Harmonized approach for earthquake - induced landslide susceptibility and risk assessment in Vodno urban area

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Abstract During the last 20-25 years Skopje, and more specifically Vodno mountain, has been exposed to intense urbanisation, population growth, followed by intense anthropogenic processes such as application of structural loads, vegetation cuts and excavations, which have significantly changed the initial conditions of the terrain. These factors, along with the continual changes and degradation of the terrain, have provoked numerous instabilities in the area, and thus raised great concern and interest among the media and the scientific community, which work in the field of landslide hazard and risk assessment. As well, it should be emphasised that this area contains critical infrastructure, such as hospitals, schools, kindergartens, police station, roads etc., as well as around eleven international embassies and residences, which accentuates the problem furthermore.

In this paper, we provide a harmonised approach for earthquake induced landslide susceptibility in this urban area, through the infinite slope limit equilibrium method. For the analysis we used several datasets such as geomorphological (DEM raster file), detailed plan of the buildings and loads, geological and finally seismological datasets. The results obtained are shown accordingly in QGIS open-source software for spatial analysis. It has been proven that the influence from the constructions with different loads and typology, is of great importance for the analysis of the stability and the risk evaluation as a result. This approach proves the combined effect of anthropogenic influences on the terrain through the non-controlled urbanisation process, on the stability of the Vodno urban area under expected seismic scenario. Furthermore, the paper provides directions for reduction of the vulnerability of the people in the aforementioned area, through the process of the future spatial planning in synergy with scientific approach and possible construction measures.

Keywords earthquake - induced landslides, landslide risk, QGIS

Introduction

According to some sources (Vale C, 2019), during the 20-th century, nearly 80 earthquakes have triggered between 100.000 - 1.000.000 movements of the earth masses, which has resulted in large material, as well as loss of several thousand human lives. Moreover, about past major landslides (period between 1900-2020) across the World, it can be emphasised that, around 50% of the total death toll is from landslides triggered by earthquakes. On another hand, the landslides triggered by rainfall are responsible for about 15% of the total casualties, even though they are 2,5 times more frequent than the ones triggered by earthquakes (Fig. 1). Another interesting insight from the analysed data of landslides is that, in time the number of casualties from rainfall-induced landslides is slightly decreasing, which is not the case with the ones triggered by an earthquake. Having in mind this, earthquakes are considered among the most significant natural trigger for landslides, due to the fact that they can't be predicted and their influence on the slope stability might be disastrous.

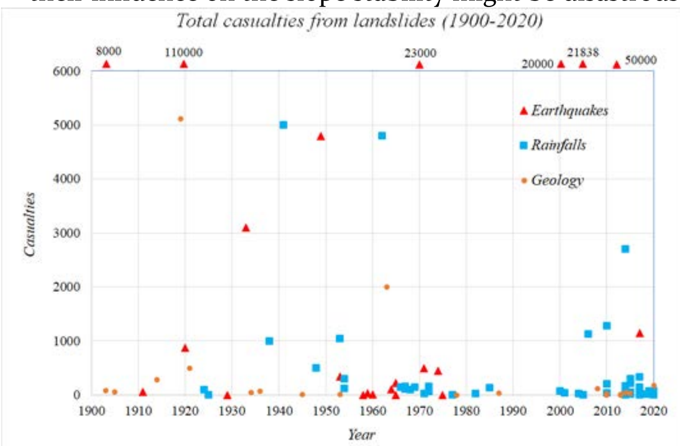

Figure 1 Human loss from landslides 1900–2020 (D. Nikolovski 2021)

The Republic of North Macedonia (25,713 km²) is a country with a hilly-mountainous morphology. Namely, almost 2% of the territory is covered by water bodies, about 19% are plains and valleys, while the largest part of about 79% are hills and mountains (*Milevski* 2018), which is a great indicator for the potential of the terrain towards geo-hazards in general. In addition, the country and especially its capital Skopje, has been and unfortunately still is, threatened by many hazards such as: earthquakes, landslides, floods, air pollution, etc. The main aim of this study is to produce a landslide hazard and risk assessment of the Vodno urbanised area, due to earthquake event with a return period of 475 years, for the first time in recent history, . This initiative is in context to reduce the risk from this type of hazard as much as possible, through constructive and non-constructive measures, as well as to adapt and be prepared for both the expected and possible earthquake induced disasters.

Case study and parameters definition

Vodno mountain stretches in an east-west direction for about 12 km, where the highest point is Krstovar peak which is at around 1066 metres ASL. The natural slope of the terrain in the Vodno suburb is at around 10 – 20°, while in the upper zones the terrain is steeper with inclinations >25°. The mountain is surrounded in all directions with urban areas of approximately 4481,0 ha. Te most densely populated area is Vodno settlement, which is part of Centar municipality. This is an area of around 1,59 km², and the population density is approx. 2498 people/km², with constantly increasing population . Some official stats provide the information that the number of households in the area has increased for around 10,0%, while the number of apartments for around 30,4% in the time span of just 20 years. Interestingly, according to the official statistics, around 66% of the population in this area are inactive and older people, which according to latest research (UN Office for Disaster Risk Reduction) has proven that are more vulnerable and experience more casualties in case of natural disasters. It's also important to emphasise that the Vodno area contains facilities, which are considered as critical infrastructure, such as 2 hospitals, 3 schools, 3 kindergartens, 1 police station, roads etc., as well as around eleven international embassies and residences.

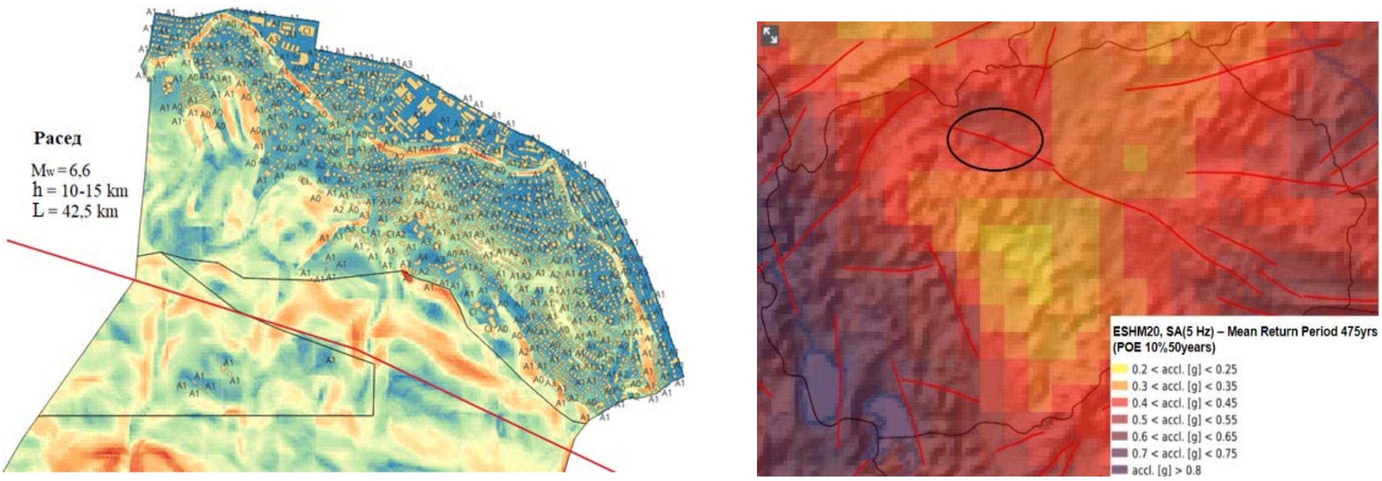

Figure 2 Digital elevation model (DEM), fault line and PGA for return period of 475 years for the study area

Related to the parameters, the identification of the slope angles (α) and heights, are derived from a detailed digital elevation model of the terrain (DEM), of 5 x 5 m spatial resolution. The lithology of the region has been investigated in the past, (Geologic Map - Skopje K 34 – 79), through detailed engineering-geologic mapping of the terrain. Furthermore, in a more detailed manner, the terrain properties have been explored during the urbanisation purposes in the last two decades, through geophysical soundings, as well as direct investigation methods (boreholes, CPT and SPT tests). The terrain investigations have shown rather complex and heterogeneous lithology of the terrain. It's composed of Pliocene clays (*Pl*) in the shallow zones, which overlay older Miocene claystone and marlstone sediments (*M3*) with thickness of around 300 m., these materials are used as foundation materials below the structures in the area, and they can be treated as quasi-homogeneous zone.

The earthquake magnitude (*Mw*) as well as the location and type of fault structures that are near the region, is defined according to the probability of seismic hazard from the European-Mediterranean seismic hazard model (ESHM-20). This model incorporates a harmonised approach to earthquake records, tectonic zoning, a list of active fault zones and information on the geological structure of the terrain, types of ground motion, etc. The results for magnitudes and fault zones, with its geometric and topological parameters are derived for the region AL-MK-BG, from the Share SHEEC 1900-2006 data file, which is aligned based on data from more than 13600 earthquakes., a seismic scenario is defined with a return period of 475 years, which is considered the age of exploitation of the objects of the analysed region. The values of maximum ground acceleration are defined by the same hazard model (EFEHR | Hazard Maps), where for the location for a period of 475 years, a value of PGA = 0.40 is obtained.

The calculated arias Intensity (*Ia*) is a function of the depth and distance of will be defined for the location of Vodno, from the database of known fault lines, that are in the Skopje Depression (Fig 2). In the literature on the European seismic hazard model ESHM-20, it can be found one active normal fault structure, which is at a depth of between *h*=10-15 km, length of 42,5 km and is with expected magnitude *Mw*=6,6. The distance of the fault from is 800 - 1000 m from the centre of gravity of the area analysed in this research paper. Furthermore, to define the arias intensity, the spatial parameters of this fault will be taken, and according to the method of *Wilson* and *Keefer* 1985:

$$\log_{10} I_a = -4{,}1 + M_w - 2\log_{10} (d^2+h^2)^{0{,}5} - 0{,}5P \quad [1]$$

Where:

I_a	arias intensity (m/s)
M_w	magnitude
d	shortest distance from the hypocentre to the fault
h	depth of earthquake occurrence (km)
P	probability

Above mentioned parameters are going to be used in further regional analysis of earthquake – induced sliding of Vodno.

Earthquake-induced landslide hazard and risk assessment

In the last two-to-three decades, GIS has been recognized among the scientific community as a powerful set of tools for collecting, storing, analysing, and displaying spatial data, for different purposes. Mostly due to the time-consuming and local based approach of the FEM analysis, it is considered that this type of approach, through the Geographical Information System, may be more efficient in the landslide hazard assessment, by application on a whole variety of spatial data and variables. Hereby, in the research paper, the landslide susceptibility as well as the risk analysis are going to be analysed through the open source QGIS platform, which is a Geographical Information System for spatial and more efficient hazard assessment. The most common method used in practice, and which will be applied in the paper, is the so-called mechanical model of a "rigid block", which in the first stage analyses the stability of slopes in seismic conditions, so that the pseudo-static factor of safety is calculated (*FS*). In addition to this, the critical horizontal acceleration (*ay*) and then the total displacements of the soil block (*U*) based on deterministic methods are going to be defined.

$$FS = \frac{c' + (\gamma H \cos^2\alpha - \gamma H k \cos\alpha \sin\alpha - \gamma_w h_w \cos^2\alpha)\tan\phi'}{\gamma H \sin\alpha \cos\alpha + \gamma H k \cos^2\alpha} \quad [2]$$

As it was explained before, landslides are in function of wide variety of natural and anthropogenic variables, while in this study, the landslide susceptibility in function of five (5) predisposing factors: lithological composition of the region, slope angle (α), height, seismicity of the region and finally the type, position and loads from the structures (1860 buildings) in the urban area of Vodno. Previously, it was explained how all the variables needed for the analyses have been defined, while there has always been discussion regarding the height of the sliding plane (*H*) in relation to the slope of the terrain. To reduce the possibility of subjective error in the analyses, previous experience of landslides caused by earthquakes was consulted. Thus, it is quite interesting that based on a statistical analysis of a large number of landslides (144) caused by earthquakes in El Salvador, it was concluded that 76% of the earthquake-induced landslides have a sliding depth of about 2-6 m, while only 15% of the landslides have a slip plane at a depth >20 m. Based on this fact, in the research paper, the slip plane will be assumed at a depth of *H*=5 m below the ground surface, parallel to the slope. The anthropogenic influence from the residential buildings is added through the change/increase of the height of the lamella (*H'*), depending on the calculated contact stresses that they transfer in the base. The analysed region is divided into a net of square segments with dimensions 50 x 50 m, and all of the variables and assessments about the output results are done for such raster as it is shown on figure 3 below.

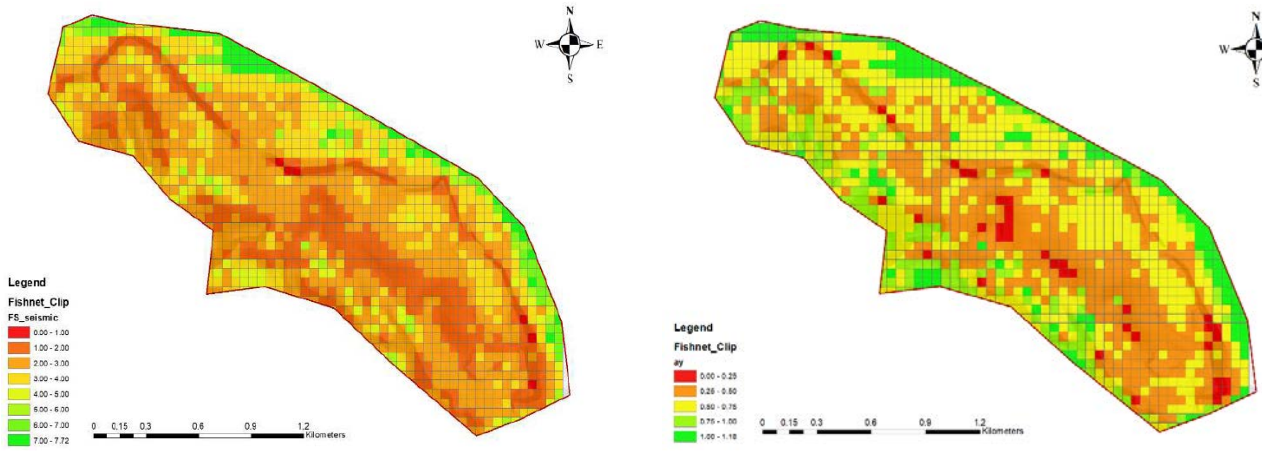

Figure 3 Factor of safety and critical acceleration (*ay*) of the Vodno urbanised area due to earthquake

On the given figure, we can see the results about the pseudo-static stability of the urbanised region, where we can draw important conclusions. Firstly, it's essentially important to underline that the zones which fall in the area of FS<1, correspond in large extent to the situation on the field; the locations found as critical through the spatial QGIS analysis, correspond to some of the instabilities that were already registered. Furthermore in this context, it is evident that the zone which has been with significantly steeper incline, in the toe of the slope of the mountain is more susceptible towards instability, where the factor of safety reaches on some positions even below 1,0. Furthermore, the urbanised region, the factor of safety is between 1,0-2,0, while interestingly, for the same inclination of the terrain and same lithological conditions, but without structural loads, the stability is significantly higher-reaching values of *FS*=3,0-4,0. This is surely, great indicator, about the influence on the loads and density of the structures on the terrain stability in earthquake conditions. According to the pseudo-static stability of the terrain, we are about to calculate the dynamic resistance of the earth mass. This parameter known as dynamic resistance (*ky*), is a value necessary for the movement of a potentially unstable soil mass. This coefficient practically represents the overall dynamic resistance of the geological environment, but in this study also by considering the loads from the structures in the urban area. Hereby, we are going to use the theory of *Newmark* (1965). Finally, after all the necessary parameters are defined, we can calculate the earthquake - induced sliding displacements (*U*), which are necessary to assess the seismic performance of slopes and risk analysis. These displacements represent the cumulative, downslope movement of a rigid sliding block, due to earthquake shaking. In this research paper, we are going to use, the formula derived from *Jibson* and *Keefer* 1993, which represents classic regression formula, based on large data on measured displacements, provoked by earthquakes in California – USA:

$$\log U = 1{,}521 \log I_a - 1{,}993 \log a_c - 1{,}546 \qquad [3]$$

While the sliding block model is a simplified representation of the field conditions, the displacements predicted from this approach, have been shown to be useful to define so-called hazard maps. Here, it is necessary to emphasise that from a theoretical point of view, an effort has been made to define the displacements of the slopes as precisely as possible under the conditions of an earthquake with a probability of occurrence of 475 years, through the so-called limit equilibrium methods. However, since in this type of regional analyses, we have more natural variables, both in time and in space, we can't determine with certainty whether the specific/calculated ground displacements would occur under certain conditions. However, the relative difference in field behaviour exists, depending on the variables that are assigned in each cell in the analysis. This concept is explained in detail in the paper by *Jibson* et. al. 2000, where it is emphasised that the predicted displacements according to the analytical method of a rigid block should be understood as an index that would correlate with the behaviour of the terrain in certain conditions, and not a "real" displacement that we should expect. Thus, for this reason, when evaluating the degree of hazard, the slope behaviour index will be used, which is defined in the following limits 0 - 25 cm - low hazard (green), further 25 - 50 cm - medium hazard (yellow) and >50 cm - high hazard (red colour), as adopted in *J. Bojadjieva* et al (2017). In the following steps, after the hazard identification and assessment, depending on the elements at risk and exposure, for which we have detailed spatial and numerical data, we can conclude the landslide risk analysis.

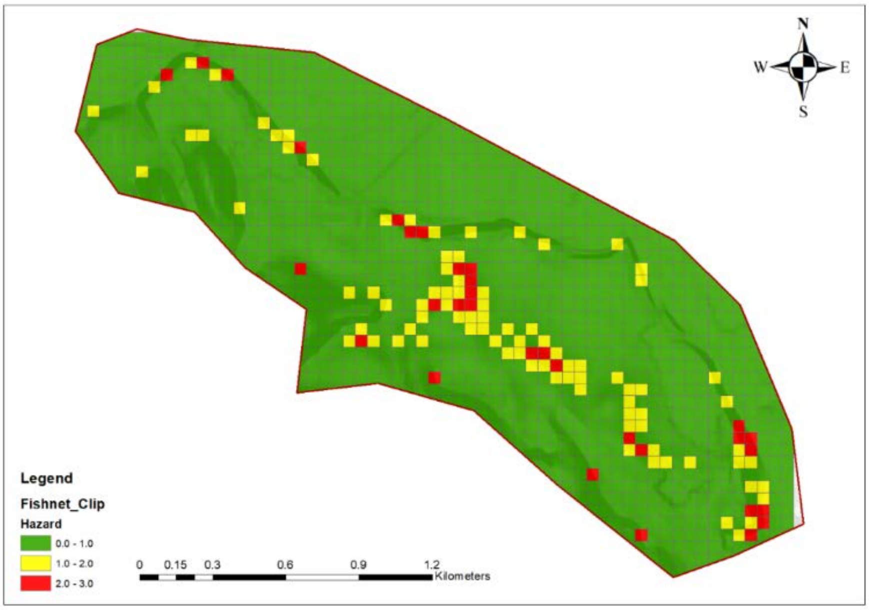

Figure 4 Risk map from earthquake-induced landslide for urbanised Vodno study area

From the obtained results, the distinction in risk is evident, where in the urbanised part, especially the one where we have significantly higher buildings, the risk is significantly increased. From the output results we can conclude that about 15,7 ha fall into a high-risk zone, while 36,4 ha are in a medium-high risk zone. Of these, 728 m^2, and 2806 m^2, are critical infrastructure facilities affected by high and medium-high risk accordingly.

Such maps are typically intended for use in disaster planning and for incorporation in decision support systems. But in cases when we already have developed urban area, they can be also used as a great resource in the allocation and design of remediation measures in the zone of high risks.

Conclusions

The paper has presented a harmonised approach for earthquake – induced landslide hazard and risk evaluation, for urbanised slopes, according to a deterministic approach, by the infinite slope theory.

The most significant contribution of this research paper is the quantification of the anthropogenic impact of the structures in the assessment of the risk of landslides under dynamic conditions. Thus, it has been proven that under construction conditions of relatively high buildings of >6 floors, under the influence of an earthquake with a return period of 50 years, the risk of landslides increases by significant 52-60%. While, in conditions where we have low-rise structures of type A0, A1, A2, the risk increases insignificantly, by 3-4%, which in fact is related to the excess earthquake force and not the structural loads necessarily. Thus, we can easily see what the impact of urbanisation on the terrain is, on its general stability, under some earthquake scenario.

Considering the fact taken from the State Statistics Office of North Macedonia, that mainly inactive population of about 66%, means high exposure, but also vulnerability in the area. This fact provides forecast estimates for the affected population, in the high-risk zone, range between 2900 - 3400 people. Although, in the area of mid-risk the numbers are significantly higher. Here, worth mentioning is that in this paper, we have analysed only the cells that are affected, and no kinematic type of failure - interaction scenario was considered. The area around those zones should be investigated in further detailed manner. In case that those detailed analysis, confirm this unfavourable scenario, some remediation measures must be designed to reduce the risk as low as reasonably possible (ALARP).

Through the methodology proposed in this research paper, it is possible to generate earthquake induce landslide hazard maps, and in other similar regions because it relies on analytical methods and not on rough regionalization and "experience". In this way, it is possible to identify different zones that in the urbanisation phase in the future will make appropriate spatial planning, and to propose the type of buildings that can be built depending on a series of parameters. On the other hand, in conditions where the region is already affected by uncontrolled urbanisation, this type of analysis can be used to reduce the risk through the so-called constructive measures, up to some level of acceptable risk. Furthermore, such analyses aim to identify potential hotspots in a wider region, but for a more detailed analysis of the time, mechanism as well as the conditions of occurrence of landslides, it is necessary to conduct FEM analyses. By this approach, through precise geometry and appropriate material laws for the behaviour of materials, an assessment of the nonlinear and dynamic response of the environment will be made, which will certainly be a significantly longer process. For this reason, we consider it as necessary to analyse the problem multi-disciplinary through the synergy of these two different methodologies.

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