

## “Efficient” Landslide Mitigation Strategies for Roadlines in Earthquake Prone Areas

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### ABSTRACT

The objective of this study is to introduce an “efficient” mitigation strategy for roadlines subjected to landslides, through a three-level seismic risk assessment methodology as a result of earthquake and/or rain/snow precipitation. Initially, the spatial distribution of landslide hazard, along the weathered zone-rock interface, is determined in a buffer zone extending on both sides of the road by the use of limit equilibrium methods of analysis that evaluate the safety factor against failure categorizing the area as stable, conditionally stable and unstable according to a number of produced scenarios. Afterwards, a quantitative landslide risk assessment is applied into selected slopes using the safety factors determined for circular or multilinear type of failure, for scenarios that utilize the available site-specific data. Finally, the stability of rock slopes is estimated to access the possible road closure. The implementation of the methodology is given for Serres-Lailias road in Greece, for a selected scenario, illustrated via GIS.

### Introduction

Landslides pose a serious threat to people (resulting in injuries or fatalities), building structures, land properties and lifelines located nearby. In particular, roadlines in mountainous terrains, as result of landslides, may account performance malfunctions that could lead to reduced serviceability or even road blockage. The severity of the consequences of landslides in socio-economy of the affected area depend on the local site conditions, the type of the triggering event (earthquake, precipitation, erosion, excavation etc), the form of landslide (individual rock falls versus to large creep failures) and landslide’s characteristics (number, timing, location, size, mobility etc.).

The minimization of landslide’s risk is achieved through reliable risk reduction studies and prioritization policies. This paper proposes an integrated three – level methodology for landslide risk analysis of roadlines in rural and mountainous areas, in order to improve the efficiency of emergency response and mitigation plans. The proposed methodology includes several

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individual approaches (1<sup>st</sup>, 2<sup>nd</sup> and 3<sup>rd</sup> level of analysis) for the evaluation of landslide risk of nearby roadlines, caused by natural hazards (earthquake hazard and rain/snow precipitation). Its implementation can be adapted according to the available time, data and money and is closely related to the acceptable and tolerable risk assessment criteria. These criteria can vary according to the country, the specific location and the decision makers' opinion. A case study of the methodology is presented for the main road axis connecting Serres city to Lailias in Central Macedonia (Greece).

### Methodology

The major steps for implementing the proposed “efficient” landslide mitigation policies for roadlines in earthquake prone areas are illustrated in Figure 1:

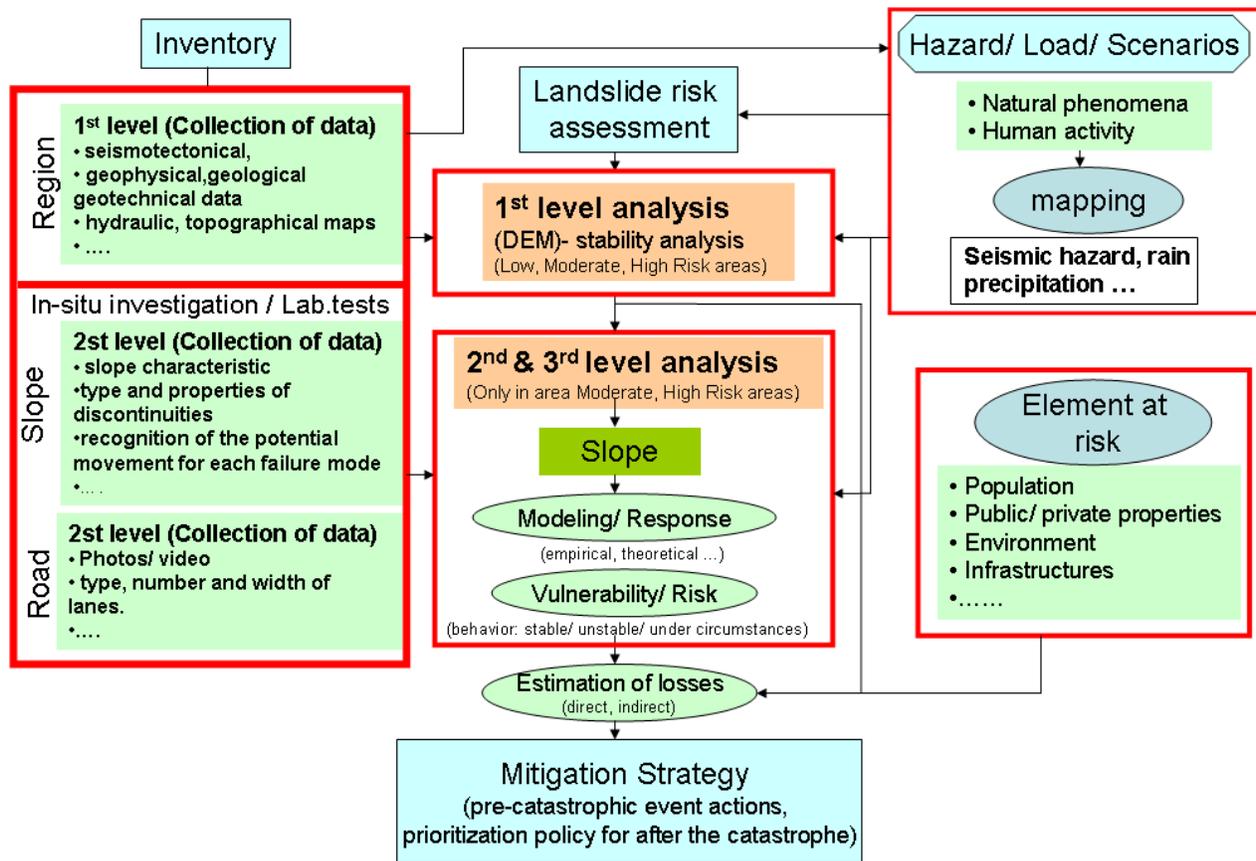


Figure 1. Flowchart of the proposed methodology

**Inventory:** The inventory is cost and time consuming process, with large uncertainties due to the poor knowledge of several components (e.g. structural characteristics of the rocks, the state of weathering and the properties of the soil-rock interface) and the complexity of interrelated terrain parameters (e.g. hydrological conditions, vegetation, land use). It includes the collection of all available data, maps and images. Furthermore, it requires technical visits, collection of slope's characteristics and photographic material of the roadline under investigation. More detailed in-situ investigations (individual characteristics of slopes, laboratory tests) are needed for the 2<sup>nd</sup> and 3<sup>rd</sup> level analysis in “high” and “moderate” risk areas.

***Element at risk:*** The severity of the consequences of landslides depends mainly on the “element at risk” nearby the study roadline. The identification of the “element at risk” (lifelines, building stock, humans or cars passing through possible unstable slope etc) is a first step priority as rockfalls or soil sliding mass may lead to structural collapse, injuries or even fatalities and can create maintenance problems in nearby infrastructures.

***Hazard / Load / Scenarios:*** The spatial distribution of roadlines greatly expose them into potential damage due to natural (e.g. earthquakes, changes in watertable, rapid snowfalls etc) or man-made hazards (irrigation, lawn watering, draining of reservoirs, improper excavating or grading on slopes) as result of wave propagation, permanent ground deformation (PGD), slopes failures etc. Seismic input is provided by different seismic hazard scenarios (mean return period, near-field and far-field earthquakes, duration) appropriate to the seismotectonic environment and the observed seismicity of the area. Rain-snow precipitation scenarios are described by different height of watertable levels, as result of the rain/snow accumulation. Seismic hazard is estimated nearby the roadline, through deterministic or probabilistic analysis of different earthquake scenarios using regional models, seismicity parameters of Seismic Source Zone (SSZ) and active Faults that are close by or intersect the roadline. A simplified soil classification is proposed for the estimation of the spatial distribution of seismic load.

***Landslides risk assessment:*** Modeling - Response - Vulnerability - Risk: Qualitative, semi-quantitative and quantitative predictions are used for the determination of the risk and the probability of landslide occurrence. In the proposed 1<sup>st</sup> level analysis, modeling includes the production of digital elevation model (DEM) of the study area, in terms of pixels, after the compilation of high resolution satellite images, maps and other available information. A calculation of the stability of each individual pixel using data collected in the inventory phase lead to hazard maps for different loading conditions (static, hydraulic, earthquake) for the study area and the consequent identification of “low, moderate or high” risk areas for landslide. In the 2<sup>nd</sup> and 3<sup>rd</sup> level analysis, a quantitative landslide risk assessment is addressed to specific slopes in “high” and “moderate” risk areas. Analytic slope stability utilizes detailed data from in-situ investigations and laboratory tests, correlating with slope modeling (Limit equilibrium, FEM, FDM, DEM, etc) and slope failure mode type.

***Losses/Mitigation Strategy:*** The proposed methodology is based on seismic and rain/snow precipitation scenarios and it can be accounted for both pre and after-event response as it pinpoints specific areas or slopes. It can help to reduce the required funds for the construction or the repair of a roadline, taking into account that the human and material resources are limited and the operation of the road - system should be restored in the minimum available time. The selection of the appropriate policy is based on analyses of the direct and indirect losses in terms of road serviceability, human fatalities and loss of private properties (vehicles).

An application of the methodology briefly described above will be given for Serres- Lailias road in Greece, illustrated via GIS.

## Application in Serres- Lailias Roadline

The roadline connecting the city of Serres with the Lailias ski resort (Figure 2) is located in North-eastern Macedonia, Greece and is especially important in winter because of the increased traffic to and from the ski resort. A significant number of slope failures, mainly in the form of rockfalls and debris flow, have occurred over the last few decades nearby the route of the study road as a result of natural and man-made hazards. The mountainous, seismically active terrain with the heavy snowy winters (rich snow that lasts 3-4 months) and high rain precipitation in spring and autumn are the primary reasons for the slope failures in the study area.

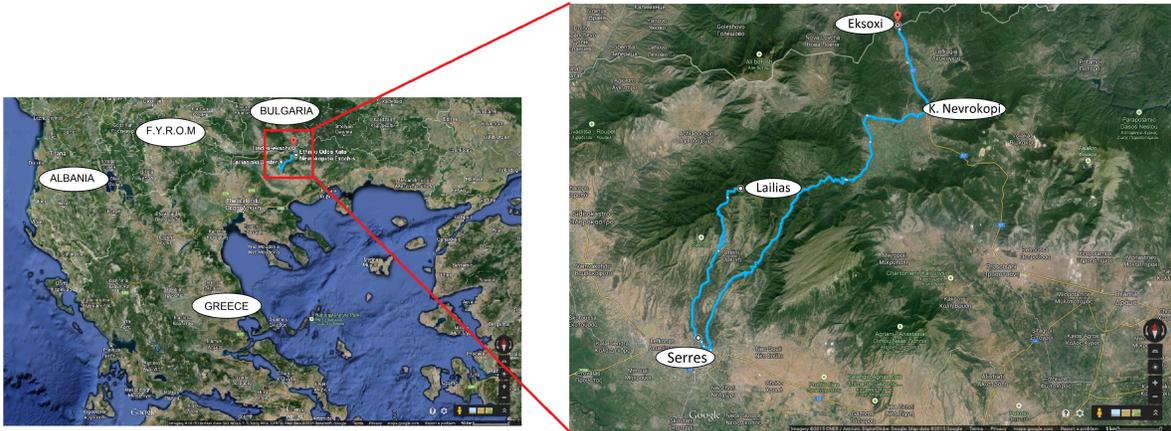


Figure 2. Map of the study area (red rectangular)

Seismotectonical, geophysical, geological, geotechnical, hydraulic, rain precipitation, satellite images and topographical maps, as well as historical records of earthquakes and landslides of the area were obtained after the intensive inventory of the study region. A digital elevation model (DEM) of the study area was created in terms of pixels (2m x 2m) after the compilation of high resolution satellite images and topographical maps 1:5000. Taking into account the digital elevation model, slope angle was estimated for each pixel (Figure 3a).

Effective cohesion ( $c'$ ) and effective friction angle ( $\phi'$ ) were defined based on laboratory tests, in-situ measurements and bibliographic data. The depth of weathered zone-rock interface ( $z$ ) was determined on the basis of geological formation and slope angle ( $\beta^\circ$ ). Relative heights of water table level in the weathered zone ( $m$ ) were selected ( $m=0\%$ ,  $m=33\%$ ,  $m=50\%$ ,  $m=67\%$  and  $m=100\%$ ) according to rain and snowfalls data of the area.

Several scenarios are produced related either to groundwater levels or to earthquake loadings (related to seismic hazard scenarios). The seismic scenarios (return period of earthquakes: 50, 100, 475 years) uses regional models of Seismic Source Zone (SSZ) according to Papaioannou & Papazachos (2000), Poisson model for the seismicity, Ambraseys N.N et al (1996) characterization for soil classification and Skarlatoudis et al (2003) attenuation relationship for the estimation of the spatial distribution peak ground acceleration (PGAs) in 100m x 100m grid and CRISIS 2007 software capabilities (Figure 3b).

Landslide risk assessment (1<sup>st</sup> level analysis) is based on the calculation of the safety factor against sliding along the weathered zone-rock interface, for each raster cell in a buffer zone around the road for each of the selected scenarios, according to the method of Van Westen & Terlien (1996). “Low”, “Moderate” or “High” landslide risk areas are identified. For illustration purposes (Scenario 5: Slope’s Self Weight &  $m=100\%$ ), landslide risk classification is given by the number of raster cells (2m x 2m) per failure mode (“Low” landslides risk areas: 233,362 raster cells, 90.74% of the study area; “Moderate” landslides risk areas: 13,743 raster cells, 5.34% of the study area; “High” landslides risk areas: 10,070 raster cells, 3.92% of the study area) and via GIS landslides maps (Figure 4). Limitation of the applied methodology is that failure along the weathered zone-rock interface is not the only type of failure mode.

The analyses conducted in the study area, indicate that in the case of a “minor-moderate” earthquake (earthquake with return period < 475 years), the obtained results are affected more by the water table level than the earthquake. In the case of “strong” earthquakes (earthquake with return period > 475 years), landslides risk is mainly influenced by them and secondly by the water table level. There is an increase of 2.5 times of the “high landslides risk” regions for the case of earthquakes with 475 years return period, independently of water table level ( $m=33\%$  or  $50\%$ ). The influence of water table level (Scenario: Self-weight of the slope, water table:  $m=33\%$  & earthquake 100 years earthquake return period) is similar in terms of numbers with the case of dry soil and to earthquake with return period of 475 years. “Minor” or “moderate” earthquakes provoke no important landslide failure or road blockage.

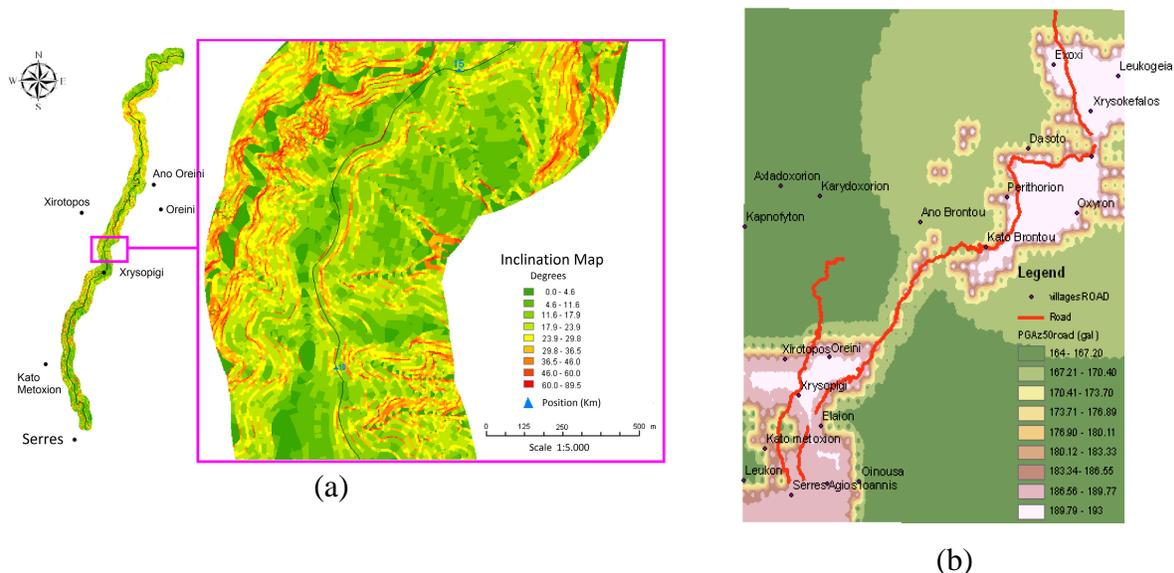


Figure 3. (a) Inclination map, (b) Spatial distribution of peak ground acceleration (Attenuation relation: Skarlatoudis et al, 2003, Soil Type: Simplified geotechnical characterization, Probabilistic analysis, Seismic Scenario: 50 years earthquake return period, Seismic Source Zones)

However, in-situ technical visits and GIS landslides maps lead to the identification of 52 slopes susceptible to landslides nearby the roadline which need further investigation (2<sup>nd</sup> & 3<sup>rd</sup> level analysis). Potential failure mode (e.g. sliding, toppling etc.) and information (slope angle, height,

material type, properties of discontinuities, cohesion, friction angle etc) for slope modeling is collected for the 52 slopes (2<sup>nd</sup> level collection of data). In-situ pull tests, Schmidt hammer tests and laboratory tests including unconfined compression, point load, triaxial and direct shear tests, water content, porosity and slake durability tests on rock samples and density, porosity, grain size distribution and Atterberg limits on the soil samples, are conducted on several samples. The strength parameters of rock sites is determined based on Geological Strength Index (GSI) as proposed by Hoek & Brown (2000) while the parameters of shear resistance of discontinuities are based on the results of in-situ and laboratory tests.

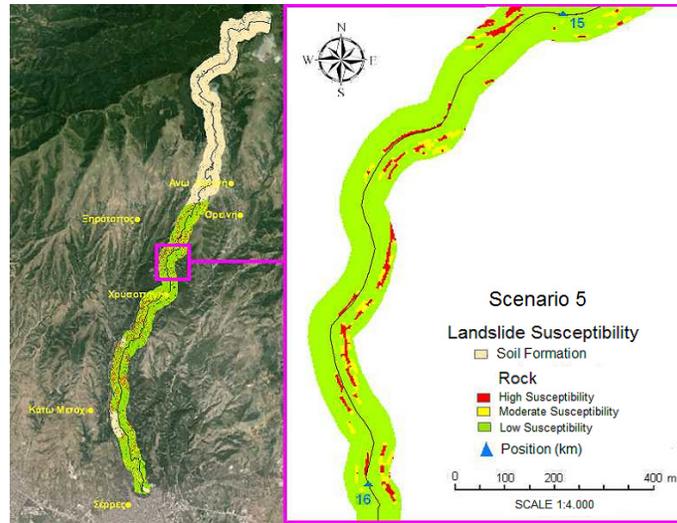


Figure 4. Spatial distribution of landslide susceptible areas (Scenario 5)

The susceptible to landslides slopes are identified and analyzed with 2-D limit equilibrium slope stability analysis software (Slide v.5.0) for different loading combinations (self-weight of the slope: SW, water table changes: W, earthquake with different years return period: E) and two (2) types of failure (circular: C, multilinear type: MT) -Figure 5a. The estimation of the safety factor for the susceptible slopes classifies them as “stable”, “unstable” or “stable under circumstances” (2<sup>nd</sup> level analysis). Indicative examples of the analysis conducted with Bishop method for circular, multilinear type failure are illustrated through the calculation of safety factors of slopes at specific locations for 6 scenarios as provided in Table 3 (“stable slopes”-S, “stable under circumstances”-SC, “unstable”-UN). Figure 5b also illustrates the spatial distribution of susceptible slopes to landslide hazard.

Table 3. Safety factors of slopes at indicative locations for the 6 scenarios

Location	Height (m)	Sc.1	Sc.2	Sc.3	Sc.4	Sc.5	Sc.6
0+500L	1,557	1.60 (S)	1.39 (S)	1.20 (S)	1.63(S)	1.30(S)	1.13 (S)
26+500L	68	1.41(S)	1.09 (SC)	0.99 (UN)	1.39 (S)	1.01(SC)	0.93 (UN)
35+400L	425	1.44 (S)	1.07 (SC)	0.97 (UN)	1.41(S)	1.05 (SC)	0.93 (UN)

where: Sc.1: SW & C, Sc.2: SW & W & C, Sc.3: SW & W & E & C, Sc.4: SW & MT, Sc.5: SW & W & MT, Sc.6: SW & W & E & MT

Taking into account the obtained results using Bishop method and the two types of failure, 23% of slopes (12 from 52) are “stable” and one (Location: 84+900) is expected to fail for all the scenarios. Pre-event actions are advised to stabilize the specific slope. The rest of the slopes state “stable”, “stable under circumstances” or unstable depend on the scenario.

The 3<sup>rd</sup> level analysis is concentrated on the stability of specific surface wedges in rock slopes, on rockfalls and on soil sliding mass. Rockfall assessment is performed using ROCFALL (Rocscience) that takes account in-situ investigations and laboratory tests in 27 rock slopes, with weights of rock pieces ranging between 10kg and 100 kg. Energy, velocity and "bounce height" envelopes for the entire slope and the location of rock endpoints are determined.

Mitigation strategies, account the consequences of slopes sliding on the element at risks as result of the estimation of the spread of rocks compared with the width of the roadline (Figure 5c), of the road serviceability (Table 4) and the probability of a rock fall onto a moving vehicle.

Table 4. Road serviceability as result of rockfalls

Chainage	Road width (m)	Road shoulder (m)	Max. Spread of rock pieces (m)	Road serviceability
5+250R	5.4	0.6	-	100% “Fully Open”
5+500R	5.4	0.8	3.44	45% Open → “Partially Open”
7+000R	5.8	0.5	6.00	5% Open → “Blocked”

The probability of a rock fall onto a moving vehicle can be estimated according to the method proposed by Australian Geomechanics Society (AGS, 2002). According to the obtained results, even in the extreme case of a rock fall occurrence, more than 60 to 70% of the road width is expected to be open. The fact that there is no alternative routing in the case of “blocked” Lailias – Serres road, immediate stabilization actions and measures should be taken. These measures may fall in one of the following practical groups suggested by IUGS WG/L: (1) modification of slope geometry (2) drainage (3) retaining structures and (4) internal slope reinforcement

### Conclusions

The scope of this research paper was to present a methodology for an “efficient” landslide risk assessment and management for roadlines on earthquake prone areas. The methodology was applied to Lailias-Serres roadline in the North-eastern part of Greece. An extensive inventory and data collection binned with systematic field observation, a geology-based zonation, an in-situ investigation and laboratory tests are necessary for the further evaluation of possible “high” and “moderate” risk areas with landslides instability problems. Different loading cases (scenarios) arising from the combination of the weight of the slope and the actions of water and earthquake were considered for the analysis. Slope modeling was accounted, in the 2<sup>nd</sup> and 3<sup>rd</sup> level analysis, through appropriate software (SLIDE, ROCFALL) that estimate the possibility of slope failures and rock spread in the case of rock falls. Applying the proposed methodology, it was possible to estimate the direct losses in terms of human fatalities or private properties (vehicles) and propose, where necessary, appropriate mitigation actions. A case study was used to demonstrate the application of the proposed methodology.

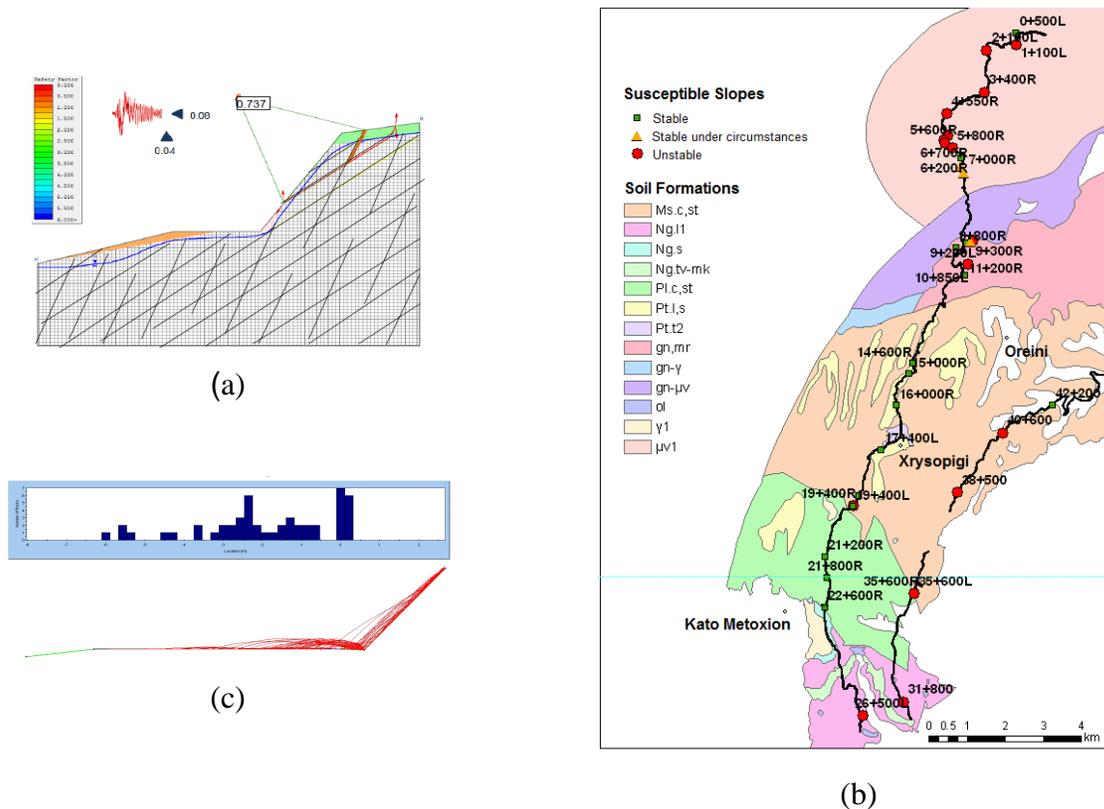


Figure 5. (a) Geotechnical model of slope at chain. 84+900 (seismic loading), (b) Spatial distribution of susceptible slopes to landslide hazard Lailias- Serres road (Scenario No 6), (c) Potential paths of the rock blocks falling from the top of the slope (Location: 7+000R)

### Acknowledgments

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