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Landslide Hazard Assessment Models at Regional Scale – *(SciNet NatHazPrev Project)*

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Activity 3.1:

Landslide Hazard Assessment (LHA) at a regional scale based on the adopted/ adapted methodology

Activity 3.4:

Slope stability analyses on natural and cut slopes in order to propose preventive measures.

Scales:

Regional (1:250,000 to 1:25,000)

Local (1:25,000 to 1:5,000)

Site – Specific (< 1:5,000)

As defined in SafeLand project (Corominas et al, 2013)

Susceptibility and Hazard Maps are often based on the following assumptions:

- *homogeneous geological conditions*
- *all slopes have the same probability of failure*
- *exact location of slope failure NOT required*
- *all landslides are of similar size*
- *runout distance is NOT calculated; NOR spatial distribution and intensity*

This could be improved! HOW??

By introducing STRUCTURAL information

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1. Landslide Susceptibility (static conditions) *according to FEMA method*

1. Geology (lithology per geologic group)
2. Slope angle (slope inclination)
3. Underground Water Table

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Table 1. Landslide susceptibility of geologic groups under static conditions (HazUS MH, Chapter 4 – PESH.) – FEMA method

Geologic Group		Slope Angle, degrees					
		0-10	10-15	15-20	20-30	30-40	>40
(a) DRY (groundwater below level of sliding)							
A	Strongly Cemented Rocks (crystalline rocks and well-cemented sandstone, c' =300 psf, ϕ' = 35°)	None	None	I	II	IV	VI
B	Weakly Cemented Rocks and Soils (sandy soils and poorly cemented sandstone, c' =0, ϕ' = 35°)	None	III	IV	V	VI	VII
C	Argillaceous Rocks (shales, clayey soil, existing landslides, poorly compacted fills, c' =0 ϕ' = 20°)	V	VI	VII	IX	IX	IX
(b) WET (groundwater level at ground surface)							
A	Strongly Cemented Rocks (crystalline rocks and well-cemented sandstone, c' =300 psf, ϕ' = 35°)	None	III	VI	VII	VIII	VIII
B	Weakly Cemented Rocks and Soils (sandy soils and poorly cemented sandstone, c' =0, ϕ' = 35°)	V	VIII	IX	IX	IX	X
C	Argillaceous Rocks (shales, clayey soil, existing landslides, poorly compacted fills, c' =0 ϕ' = 20°)	VII	IX	X	X	X	X

✓ **Steps to realize**

1. **classification of geologic group**
2. **slope angle**
3. **hydraulic conditions (dry / wet)**

Arbitrary scale

✓ **scale I:** less susceptible

✓ **scale X:** most susceptible

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2. Landslide Susceptibility (seismic conditions) *according to FEMA method*

1. Geology (lithology per geologic group)
2. Slope angle
3. Water table

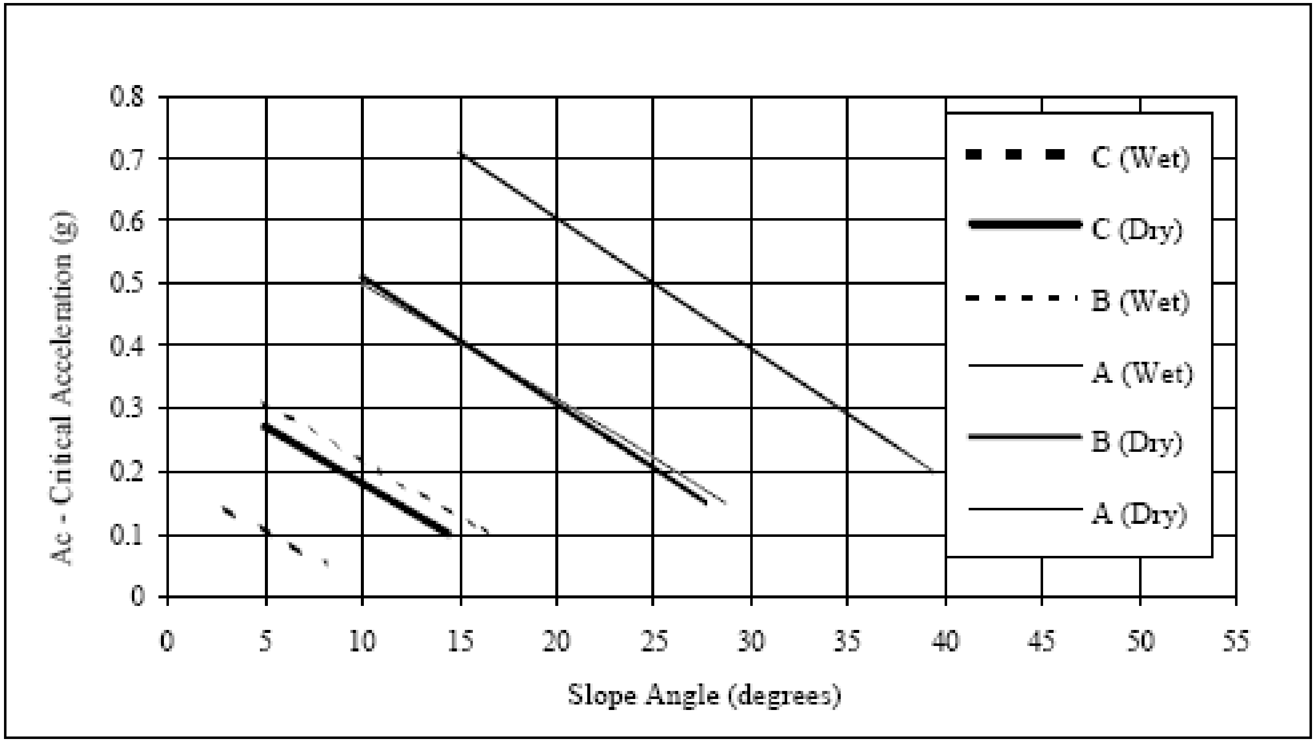
Already considered for static conditions !

Based on the principal of a Limit Equilibrium Method, an earthquake is considered as an horizontal force (seismic coefficient x weight of the potentially sliding mass of a slope)

4. **Critical Acceleration (A_c) defined as the horizontal acceleration that produces a FoS = 1.0**

Critical acceleration (A_C) is a complex function of **slope**, **geology**, **steepness**, **groundwater table**, **type of landsliding** & **history of previous slope performance**.

The Wilson and Keefer (1985) relationship is utilized in the method adopted herein.



Critical Acceleration as a Function of Geologic Group and Slope Angle (Wilson and Keefer, 1985).

Lower Bounds for Slope Angles and Critical Accelerations for Landsliding Susceptibility

Group	Slope Angle, degrees		Critical Acceleration (g)	
	Dry Conditions	Wet Conditions	Dry Conditions	Wet Conditions
A	15	10	0.20	0.15
B	10	5	0.15	0.10
C	5	3	0.10	0.05

Critical Accelerations (a_c) for Susceptibility Categories

Susceptibility Category	None	I	II	III	IV	V	VI	VII	VIII	IX	X
Critical Accelerations (g)	None	0.60	0.50	0.40	0.35	0.30	0.25	0.20	0.15	0.10	0.05

“Shallow” landslides susceptibility under seismic conditions

“Shallow” landslide susceptibility to earthquake-induced displacements, as specified by the index Ac/PGA

Based on what criterion?

Index A_C/PGA and a “subjective” categorization

- **Very high: < 0.3**
- **High: 0.3 – 0.6**
- **Moderate: 0.6 – 0.8**
- **Low: 0.8 – 1.0**
- **Very Low: 1.0 – 3.0**
- **None: > 3.0**

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Landslide Hazard Assessment

(regional scale)

• **Physically based landslide hazard** assessment methods are based on ***modeling of slope failure processes***

• Applicable over large areas if geological & geomorphological conditions are fairly homogeneous and landslide types relatively simple

• Applicable to areas with **incomplete or even non - existing landslide inventories**

• Most of them apply the **infinite slope model**, therefore they are applicable in the case of **shallow landslides**

• Also, a deterministic model for **plane or circular landslides** can be applied

• They account for different triggering parameters: **rainfall** and transcient groundwater response or to the effects of **earthquake excitation**

Major advantages:

- They can be easily implemented in a GIS framework
- Results are more concrete & consistent compared to other approaches
- Higher predictive capability and most suitable to quantify the influence of individual parameters contributing to shallow landslide initiation
- Based on slope stability models, they allow the calculation of quantitative values of stability (safety factor, probability of failure)

Some drawbacks:

- Parameterization can be a difficult task; access to critical parameters (soil depths, transient slope hydrological processes & temporal changes in hydraulic properties)
- Degree of simplification encountered / need for considerable amounts of reliable input data

Corominas et al., 2013

3. Landslide Hazard Assessment

(*under static & seismic conditions*)

Two (2) approaches for landslide hazard assessment are implemented:

- HazUS method proposed by FEMA adapted to Hellenic data **(triggering: earthquake)**,
- the factor of safety F_S computation method **(triggering: static/hydraulic conditions)**.

3. Landslide Hazard (static / hydraulic conditions) *according to the safety factor method (a)*

3.1 Infinite Slope Model

Factor of Safety Assessment:

$$FS = \frac{c'}{\gamma t \sin a} + \frac{\tan\varphi'}{\tan\alpha} - \frac{m\gamma_w \tan\varphi'}{\gamma \tan\alpha}$$

ϕ': effective angle of friction of geomaterial (^{0})

c’: effective cohesion of geomaterial (kPa),

γ: specific weight (kN/m^3),

a: slope angle (Deg),

γ_w: specific weight of the water (kN/m^3),

t: normal thickness of the failure slab (m)

m: percentage of the water saturated failure slab (%)

Infinite Slope Model

$$FS = \frac{c'}{\gamma t \sin a} + \frac{\tan \varphi'}{\tan \alpha} - \frac{m\gamma_w \tan \varphi'}{\gamma \tan \alpha}$$

Absolutely Necessary Data:

1. Geological maps of relevant scale (lithology per geologic group)
2. Topographic maps of relevant scale to define slope angle (a)

Necessary Data calculated or estimated:

3. Geotechnical parameters per geological formation/group **(φ’, c’, γ)**

- **IF geological formation is a ROCKMASS**, then Hoek and Brown failure criterion is used in order to establish two pairs of (φ’ & c’) for low and high normal stress (small slope and high slope). **GSI (Geological Strength Index) and uniaxial compressive strength** must be estimated according to rockmass lithology and the condition of the rockmass.

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H=5m

Analysis of Rock Strength using RocLab

Hoek-Brown Classification
intact uniaxial comp. strength (sigci) = 25 MPa
GSI = 32 mi = 8 Disturbance factor (D) = 1
intact modulus (Ei) = 16875 MPa
modulus ratio (MR) = 675

Hoek-Brown Criterion
mb = 0.062 s = 1.2e-5 a = 0.520

Mohr-Coulomb Fit
cohesion = 0.027 MPa friction angle = 34.17 deg

Rock Mass Parameters
tensile strength = -0.005 MPa
uniaxial compressive strength = 0.069 MPa
global strength = 0.723 MPa
deformation modulus = 503.42 MPa

http://www.rocscience.com

c' = 27kPa

φ' = 22^{0}

H=30m

Analysis of Rock Strength using RocLab

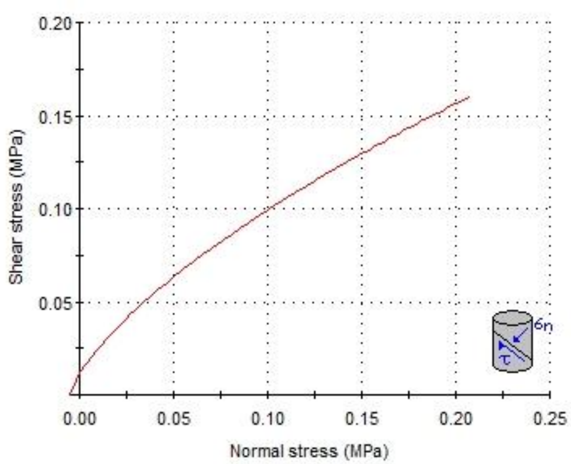
Hoek-Brown Classification
intact uniaxial comp. strength (sigci) = 25 MPa
GSI = 32 mi = 8 Disturbance factor (D) = 1
intact modulus (Ei) = 16875 MPa
modulus ratio (MR) = 675

Hoek-Brown Criterion
mb = 0.062 s = 1.2e-5 a = 0.520

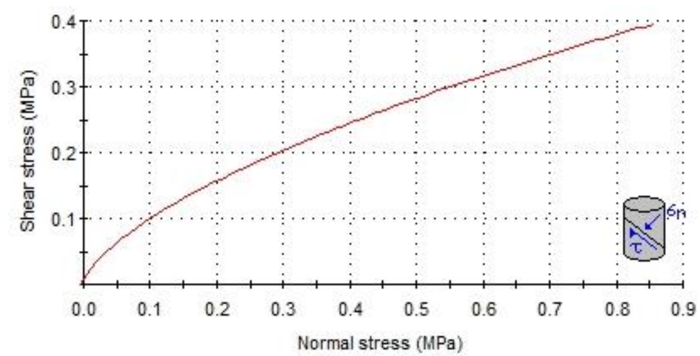
Mohr-Coulomb Fit
cohesion = 0.072 MPa friction angle = 21.91 deg

Rock Mass Parameters
tensile strength = -0.005 MPa
uniaxial compressive strength = 0.069 MPa
global strength = 0.723 MPa
deformation modulus = 503.42 MPa

http://www.rocscience.com



A reliable freeware software **"RocLab"**



3. Geotechnical parameters per geological formation/group **(φ', c', γ)**

- **IF geological formation is a SOIL**, then according to the geological description (see geological maps) values of φ', c' and γ can be attributed according to international bibliography and our experiece.

No matter if **SOIL** or **ROCKMASS** is encountered, geotechnical parameters should be estimated or calculated in a relatively conservative way.

Data estimated : deterministic or parametric way

4. Level of ground water table (if possible)

Most difficult parameters to estimate ?

t: normal thickness of the failure slab (meters)

m: percentage of saturation of the failure slab (%)

Normal thickness of failure slab (t) is determined as a function of slope angle, in order to calculate the factor of safety.

More effort is needed on this issue!

3. Landslide Hazard (static / hydraulic conditions)

according to the safety factor method (b)

3.2 Deterministic Model for Circular Landslides

Factor of Safety Assessment:

$$F_S = 4.32 * \left[\frac{c'}{\gamma * H * \sin\beta} \right] + 1.22 * (1 - r_u) * \frac{\tan\phi'}{\tan\beta} + 0.005$$

ϕ': effective angle of friction of geomaterial (^{0})

c’: effective cohesion of geomaterial (kPa),

γ: specific weight of geomaterial (kN/m^3),

β: slope angle (Deg),

γ_w: specific weight of the water (kN/m^3)

H : height of the slope (m)

r_u: pore pressure ratio (γ_w / γ)

Ferentinou et al., 2006

3. Landslide Hazard (seismic conditions)
according to FEMA method (c)

Assessment of Permanent Ground Displacements (PGD) of "shallow" landslides

$E[PGD] = E[d/A_{is}]*A_{is}*n$

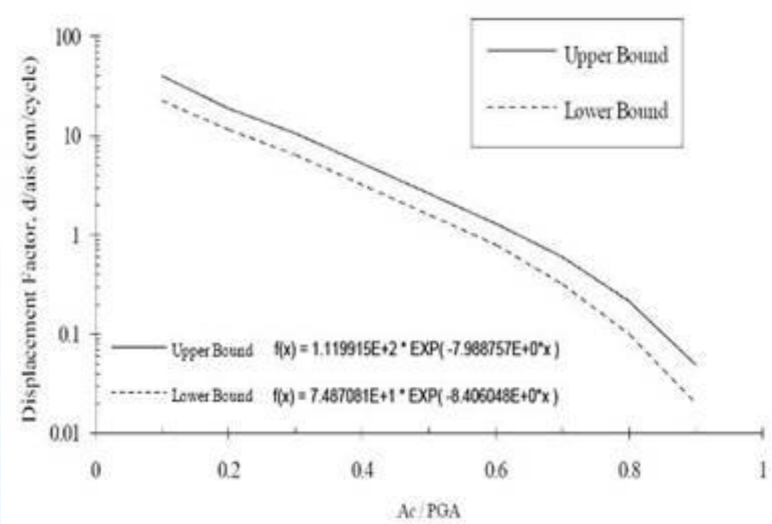
A_{is}: induced acceleration (g) – A_{is} = PGA

n: number of cycles (function of earthquake M_w)

$E[d/A_{is}]$: expected displacement factor

$n = 0.3419M_w^3 – 5.5214M_w^2 + 33.6154M_w – 70.7692$

E[d/Ais]:



A_C / PGA

Local GMPEs (Skarlatoudis et al., 2003)

$$\log PGA = 1.07 + 0.45M - 1.35 \times \ln(R + 6) + 0.09F + 0.06S \pm 0.286$$

$$\log PGA = 0.86 + 0.45M - 1.27 \times \ln(R^2 + h^2)^{\frac{1}{2}} + 0.10F + 0.06S \pm 0.286$$

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An implementation (regional scale)

Infinite Slope Model

$$FS = \frac{c'}{\gamma t \sin a} + \frac{\tan \varphi'}{\tan \alpha} - \frac{m\gamma_w \tan \varphi'}{\gamma \tan \alpha}$$

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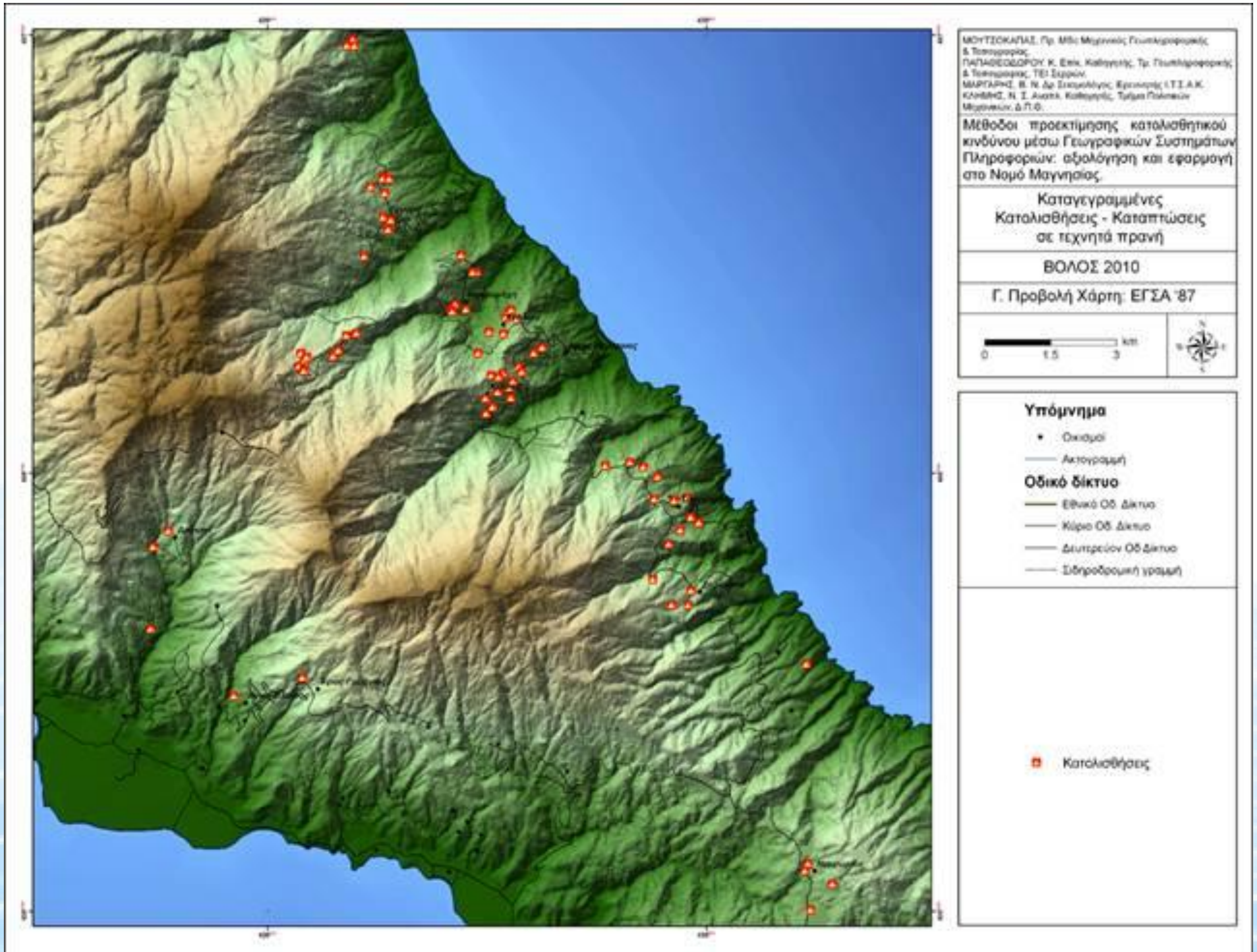
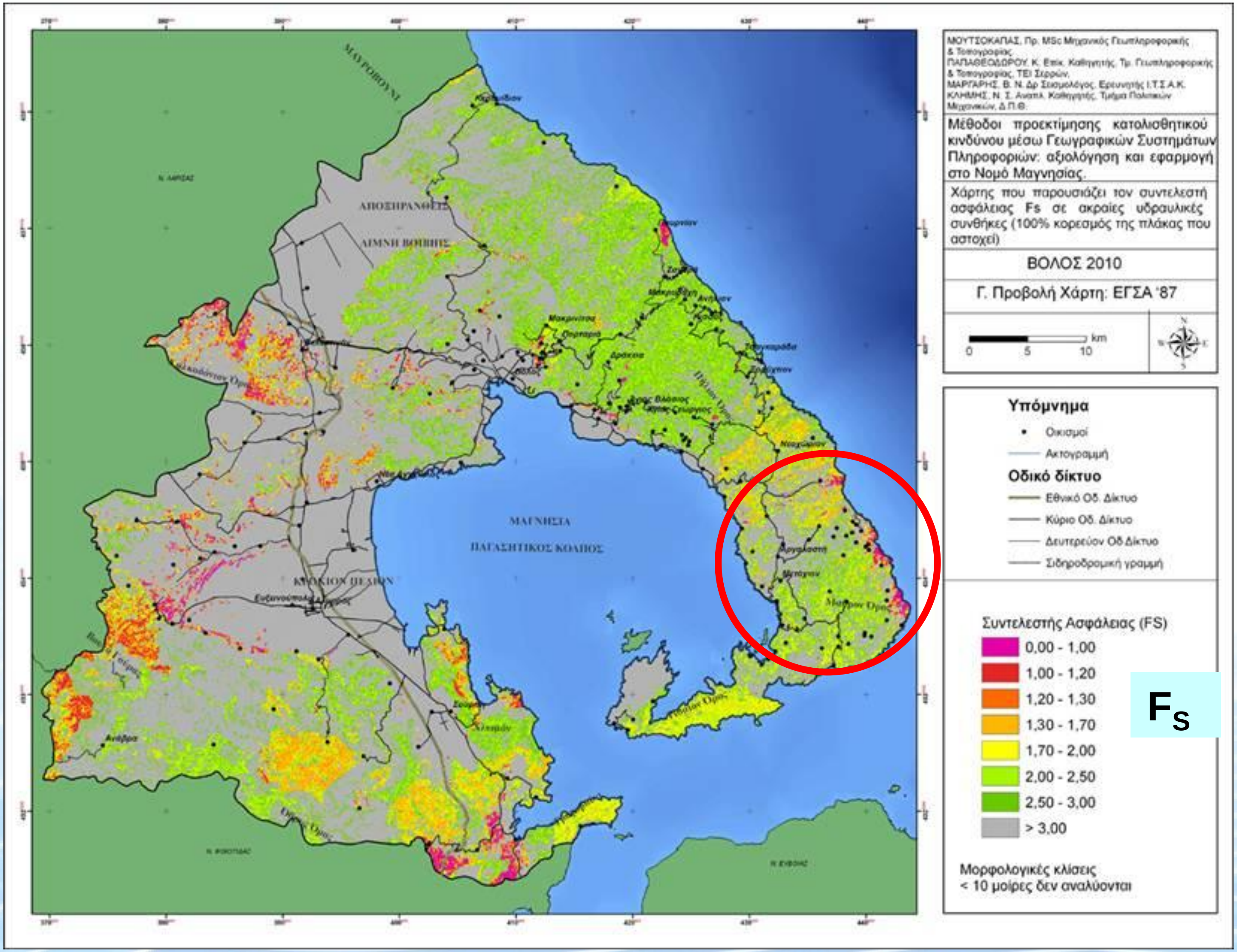


Inventory of

Landslides that occurred on cut slopes (v:h=2:1)

Scale: 1:50,000

Magnesia Prefecture



F_S

Thematic Map

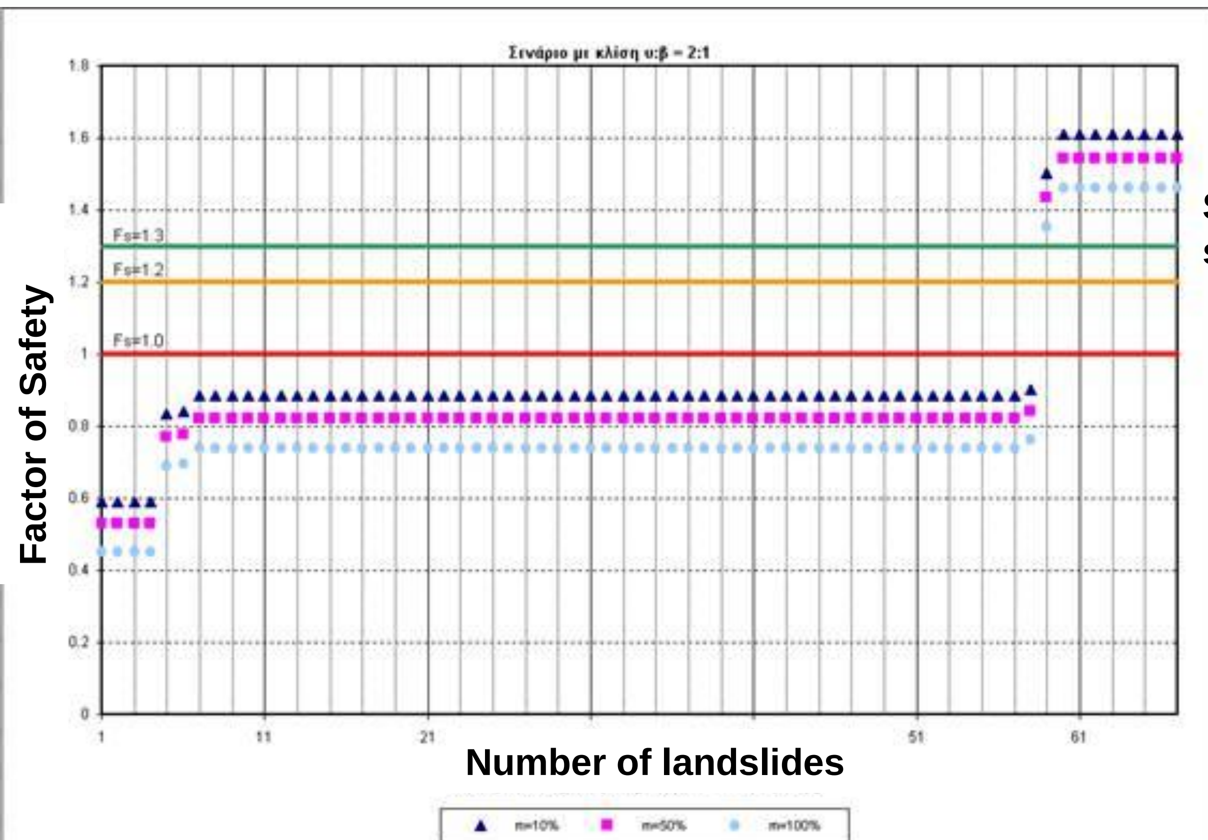
Scale: 1:50,000

Safety Factor

based on the infinite slope model

Landslide Hazard (static / hydraulic conditions) *according to the safety factor method in 67 locations where landslides occurred in cut slopes (vertical:horizontal = 2:1)*

The above method, albeit crude, reached a percentage of almost 85% success.



Parametric investigation regarding saturation (m, %) of the sliding slab.

Slope-normal thickness of the failure slab (t) correlated to the slope angle (º).

Slope angle (º)	Slab normal thickness (t)
90º – 80º	t=0.0m
80º – 70º	t=1.0m
70º – 60º	t=1.5m
60º – 50º	t=2.0m
50º – 40º	t=2,5m
40º – 30º	t=4,0m
30º – 0º	t=10m

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So, in order to CONCLUDE !!!

Landslide Susceptibility Regional Scale 1:250,000 to 1:25,000 *(static & seismic conditions)*

***FEMA method (for static conditions:* geologic maps + topography maps + hydraulic conditions) BUT needs improvement (introducing structure of soils/rocks: dip & dip direction of bedding, schistosity, interface of weathered zone and rockmass or soil over rockmass)**

***FEMA method (for seismic conditions:* geologic maps + topography maps + hydraulic conditions) + Critical Acceleration: index A_C / PGA seems to work fine with local GMPEs and “shallow” landslides**

Landslide Hazard Assessment Regional Scale 1:250,000 to 1:25,000 *(static & seismic conditions)*:

1. ***Factor of Safety method (for static conditions: geologic maps + topography maps + hydraulic conditions (% of sliding slab saturation) + geotechnical parameters (φ', c') + sliding slab normal thickness) seems to work fine for "shallow" landslides, BUT needs some improvement (regarding assessment of sliding slab thickness)***

2. ***FEMA method (for seismic conditions: geologic maps + topography maps + hydraulic conditions) + Critical Acceleration: index A_C / PGA resulting in assessment of Permanent Ground Displacements seems to work fine with local GMPEs and for "shallow type" landslides***

Activity 3.4:

Slope stability analyses on natural and cut slopes in order to propose preventive measures.

Need for site - specific scale on a scale < 1:5,000 *(static & seismic conditions)*:

Need for a user friendly software for slope analysis:

- **freeware (if possible)**
- **easy to use and understand**
- **reliable**

There is something like that under preparation

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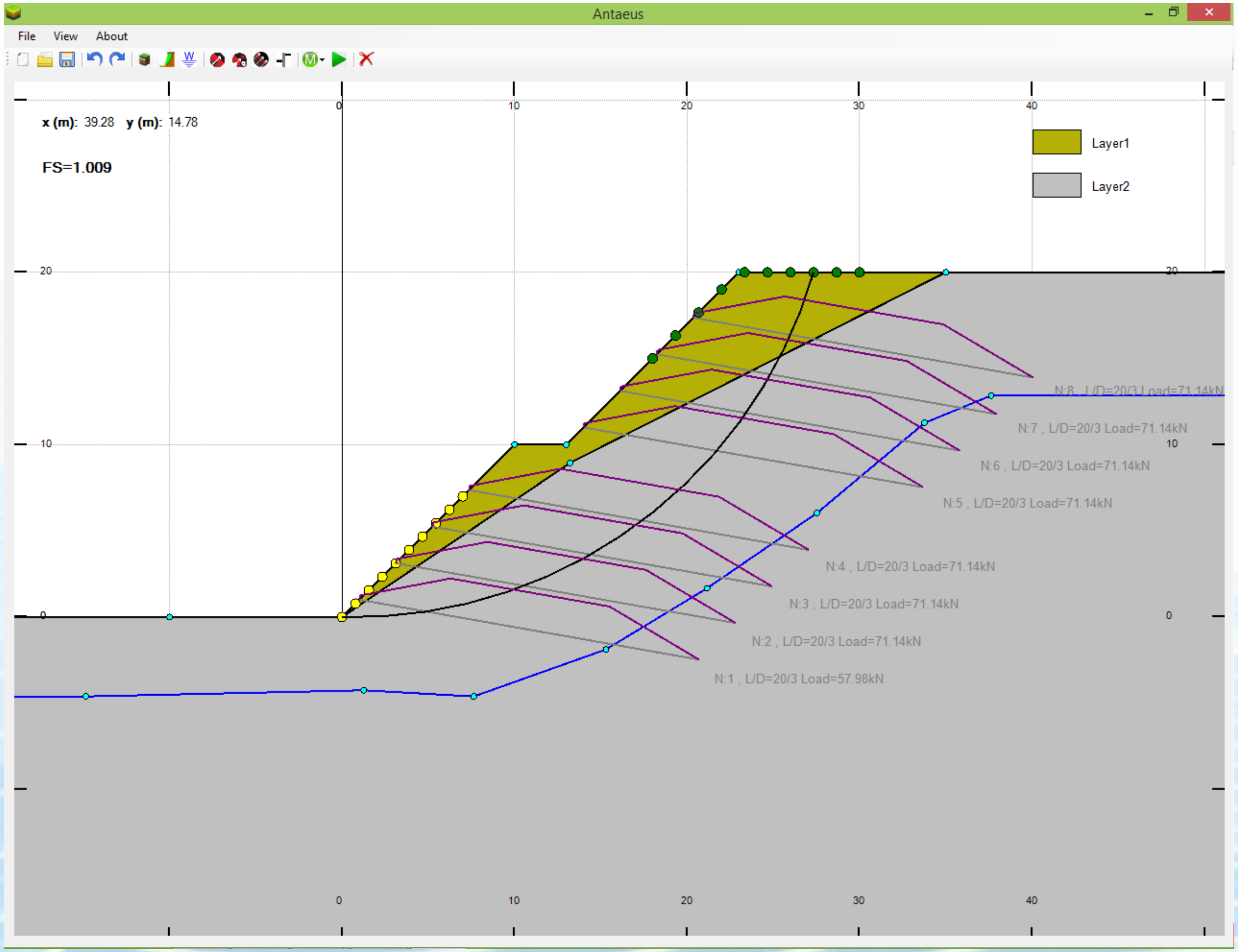

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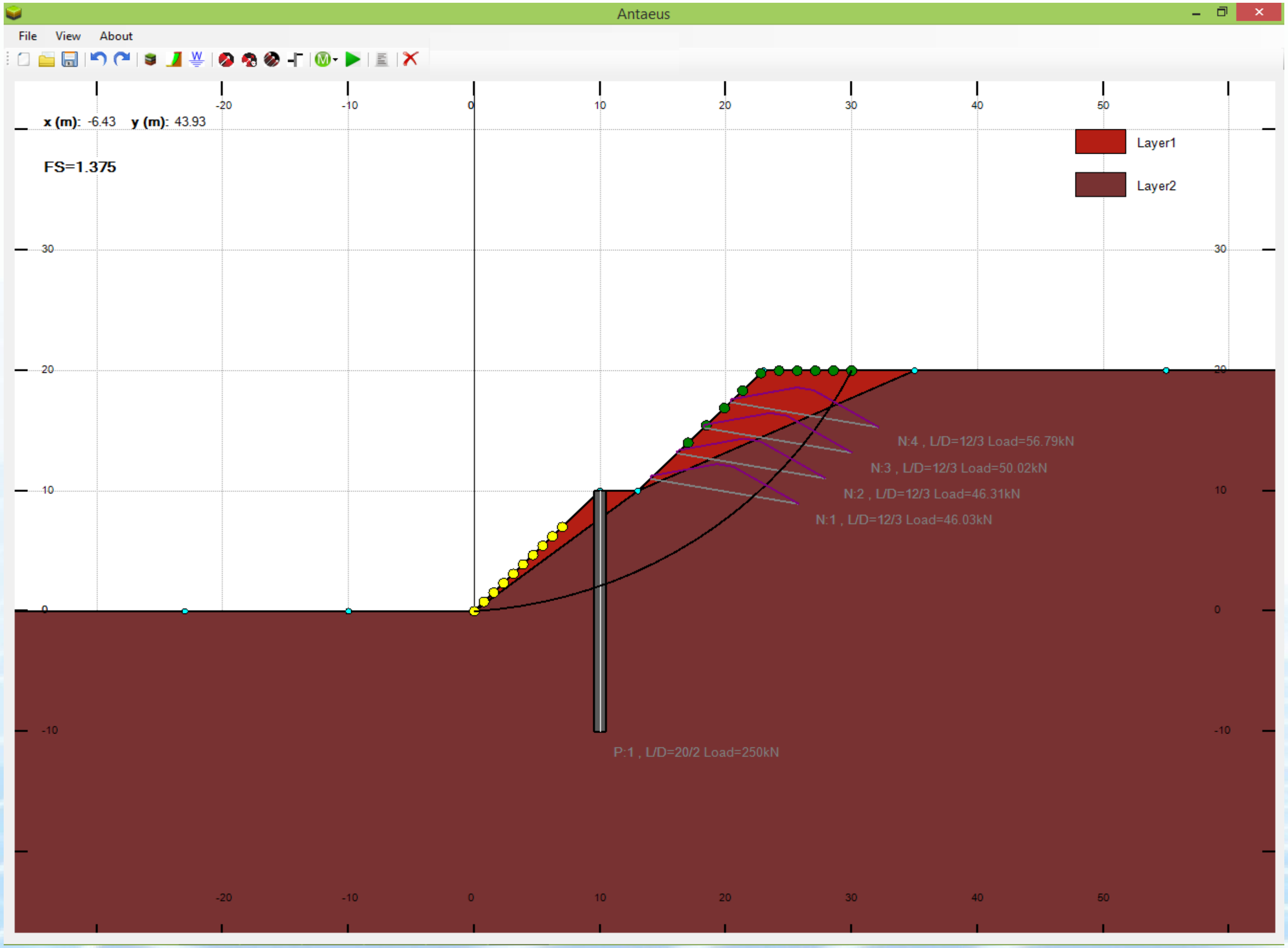

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Thank you !