Advanced 2D Slope Stability Analysis by LEM with SSAP software

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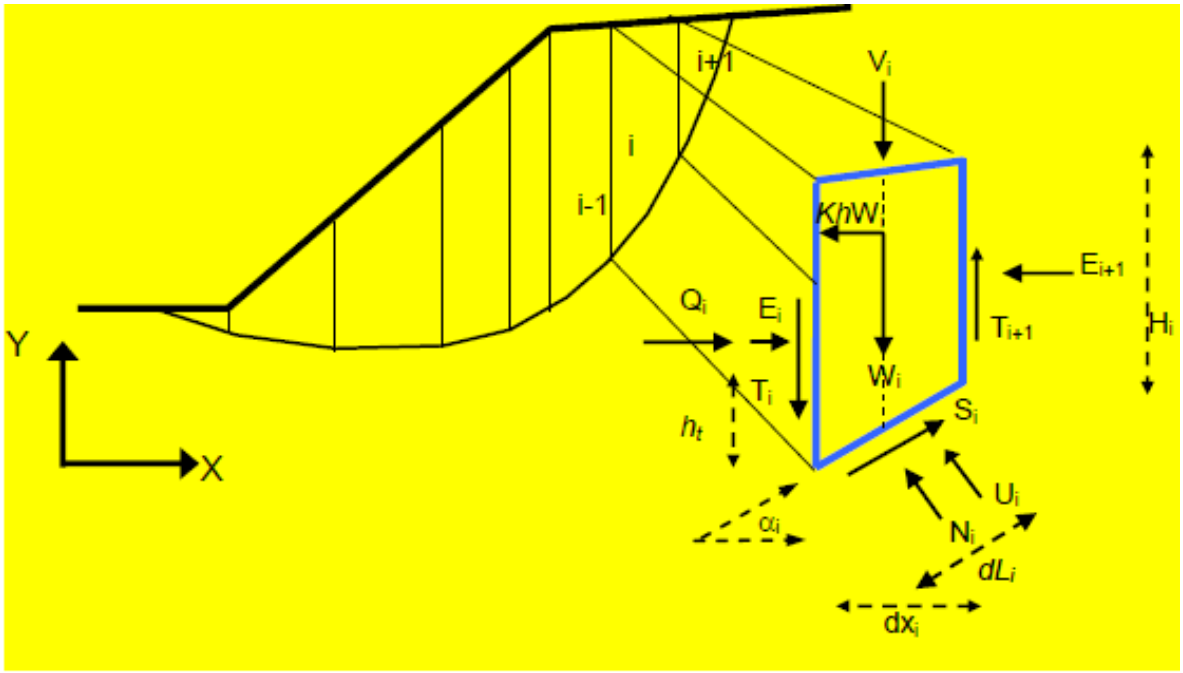
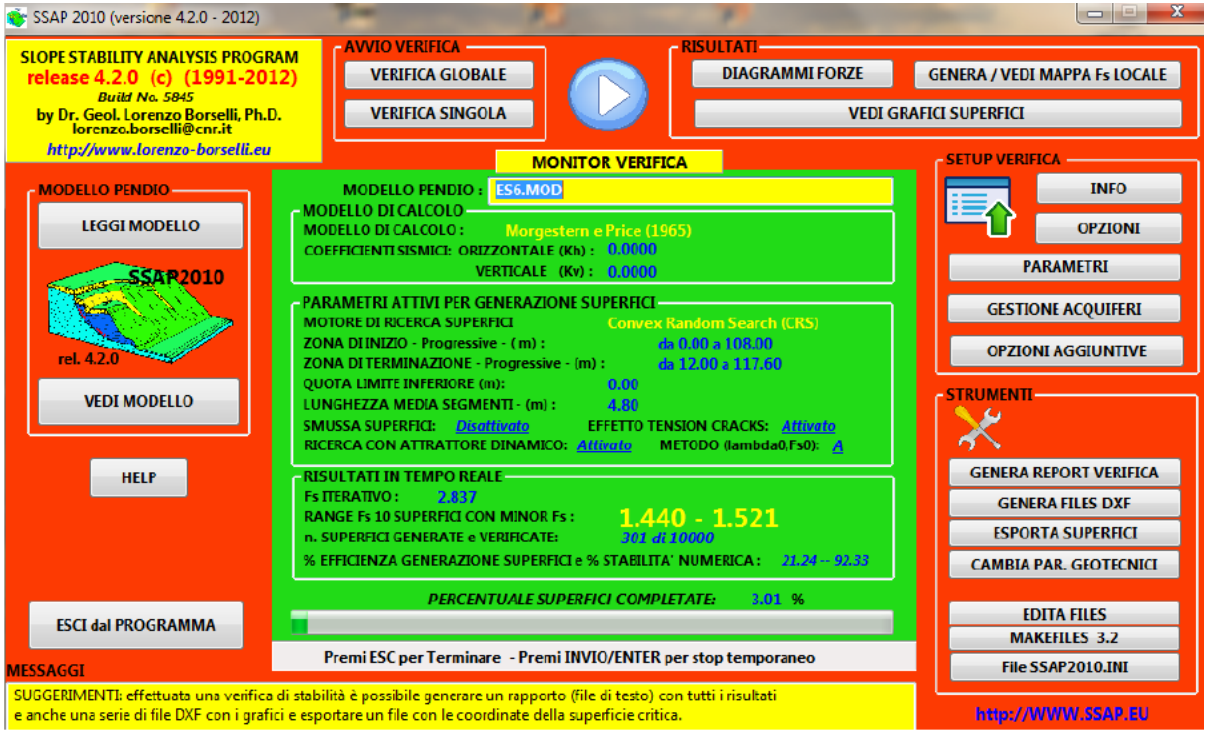
DEFINITION

The **Limit Equilibrium Method** (LEM) is a well known computational methodology for evaluating **Factor of Safety** (FOS) and stability degree of natural (or reinforced) slopes (Duncan, 1996, Krahn 2003).



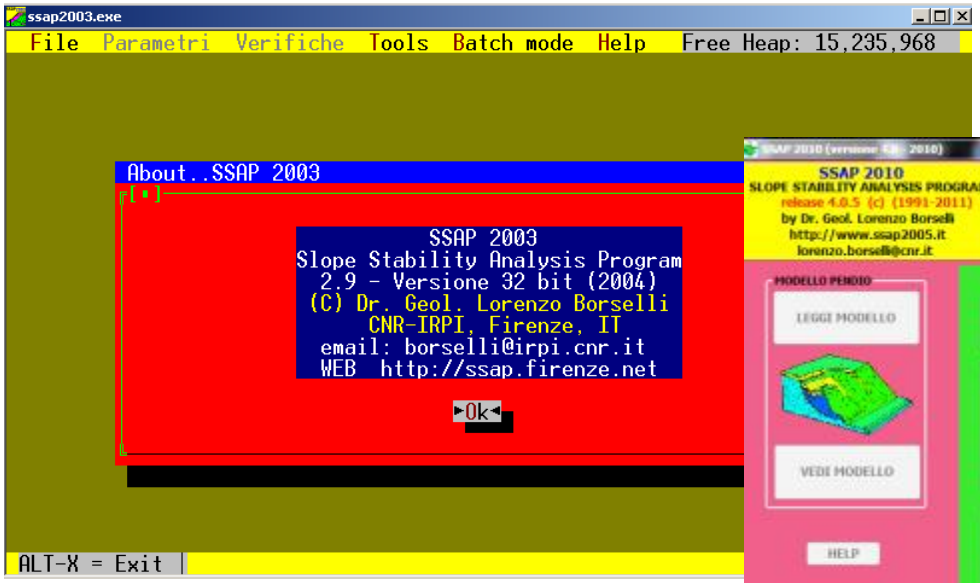
SSAP PROGRAM

The **Slope Stability Analysis Program** (SSAP version 4.2.1, 2013), is the first full freeware application for LEM implementing a series of characteristics usually available today only in commercial software.



HISTORY

SSAP has been developed during 21 years (1991-2012). All computational procedures have been developed starting from published paper on LEM and from original developments by the author.

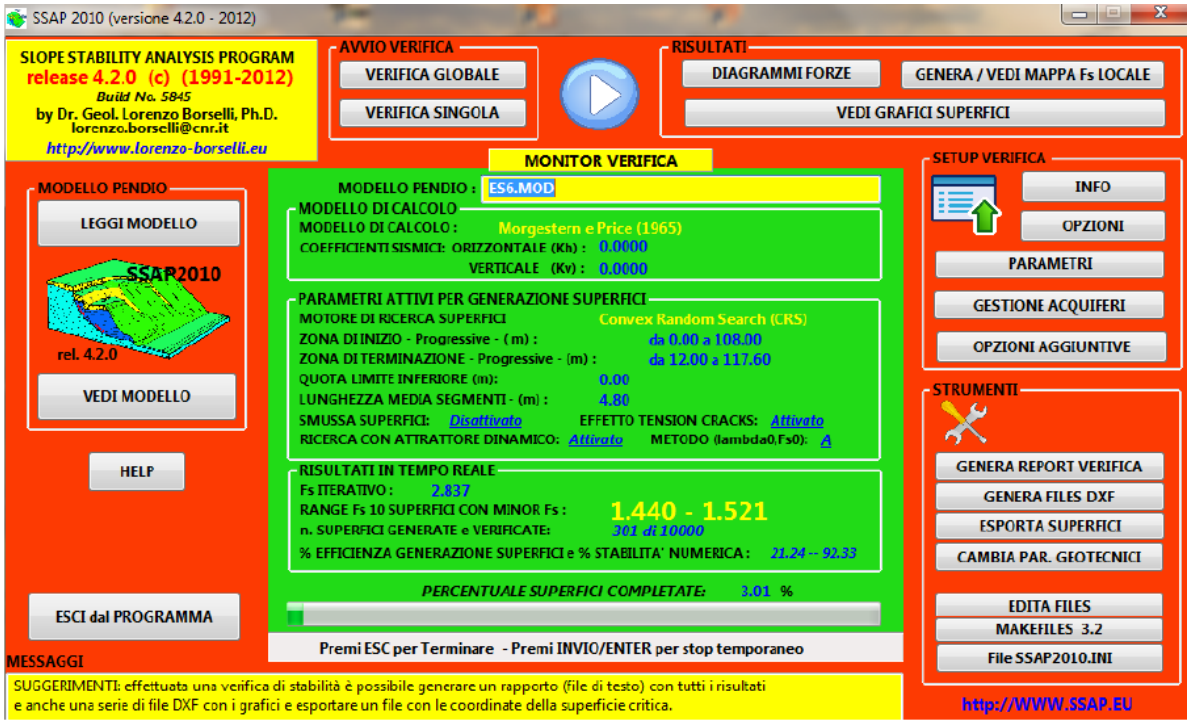


SSAP 2003

SSAP 2010 (rel. 4.0, 2010)

HISTORY

Current SSAP release (4.2.1, 2013) contains many new tools and original algorithms in order to obtain more reliable FOS values and using a more general approach to LEM with respect to the past.



SSAP 2010
(rel. 4.2, 2012)

SSAP WEB PAGE

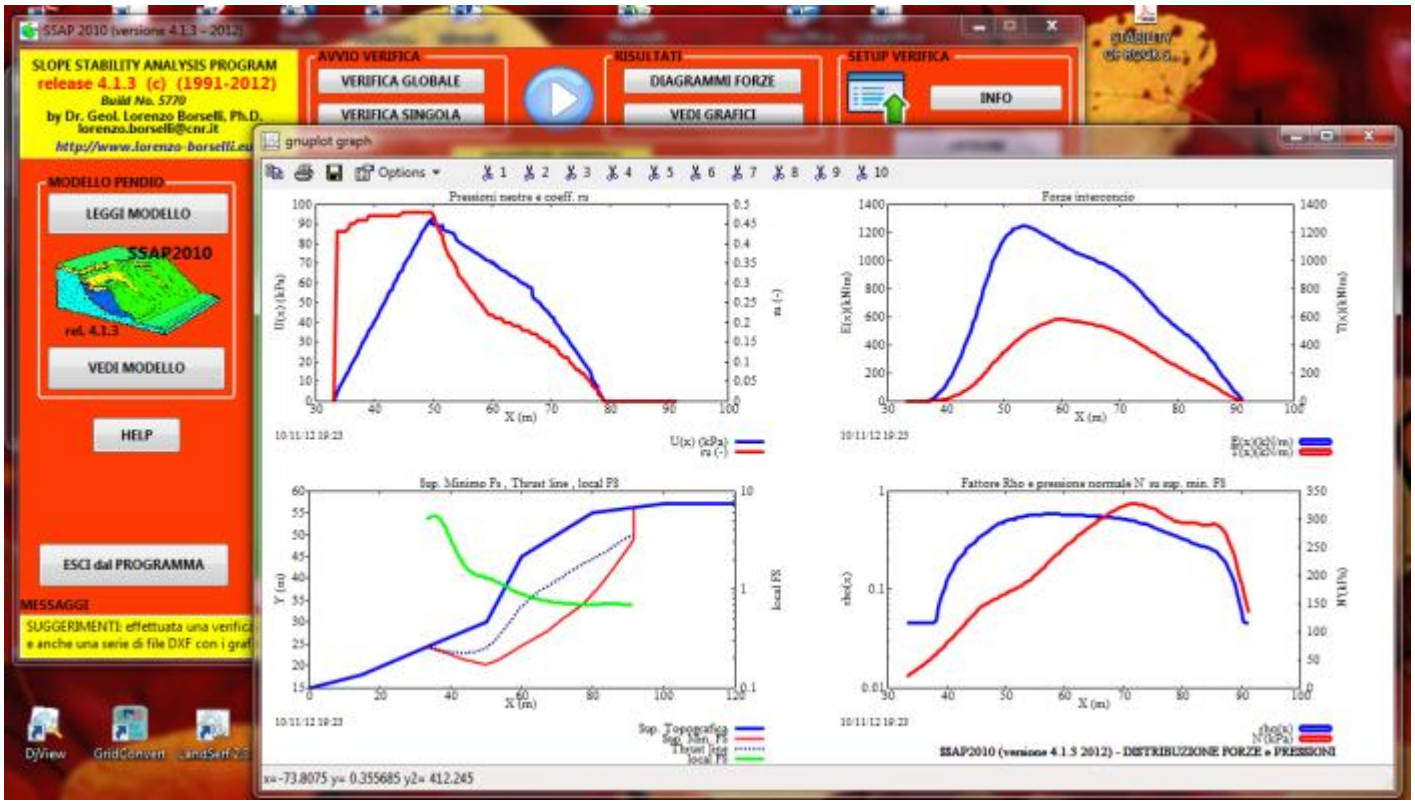
www.ssap.eu is the official web page of SSAP 2010, version 4.2.1. A translation of the software and the manual in English and Spanish languages is in progress.

GRAPHICAL INTERFACE

SSAP Interface with MAIN and OPTIONS windows.

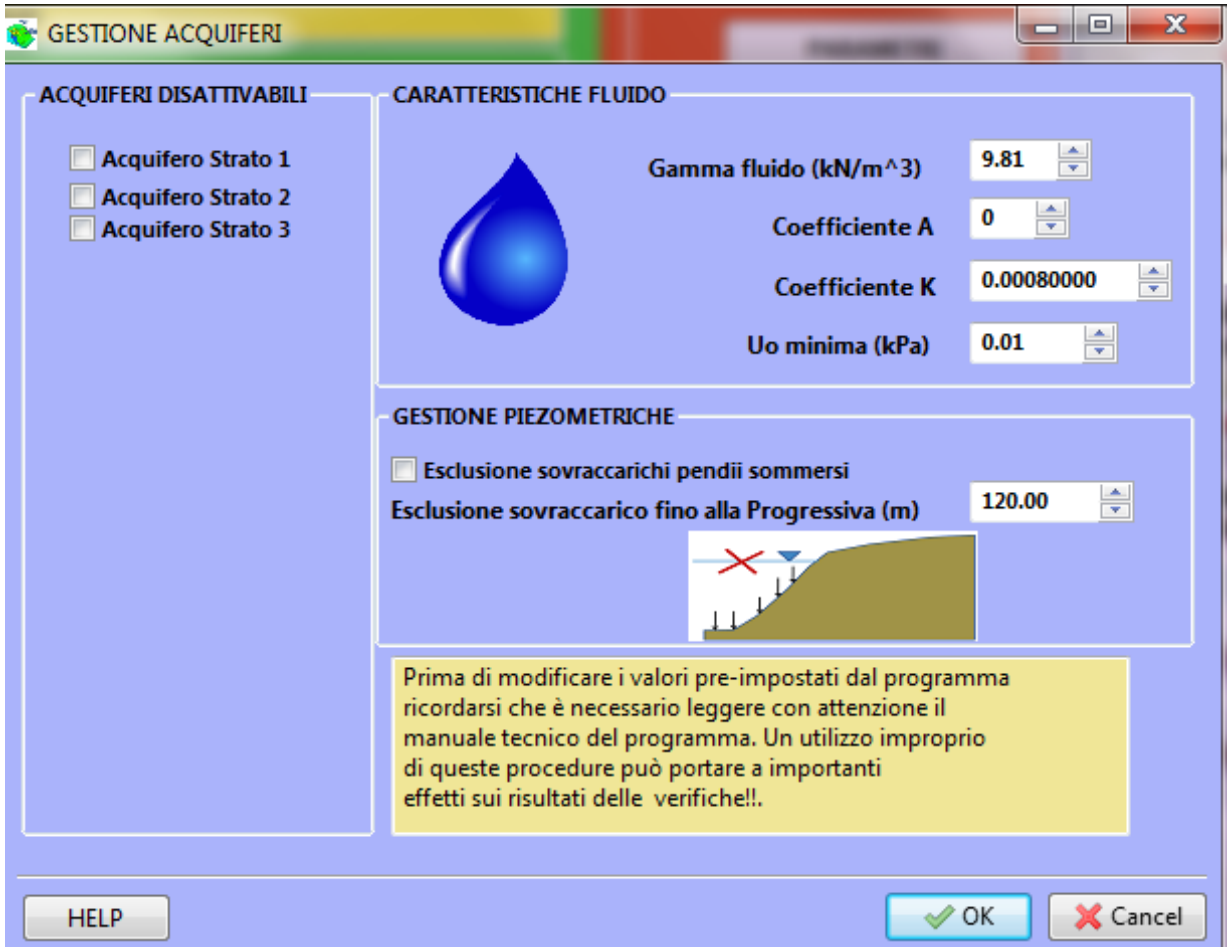
GRAPHICAL INTERFACE

Internal distribution of forces and pressures in SSAP 4.2.1 - 2013 (graphic rendering by integrated GNUPLOT 4.6, www.gnuplot.info).



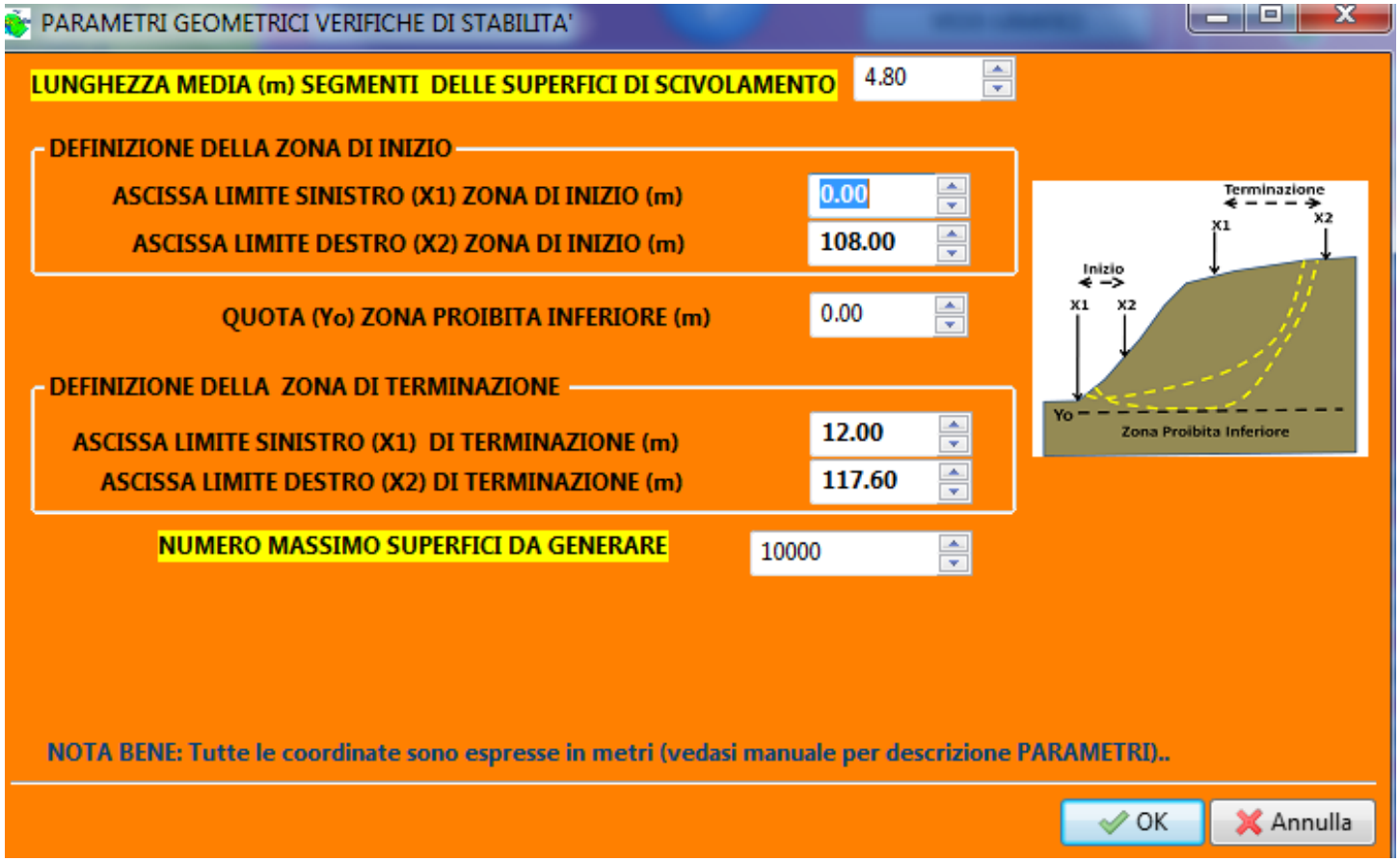
GRAPHICAL INTERFACE

Groundwater and fluid pressure module.



GRAPHICAL INTERFACE

Window with additional random surface generation parameters.



FOS CALCULATION

SSAP uses only **rigorous LEM methods*** in FOS calculation. FOS coded in a computational framework derived by Zhu et al. (2005), but generalized to any LEM method in a new generalized algorithm and computational strategy:

- Rigorous Janbu (1973)
- Spencer (1967)
- Sarma I (1973)
- Morgenstern & Price (1965)
- Correia (1988)
- Sarma II (1979)

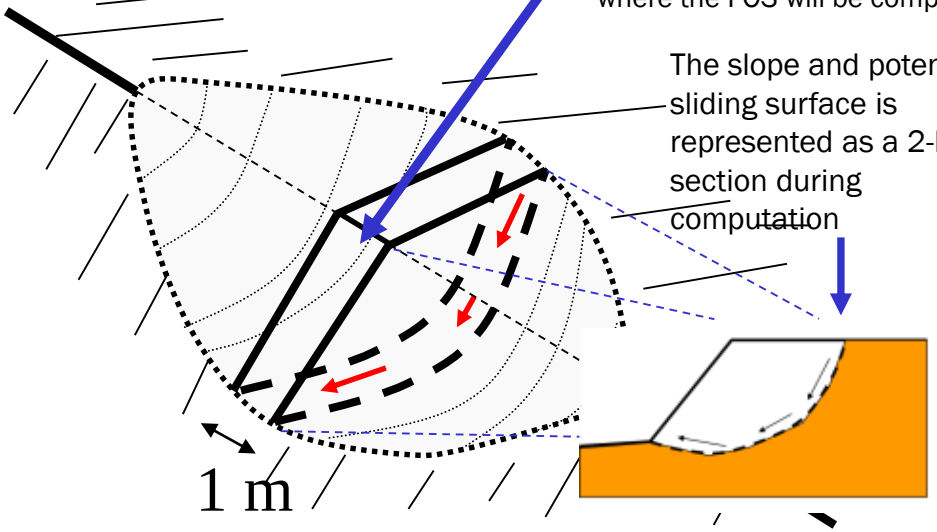
* LEM rigorous methods are able to ensure, at the same time, forces and momentum equilibrium

FOS CALCULATION

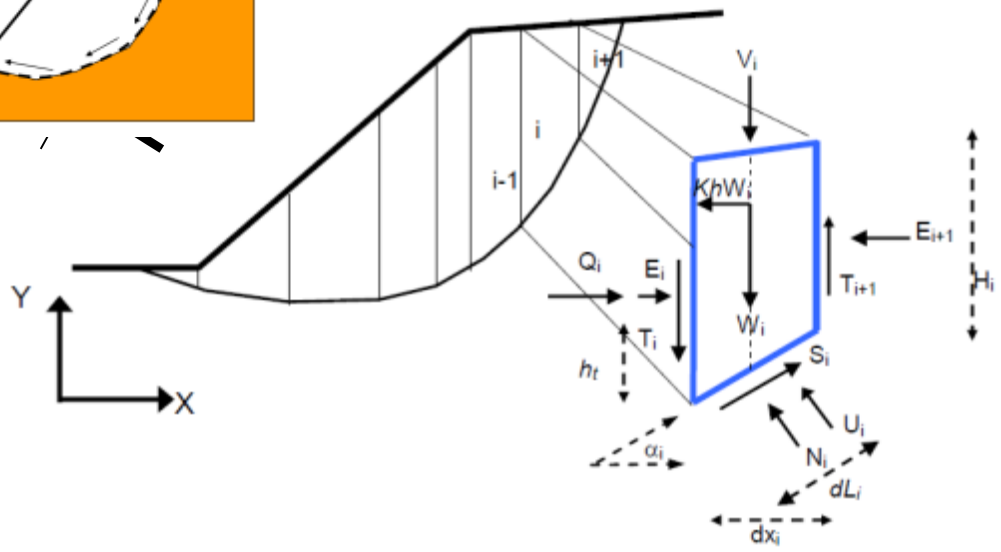
Real 3D to 2D
LEM (limit equilibrium method)
representation

A unit wide (1 m) strip is verified in 2D LEM. It represents a potentially unstable mass where the FOS will be computed

The slope and potential sliding surface is represented as a 2-D section during computation

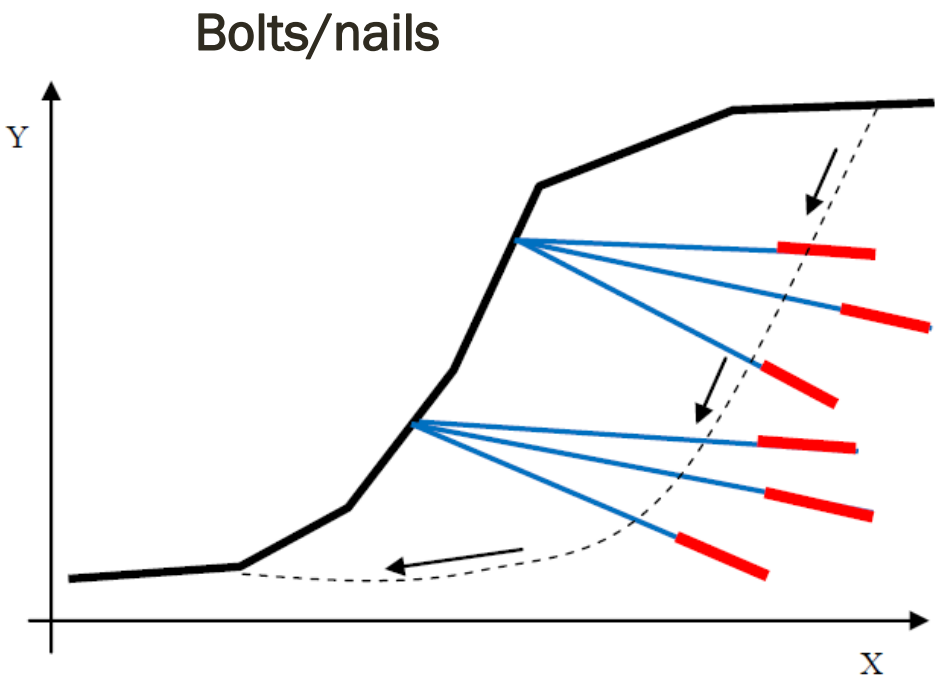


$$\begin{cases} Fs = \dfrac{f(N_{(x)}, U_{(x)}, \alpha_{(x)}, T_{(x)}, V_{(X)}, dx_{(x)}, Q_{(x)}, Fs)}{f(\alpha_{(x)}, W_{(x)}, V_{(X)}, dx_{(x)}, T_{(x)}, \lambda)} \\ \lambda = \dfrac{f(dx_{(x)}, E_{(x)}, \alpha_{(x)}, W_{(x)}, V_{(X)}, Q_{(x)})}{f(dx_{(x)}, T_{(x)}, \lambda)} \end{cases}$$



REINFORCEMENTS

In SSAP we can include different types of reinforcements integrating their effects in FOS calculation.



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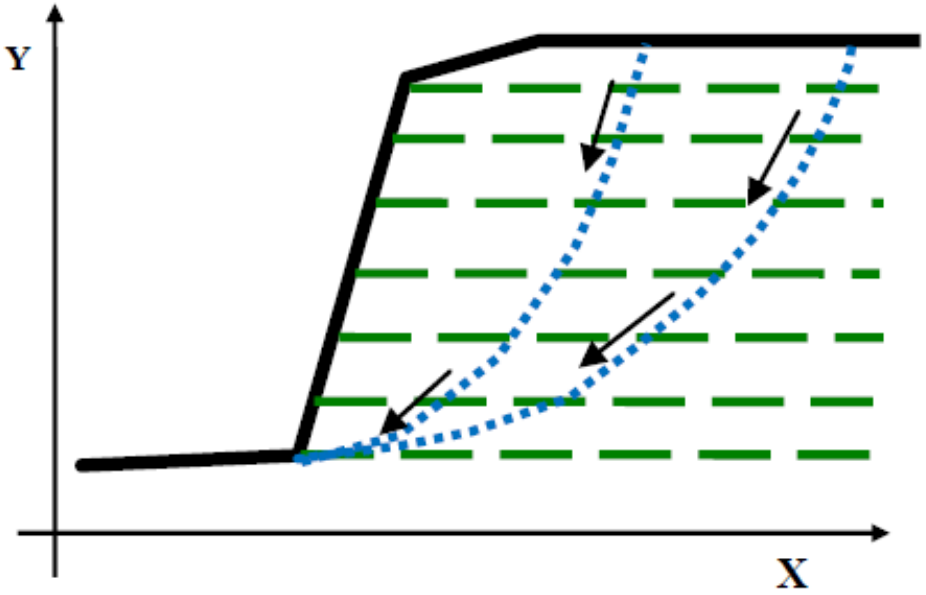
Geogrids



REINFORCEMENTS

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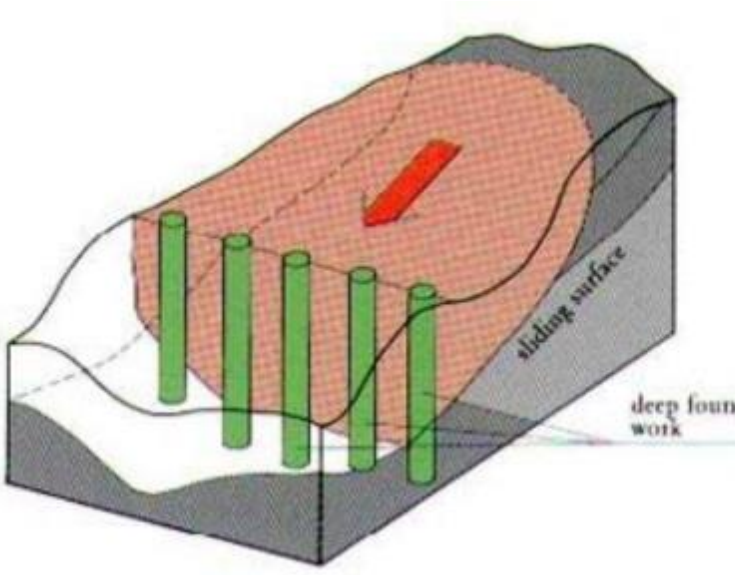
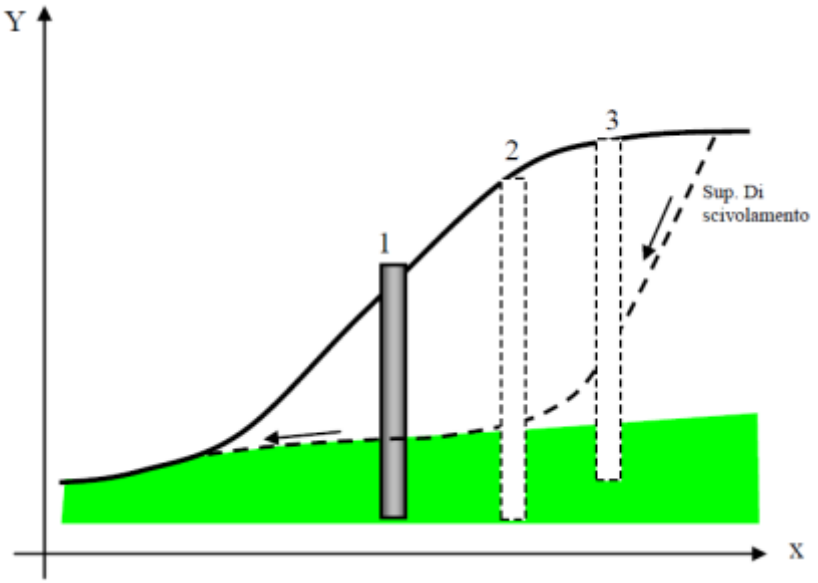
Piles row stabilising an active landslide

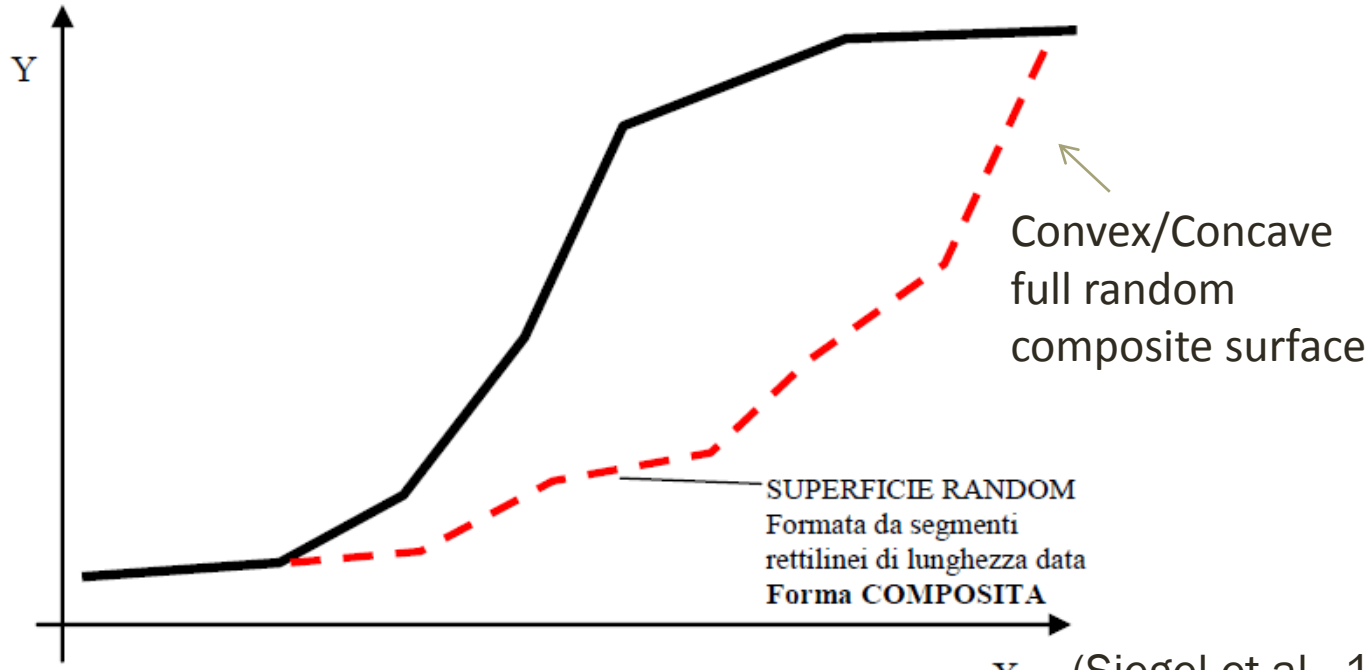




SLIDING SURFACES GENERATION

Monte Carlo methods are used to generate possible sliding surfaces.

Surface generation engine RANDOM SEARCH



(Siegel et al., 1981)

SLIDING SURFACES GENERATION

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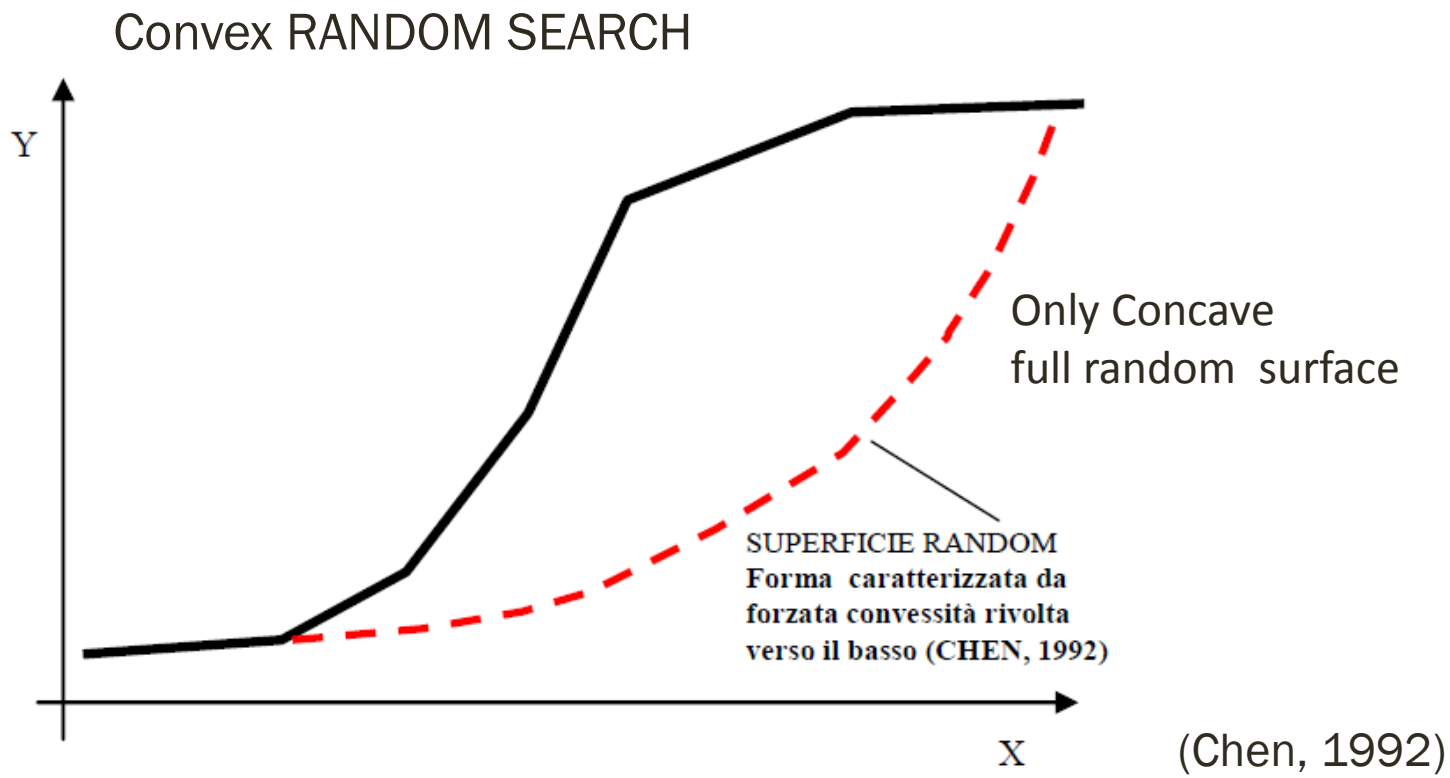
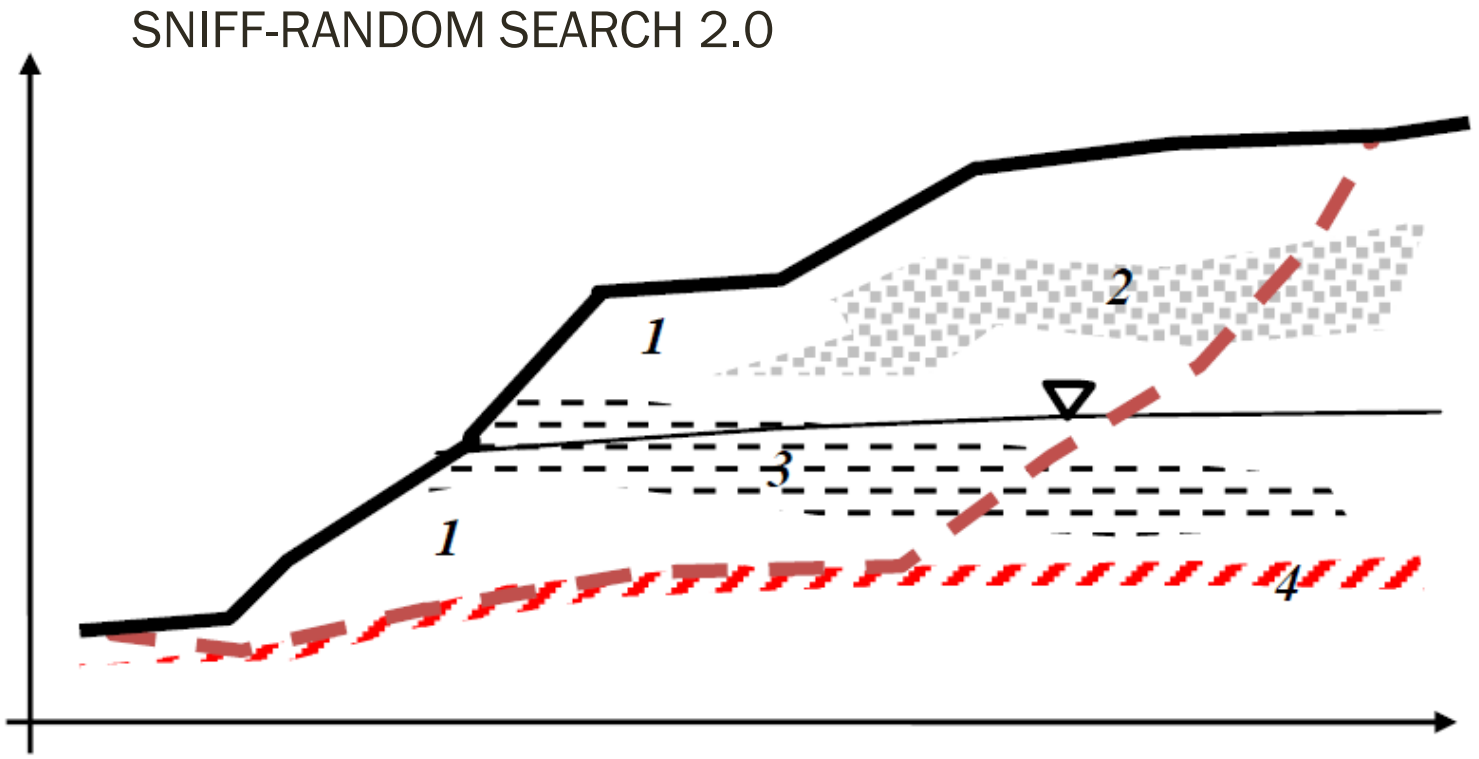


(Chen, 1992)

SLIDING SURFACES GENERATION

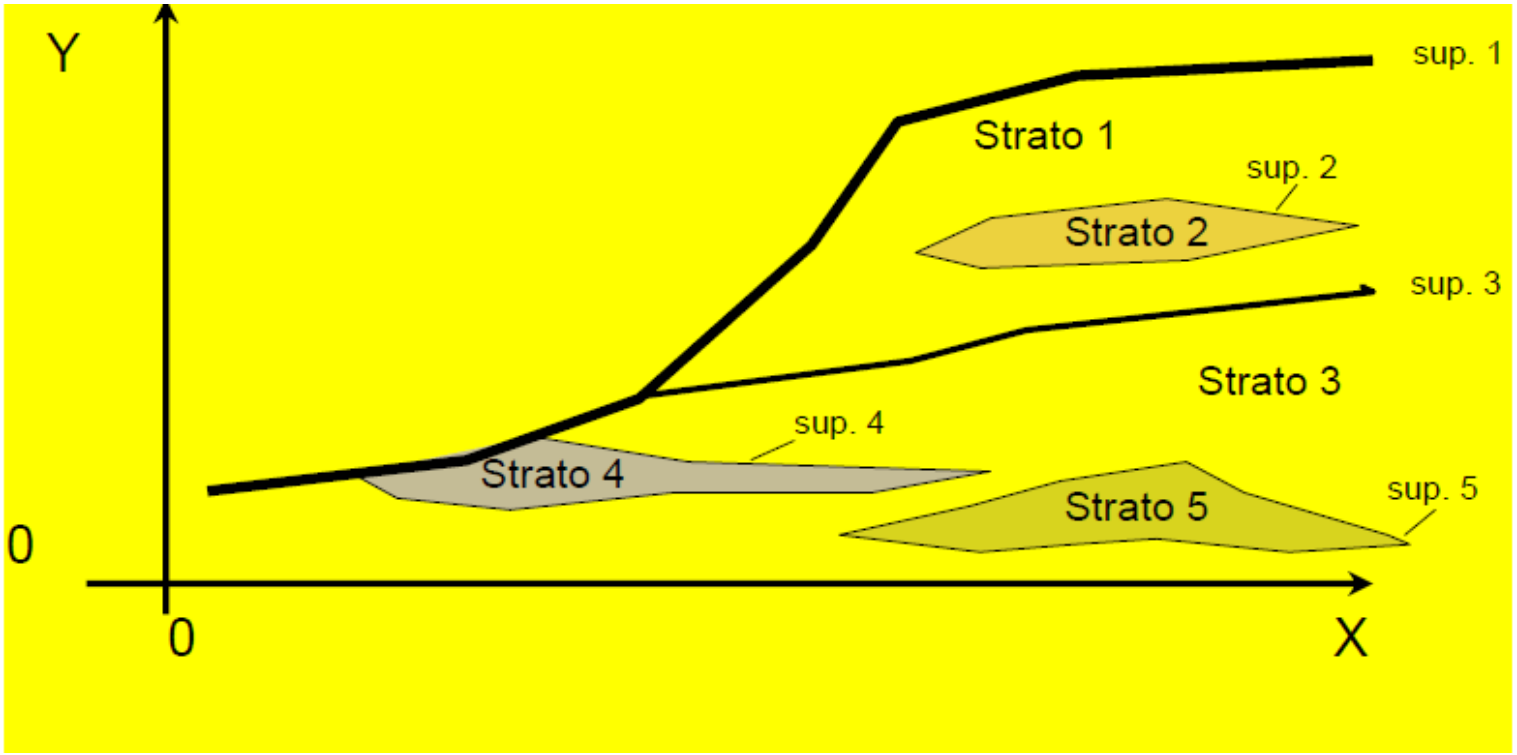
Hybrid method (expert system + Montecarlo).



(Borselli, 2012)

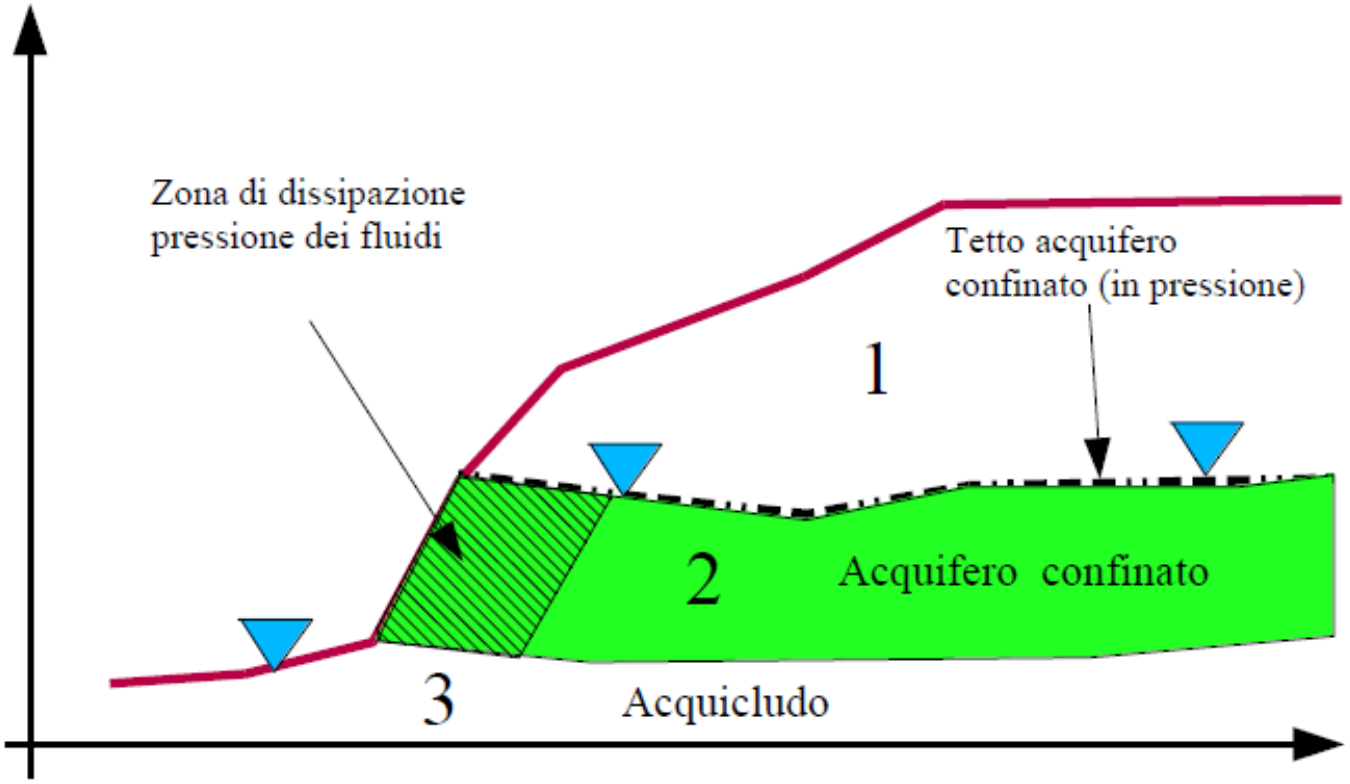
STRATIGRAPHY

Stratigraphic complexities are managed up to a maximum of 20 strata.



FLUIDS

Groundwater and fluid pressure are managed: e.g. aquicludes in pressure and perched groundwater.



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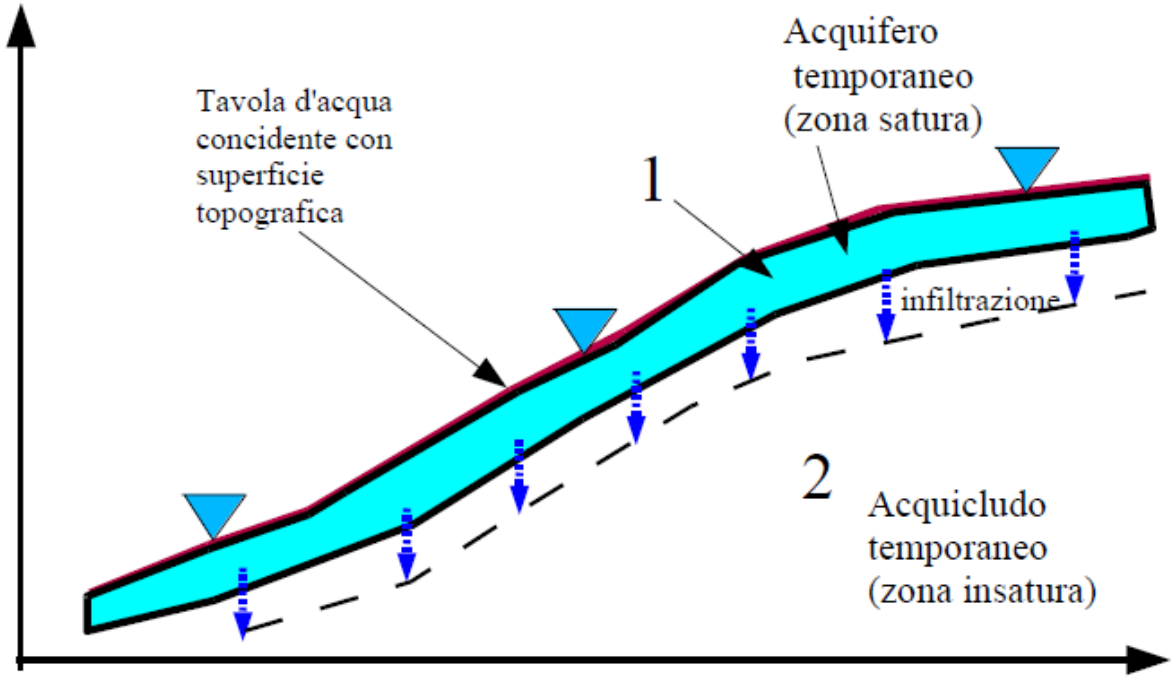
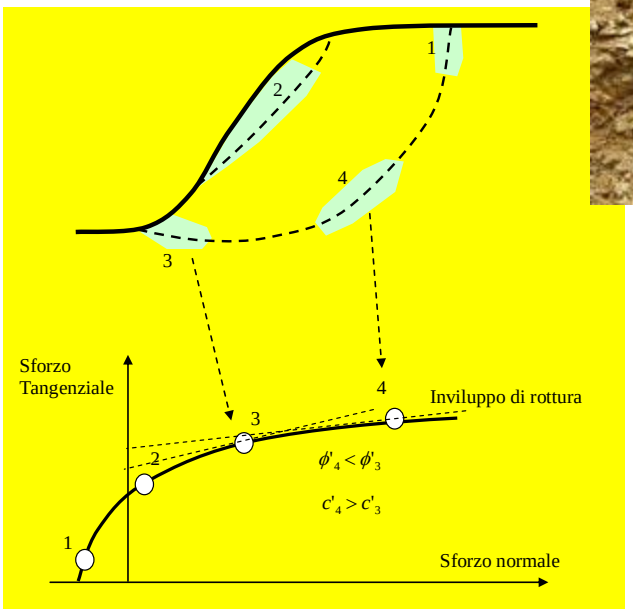
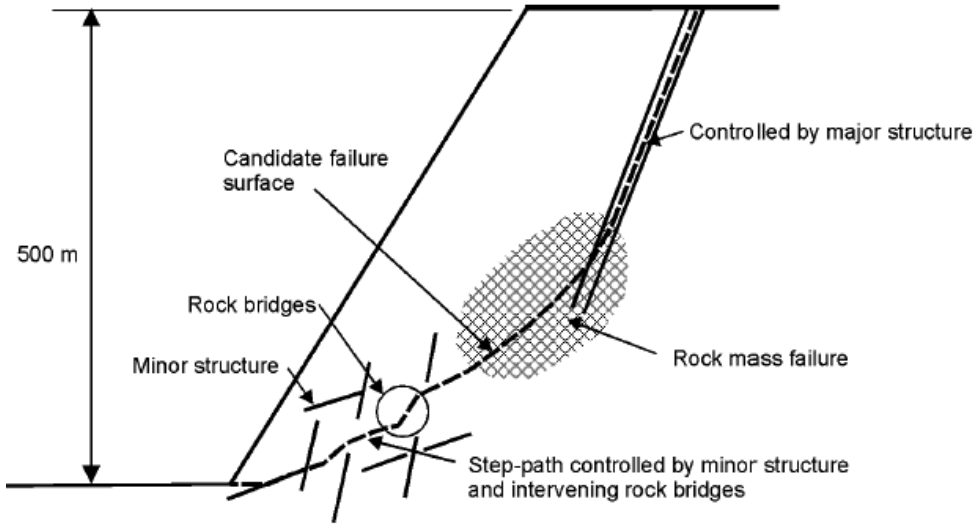


ROCK MASS STRENGTH

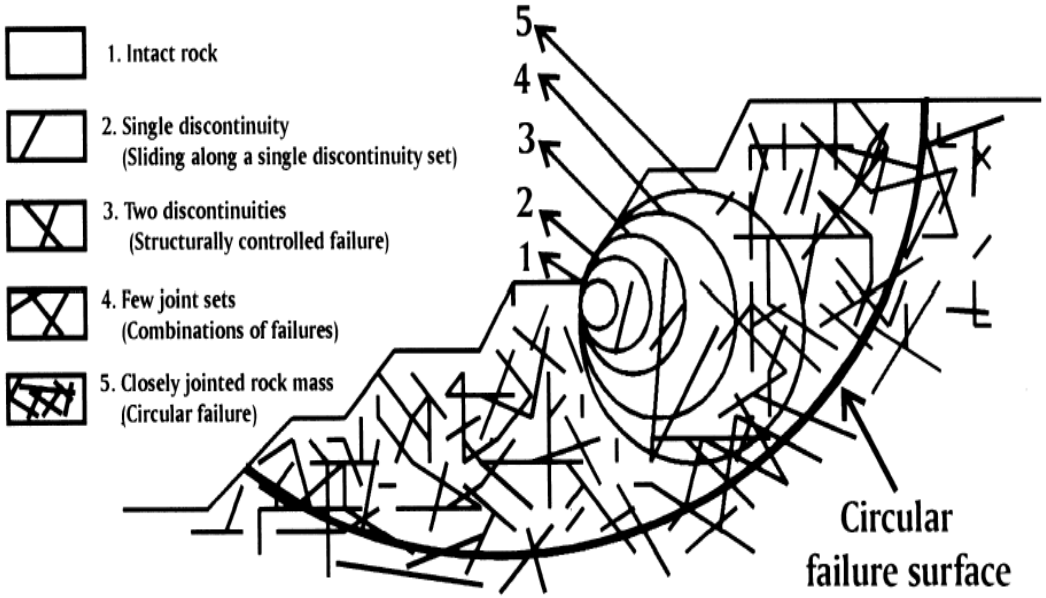
Rock mass strength criteria by Hoek et al. (2002) and Hoek (2007) and GSI method are used by SSAP as alternative to Mohr-Coulomb strength criteria.



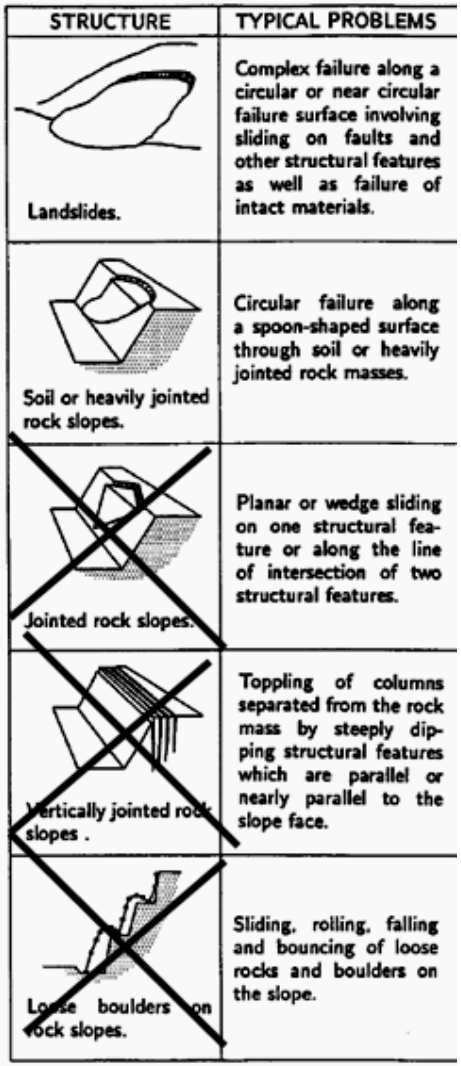


(Borselli, 2012)

ROCK MASS STRENGTH



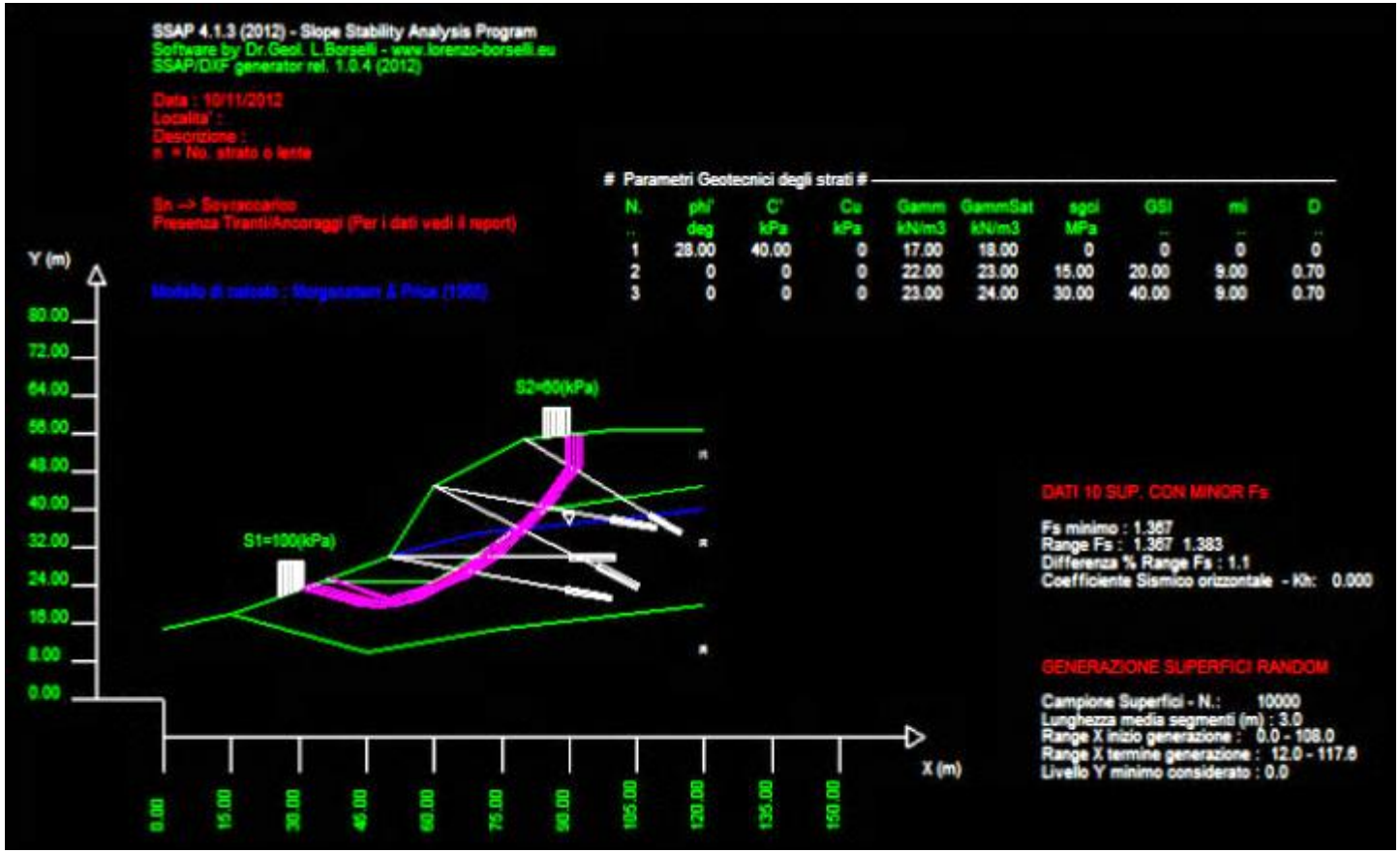
(Sonmez and Ulusay, 1999)



(Hoek, 2007, modified)

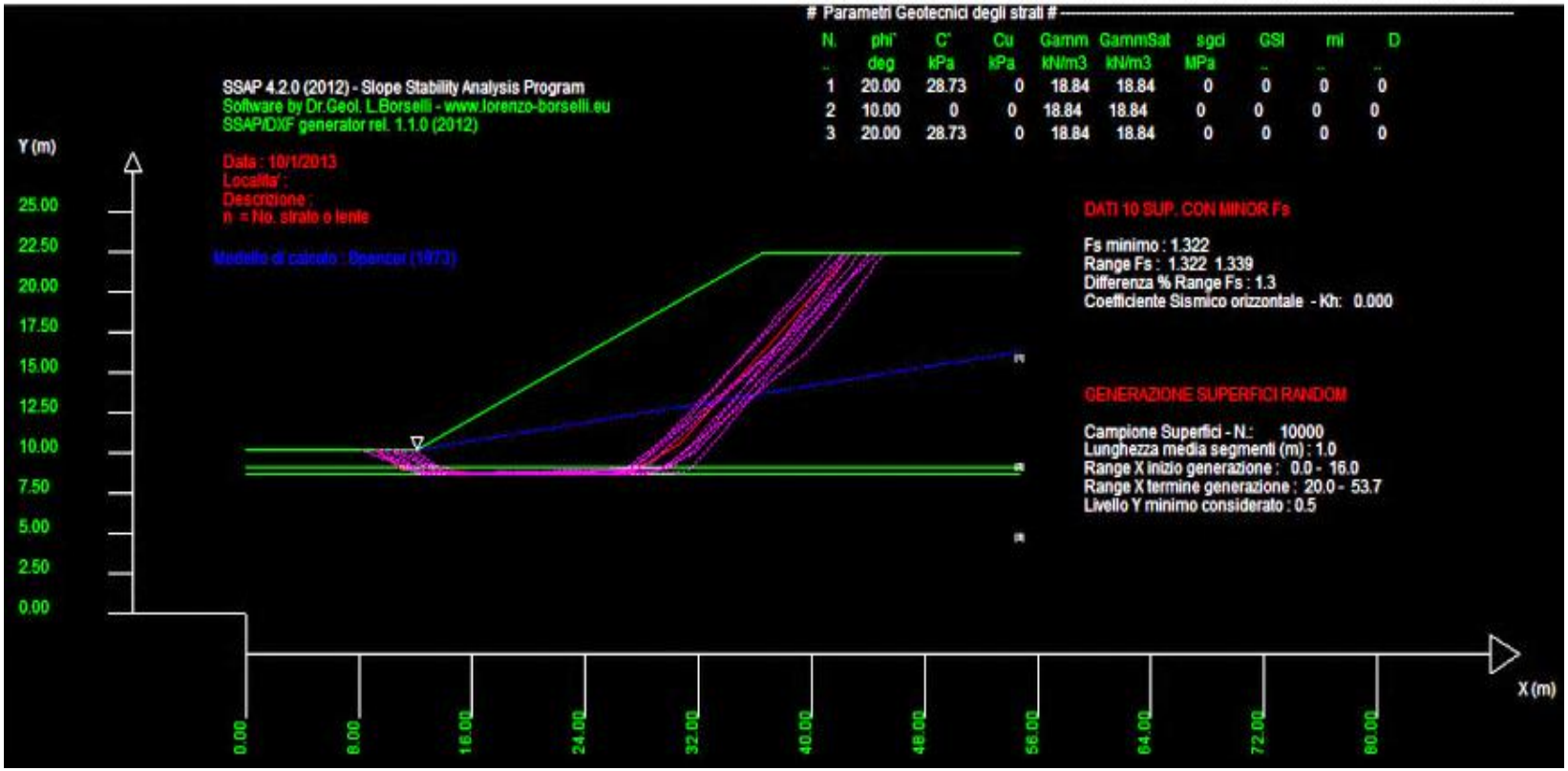
GRAPHICAL OUTPUT

Graphic rendering includes the automatic generation of DXF files (Autocad compatible).



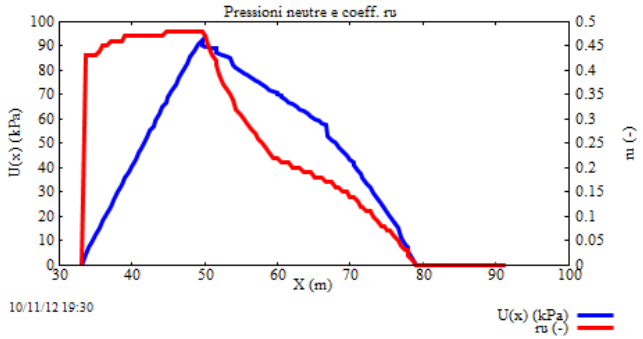
GRAPHICAL OUTPUT

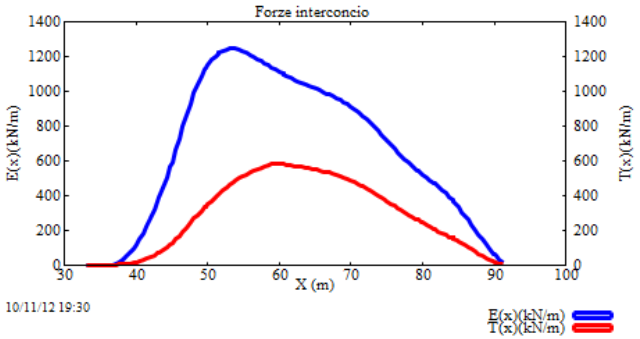
SNIFF RANDOM SEARCH 2.0 application on an earthfill above and with horizontal weak layer (example from Fredlund 1977).

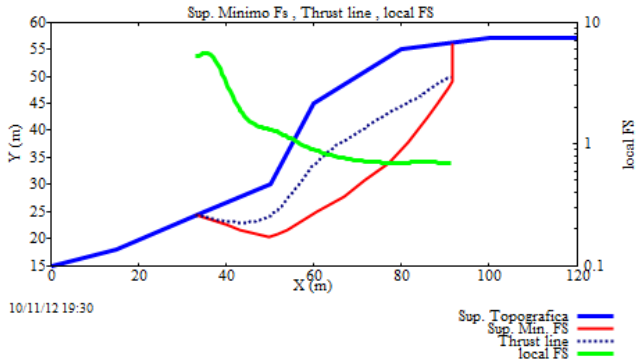


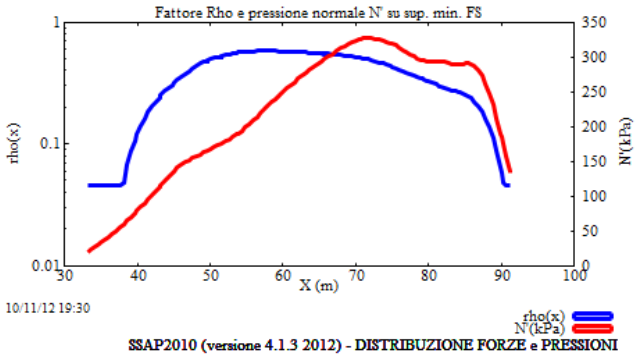
GRAPHICAL OUTPUT

Internal distribution of forces and pressure, distribution of local FOS, local distribution of RHO index (numerical reliability of general FOS numerical solution).





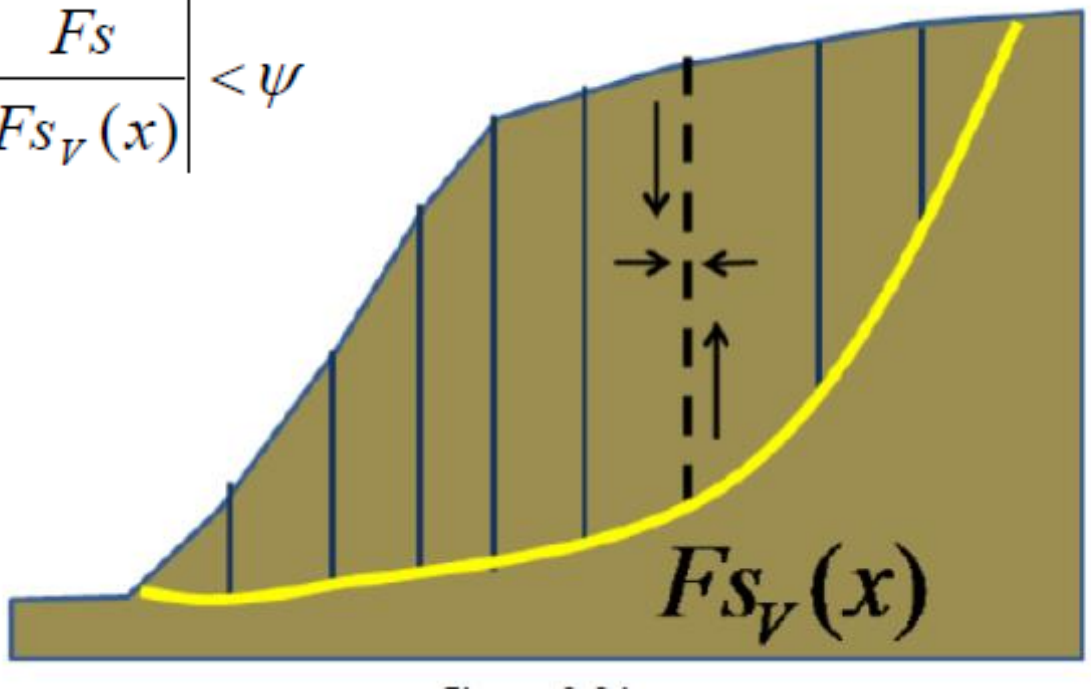




NUMERICAL STABILITY

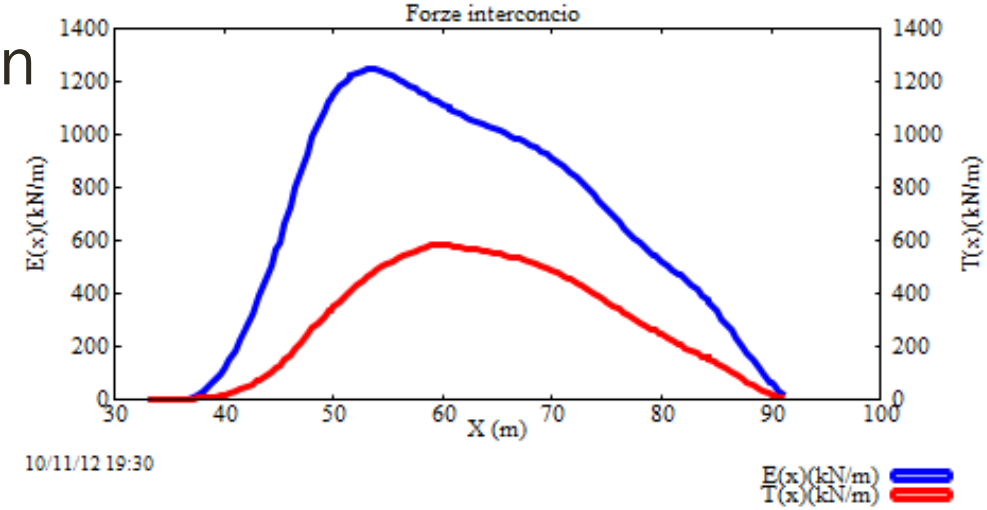
RHO index computation, its distribution and analysis for the solution's reliability.

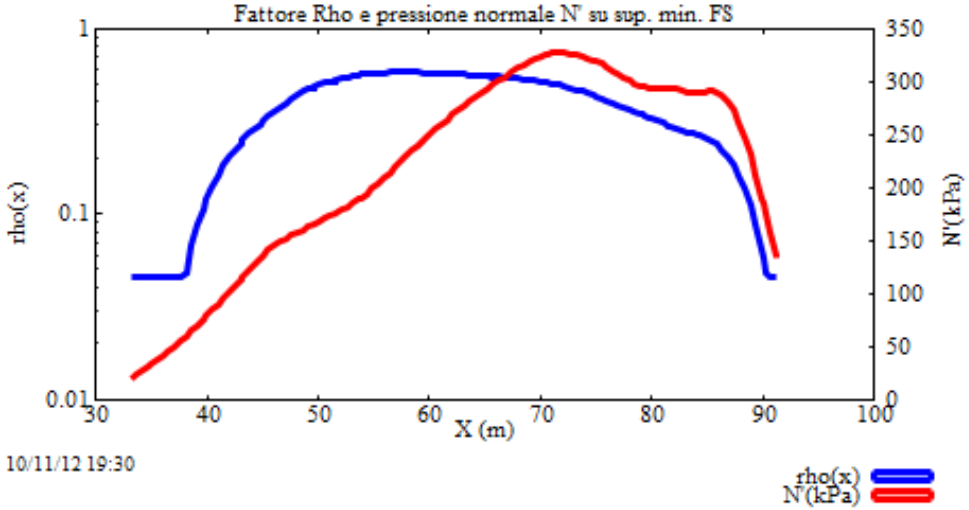
$$RHO(x) = \left| \frac{Fs}{Fs_V(x)} \right| < \psi$$



NUMERICAL STABILITY

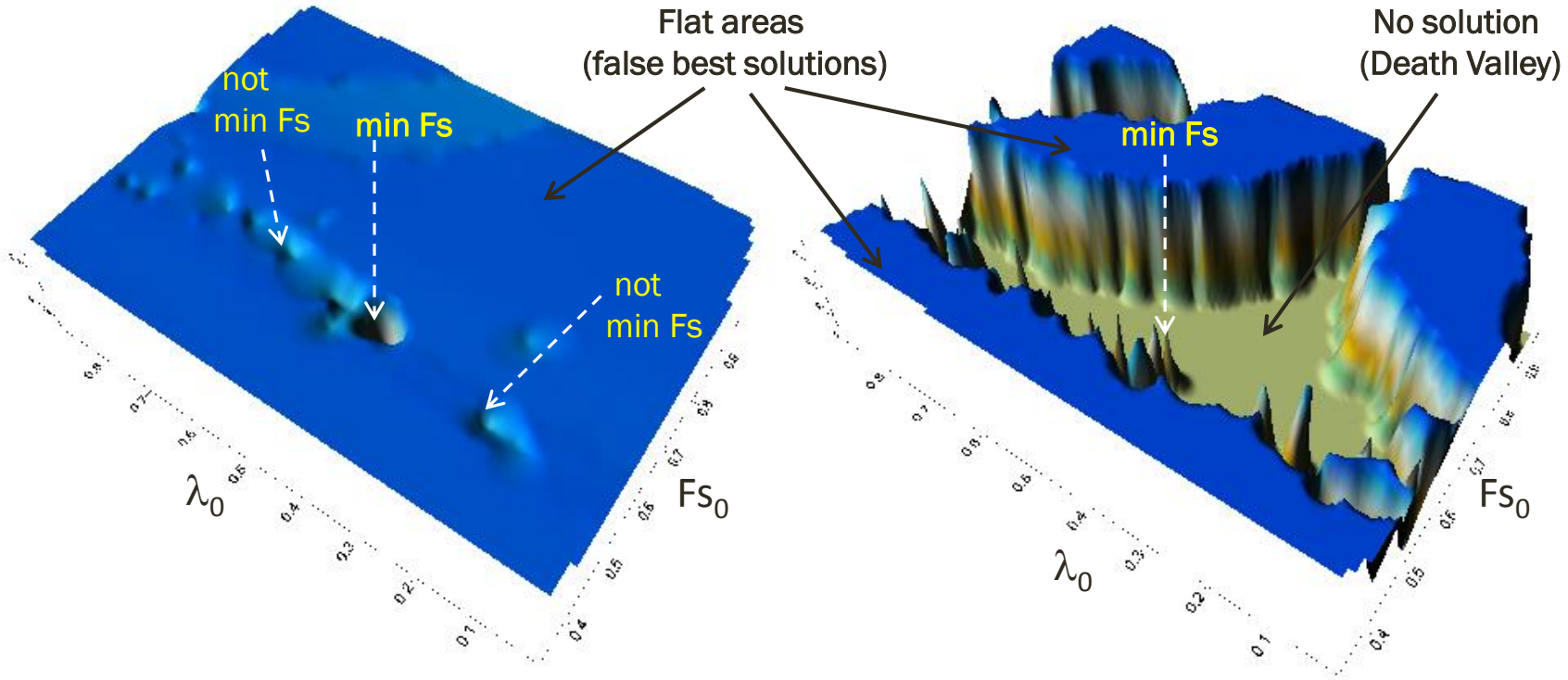
RHO index computation and its distribution.





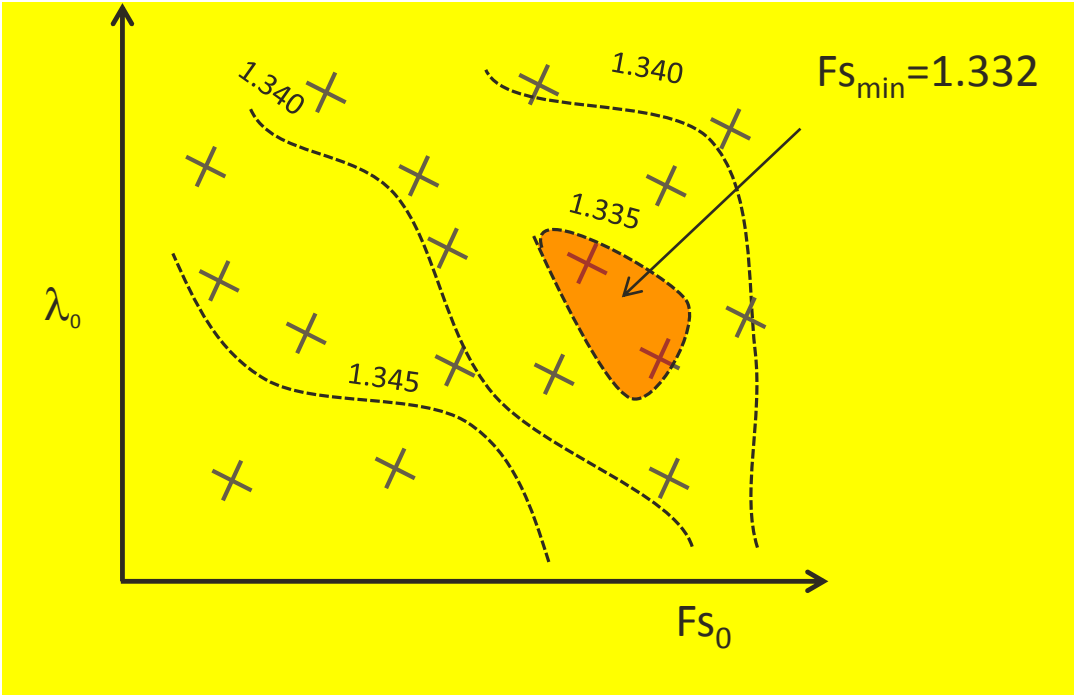
NUMERICAL STABILITY

Space (λ_0, Fs_0) exploration for best FOS searching for a given sliding surface (Borselli, 2012).



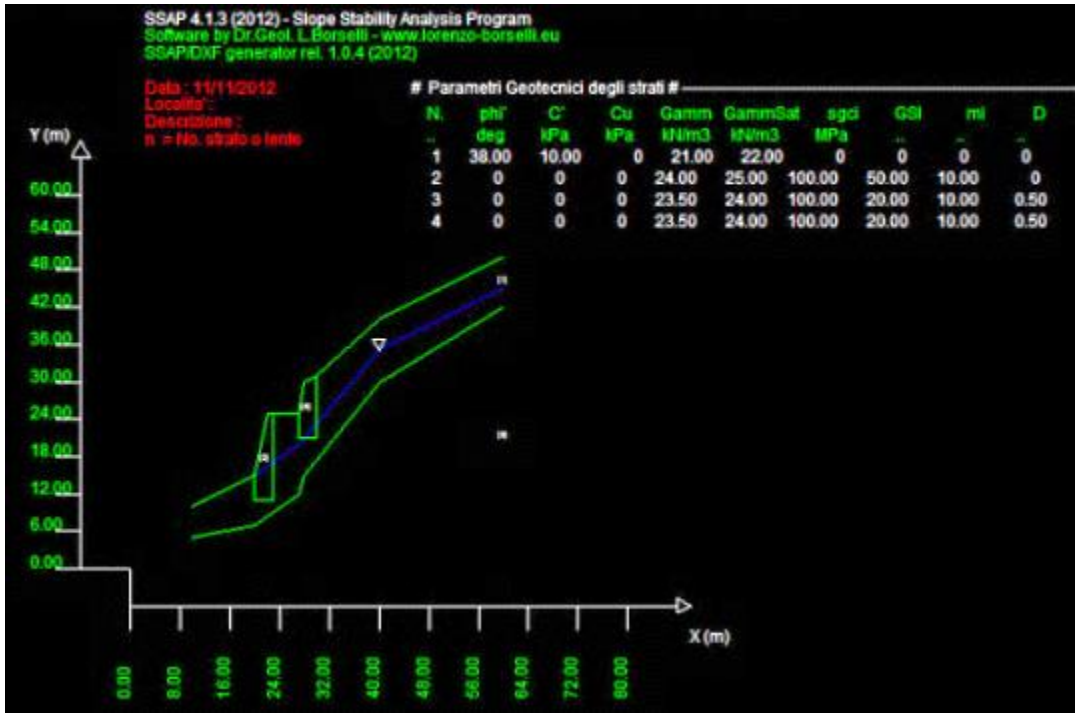
NUMERICAL STABILITY

Three different algorithms allow to explore initialization values for the computation of final FOS. The most accurate method uses global optimization by **differential evolution** (Storne and Price, 1997).



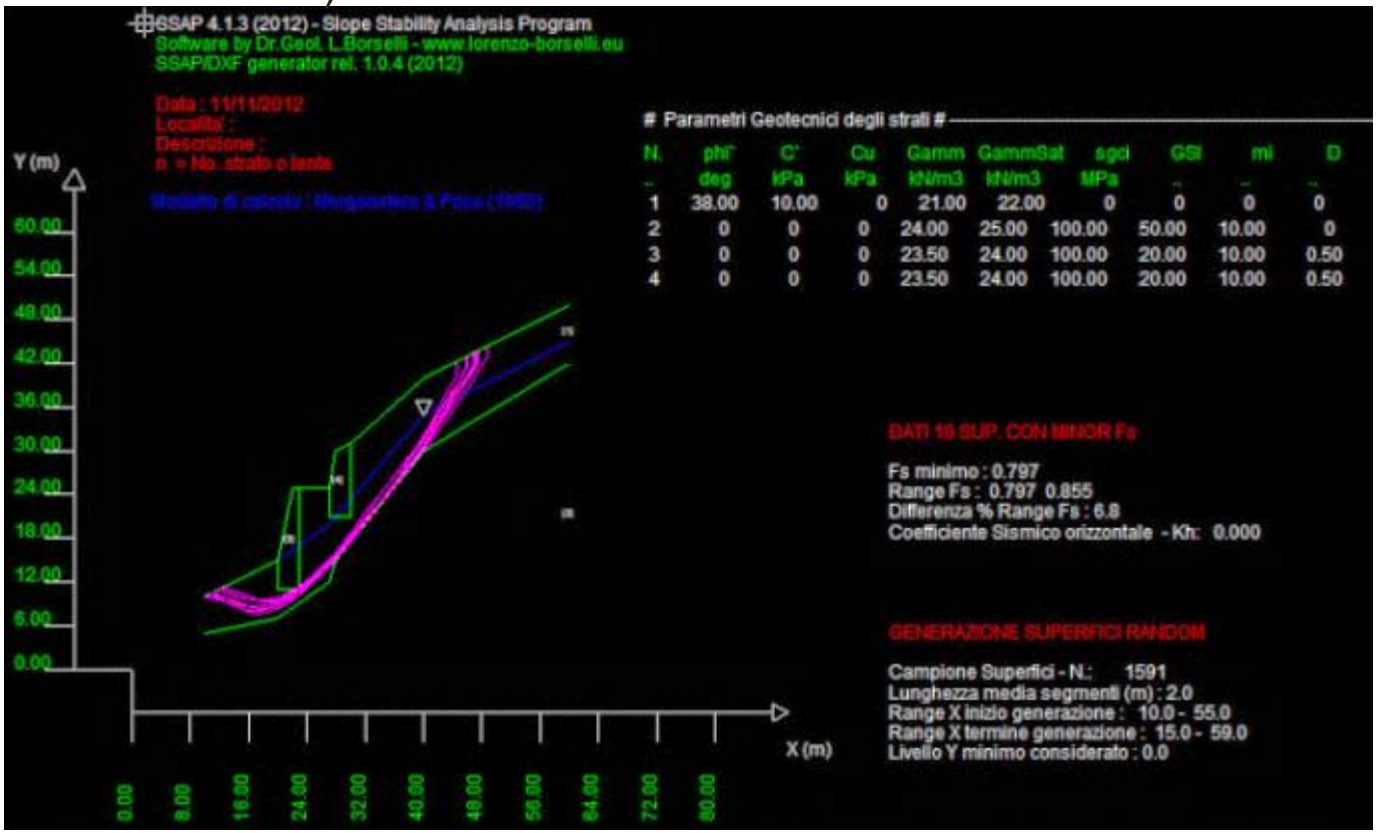
EXAMPLES: CARRARA DISTRICT

Application in Carrara district (Italy): slope with residual waste of marble (stratum 1), rockery wall in big block of marble (strata 3, 4). Rock mass of good quality (stratum 2) on marble.



EXAMPLES: CARRARA DISTRICT

Critical sliding surfaces in scenario with saturated base of the slope (in violet, 10 most critical surfaces with the lowest FOS value).



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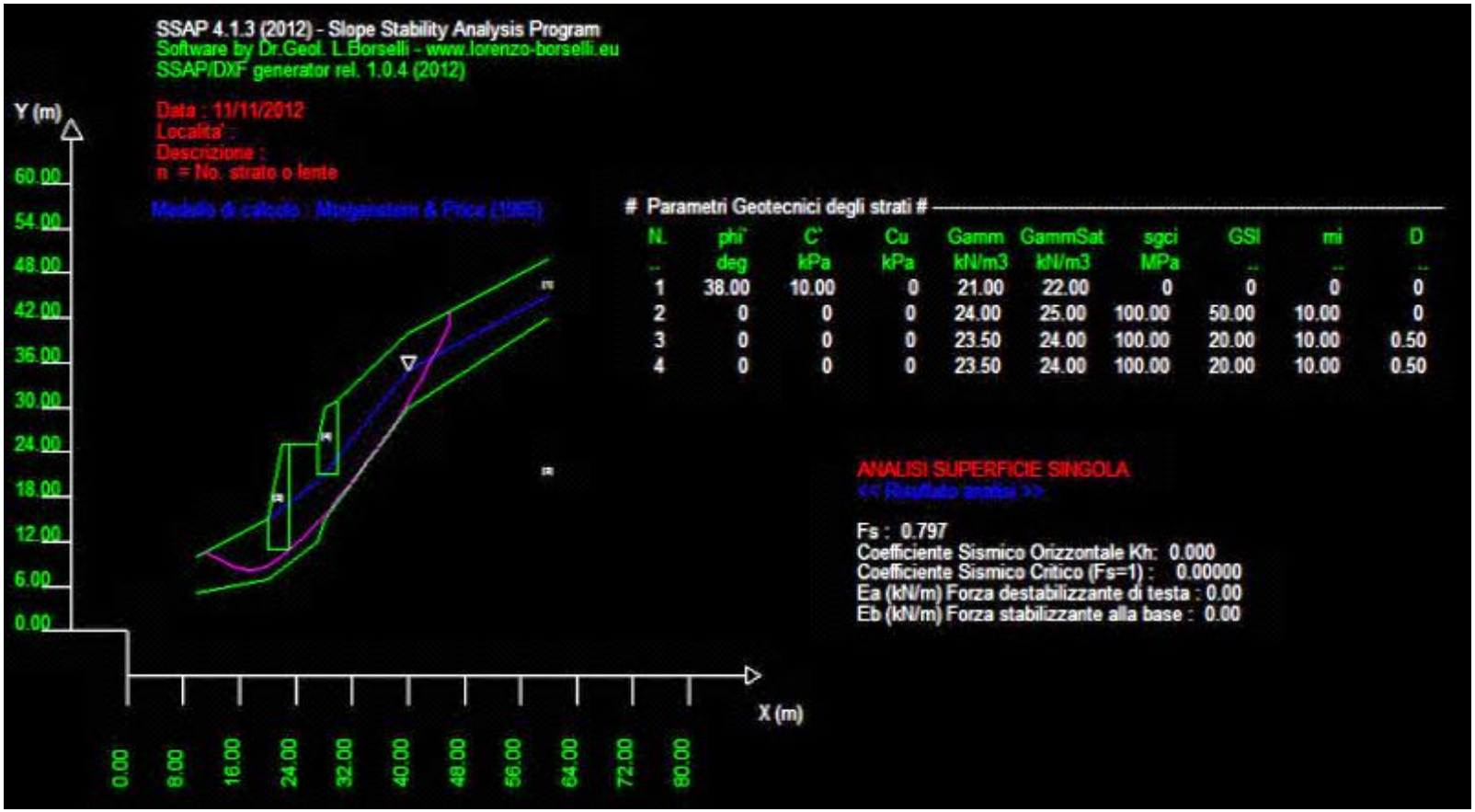
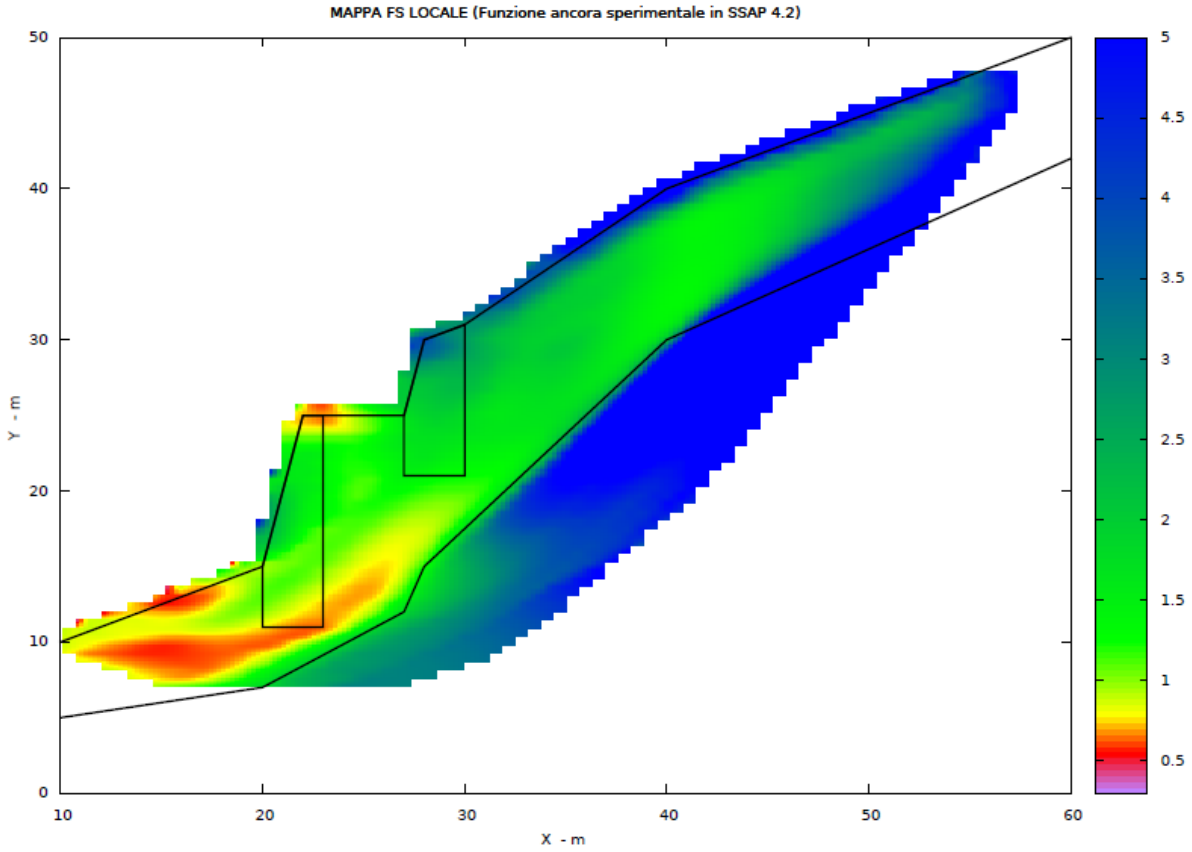
Critical sliding surface in scenario with saturated base of the slope.



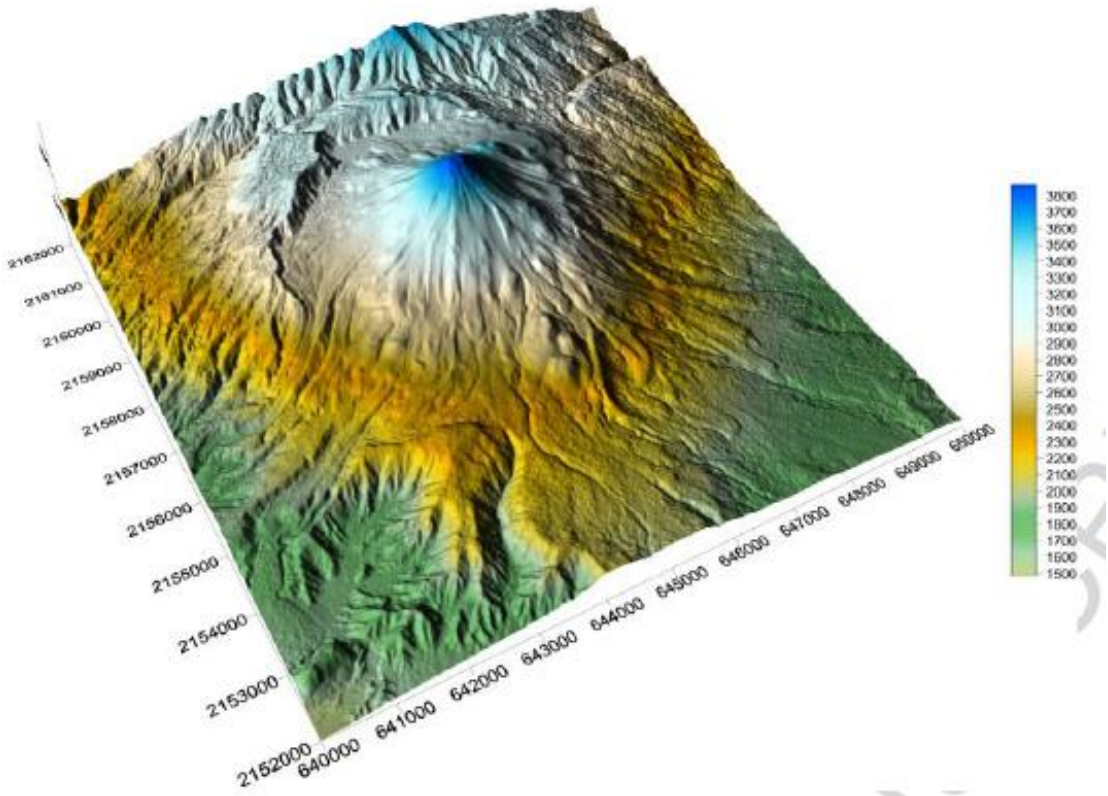
EXAMPLES: CARRARA DISTRICT

2D color map with distribution of average local FOS obtained by local stress distribution (Borselli, 2012).



EXAMPLES: COLIMA VOLCANO

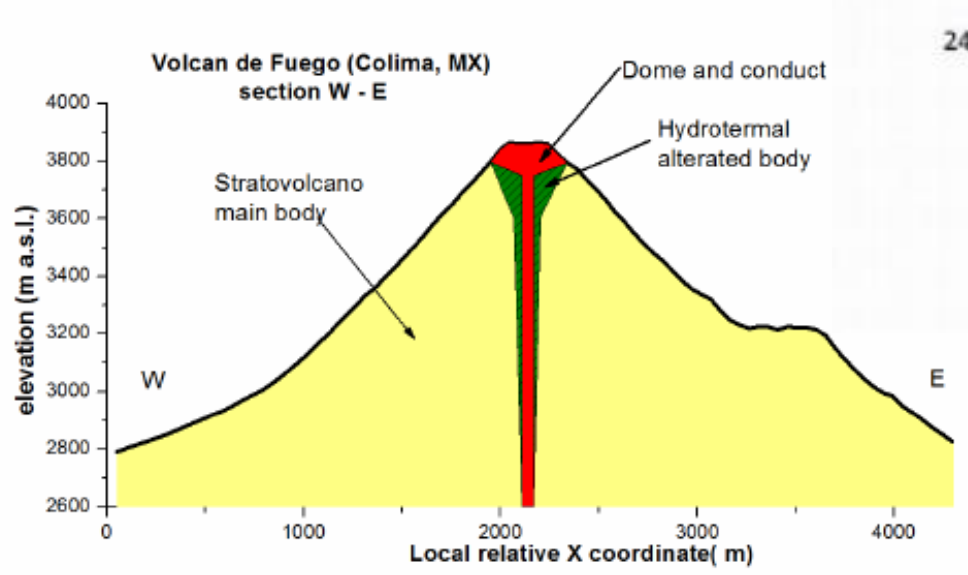
Flank Collapse and new Relative Instability Analysis Technique was applied to Colima volcano using SSAP Software (Borselli et al., 2011).

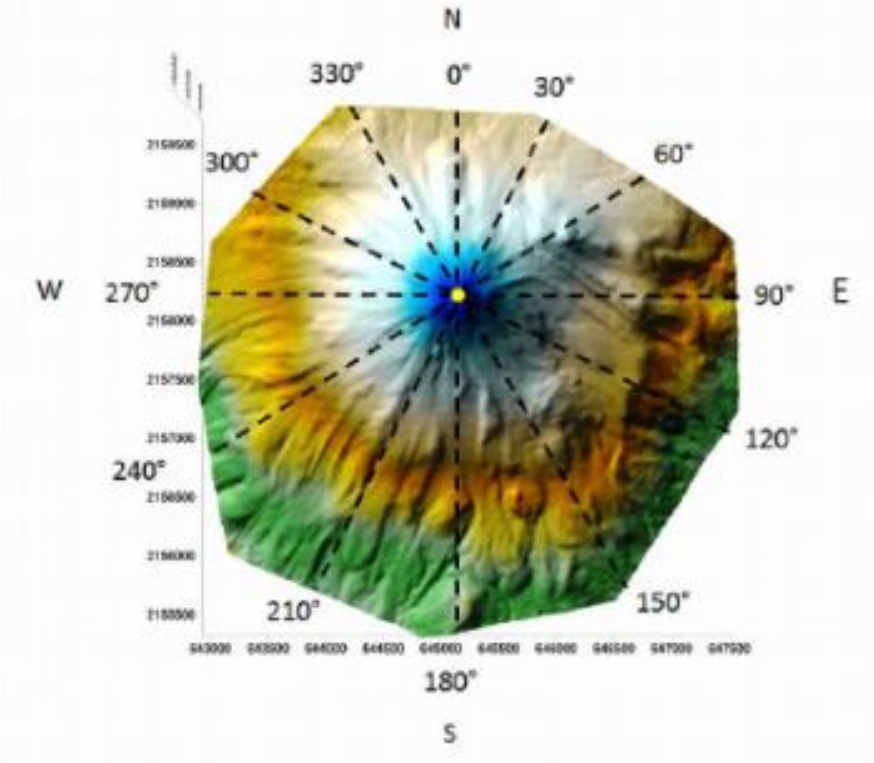


EXAMPLES: COLIMA VOLCANO

- Generic shape random search of minimum FS sliding surface by Monte Carlo method.
- Multiples 2D LEM analysis of volcano's slope profiles distributed every 30° of azimuth and passing from the edifice top.
- Rock mass strength criterion (Hoek et al., 2002; Hoek, 2007).
- Fluid pressure function (overpressure and dissipation fields inside volcanic edifice) (Borselli et al., 2011).

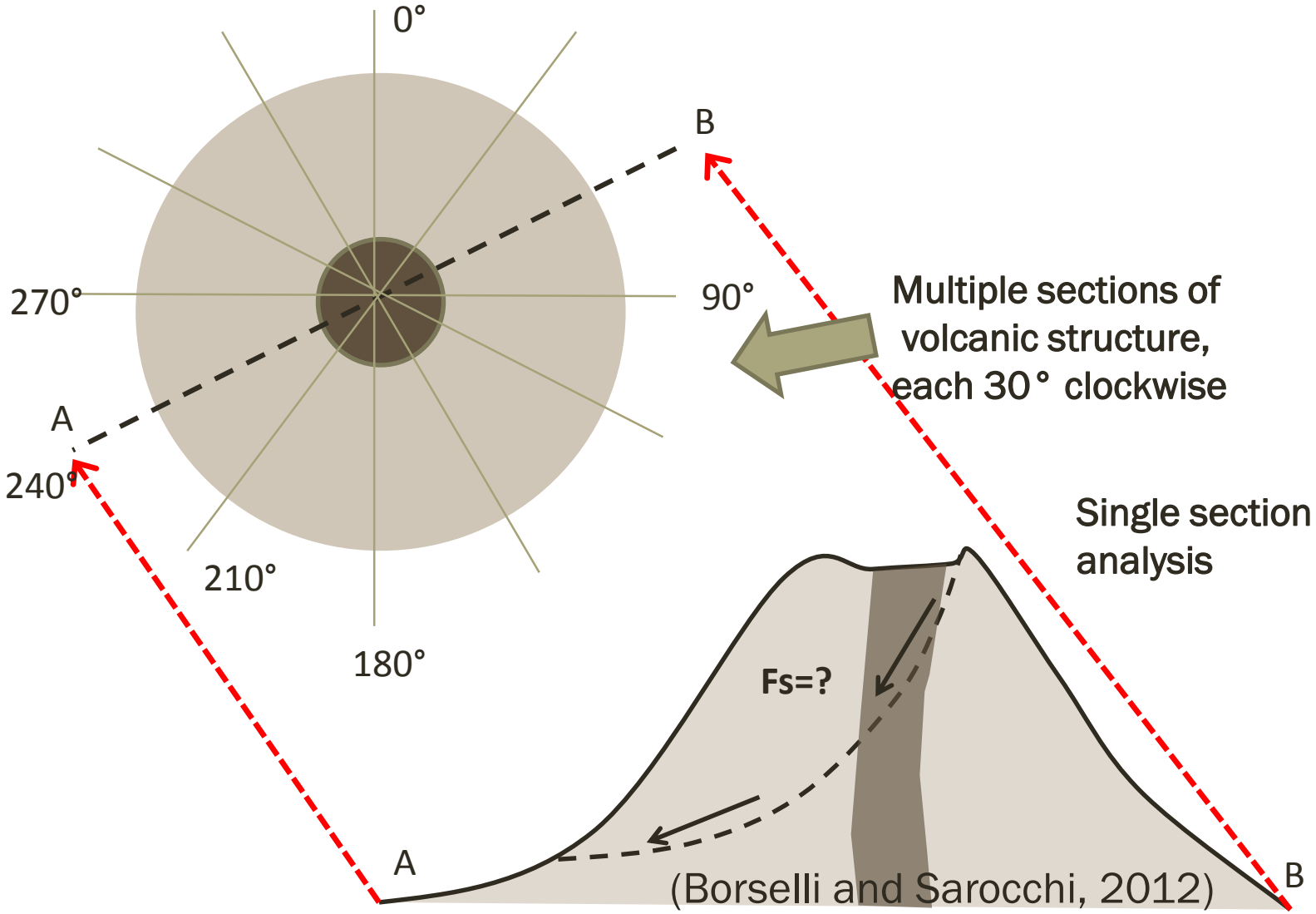
EXAMPLES: COLIMA VOLCANO





(Borselli et al., 2011)

EXAMPLES: COLIMA VOLCANO



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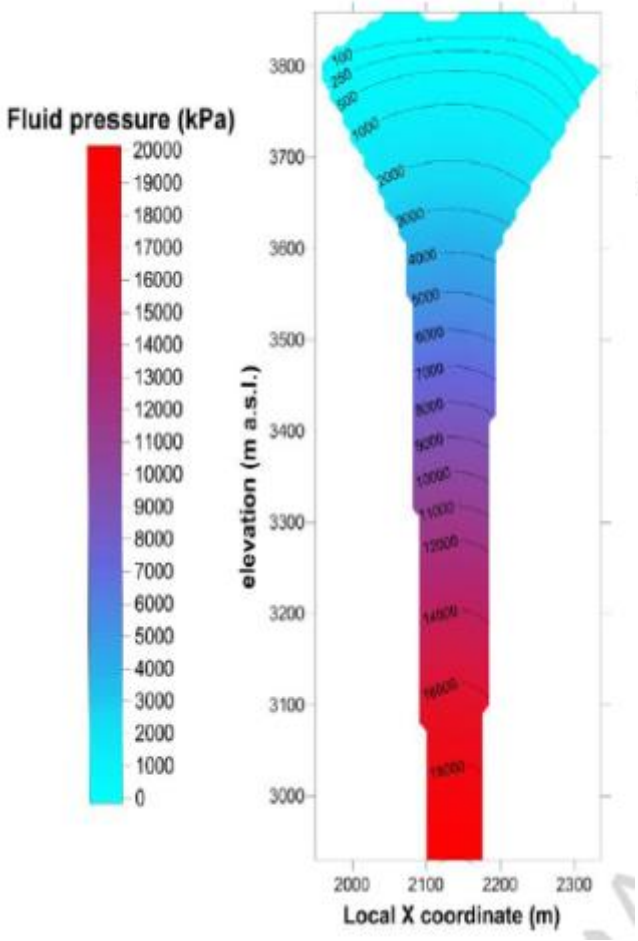
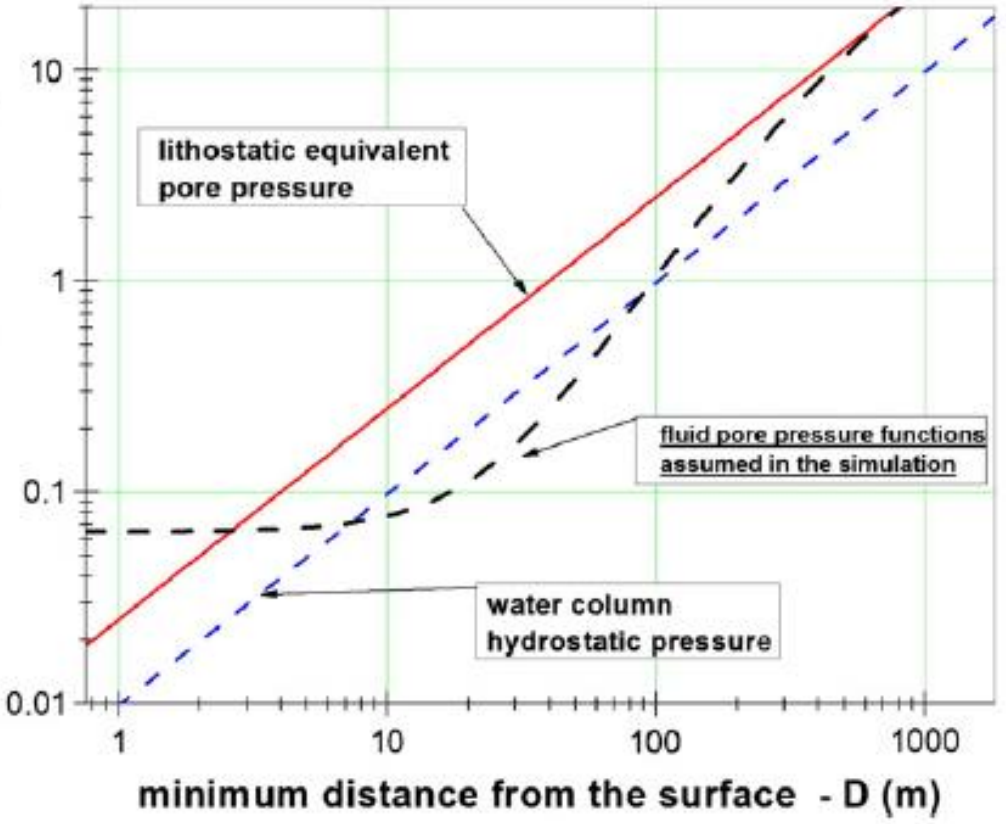


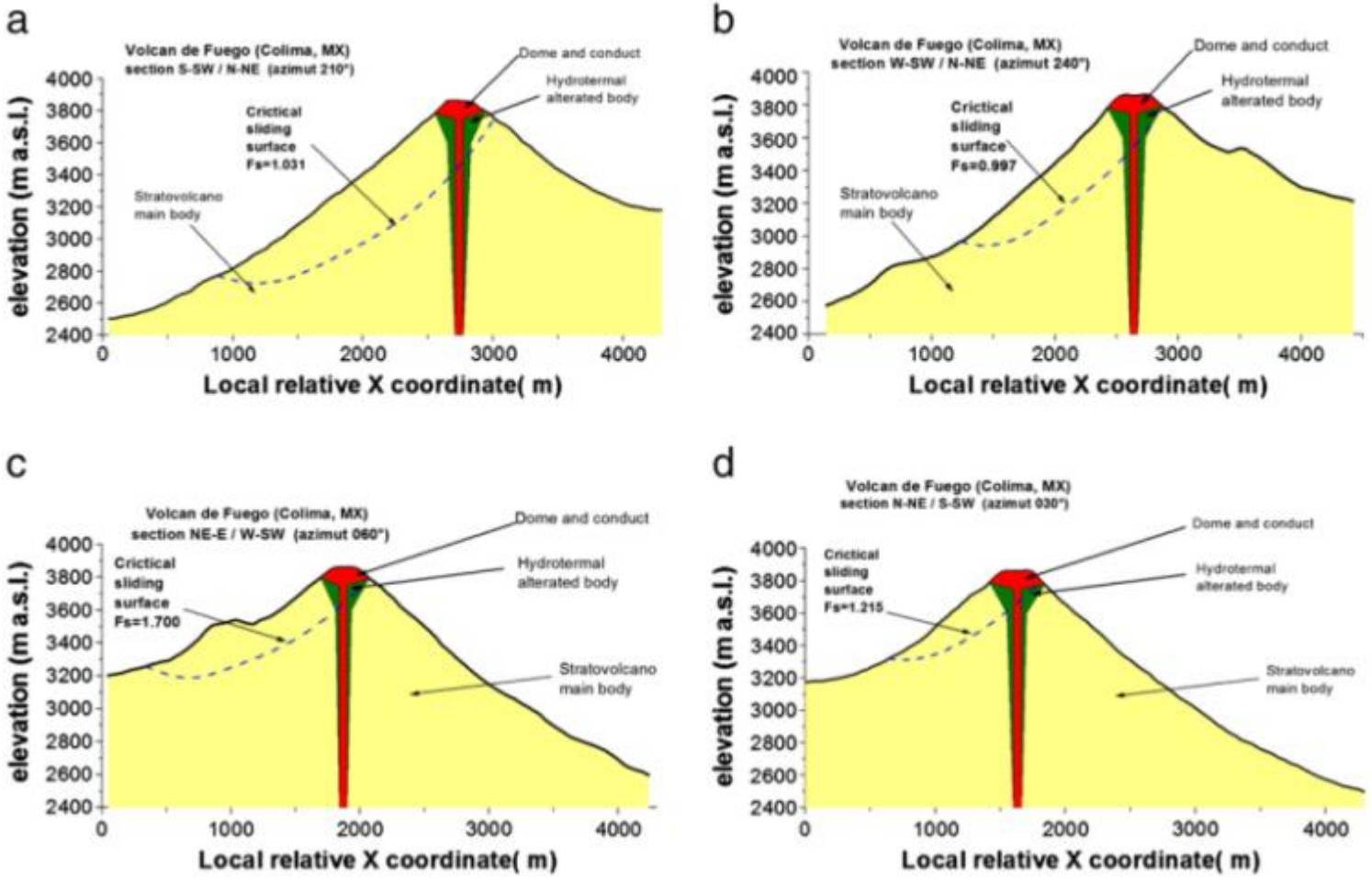


$$F_D = 1 - Ae^{-kD} \qquad \sigma_f = \gamma_w z F_D + U_{0_{MIN}}$$

(Borselli et al., 2011)

EXAMPLES: COLIMA VOLCANO

L. Borselli et al. / Journal of Volcanology and Geothermal Research 208 (2011) 51–65

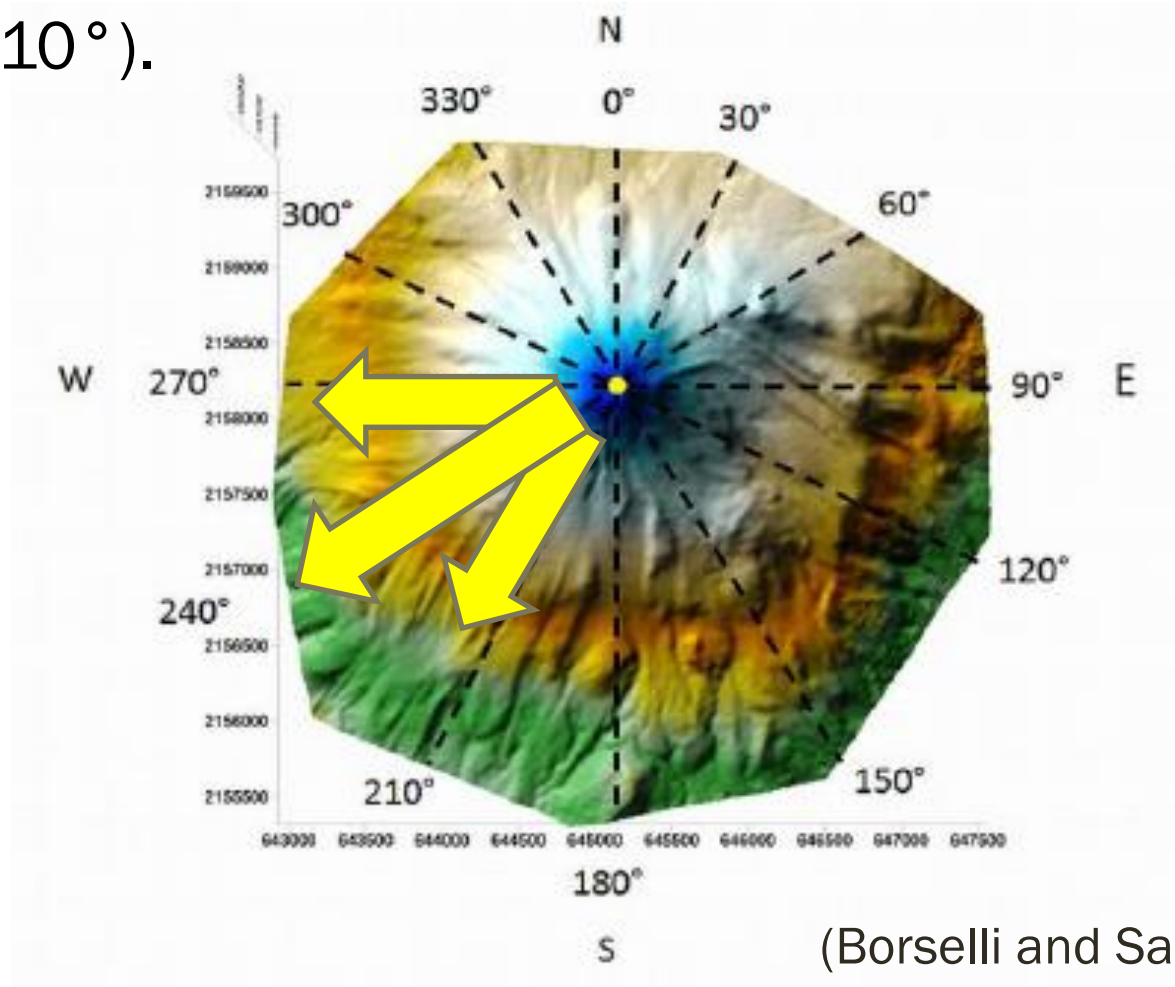


(Borselli et al., 2011)

http://www.lorenzo-borselli.eu

EXAMPLES: COLIMA VOLCANO

The most unstable flank is the W-SW (between 270° and 210°).

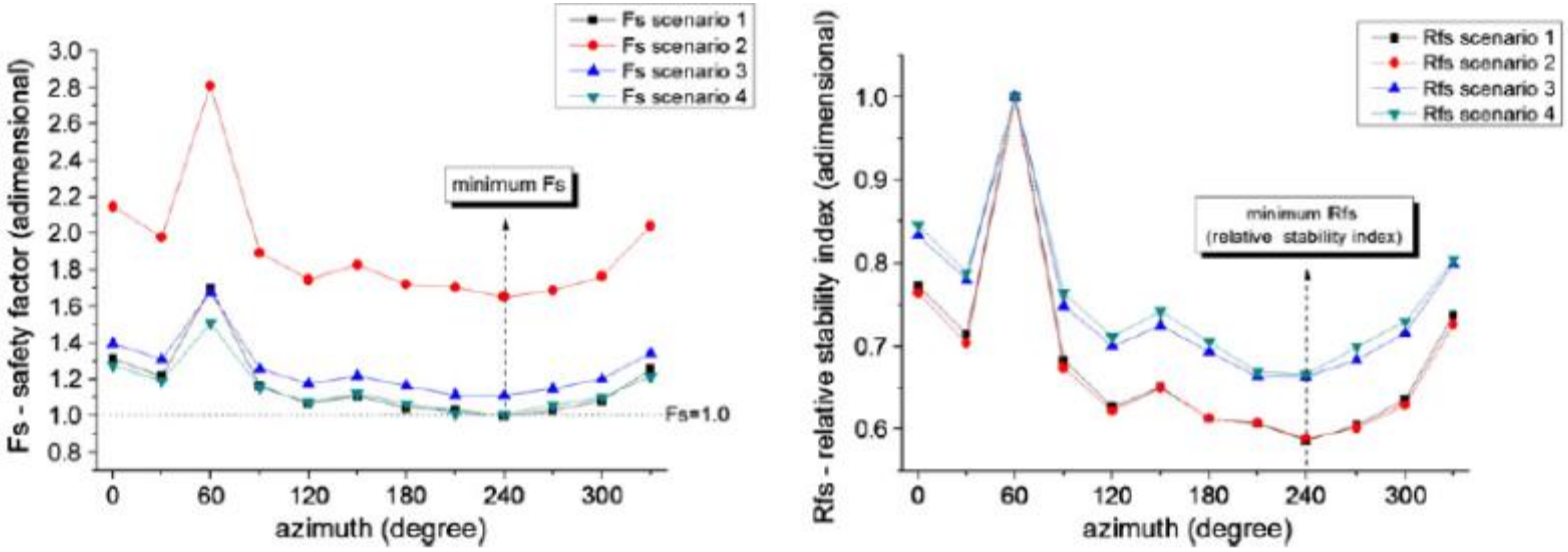


(Borselli and Sarocchi, 2012)

EXAMPLES: COLIMA VOLCANO

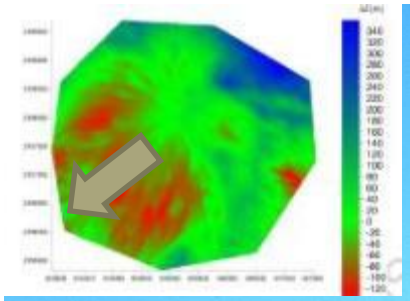
Relative stability index:

$$R_{fs_i} = \frac{Fs_i}{Fs_{\max}}$$

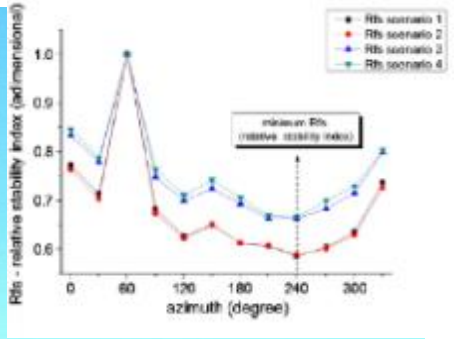


(Borselli et al., 2011)

EXAMPLES: COLIMA VOLCANO



The most potentially unstable flank: Azimuth 270°-210°



(Borselli and Sarocchi, 2012)

SSAP2010 HIGHLIGHTS

- Freeware software tool with large diffusion and use in Italy for professionals, students, researchers, and private and public companies.
- 21 years of development based on 100% original coding, testing, and continuous interaction with final users with the aims of software improvement.
- Many original algorithms (e.g. sniff random search 2.0, and 2D map of local average FOS).
- Numerical stability control and its reliability analysis; groundwater and fluid pressure management module; reinforcement structures etc.

SSAP2010 HIGHLIGHTS

- Technical documentation on-line (still in Italian) and many real examples of application in natural and reinforced slopes.
- Many application in Italy and some in México in cases with high stratigraphic, geomechanics and hydraulic complexities.
- Free download from the WEB: **www.ssap.eu.**
- Full freeware user's license for any type of applications.

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