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Landslides hazard analysis based on deterministic models using different scenarios of groundwater and seismic acceleration

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Summary

The main indicator of the steady state of slopes is the safety factor, which can be physically expressed by comparing the stress conditions in the natural earthen slopes. The safety factor can vary between the critical value, the minimum value which marks the limit of the stable condition, and large and very large values, theoretically infinite.

The leading aim of this framework is to create a deterministic model for landslides hazard analysis based on direct evaluation of safety factor, under different degrees of soil saturation and considering different scenarios of seismic acceleration. The slope stability assessment will be done using infinite slope model.

This analysis can be approached in geographic information systems taking into account a pixel basis. Therefore, the factors and parameters that trigger the slope fail and those that prevent the slope for failing will be expressed as individual maps (thematic maps). These maps will be overlaid using a created GIS function, according to the mathematical formula of the safety factor.

The proposed model has been tested in a geographic information system environment in the Bucium Hill area, located on the south-east side of the Romanian city, Iasi.

The thematic maps engine used as main input data: digital terrain model and the results of geotechnical laboratory tests from 25 bore holes (friction angle, cohesion, unit weight).

The final result will be a quantitative hazard map of failure probability assessment. The calibration will be done by comparing with other maps obtained from two different approaches.

Keywords: landslide, hazard, infinite slope, safety factor, GIS

ISSN 1582-3024

1. INTRODUCTION

The purpose of the authors' work is twofold: providing a theoretical and practical overview of landslides hazard assessment based on the infinite slope stability model and also providing pragmatic and purposeful suggestions for its utilisation.

The infinite slope model can be implemented in GIS systems by creating a two-dimensional model that divides the analysis range into discrete elements of a pixel size. Thus, using the GIS tools, the stability factor for each pixel is calculated. The effect of the neighbouring pixels is ignored.

The stability factor maps will be designed by overlapping the parameter maps, according to the mathematical formula given by the infinite stability slope model, considering four scenarios: completely dry soil, completely saturated soil, dry soil under seismic loads and saturated soil under seismic load.

The relative size of the areas that are found to be stable, critical or unstable slopes will result from the reclassification process of the final maps according to the minimum values required for the stability factor.

The practical work for landslide hazard assessment using infinite slope model, on GIS systems was built for the geographical area of the Bucium Hill and hydrographic basin of Vamasoaia River, located in Iasi City, on the south side of the Bahlui River.

The Iasi City represents a very geomorphological-active region from Romania which is certified by a large number of landslides registered over time. Predisposing, preparing and triggering factors such as intense slope, soil saturation, erosion processes and human actions are overlapping and leading to a wide variety of geomorphic phenomena.

The natural landforms extracted from digital elevation model indicate maximal altitudes between 100 – 370 m and general slopes between 10 – 20 degrees

The built model uses geotechnical data obtained in laboratory tests on samples from 25 geotechnical boreholes with depths between 2 and 10 m, executed in the field and topographic data consisting of a digital terrain model with 1m resolution. This type of models requires very high accuracy data.

In the end, two more landslides hazard maps will be presented, achieved for the same study area, using different approaches such as the bivariate statistical method and the national methodology. The way these maps are obtained will not be the subject of this paper work, but they allow comparing the final results.

2. THE PECULIARITY OF THE NATURAL LANDSLIDE HAZARD

The natural hazard of landslides is a potentially destructive physical event in which circumstances can cause property destruction, a negative social and economic impact, environmental degradation, and even injuries or loss of life. Slides of landslides may have natural triggers or may occur due to human activities [1]. Landslides hazard zonation allows delineation between stable areas and instable or potential instable area.

In the research literature, at the national and international level, can be found valuable documents and studies regarding landslide hazard assessment and its mapping methods. However, there is not a standardised method for achieving these types of maps. The landslides hazard maps can be designed using different approaches depending on user requirements, assessment purposes, mapping scale factor and very important, the quality of the available data.

Also called instability map or failure probability map, the landslides hazard map is a site plan to a conveniently chosen scale performed in a study area, which divides the entire area in polygons characterised by the same instability degree.

The first landslide hazard maps have been developed in the proximity of 1970 [2] [3].

The scientific community reveals a range of landslide hazard assessment methods. Those methods involve either qualitative evaluation such as inventory-based methods and knowledge-driven methods, either quantitative evaluation such as data-driven methods and physically based methods [4].

Very large used and recommended methods for data-driven landslide hazard assessment are bivariate statistical methods, multivariate statistical methods and artificial neural networks. The statistical methods, they are strictly dependent on landslides inventories.

Physically based methods are relayed on landslide hazard assessment using the modelling of slope failure processes. Examples of methods for physically based landslide assessment are GIS-based limit equilibrium methods (e.g. static infinite slope modelling), kinematic analysis for rock slopes, 2-D limit equilibrium methods, 3-D limit equilibrium methods and numerical modelling.

In the last three decades, collecting and processing data using automatic systems have been recorded significant developments and great progress. Now, there are available for large use many computer programs, able to process high complexity operations.

3. NATURAL AND ANTHROPIC CONDITIONS INFLUENCING NATURAL LANDSLIDE HAZARD

The natural landscapes of Iasi constitute of high fields bordered by hills or interfluvial hills with maximum altitudes between 100 and 370 m (Figure 1), developing steep slopes, some affected by erosions and landslide processes characterised by an extremely active morphodynamic.

The vulnerability of the study area, located in the Moldavian Plain reveals an area with the high potential of landslides manifestation, sometimes with great magnitude and generating significant damage.

The eastern side of the Copou Hill, the segment between Sararie and Ticau, the right overbank of the Cacaina River, the Bucium Hill, the Galata and Niculina districts are only a few examples which have registered numerous areas with high landslides occurrence. The morphodynamic activity attained a higher intensity in the early twentieth century, most likely with the beginning of slope deforestation and development of the inhabited area. The human intervention on the natural slopes and the large removal of the forest are two of the main causes of the instability slope increasing.

In the recent decades, the municipality has completed extensive work to reduce the landslides risk for Iasi city and yet the instability potential is still high.

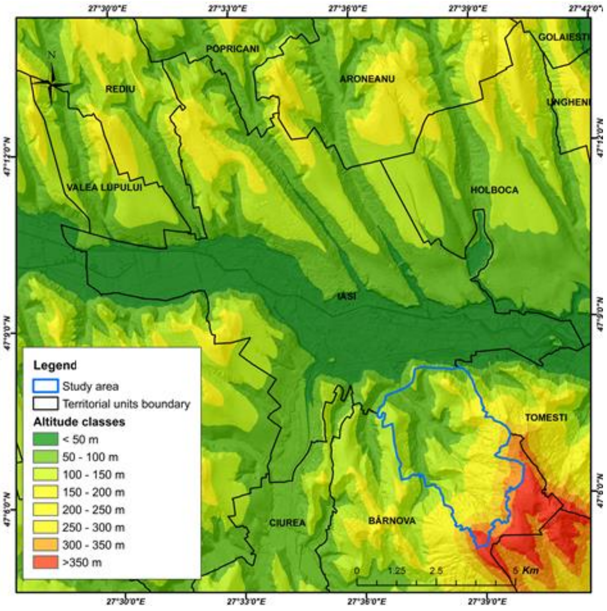

Figure 1. Terrain altitude map

From the geotechnical point of view, the soils layered in the Bucium Hill area have the following general stratification: under a filling layer with the maximum thickness of about 3 m, distinguish a succession of cohesive materials like clay, silty clay or silt with clay fractions, sandy clays, being in a mostly semi-solid consistency and plastic consistency, placed on a sandstone outline bedrock.

Sandy clay, silty clay or clay with small sands lens are generally found in the floodplains of the rivers. Clay and silty clays, with plastic consistency, are generally found in the hilly areas. Through its physical and mechanical properties, silty clay is considered a conducive environment for slip surface occurrence and slope failure.

The main trigger factor of slope failure is the presence of water (groundwater or surface water) by increasing tangential forces along the sliding plane.

The annual rainfall conditions are represented by the continental climate regime, with multi-annual averages of 518.9 mm at Airport Station and 514.8 mm at High School Negruzzi Station, with the minimum in February (25.9 mm) and March (23.8 mm) and a maximum in June (70.4 and 76.7 mm). The highest average daily amount of rainfall was recorded in June (2.2 mm) and the lowest in March (0.8 mm) and December (0.9 mm). In most years, snow has reduced thickness, in the winter of 1931-1932 was recorded the highest accumulated snow thickness (195 cm). The average annual temperature is about 9-10 degrees.
The rainfalls with long periods and slow discharge, the large melt of snow accumulations and the freeze - thaw processes are the major causes generating landslides.

4. INFINITE SLOPE STABILITY MODEL

The equilibrium state of a natural earthen slope can be assessed based on the estimation of the stability factor, a factor whose physical significance is expressed by comparing the stress conditions along the potential slip surface.

Therefore, the stability factor is determined as the ratio between the soil shear strength and the induced tangential forces as shown in Equation (1).

$$F_s = \frac{\tau_f}{\tau} \quad (1)$$

Acceptable values of safety factor which define the stability ranges are 1.5 for dry conditions, 1.3 for saturated conditions and 1.1 for infrequent loading conditions such as seismic acceleration. Lower values than 1 indicate unstable slopes. Values ranging between 1 to the acceptable minimum values indicate critical slope. The stable slopes are characterised by values higher than acceptable values.

The proposed model in this paper evaluates the stability factor based on the infinite slope model.

The infinite slope stability model is a high degree simplified model, which oversees the destabilising components of gravity in relation to the resistance components given by cohesion and friction along a failure plane, considered parallel to the natural ground surface (Figure 2).

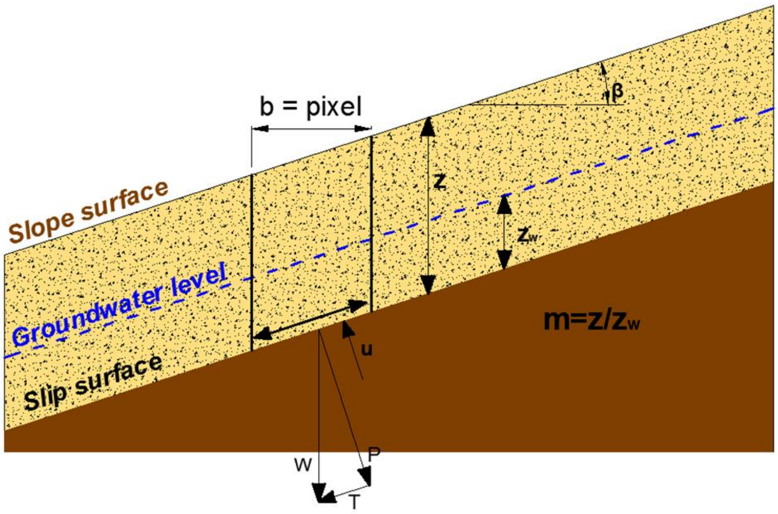

Figure 2. Infinite slope model

The infinite slope model takes into account an infinite sliding plan and calculates the stability factor according to Equation 2 [5].

$$F_s = \frac{c' + (\gamma - \frac{z}{z_w}\gamma_w) z \cos^2 \beta \tan \phi'}{\gamma z \sin \beta \cos \beta} \tag{2}$$

Where

c'	effective cohesion (Pa);
ϕ'	effective internal friction angle (°);
γ	unit weight of soil (N/m^3);
γ_w	unit weight of water (N/m^3);
z	depth of slip surface (m);

z_w height of groundwater table above slip surface (m);

β terrain slope (°).

The calculation of the stability factor under seismic conditions uses the mathematical formula given by Equation 3 [5].

$$F_s = \frac{c' + (z\gamma\cos^2\beta - z\rho\alpha\sin\beta\cos\beta - z_w\gamma_w\cos^2\beta)\tan\phi'}{\gamma z\sin\beta\cos\beta + z\rho\alpha\cos^2\beta} \tag{3}$$

Where

ρ bulk density (kg/m^3);

α peak ground acceleration (m/s^2);

The geotechnical (physical-mechanical soil parameters) and morphological parameters are the ones that determine the construction of the model and they are most often measurable and can be considered state variables that have a unique value at a given point in time and space.

The model accounts for different trigger factors such as the transient groundwater response of the slopes and/or the effect of earthquake excitation.

The soil moisture leads to the increase of water pore pressure and the decreasing of the effective normal stress, which through the internal friction angle is related to the shear strength of soil (Mohr-Coulomb failure criteria). The edge effects are considered negligible.

The infinite slope model approach applies over large areas when the geological and geotechnical conditions can be considered relatively homogeneous. It is intended to be used at a local scale, for shallow landslides (less than a few meters in depth), generally for translational sliding. It does not apply to deep-seated instability phenomena, only for simple landslide types.

It is also applicable to areas with nonexistent or incomplete landslide inventories when other methods (such as statistical methods) cannot be implemented because of their dependence of historical landslides locations map.

Infinite slope stability model has a higher predictive capability and provides more suitable and consistent results than heuristic and statistical models, which picture the underlying physical parameters leading up to the phenomena being modelled.

The disadvantages of the model are the high degree of simplification involved and the required for large field input data.

The main advantage of the proposed model is the ability to calculate the quantitative values of stability (safety factors or probability of failure).

5. SPATIAL DISTRIBUTION OF THE STABILITY FACTOR IN THE STUDY AREA

5.1. Site characterization

Bucium Hill and hydrographic basin of Vamasoaia River are located on the south side of Iasi city, in an area characterised by a monoclinic geological structure, the slopes surface being affected by land terraces erosion and sliding occurrence.

The area is generally occupied by forests, grasslands, orchards, vineyards and inhabited areas.

From the geological point of view, the study area is entirely in the Bessarabian Deposits (bs), the oldest deposits in the region and with the widest spread (Figure 3).

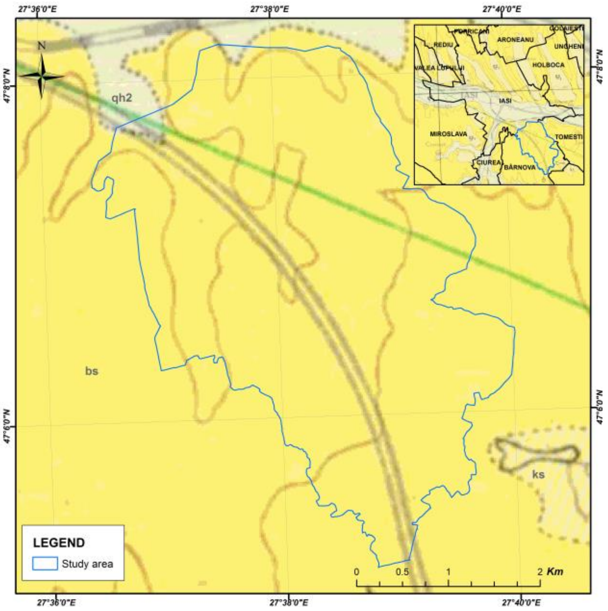

Figure 3. Geological map

Seismic activity of the study area is characterised by a peak ground acceleration value of 0.25g for earthquakes with the mean recurrence interval 225 years and the control period (corner seismic period) 0.7 sec (according to the "Seismic design code - Part I - Design provisions for buildings"- indicative P 100-1/2013).

The groundwater level intercepted in the 25 boreholes, indicates depths between 5 and 7,5 m for the high areas of the Bucium Hill and depths between 1 to 3 m depths for the Vamasoaia valley.

The soils and rocks layered in the study area have the following general stratification: under a filling layer with the maximum thickness of about 3 m, distinguish a succession of cohesive materials like clay, silty clay or silt with clay fractions, sandy clays, being in a mostly semi-solid consistency and plastic consistency, placed on sandstone outline bedrock.

Through its physical and mechanical properties, silty clay is considered a conducive environment for slip surface occurrence and slope failure.

5.2. The structure of the database used for the model construction and data processing

The database used to create the model consists of different types of data such as:

- tabular data (Table 1) that includes information from the study area, stratification description, specific geotechnical parameters (determined in the laboratory tests);
- vector data represented by "shapefile" files, representing points or polygons of the geographic location for study area and boreholes (the vector data will be used to create raster data);
- raster data represented by the digital terrain model (Figure 1), the terrain slopes maps, maps with a spatial distribution of the geotechnical parameters resulted in the interpolation/extrapolation of 25 points measured data (Figure 4).

Table 1. Geotechnical parameters determined in the laboratory tests

Borehole	Borehole depth [m]	Layer depth [m]	Groundwater table [m]	γ [kN/m^3]	γd [kN/m^3]	c [kPa]	φ [º]
FG1	6	1.4	-	18.4	15.0	78.3	21.5
FG2	6	2.5	1.7	18.6	15.2	55.0	22.0
FG3	10	2.7	3.1	19.2	15.6	64.4	21.9
FG4	10	2.8	-	18.4	15.0	78.3	21.5
FG5	6	2.8	-	19.4	16.0	39.1	30.4
FG26	6	1.4	-	18.6	15.7	70.0	25.0
FG37	6	2.4	2.4	18.5	14.6	55.4	13.5
FG38	6	3	-	17.8	14.9	53.1	28.4
FG39	6	2	-	18.8	15.2	48.0	18.0
FG40	6	1.4	-	18.5	14.6	55.4	13.5
FG53	6	1.6	1.8	18.4	15.1	39.2	17.5
FG54	6	5.4	1.8	18.9	15.1	23.0	21.7
FG55	6	2.6	1.2	18.8	15.2	48.0	18.0
FG11	2.2	2.2	-	18.7	16.0	53.7	29.8
FG12	5.2	5.2	-	18.5	15.2	66.7	24.1
FG13	10	5.3	7.5	17.9	14.9	96.3	26.8
FG14	4.7	3	-	18.6	16.2	75.3	25.7

Borehole	Borehole depth	Layer depth	Groundwater table	γ	γd	c	φ
FG15	1	1	-	18.6	15.7	70.0	25.0
FG16	1.7	1.7	-	17.7	15.7	60.0	27.0
FG17	9	1.4	6	20.1	17.7	14.8	21.7
FG18	10	2.2	-	18.4	14.8	50.7	27.9
FG19	3.2	1.8	-	18.6	15.7	70.0	25.0
FG20	3.2	2.3	-	15.7	14.7	65.0	25.0
FG21	1.3	1.2	-	18.7	16.0	53.7	29.8

All used data and built maps are raster format and following the Stereo 70, S42 Romania coordinate system.

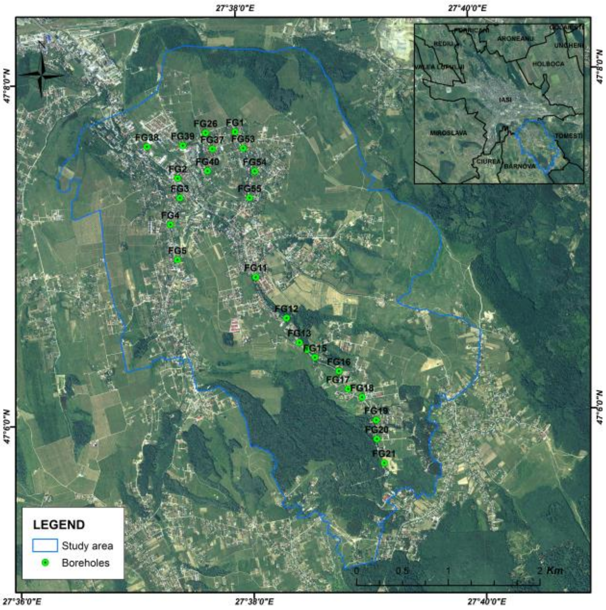

Figure 4. Geotechnical boreholes location

The maps representing the spatial distribution of geotechnical parameters like cohesion map (Figure 5.a), internal friction angle (Figure 5.b), dry soil weight map (Figure 5.c) and soil depth (Figure 5.d), were built by interpolating the measured data.

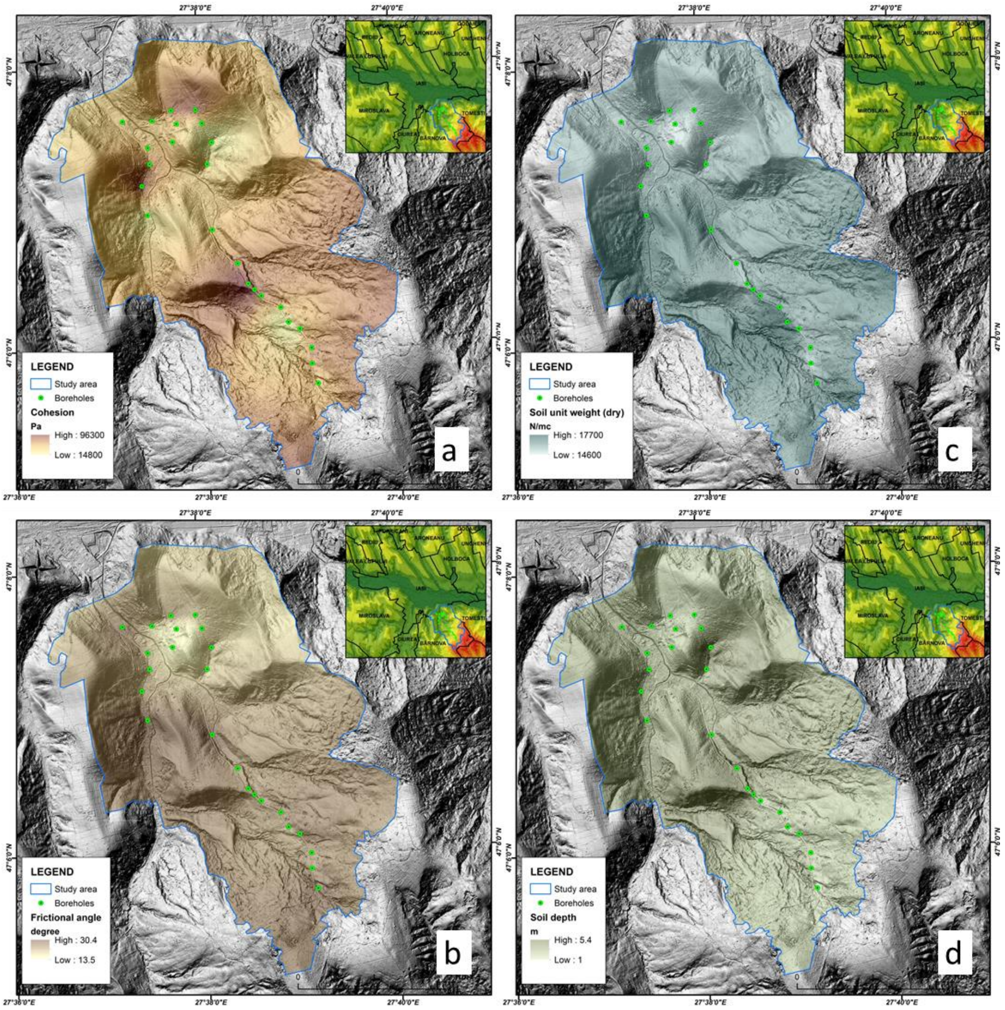

Figure 5. Spatial distribution of soil parameters: a. cohesion, b. internal frictional angle, c. soil unit weight, d. soil depth

The terrain slope expressed in degrees (Figure 6.a), well as the sinus function (Figure 6.b) and cosine (Figure 6.c) function applied to the slope, result from the digital terrain model with 1m precision, using the GIS tools.

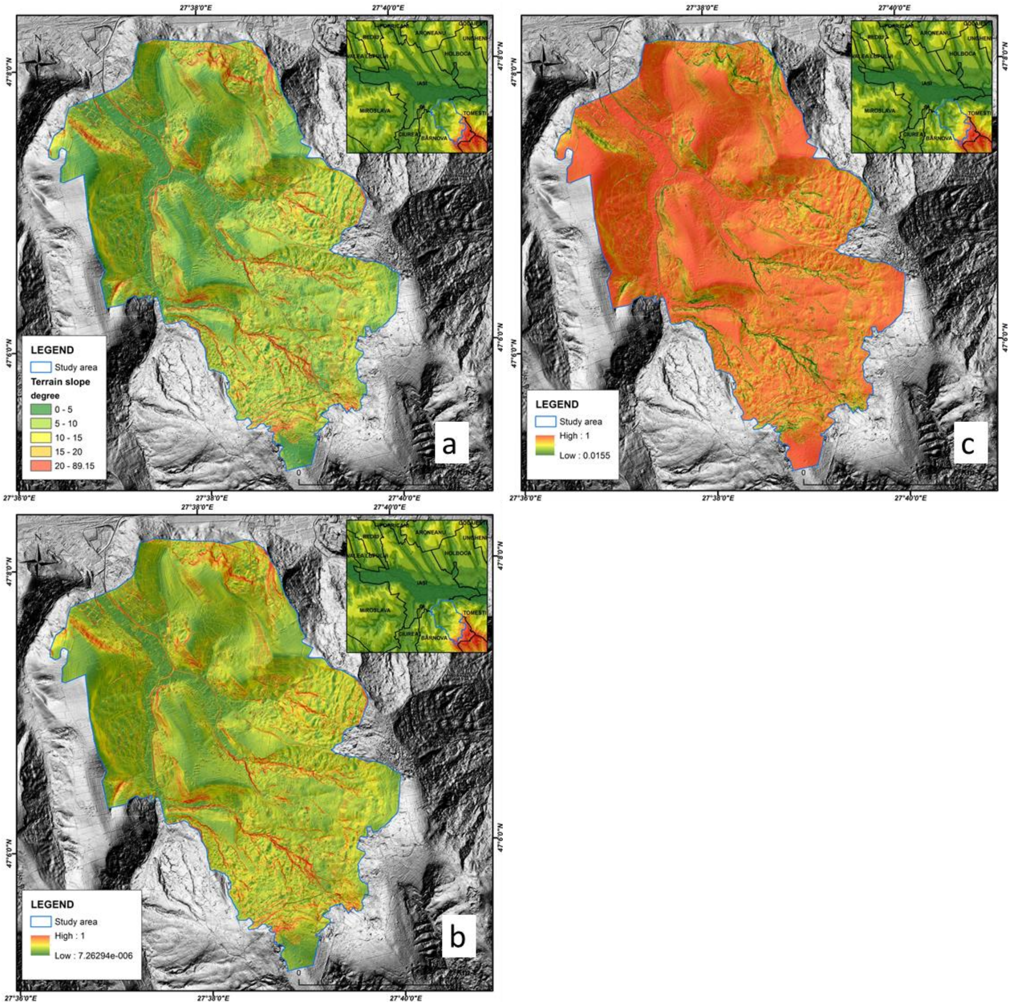

Figure 6. Terrain slope: a. slope (β), b. sin (β), c. cos (β)

5.3. Stability factor assessment

Applying Equation 2 and Equation 3 on the GIS parameter maps presented above, will outcome the spatial distribution maps of the stability factor, for different scenarios of groundwater and seismic acceleration. The stability model is generated as GIS functions. The four different scenarios are calculated by changing the variables of these functions.

5.3.1. Scenario 1 – Spatial distribution map of the stability factor considering dry conditions

The safety factor is evaluated under the assumption the soil is completely dry, so the groundwater table is equal to 0. The completely dry scenario is an extreme situation and may not occur in a region such as Iasi.

In these conditions, the Equation 5 substitutes the Equation 2, by replacing the parameter given by Equation 4.

$$z_w = 0 \tag{4}$$

$$F_s = \frac{c' + \gamma z \cos^2 \beta \tan \phi'}{\gamma z \sin \beta \cos \beta} \tag{5}$$

Applying Equation 5 in GIS platform outcomes the factor stability maps as shown in Figure 7.

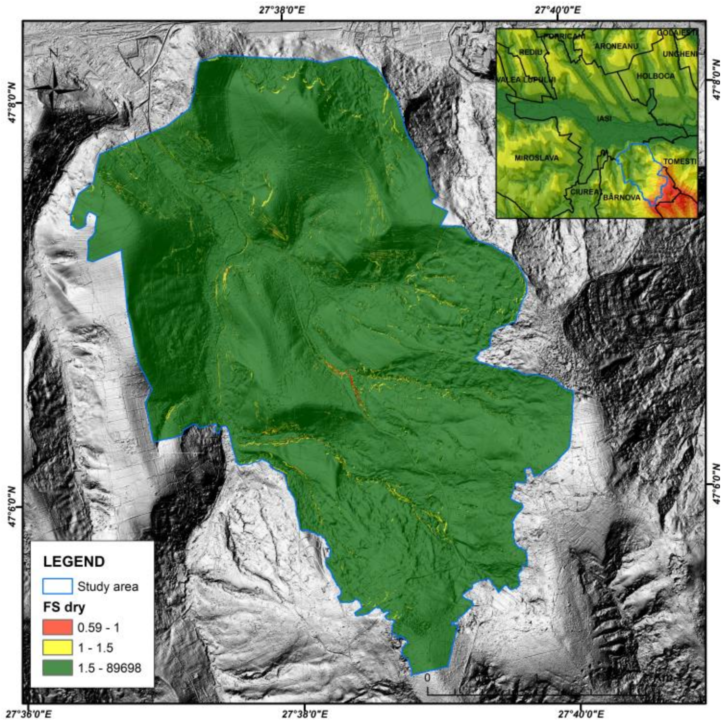

Figure 7. Spatial distribution of stability factor considering dry conditions

The completely dry scenario result indicates the most stable situation.

5.3.2. Scenario 2 – Spatial distribution map of the stability factor considering saturated conditions

The second scenario aims the stability assessment under the assumption the soil is completely saturated. This requires a diminution of the shear resistance parameters (cohesion and internal friction angle).

The Equation 7 substitutes the Equation 2, by replacing the parameters given by Equation 6.

$$z_w = z \tag{6}$$

$$F_s = \frac{c' + (\gamma - \gamma_w) z \cos^2 \beta \tan \phi'}{\gamma z \sin \beta \cos \beta} \tag{7}$$

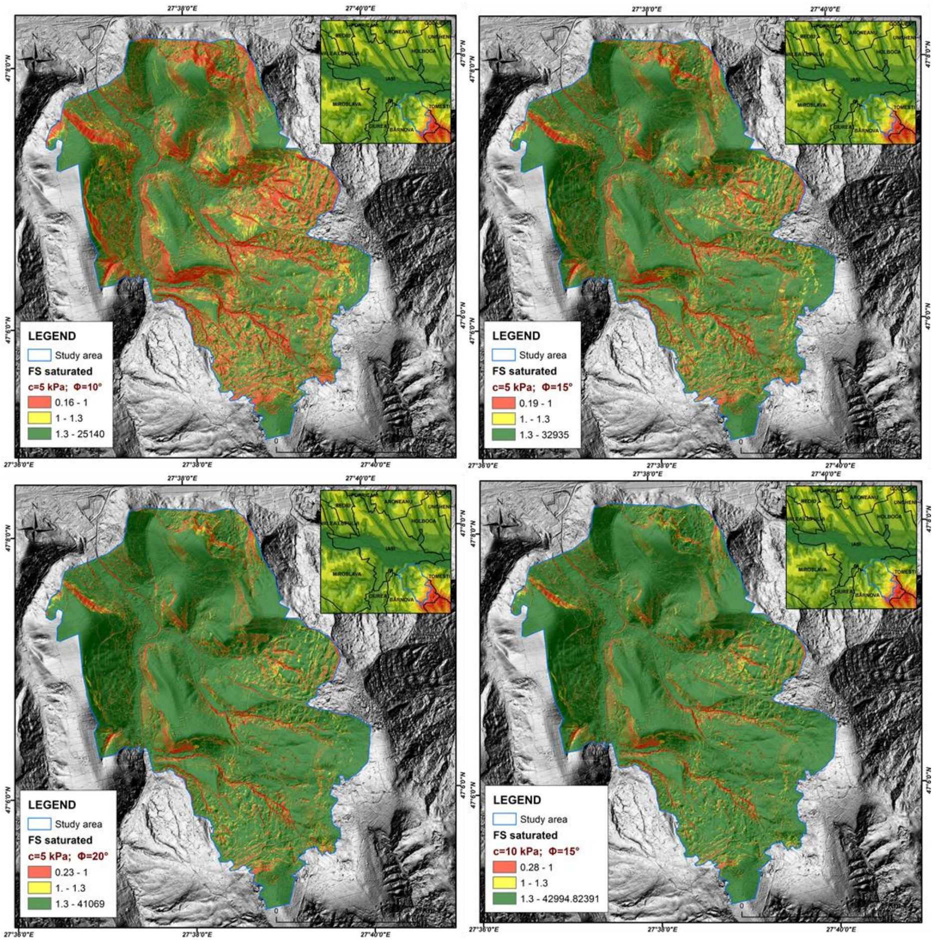

Figure 8. Spatial distribution of stability factor considering saturated conditions

Applying Equation 7 in GIS platform outcomes the factor stability maps as shown in Figure 8.

It is noticed that the presence of the groundwater table does not produce a significant increase in the potentially unstable surfaces and the study area surface remains still generally stable or partially stable.

5.3.3. *Scenario 3 – Spatial distribution map of the stability factor considering dry conditions and seismic action*

The third scenario assesses the stability factor considering completely dry conditions and seismic loads, associated with the peak horizontal ground acceleration.

In these conditions, the Equation 8 substitutes Equation 3, by replacing the parameters given by Equation 4 and considering the peak ground acceleration equal to 0.25g.

$$F_s = \frac{c' + (z\gamma \cos^2 \beta - z\rho\alpha \sin \beta \cos \beta) \tan \phi'}{\gamma z \sin \beta \cos \beta + z\rho\alpha \cos^2 \beta} \tag{8}$$

Overlapping the parameter maps according to the Equation 8 will disclose the stability factor maps as shown in Figure 9.

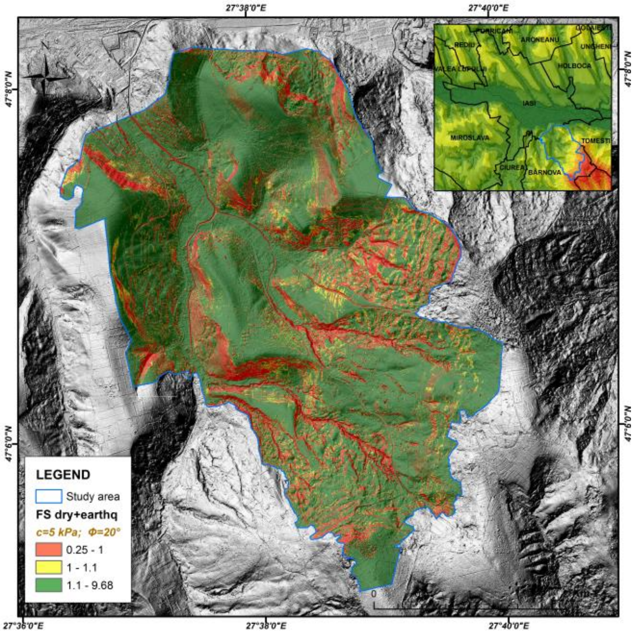

Figure 9. Spatial distribution of stability factor considering dry conditions and seismic action

The influence of the seismic acceleration has led to enlarged unstable surfaces than the unloaded situation simulated by scenario 1.

5.3.4. Scenario 4 – Spatial distribution map of the stability factor considering saturated conditions and seismic action

Considering completely saturated soil and seismic loads associated with the peak horizontal ground acceleration are not very realistic conditions but gives the most pessimistic situation.

Applying Equation 3 on the parameter maps outcomes the factor stability maps as shown in Figure 10.

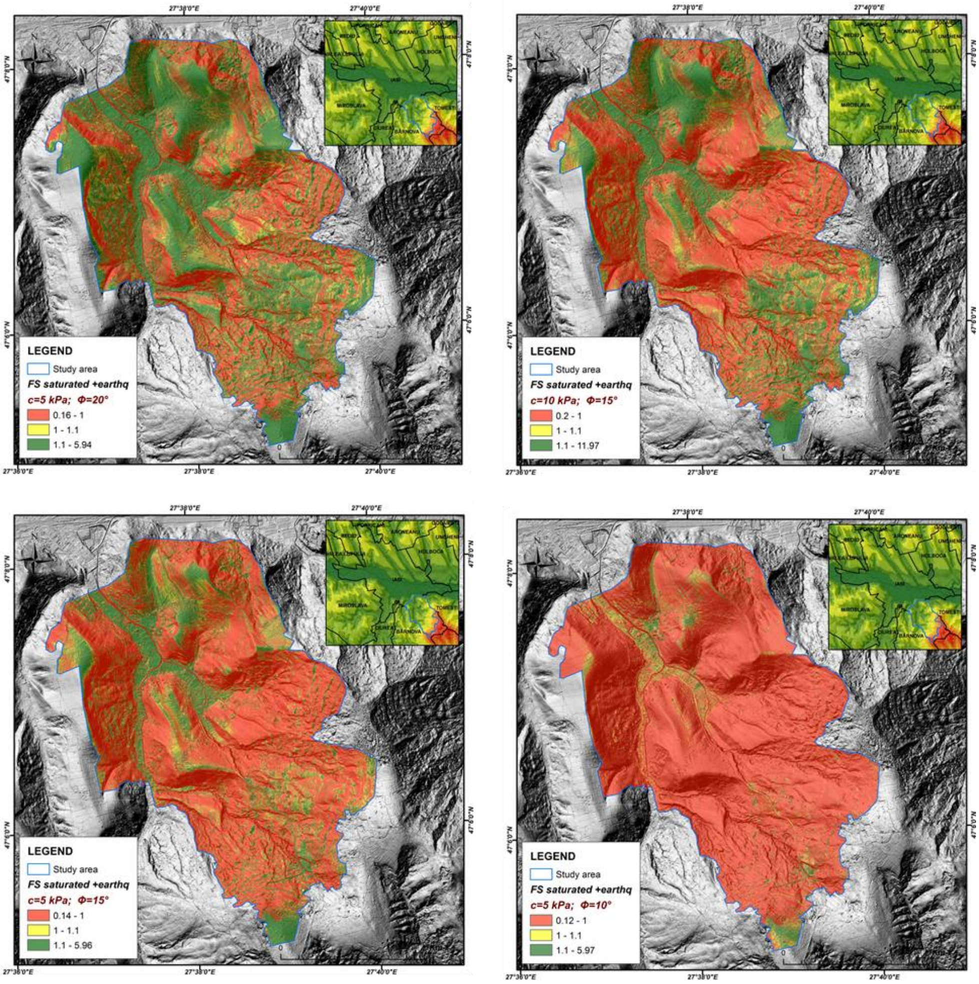

Figure 10. Spatial distribution of stability factor considering saturated conditions and seismic action

3. CONCLUSIONS

The results of the analyses indicate the values of the stability factors, calculated according to four scenarios: completely dry conditions, completely saturated conditions, dry conditions and seismic action, saturated conditions and seismic action.

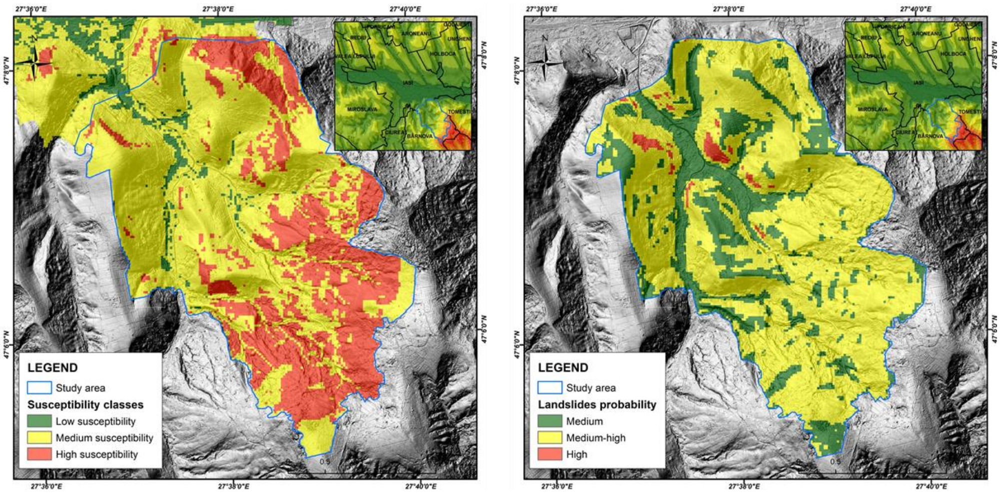

Figure 11. Landslides hazard maps: a. bivariate statistical method, b. national methodology

The landslides hazard assessment using slope stability models, similar to the one created in this paper, have higher prediction capability than other qualitative or quantitative methods (Figure 11), for example statistical methods, because it evaluates the potential slip following a calculation based on the parameters measured in the field, while the other quantitative methods are based on historical data (landslides inventories), and this can lead to results with high degrees of uncertainty.

These types of analyses are more suitable for soil layers less than a few meters in depth, with high superficial landslides occurrence and which are characterised by the presence of cohesionless soils or poorly cohesive soils.

One disadvantage of using the method is the high degree of simplification of the slope failure mechanism.

The landslides hazard assessment based on the stability factor is preferable to be used for local analyses. It can hardly be applied at national scales due to the variability of geotechnical data and the difficulty of building a national geotechnical database with high precision.
The stability factor maps keep the purpose and the quality of the hazard maps and will not serve the constructions design activities..

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