17

Piles used as stabilising structures

Simplified modelling of resistence given by a pile as simulated in the software





Total shear resistence T (pile cross section):

$$T = \tau_{CLS} \cdot \pi \cdot r^2$$

$$\tau_{CLS} = 25000 \frac{kN}{m^2}$$

Pile diameter (2r):

30cm	micropiles
30-80cm	medium diameter piles
>80cm	large diameter piles

Summary

- **SINGLE SLOPE SCALE**

LEM

GeoWizard
Geo-Engineering Programs

HYRCAN 2.0
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rocscience

Landslide inventory (+ MAP):

- Date (day/month/year)
- Position (on the map)
- Shape (edge as polygon on the map)/2D profile
- Type
- Type of material (rock of soil)
- New or re-activated
- Land use
- Damage
- Photo

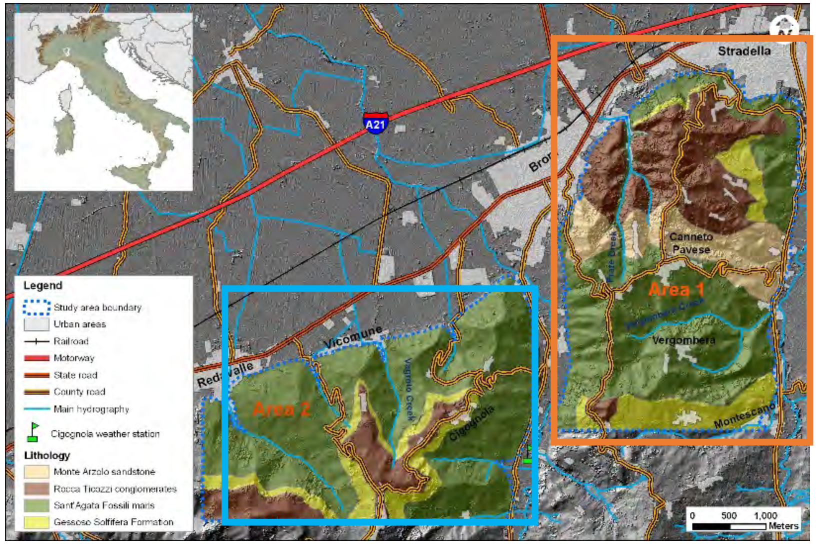
Data collection:

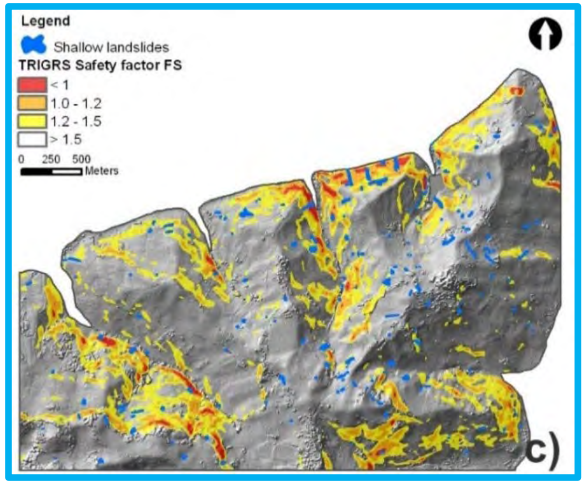
✓ Soil/rock samples
✓ Lab tests for classification and mechanical characterization

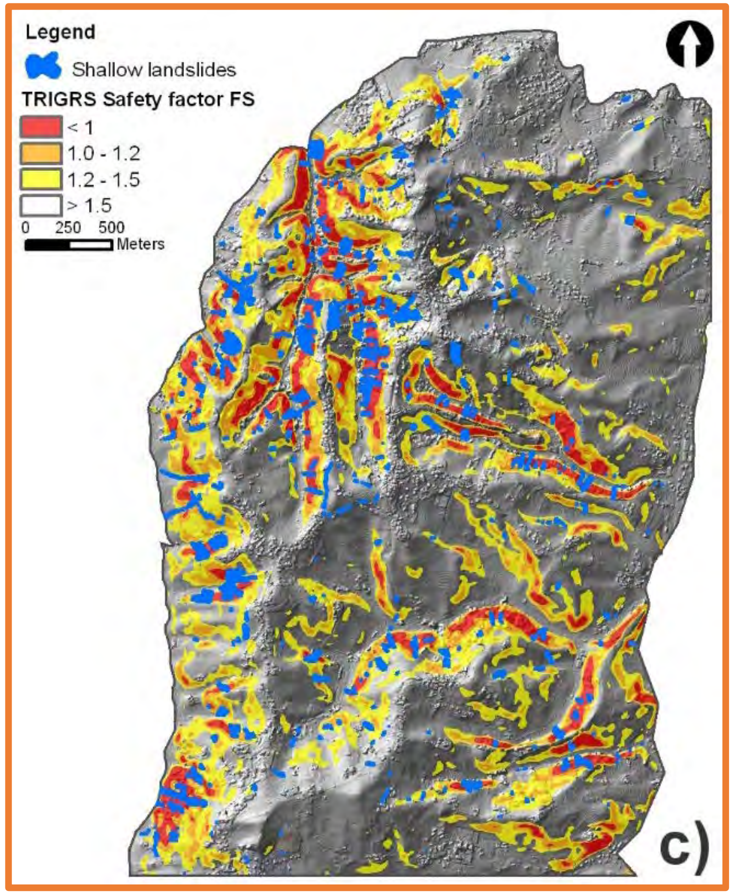
SLOPE STABILITY ANALYSIS AT LARGE SCALE

SLOPE STABILITY ANALYSIS AT LARGE SCALE

TRIGRS - Transient Rainfall Infiltration and Grid-Based Regional Slope-Stability Analysis (Baum et al., 2008)







TYPE OF LANDSLIDE: SHALLOW LANDSLIDES INDUCED BY RAINFALL


Alta Versilia – 19.06.1996 (*Tuscany*)


Sarno – 05.05.1998 (*Campania*)


Ceriana – 23.11.2000 (*Liguria*)


Oltrepo Pavese – 26.11.2002 (*Lombardy*)


App. Reggiano – 10.04.2005 (*Emilia Romagna*)

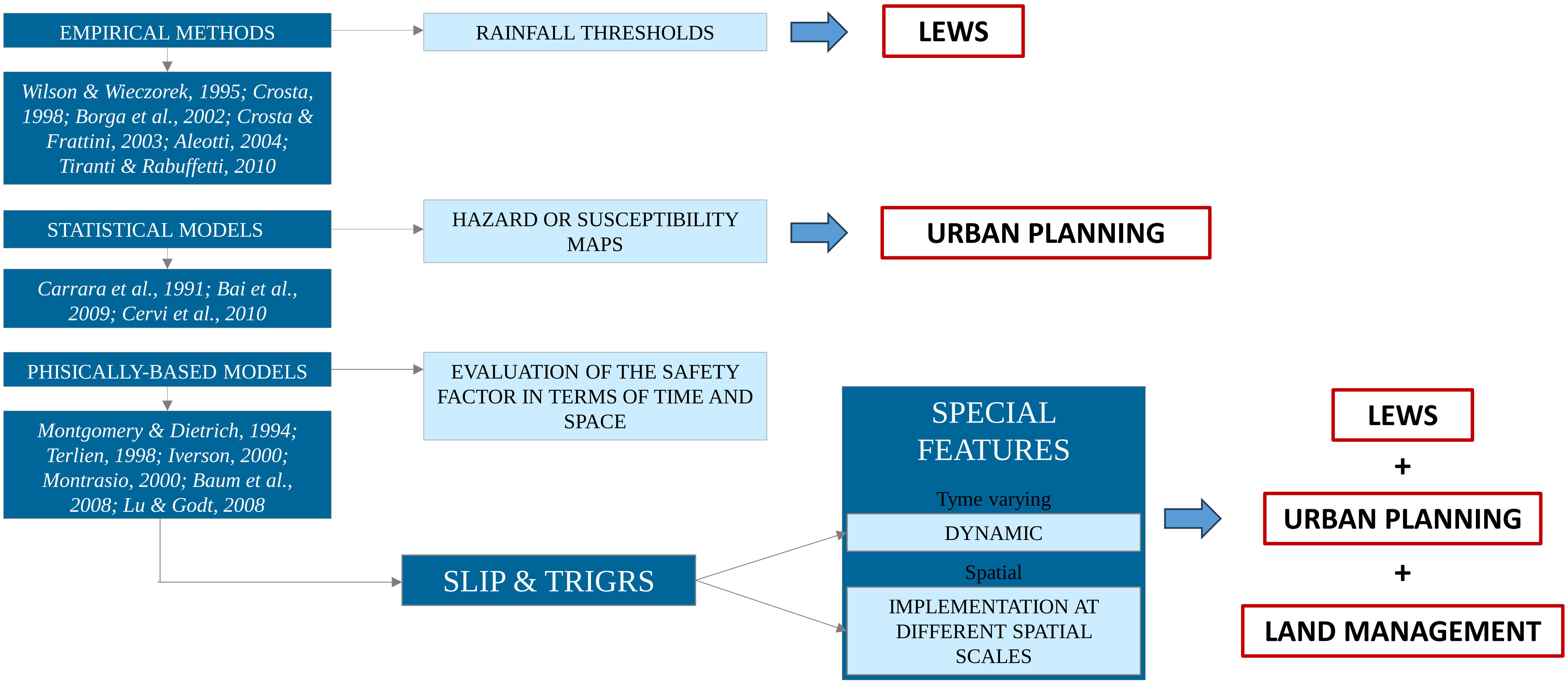

Giampilieri – 01.10.2009 (*Sicily*)


Casamicciola Terme – 10.11.2009 (*Campania*)


San Fratello – 14.02.2010 (*Sicily*)

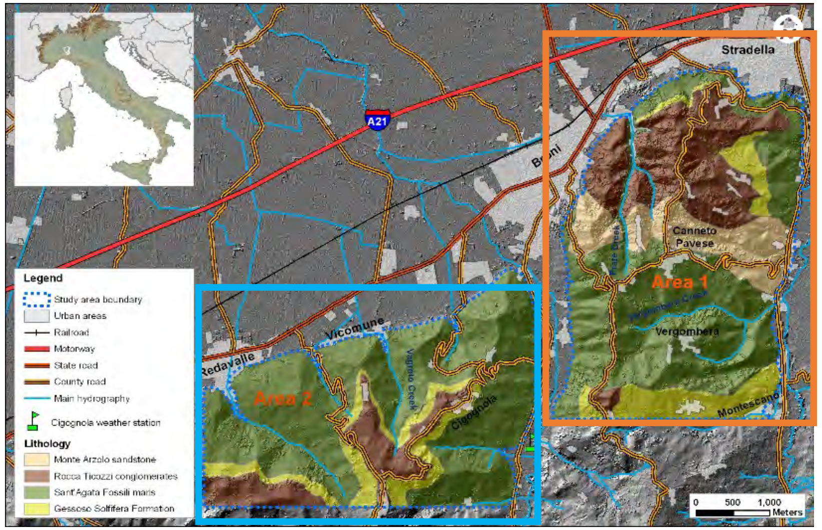

Massa Carrara – 01.11.2010 (*Tuscany)*

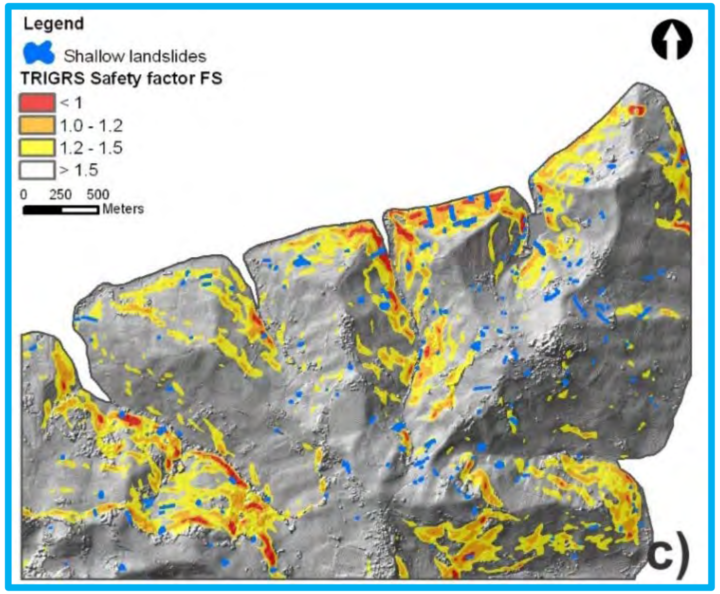
«DISTRIBUTED» SLOPE STABILITY ANALYSIS

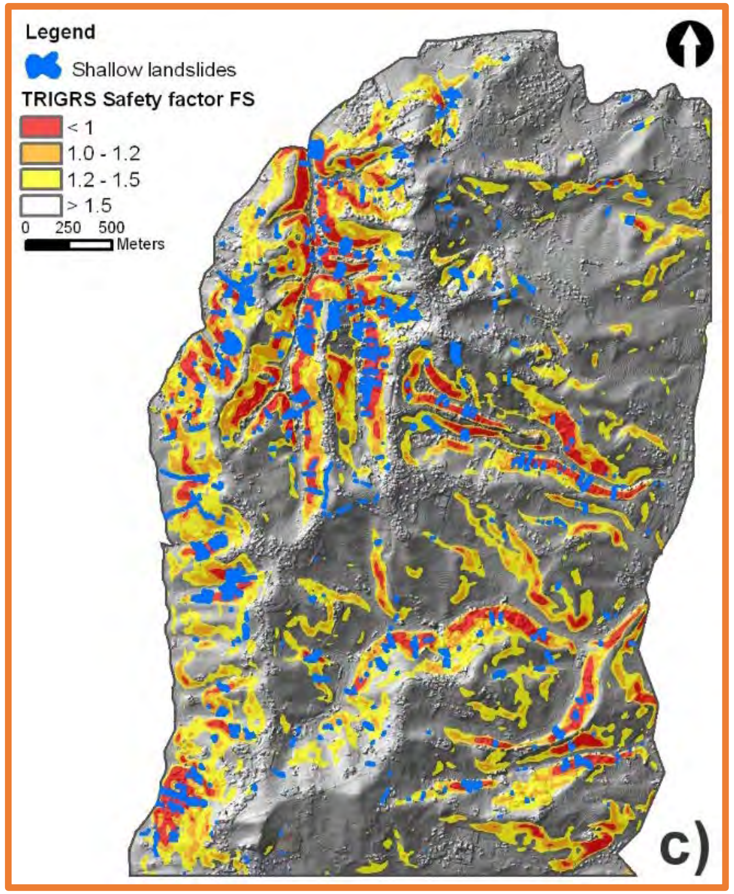


LARGE SCALE MODELING

TRIGRS - Transient Rainfall Infiltration and Grid-Based Regional Slope-Stability Analysis (Baum et al., 2008)

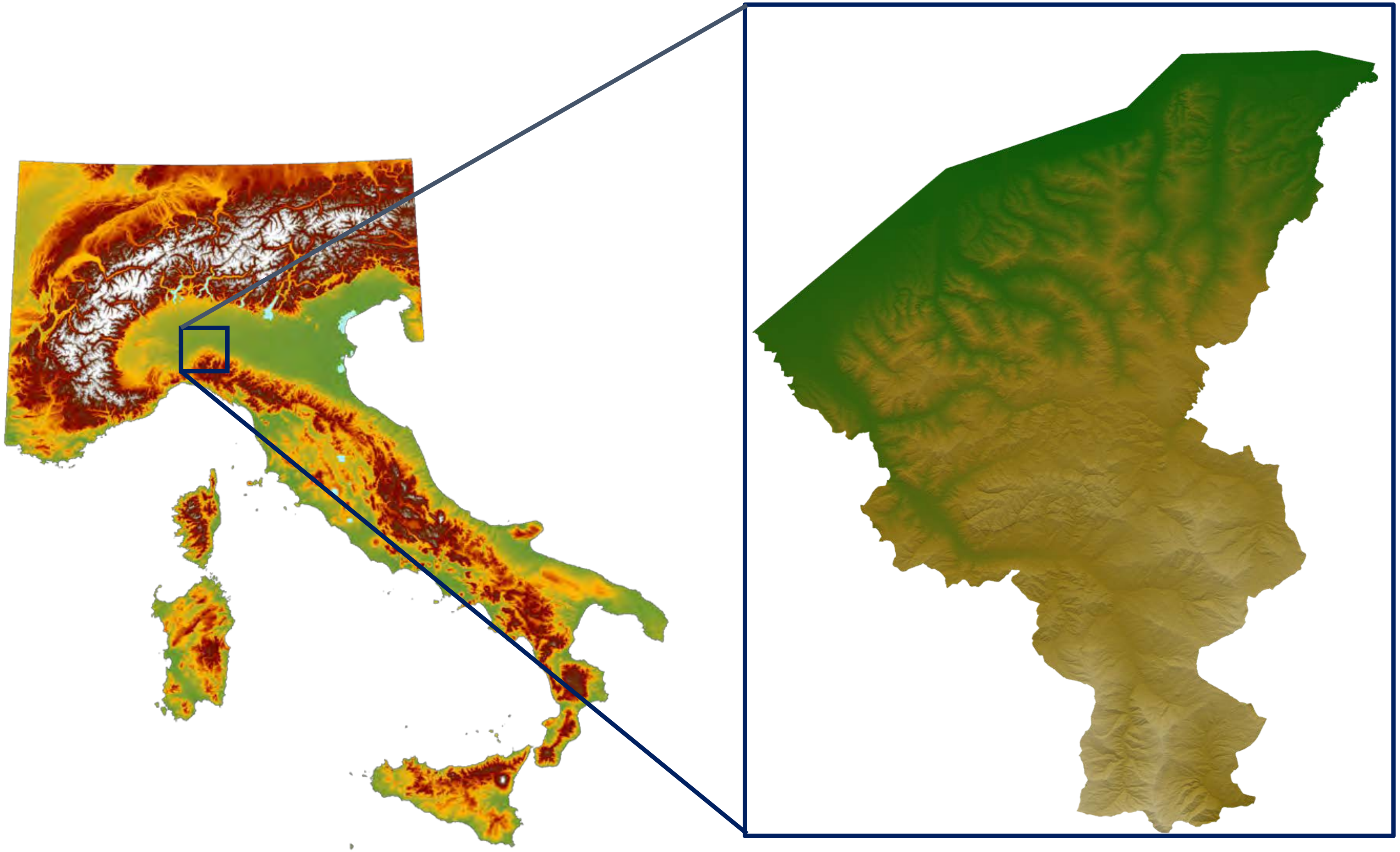






Case study in Italy: Oltrepò Pavese, April 2009

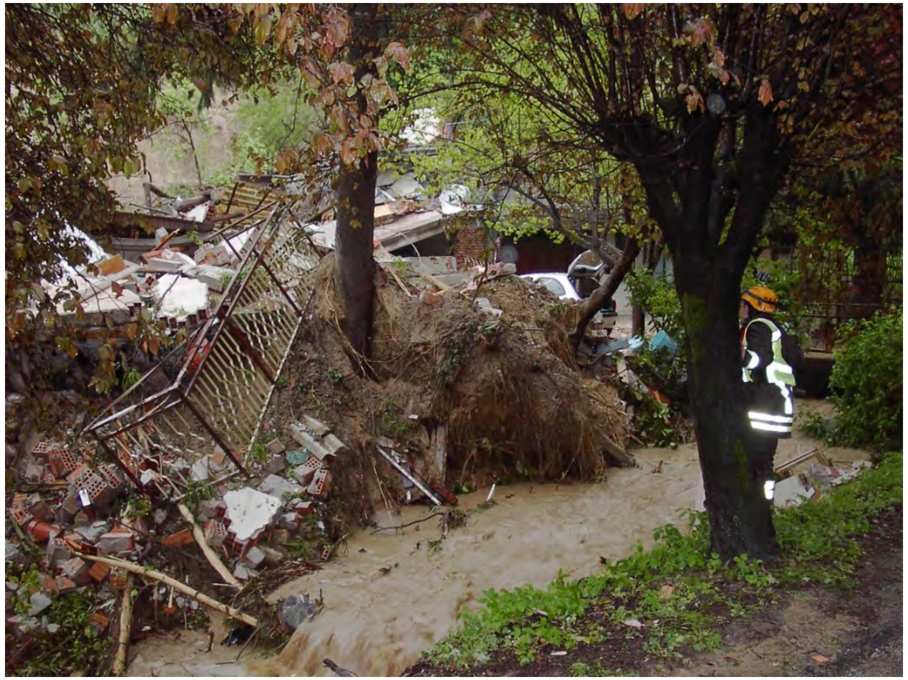
Oltrepò Pavese is in the north-west of Italy and lies to the south of the Po river.

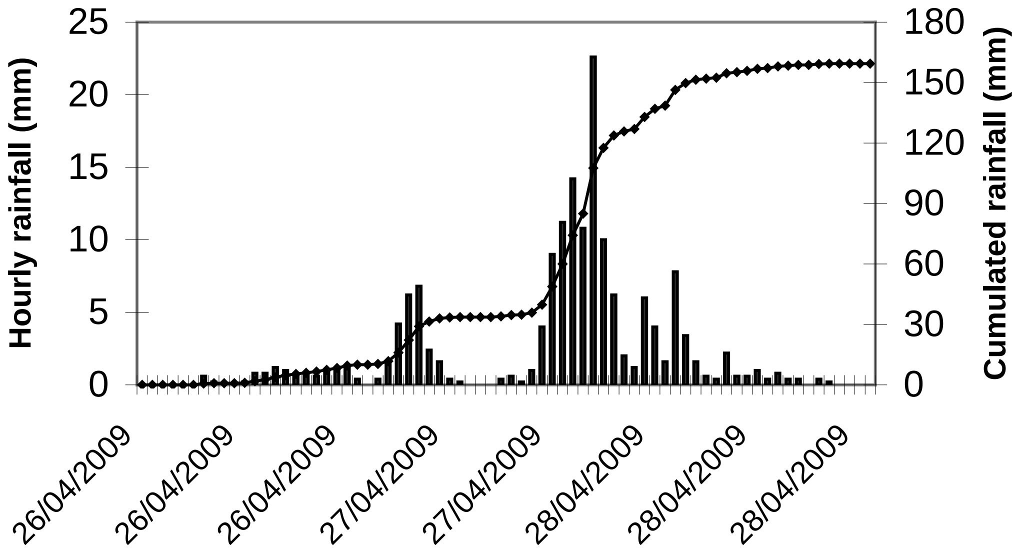


Case study in Italy: Oltrepò Pavese, April 2009

- On the 27 and 28 April 2009, the northeastern sector of Oltrepò Pavese experienced an extreme rainfall event. On the 28 April, the nearest rain-gauge station recorded 150mm of rain in 48 h (20% of the annual average amount), with a maximum rainfall intensity of 22mm per hour

- After this rainfall peak, several shallow landslides were triggered, causing one fatality and loss of agricultural land, as well as damaging/blocking roads in several places





Case study in Italy: Oltrepò Pavese, April 2009

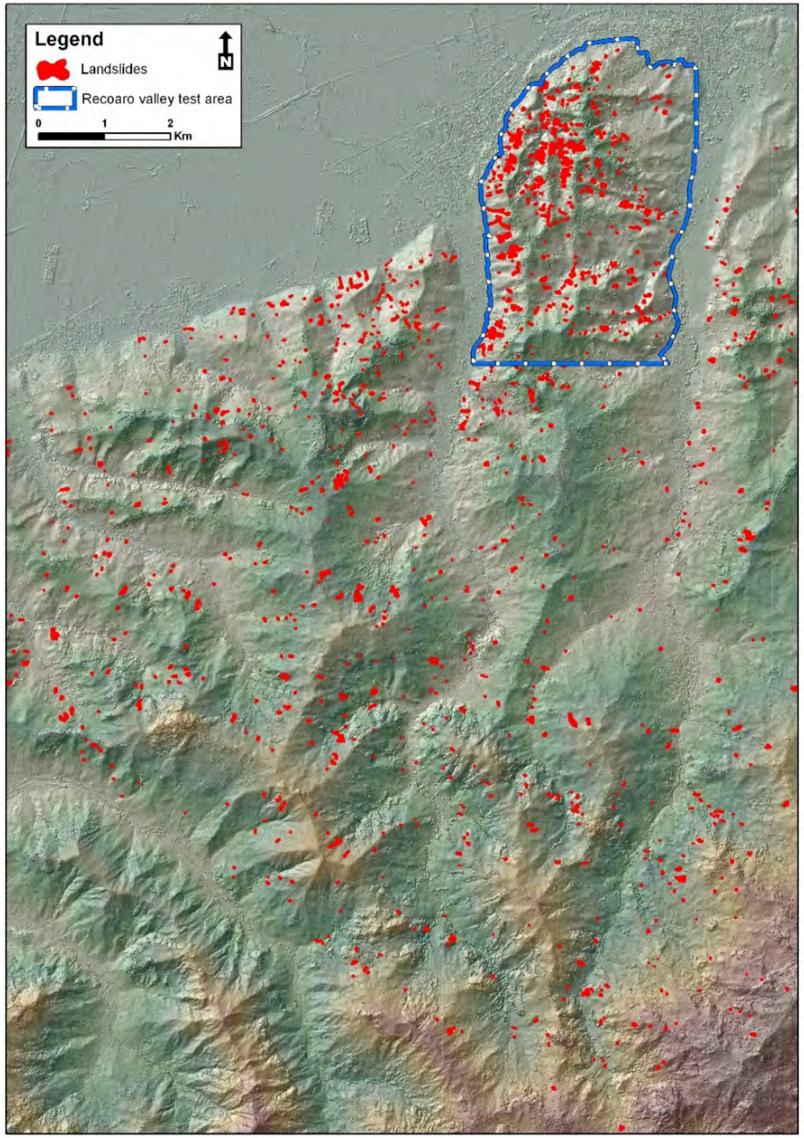
Case study in Italy: Oltrepò Pavese, April 2009

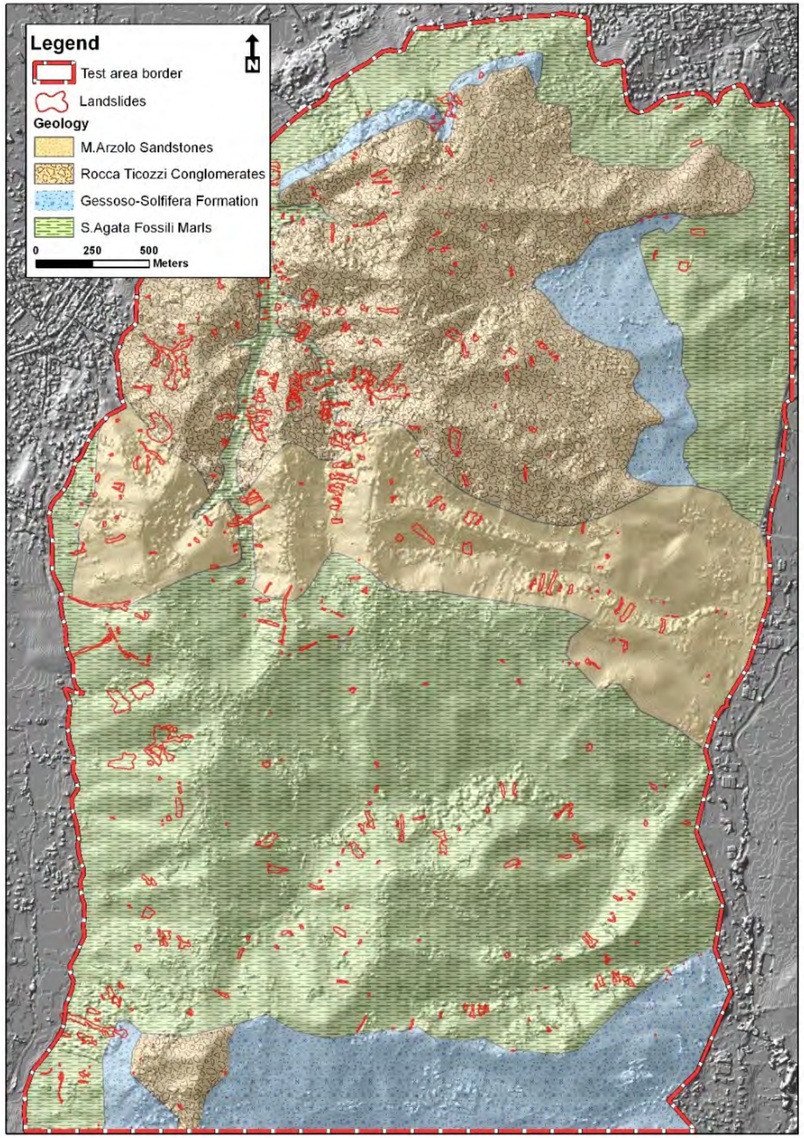
The Recoaro Valley was the most affected area by this event

Case study in Italy: Oltrepò Pavese, April 2009

More than 1600 landslides in 180 km^2

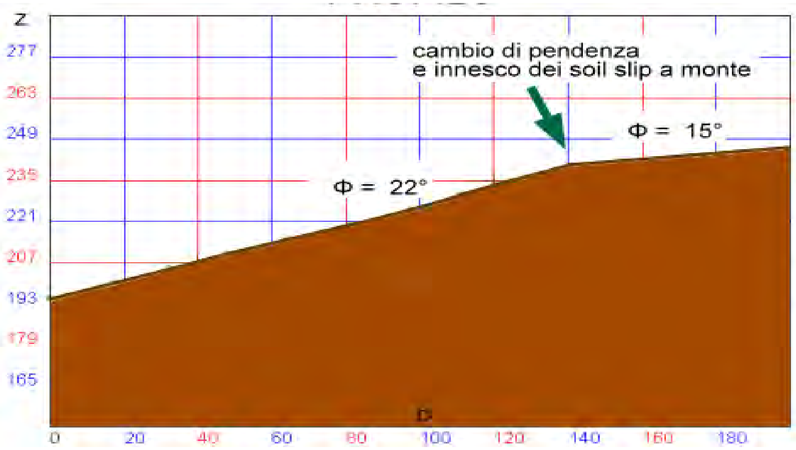
No. 491 landslides in 17 km^2





Case study in Italy: Oltrepò Pavese, April 2009

Predisposing factors



❑ Most of the landslides seems to be concentrated in areas where the slope angle changed from a gentle slope to a steep slope

❑ These areas correspond to morphological or anthropogenic slopes characterized by a greater thickness of the soil, often coincident with the passage vineyard-forest

Case study in Italy: Oltrepò Pavese, April 2009

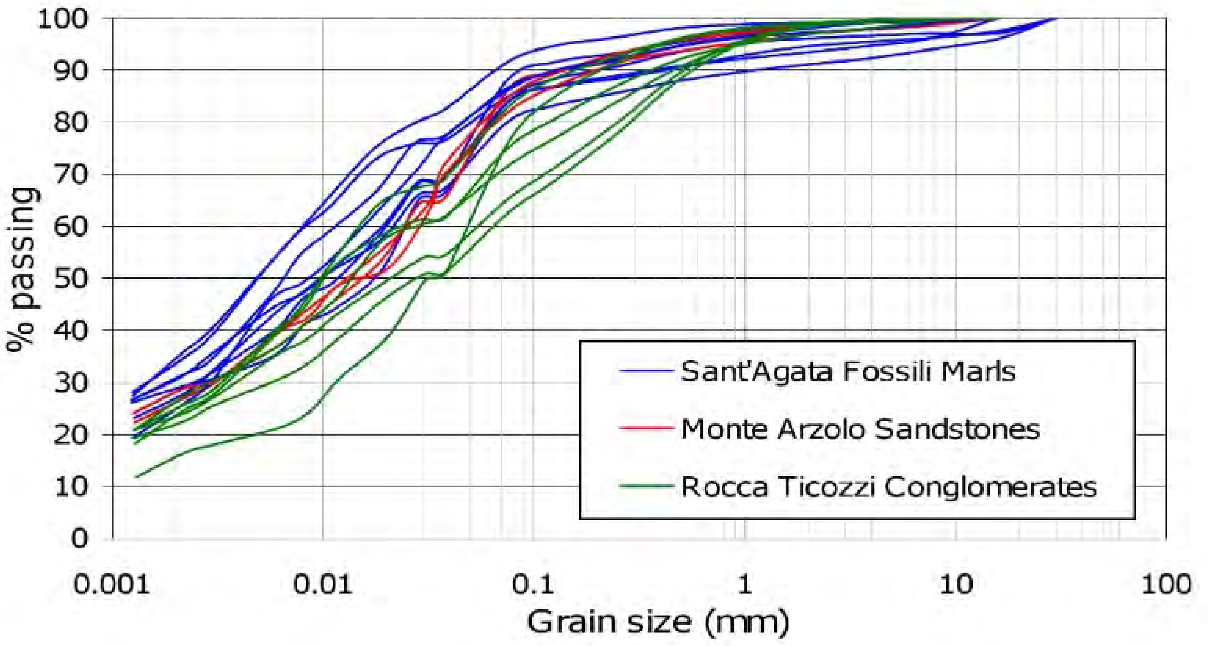
Collection of soil samples
(undisturbed and disturbed)

Case study in Italy: Oltrepò Pavese, April 2009

Soil classification

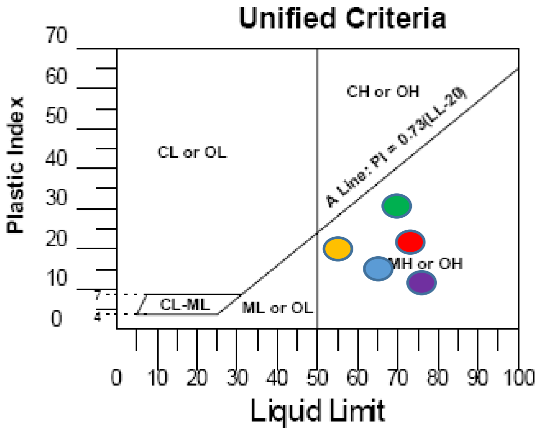
SEDIMENTATION

SIEVING



LIQUID LIMIT

PLASTIC LIMIT



Case study in Italy: Oltrepò Pavese, April 2009

Soil mechanichal characterization: triaxial tests

SATURATION

CONSOLIDATION

FAILURE

SHEAR STRENGTH PARAMETERS

B *(Skempton)* $\geq$ **0.9**

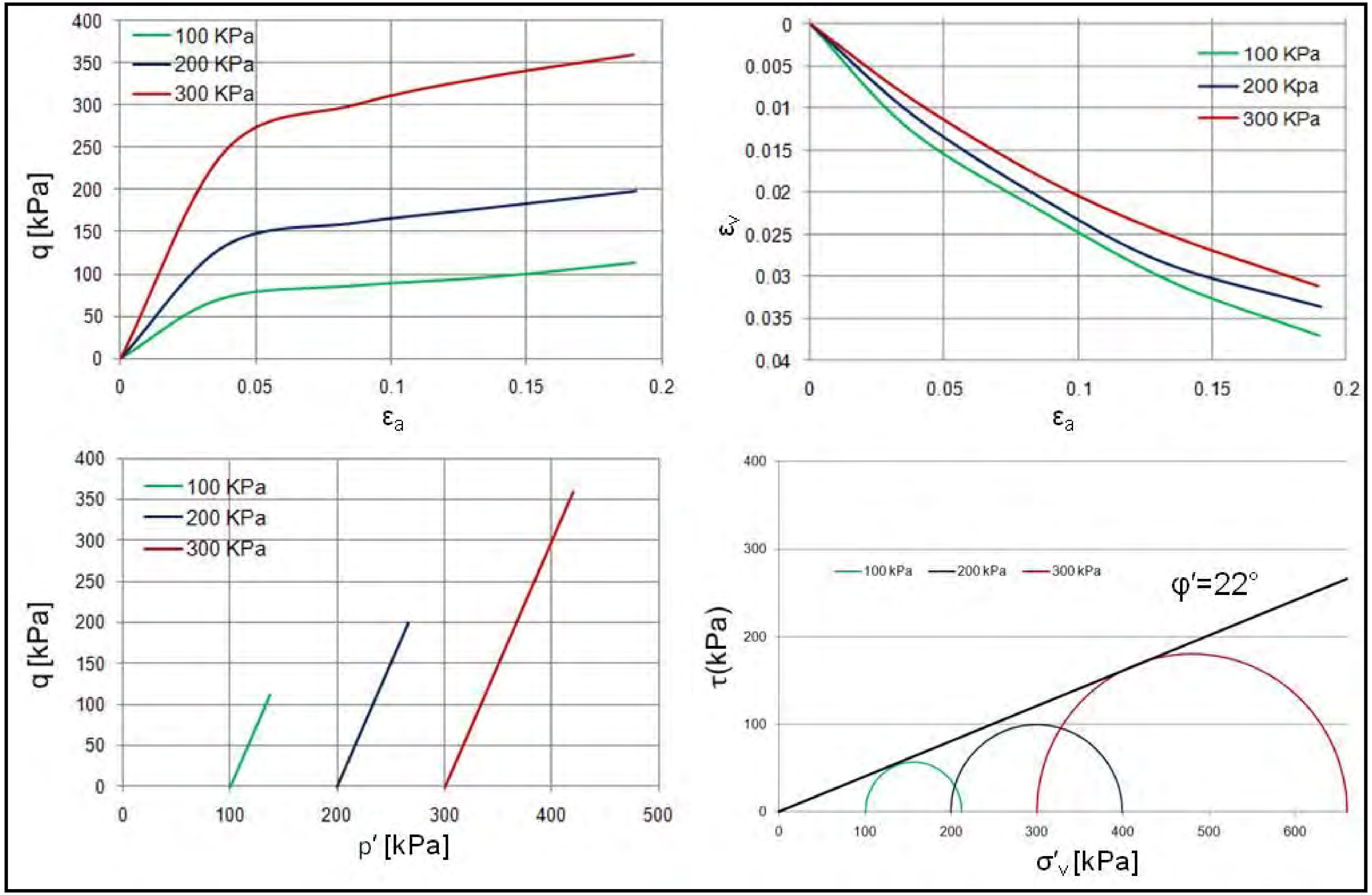
$\sigma_a = \sigma_r =$ **50kPa** (100kPa)
$\sigma_a = \sigma_r =$ **100kPa** (200kPa)
$\sigma_a = \sigma_r =$ **150kPa** (300kPa)

$\sigma_a > \sigma_r$

ε_a ; ε_v

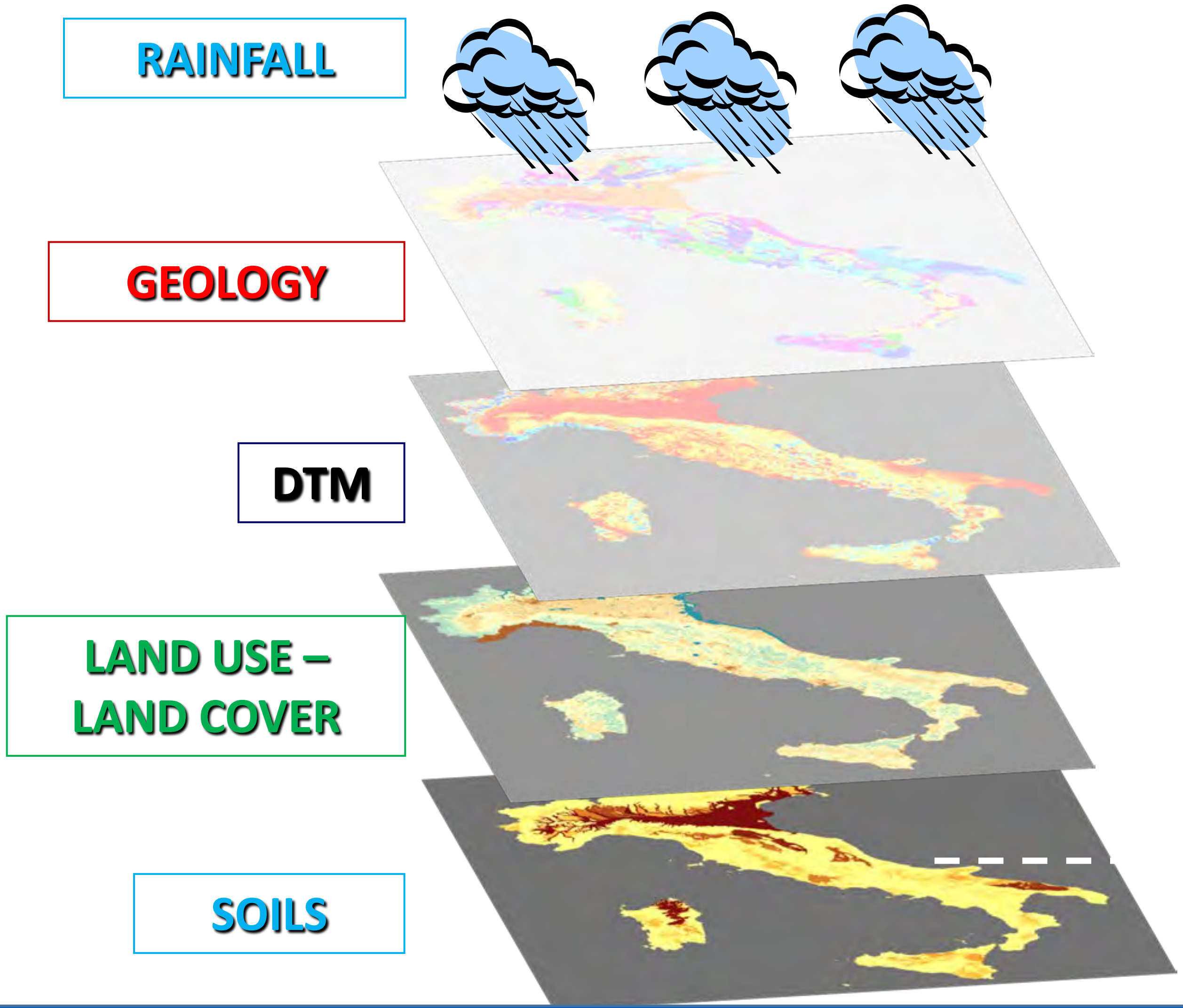
Case study in Italy: Oltrepò Pavese, April 2009

Soil mechanichal characterization: results of triaxial tests



Case study in Italy: Oltrepò Pavese, April 2009

Implementation of a distributed slope stability model at regional scale



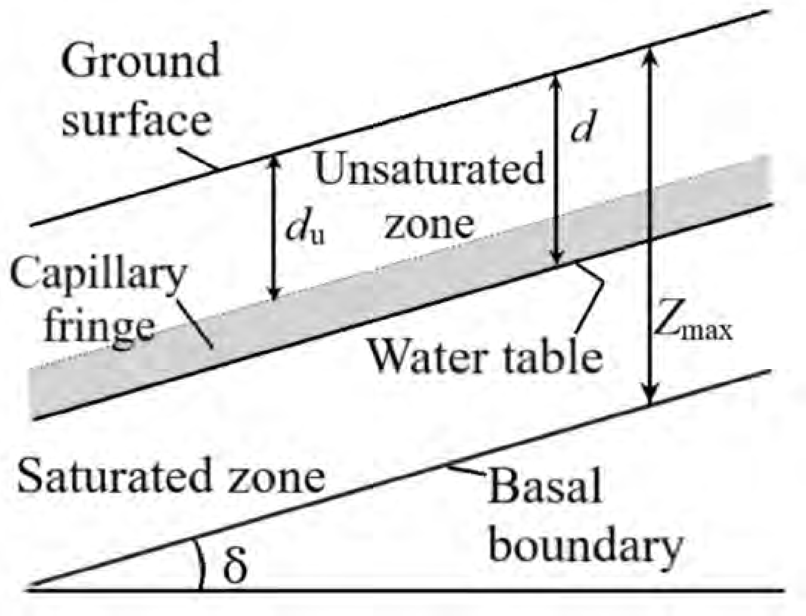
Pre-Processing:

Data at large scale are acquired at the maximum available resolution.

Use of GIS

Case study in Italy: Oltrepò Pavese, April 2009

- ❑ ***TRIGRS*** (Transient Rainfall Infiltration and Grid-based Regional Slope-stability analysis) model designed for modeling the timing and distribution of shallow, rainfall-induced landslides (Baum et al., 2002; Baum et al., 2008)
- ❑ The program computes transient pore-pressure changes, and attendant changes in the factor of safety, due to rainfall infiltration
- ❑ The program models rainfall infiltration, resulting from storms that have durations ranging from hours to a few days, using analytical solutions for partial differential equations that represent one-dimensional, vertical flow in isotropic, homogeneous materials for either saturated or unsaturated conditions
- ❑ TRIGRS uses an infinite-slope model to compute a factor of safety (FS) calculation for each grid cell.



$$Fs(Z;t) = \frac{\tan\varphi'}{\tan\beta} + \frac{c' - \psi(Z;t)\gamma_w \tan\varphi'}{\gamma_s Z \sin\beta \cos\beta}$$

Model inputs:

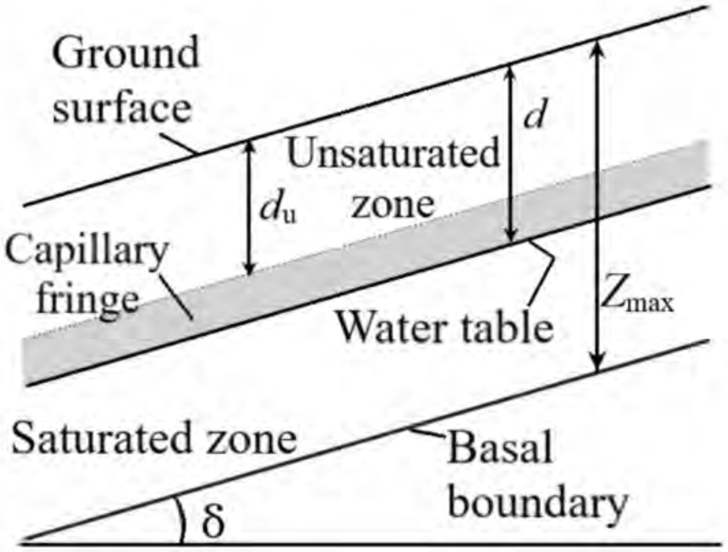
β = slope angle (input as grid)
φ'= friction angle of the soil
c' = effective cohesion
γ_s = soil unit weight
γ_w = water unit weight

Z = depth to bedrock (input as grid)
Ks = permeability
D = hydraulic diffusivity
Rainfall intensity and duration
Water table depth (d)

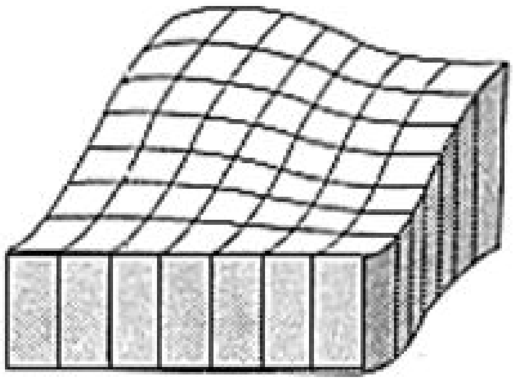
Case study in Italy: Oltrepò Pavese, April 2009

❑ TRIGRS uses an infinite-slope model to compute a factor of safety (FS) calculation ***for each grid cell***.

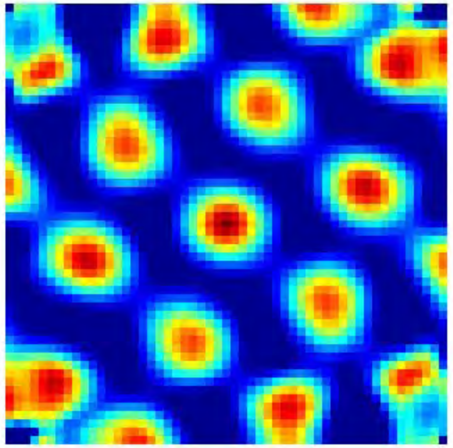
$$Fs(Z;t) = \frac{\tan\varphi'}{\tan\beta} + \frac{c' - \psi(Z;t)\gamma_w \tan\varphi'}{\gamma_s Z \sin\beta\cos\beta}$$



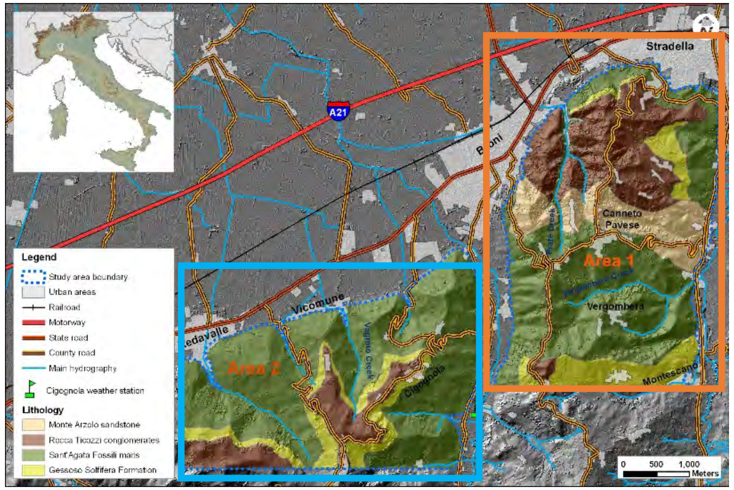
Elementary grid cell 10m x 10m

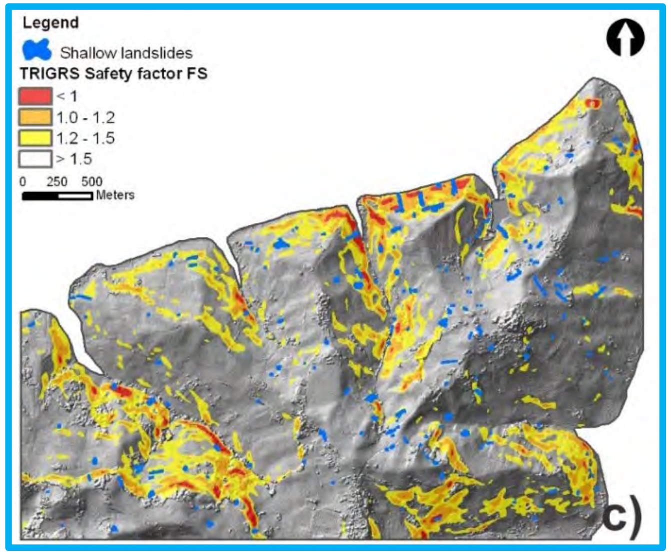


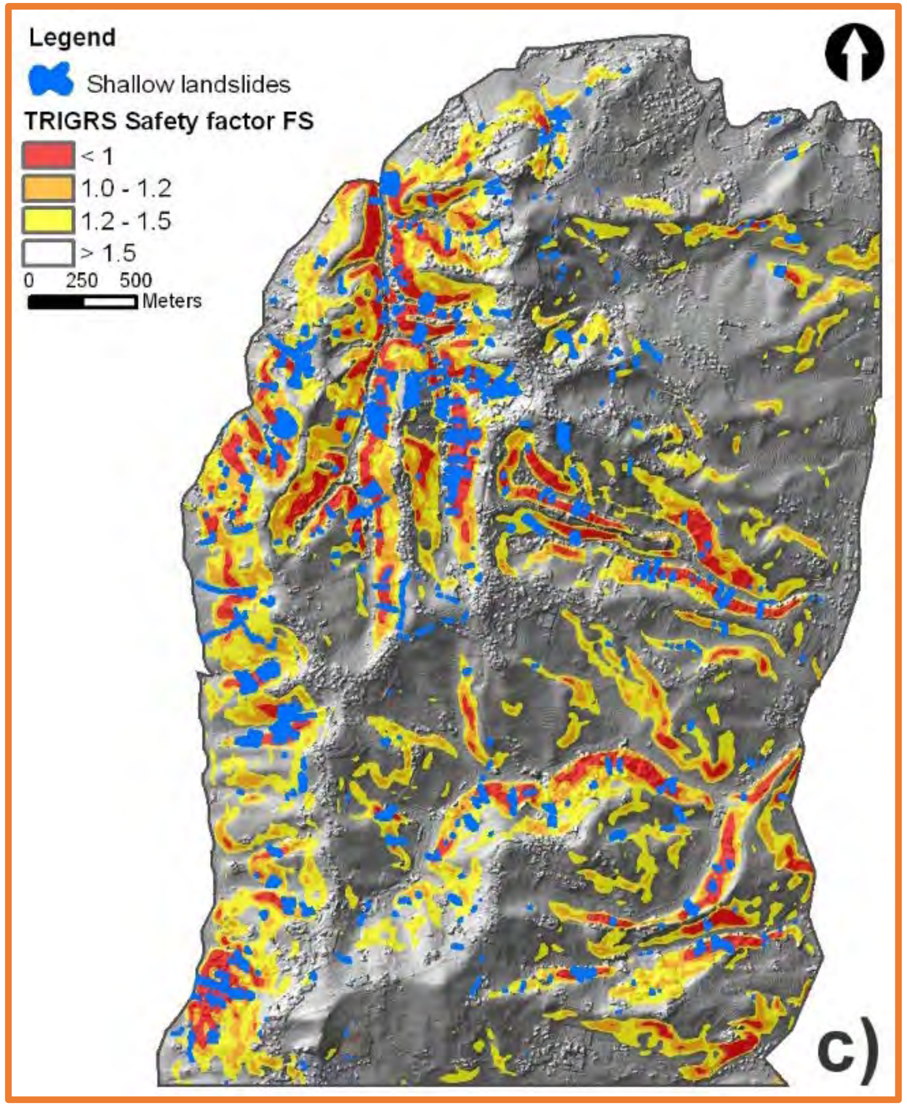
Fs map



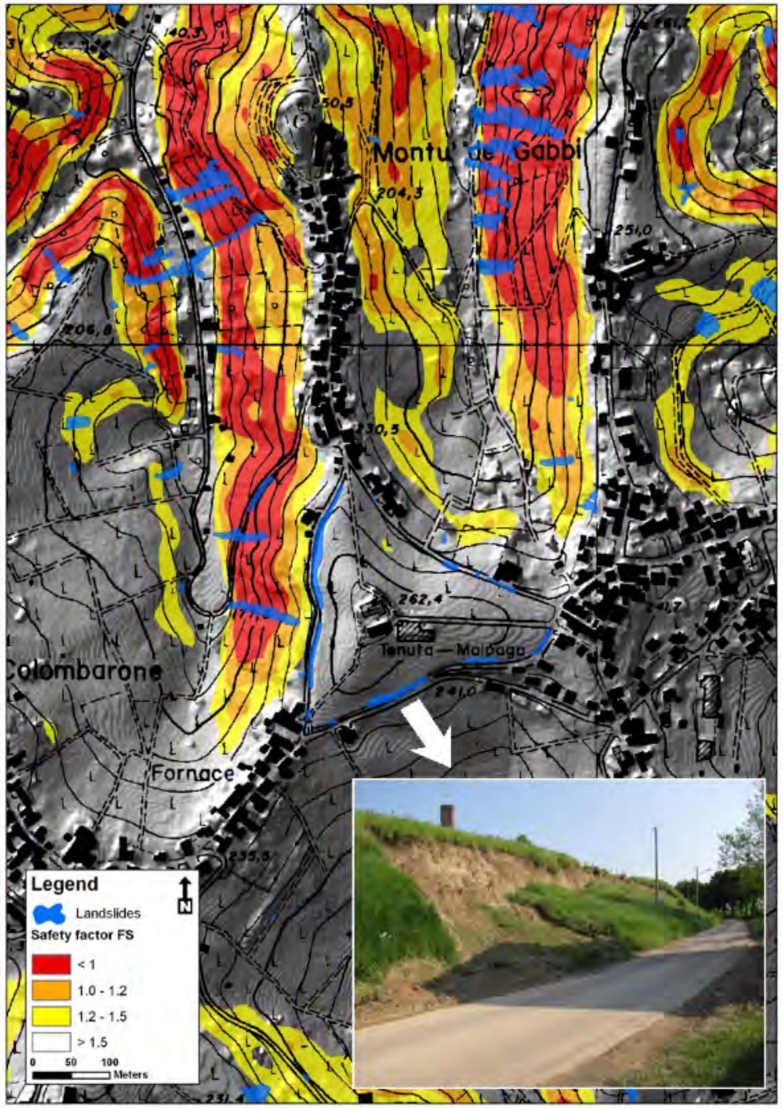
Case study in Italy: Oltrepò Pavese, April 2009

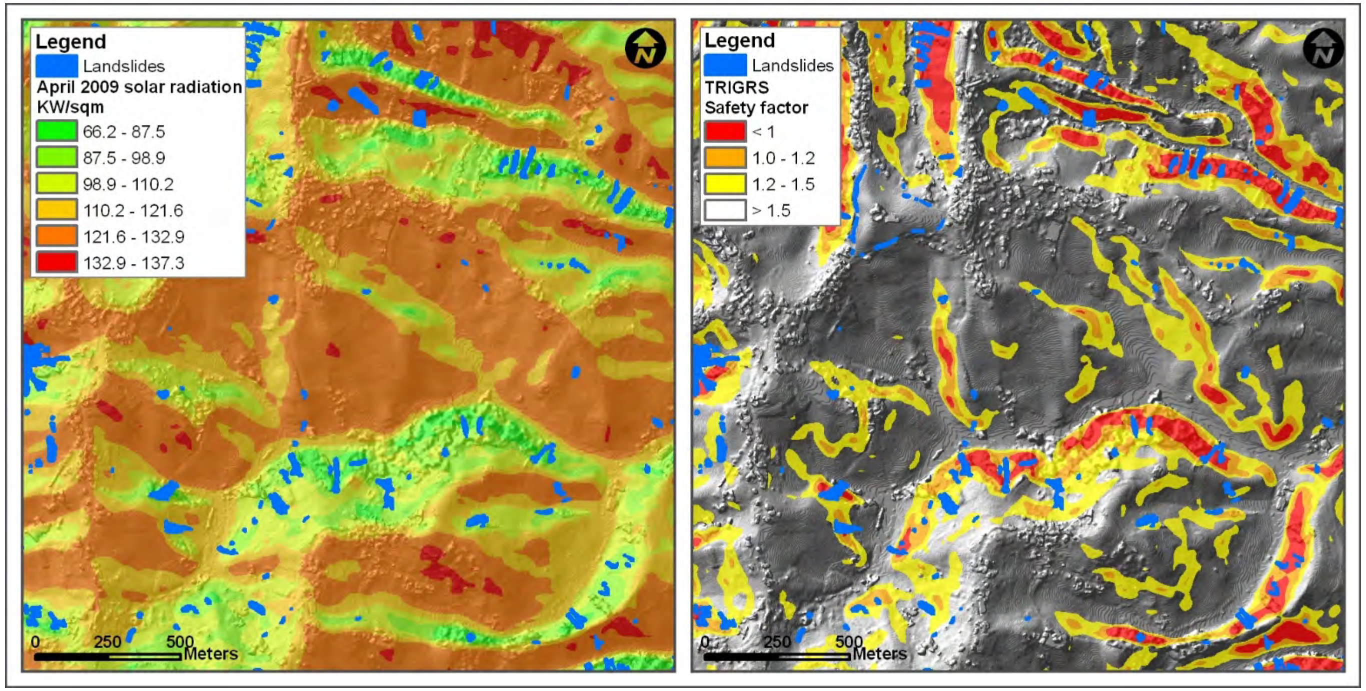






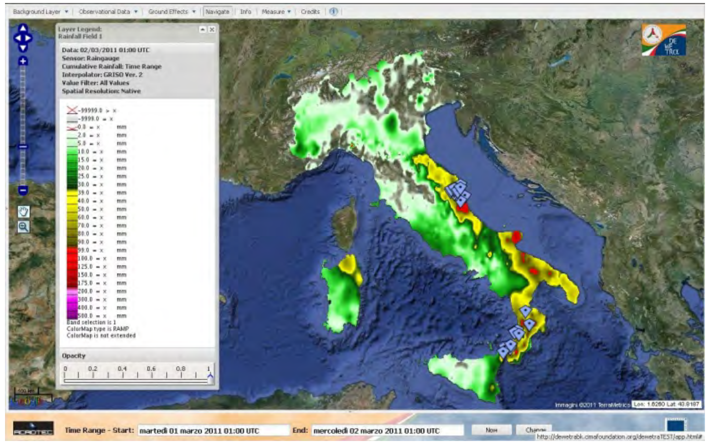
Case study in Italy: Oltrepò Pavese, April 2009





SLIP model at national scale in Italy

Rainfall map



Geospatial data

SLIP model

Safety Factor (F_s) on elementary cells 20m x 20m

DEWETRA

reference operative system aimed to prevent, detect and mitigate potential weather related risks

NATIONAL CIVIL PROTECTION CENTRE

INSTABILITY INDEX

Ratio between number of elementary cells having Fs≤1 and total cells on areas 1km x 1km

ALERT LEVELS

Low

Ordinary

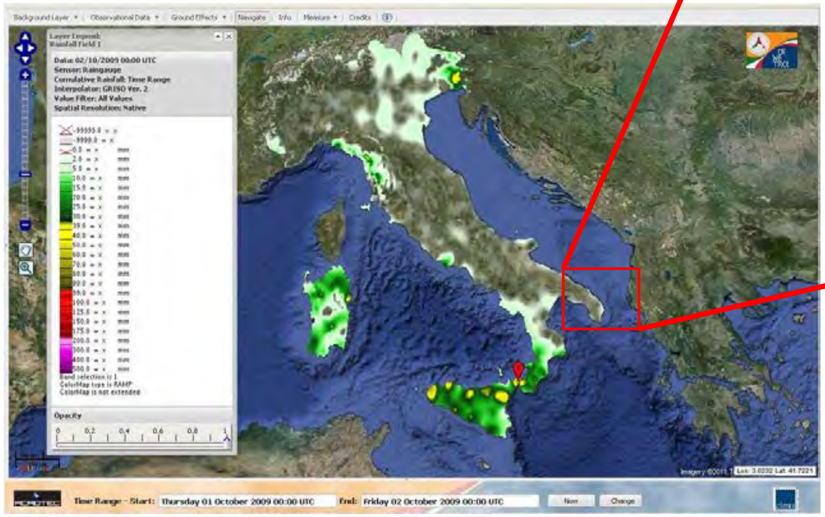
Moderate

High

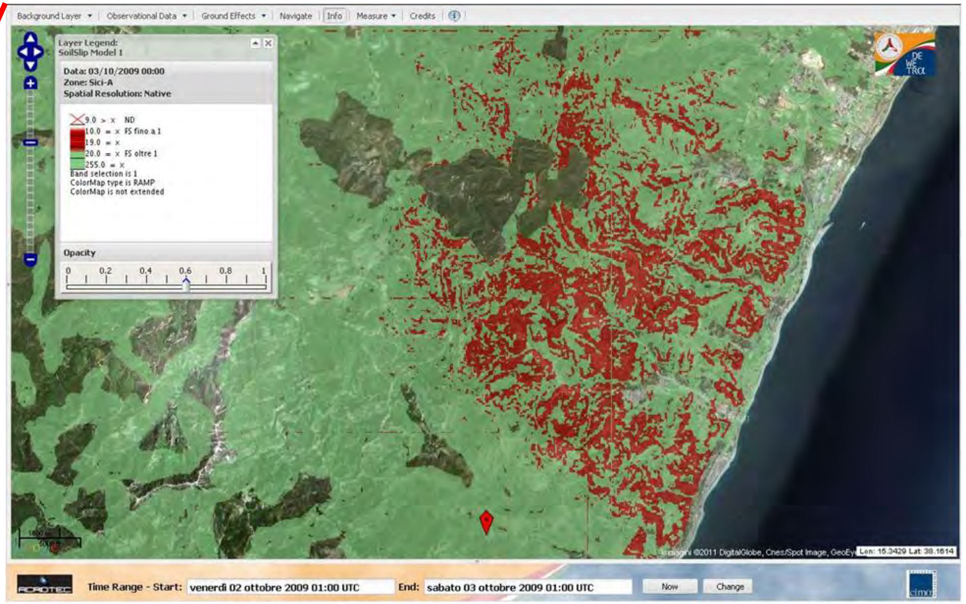
SLIP model at national scale in Italy

Event occurred at Giampilieri (ME) on the 1st of October 2009 (37 victims)

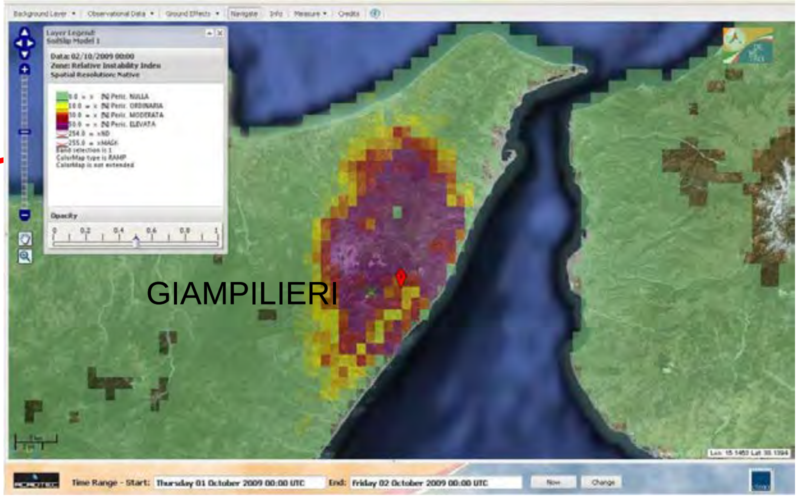
Rainfall map



F_s map (20m x 20m)



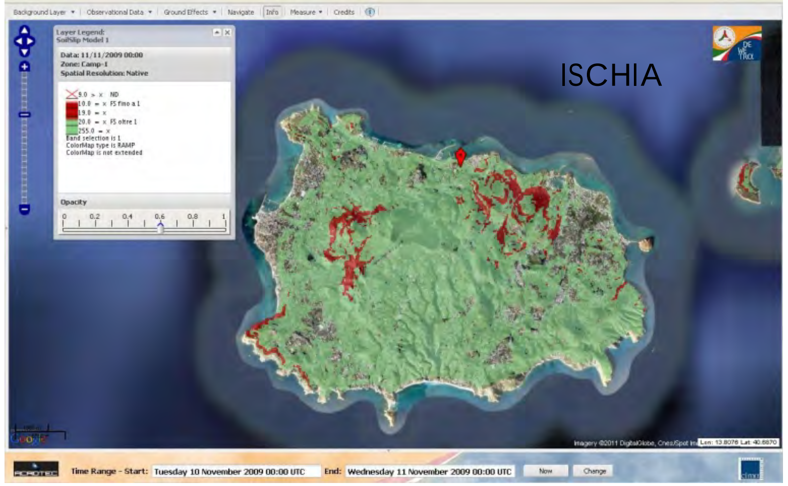
Instability index



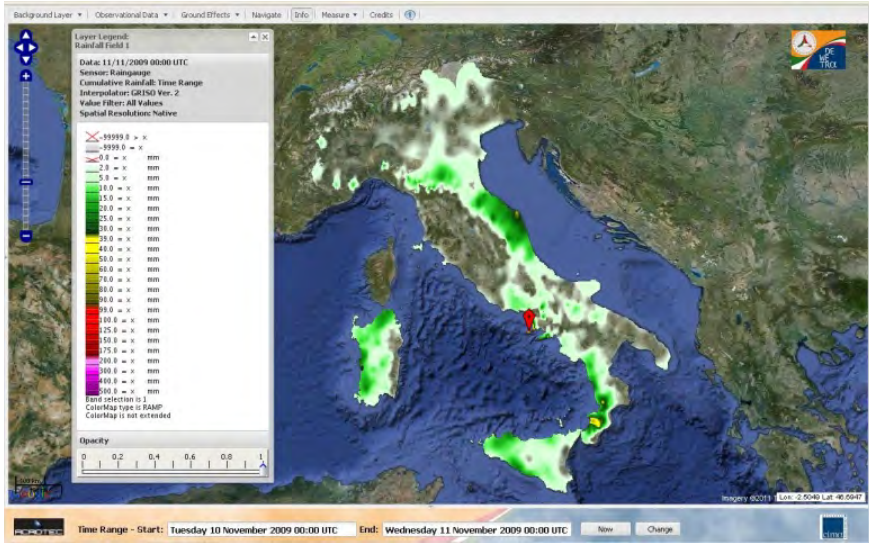
SLIP model at national scale in Italy

Event occurred at Casamicciola Terme (Isle of Ischia) on the 10th of November 2009 (1 victim)

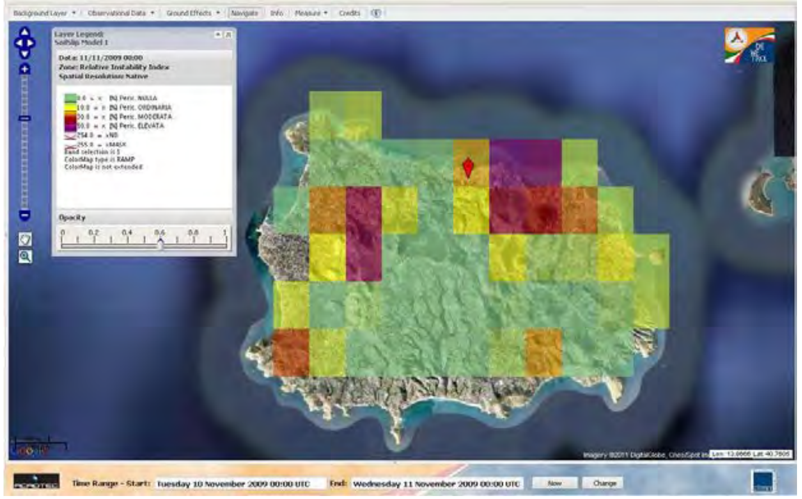
F_s map (20m x 20m)



Rainfall map



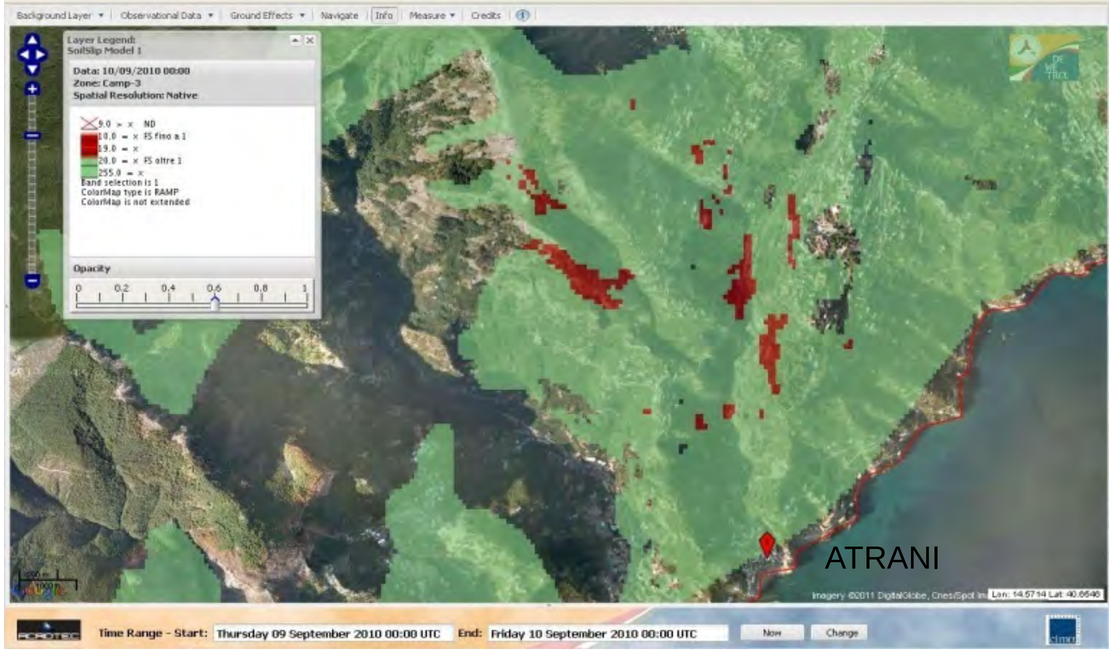
Instability index (1km x 1km)



SLIP model at national scale in Italy

Event occurred at Atrani on 9th of September 2010 (1 victim)

F_s map (20m x 20m)

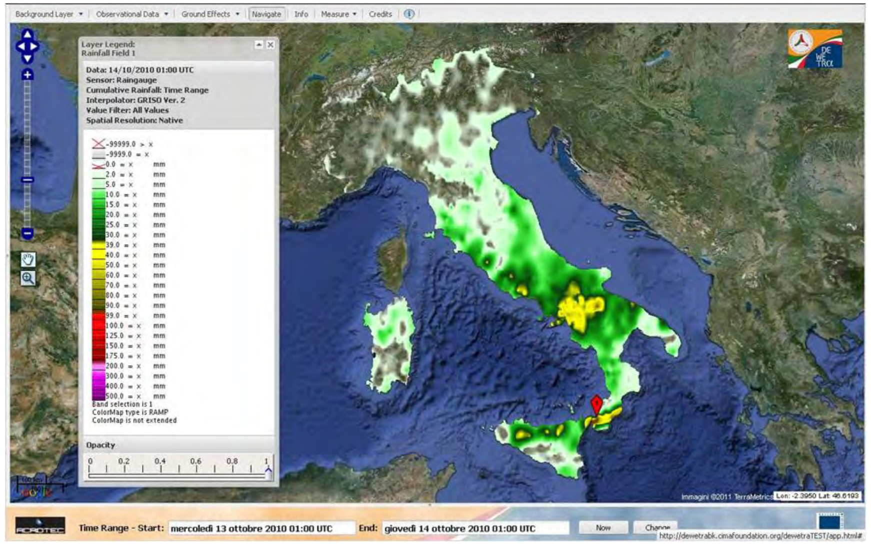


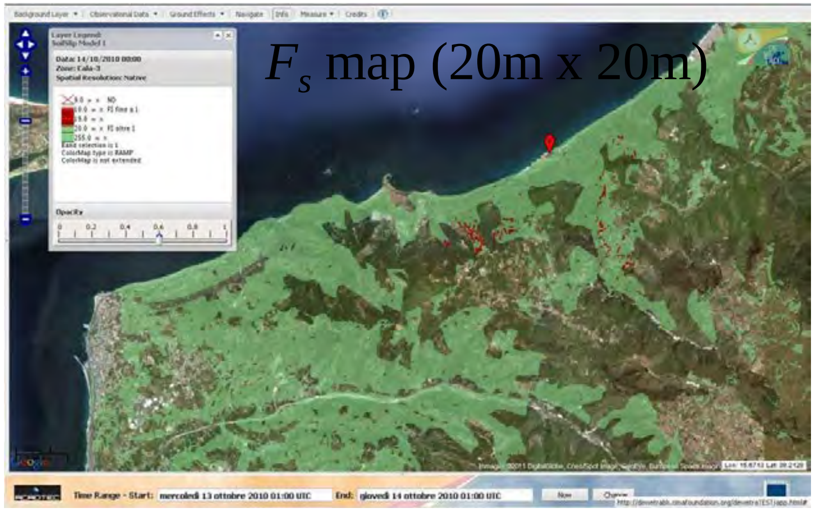
Zoom on the triggering areas

SLIP model at national scale in Italy

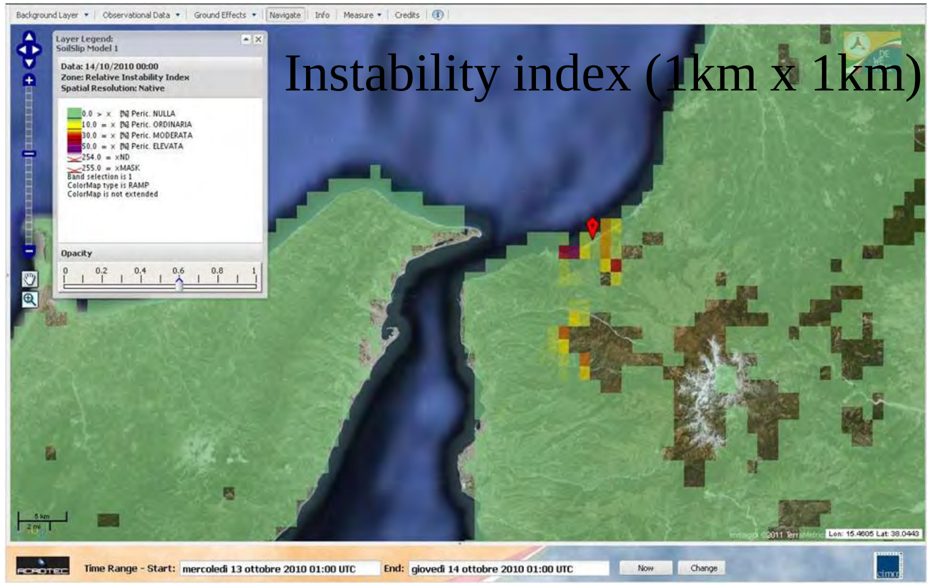
Event occurred at Reggio Calabria on the 13th of October 2010

Rainfall map





F_s map (20m x 20m)

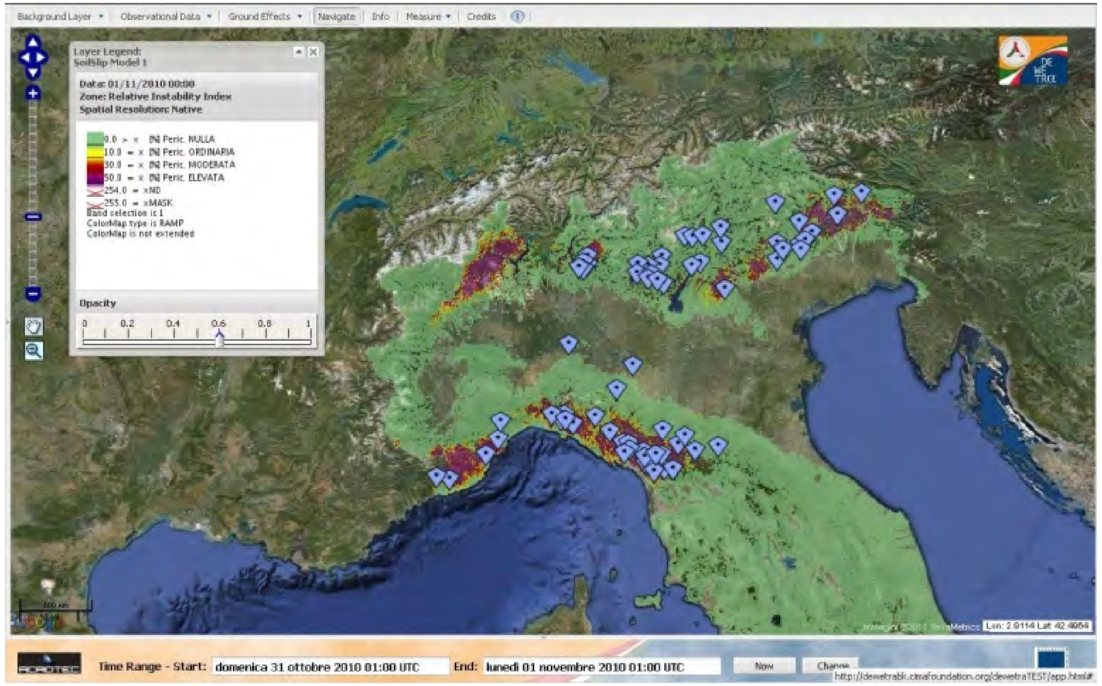


Instability index (1km x 1km)

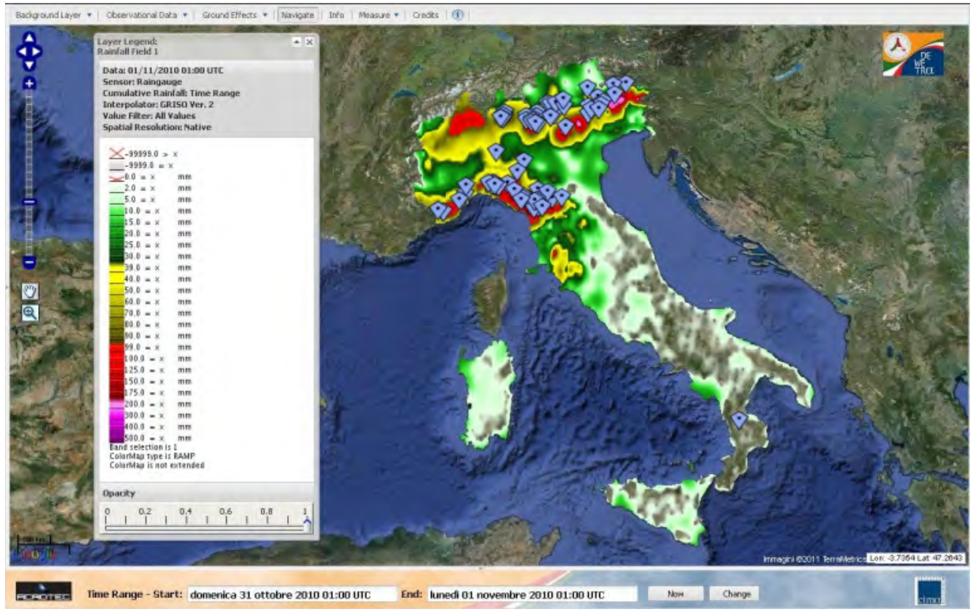
SLIP model at national scale in Italy

Event occurred in Northern Italy on the 31st of October 2010 (3 victims)

Map of instability index



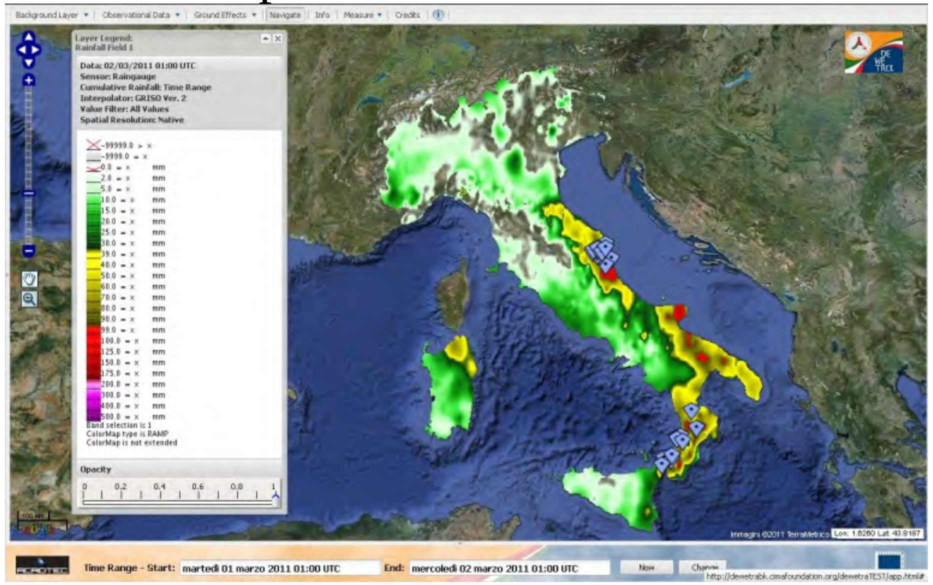
Rainfall map



SLIP model at national scale in Italy

Events occurred on the 1st of March 2011 in Marche and Calabria

Rainfall map



Instability index

Summary

LEM

- **SINGLE SLOPE SCALE**

GeoWizard
Geo-Engineering Programs

HYRCAN 2.0
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rocscience

- **LARGE SCALE**

  TRIGRS
  SHALSTAB
  SINMAP
  SLIP

Landslide inventory (+ MAP):

- Date (day/month/year)
- Position (on the map)
- Shape (edge as polygon on the map)/2D profile
- Type
- Type of material (rock of soil)
- New or re-activated
- Land use
- Damage
- Photo

Data collection:

✓ Soil/rock samples
✓ Lab tests for classification and mechanical characterization

THANK YOU