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Kateryna E. Boyko

Department of Hydrogeology and Engineering Geology
Taras Shevchenko National University of Kiev

Application of a complex assessment of landslide hazards in mountain regions

Key words: shallow landslides, GIS, factor analysis, weight score, stability index, SINMAP

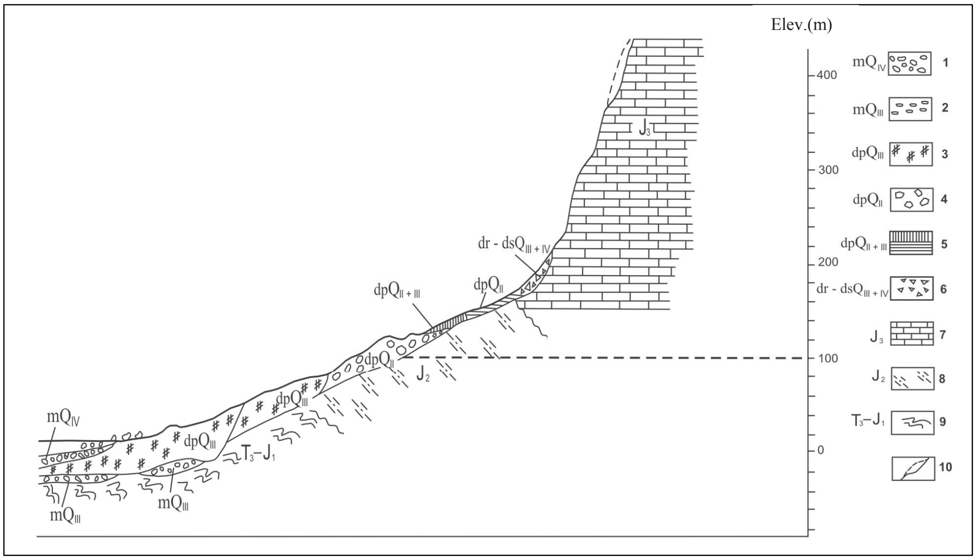
Introduction

Engineering and geological development of a mountain region, which is an active geodynamic geological structure, is always complicated by proliferation of a number of exogenous geological processes, including the intensive landslides. For decades, landslide protection measures have been implemented in the territory of the South Coast of Crimea; the shore protection structures and objects for slope stabilization (poles, anchors, bored piles) were built, the drainage systems were improved, and the methods of relief unloading were used. Numerous researches allowed accumulating a system of theories and compiling a fundamental series of papers explaining the essence of the process. However, the landslides continue to emerge and become more active in this area. The analysis of the incidence of landslides over the past 10 years has shown that most of the growth of active landslides is formed due to shallow landslides, mainly of erosion and man-made origin (Rud'ko & Erysh, 2006). The area of potential impact of the latter covers important economic facilities, so their early forecasting and modeling, as well as assessment of the risks of their behavior in the areas of process appearance remain priorities for engineering geology. The existing conventional methods of the landslide hazard forecasting and assessment in the mountain regions of Ukraine (Emelyanova, 1972; Erysh & Salomatin, 1972) are based on statistical analysis of data sets, mapping the extent of the impact of certain factors on landslide activity. The main condition for correct application of such methods for the purpose of forecasting is the continuity of data, guaranteed by permanent highly informative regime observations. Today, however, due to the partial financing of stationary works in the reference ranges, the continuity of database filling was lost. Besides, the existing probabilistic methods of landslide hazard assessment are based on the use of common factors of area affectedness, which do not reflect the nature and direction of the development process.

This article proposes a methodology of construction and substantiation of a complex model of landslide hazard based on the use of geospatial data, mapping the changes of modern relief, data of the results of the previous studies, and the use of modern tools of analysis and processing, i.e. geographic information systems. The object of research is potentially landslide-hazardous and landslide--prone territories of the South Coast of Crimea. The subject of research are the factors and conditions of emergence and intensification of the modern landslides of cover type.

Material and methods

The landslides origination and extension mechanism within the South Coast of Crimea is generally determined by the following global factors and conditions – geological, geological and morphological, hydrogeological and the secondary variables. At the same time, the tectonic features control the geological structure of a territory. Thus, the mutual relationship between landslides (proven by Borysenko, Chebanenko, Shatalov, Novik & Salomatin, 1988) and tectonics appears in the territorial distribution of landslide initiation cracks near the faults intersections. Current tectonic movements processing from the late Pleistocene to the present day cause the constant relief rejuvenation, whereas the arched dome of the Main Ridge of the Crimean Mountains and the Black Sea level fluctuations cause the movement of erosion base level up the slope of the south-western coast. Thus, abrasion and denudation as determinants of landslide formation in this territory depend on the tectonic regime of the latter in the same way. Therefore, newly formed landslides serve as indicators of tectonic movements and geological conditions of the South Coast of Crimea as a whole. Modern shallow landslides belong to the landslides of the second and higher orders formed within the bodies of much more aged units as a result of undermining of the latter with a contemporaneous erosional pattern in the upper parts of the slopes (Emel'yanova, 1972). New shallow landslides originate in the top weathered part of flysch formation of Middle Jurassic (J_2) and Tauric suite ($T_3 – J_1$) – Figure 1. Covering deposits form geological-genetic complexes characterized by specific physical and mechanical properties of rocks that may be differ greatly on different spots. It is caused by local spreading of groundwater within the study area, availability of fault zones etc. The greatest changes during the weathering agents' impact take place in the upper part of flysch – its argillaceous component. Disintegrating mudstones form a powerful eluvium zone consisting of clay and thin lamellar modifications and clay. The elluvial geologic-genetical complex rocks are characterized by the solid cementation cohesion waste, and consequently transit to unstable fluid



1 – sea pebble stones and Holocene sandstone; 2 – blocky limestone; landslide deposits, upper pleistocene; biased masses of 3 – sandstones and argillites of Middle Jurassic and Tauric suite; 4 – of limestone of Upper Jurassic; 5 – dealluvial middle and upper pleistocene loamy and rubble formations; 6 – banked – talus formations; 7 – limestones of Upper Jurassic; 8 – sandstones, argillites, siltstones of Upper Jurassic; 9 – argillites and sandstones of Tauric suite; 10 – recess of subsidence.

FIGURE 1. Schematic geological cross-section of Southern Crimean Coast (Zolotarev, 1983)

state. Loamy and clayey eluvium under the water saturation is able to move in a fluid state and very soft soil on the slopes and to slide.

The method of landslide hazard assessment as used in this study is based on a integrated analysis of the factors determining the propensity of certain areas to the landslides, as well as influencing the dynamics of their development. In order to identify the spatial and temporal characteristics of the shallow landslides, we proposed a method of constructing separate models, static and dynamic, collectively describing the nature of the process. To do this, all of the factors determining the propensity of the territory of the South Coast of Crimea to extension of the landslide process were divided into actual factors, reflecting the regional peculiarities of the territory and forming the landslide-prone slopes (static model), as well as trigger factors (Dhaka, Amada & Aniya, 2000) initiating the landslide process and determining its activity (dynamic model).

Static model was constructed using information theory assumption and the use of the method of weighting coefficient assessment (Quinn, Hutchinson, Diederichs & Rowe, 2010). The method implies determination of the degree of significance (impact, weight) of each of the factors considered in formation of landslides (Carrara,

TABLE 1. The values of the physical-mechanical and hydrogeological properties of rocks range within Batiliman area

Internal friction angle φ [°]	Cohesion c [kPa]	Soil transmissivity T [$m^2 \cdot h^{-1}$]
9–25	27–55	0.15–2.50

Cardinali & Detti, 1991). The following factors have been identified and analyzed in order to create this model:

– geological and lithological (genetic-lithological type and thickness of the landslides masses), stratigraphic correlation of bedrocks and quaternary rocks). The surficial materials within the study area shown in Table 1 include six different soil types, each describing broad categories of materials with similar genesis. The method of soil thickness ranging is natural break;
– tectonic (availability of tectonic fractures);
– geomorphology (slope angle, slope exposure);
– anthropogenic (transport network).

The cartographic material created by experts of the landslide batch at different stages of studying the nature of the region landslides region was used as a source of information characterizing the distribution of the basic parameters of above factors (Erysh, 1999, Bilets'kyy, 2006). The main source of geological information is the map of the geotechnical zoning of the South Coast of the Crimea compiled by Neklyudov, where areas with different types of geological-stratigraphic and hydrogeological components, as well as tectonic disturbances on a scale 1 : 25 000 are indicated (Neklyudov & Storchak, 1976). In order to assess the direct impact of the relief-forming processes in formation of the landslide erosion and anthropogenic genesis a mapping model of residual relief was established by subtracting of the basal surface (modern erosion level) from the hypsometric one. This model shows the distribution of the volume of the weathered rocks, which can further be removed by erosion and denudation given the existing geological and geographical conditions (Filosofov, 1975). Naturally, this value could be correlated with the capacity of landslide rocks within the South Coast of Crimea in relation to the type of shallow landslides, as the difference in height of the modern relief and the modern basic surface characterizes the reserves of the potential energy relief (Emelyanova, 1972). The peculiarity of forming the relief on the southern slopes of the Crimean Mountains is the continuous strengthening of denudation processes, active abrasion of the shoreline in connection with expansion of the deep-sea basin of the Black Sea and mainland immersion (Zolotarev, 1983).

The data characterizing the distribution of parameters of each factor were converted to geospatial objects. As a result, a set of mapping digital layers in a raster grid format, which allows for their further processing by means of geoinformation platform (ESRI ArcMap, Arcview), was created. The original base was a digital elevation model with 30-meter resolution (grid size 30 × 30 m^2).

Dynamic model of the landslide hazard was built, taking into account the indirect factors affecting the process extension in time. It is known that the main "trigger" of landslide displacements within the South Coast is the hydrological factors (precipitation and their pattern), as well as a surface drainage, rock wetness, strength and deformation properties of soils. As a mathematical basis for creation of a dynamic model of the landslide hazard assessment based on the calculated stability coefficient values, SINMAP special module was used.

Stability index mapping (SINMAP) is a method of mapping by index stability (Pack, Tarboton & Goodwin, 1998). It is based on calculation of slope stability according to the pattern of an infinite slope (Tarolli & Tarboton, 2006), taking into account the impact of the hydrogeological component, making it suitable to assess the stability of slopes prone to shallow landslides. The authors of method propose to use the parameters of hydrogeological and topographical models to determine the relative wetness of soil. Calculation of the value of the latter at each point of the grid surface using the following formula:

$$W = \min\left(\frac{R}{T} \times \frac{a}{\sin\theta}, 1\right)$$

where:

W – relative wetness;
R – steady state recharge [$m \cdot h^{-1}$];
T – soil transmissivity [$m^2 \cdot h^{-1}$];
a – specific catchment area [m^2];
θ – slope angle [°].

The input data required for correct operation of the module are grid surfaces characterizing the spatial distribution of parameters and are thematic layers of the working set of the program:

– digital elevation model (DEM) of study area;
– a themed point layer displaying the distribution of landslides identified within the study area;
– area zoning map by the physical and mechanical properties of soils (by adhesion, angle of internal friction), as well as hydrogeological parameters (with respect to evaporation of precipitation and transmissivity of rocks);
– quaternary complex rock capacity map obtained by subtracting of the basal surface (modern erosion level) from the hypsometric one considering that the landslides arrays profiles of mass balance forming occurs towards constantly updated denudation basis and it is expected that shallow landslides roof break cracks are confined to the base surfaces of valleys of the first and fsecond orders.

In order to further calculation of the R-value, a long-term pattern of precipitation in individual sections of the South Coast of Crimea was analyzed and the average seasonal maximum and minimum precipitation was identified. To simulate the boundary conditions of the slope condition subject to an unfavorable combination of factors ($R \rightarrow$ max; $C \rightarrow$ min; $\varphi \rightarrow$ min), the maximum daily average precipitation was used in the calculation. The values of the physical-mechanical properties of eluvial rocks (of weathering crust) characteristic of the study area are within the range indicated in the Table 2.

TABLE 2. Results of calculating the prevalence and weights for each class factors

Factors	Classes	W_i
1	2	3
Geological and lithological		
Soil thickness [m]	0–10	3.37
	10–20	2.31
	20–40	2.44
	40–70	–2.28
Deviation angle between aspect angles of sedimentary rocks and bedrocks [°]	0–25	2.88
	25–50	2.71
	50–75	2.64
	75–100	2.22
	100–125	1.59
	125–150	–0.64
	>150	–1.91
Soil type classes	eluvial-deluvial loams	–0.51
	colluvial deposits	–0.07
	proluvial rocks depris and loams	0.82
	colluvial deposits with loamy filling	–0.08
	landslades' deposits	1.76
	bedrocks (flysh)	1.00
Tectonic		
Distance between landslides and faults [m]	0–50	1.34
	50–100	1.76
	100–150	1.83
	150–200	1.58
	200–250	0.07
	250–300	–3.62
Geomorphological		
Slope angle [°]	0–10	2.27
	10–20	2.36
	20–30	2.52
	30–40	0.06
	40–75	–2.62

TABLE 2 cont.

1	2	3
Slope aspect	N	–
	NE	–
	E	–0.50
	SE	–0.67
	S	2.93
	SW	2.37
	W	1.66
	NW	–2.06
	W	–
Distance between the main road and landslides [m]	0–40	2.60
	40–80	2.84
	80–120	2.81
	120–160	2.59
	160–200	2.56

Results and discussion

The article describes the results of constructing the models of landslide hazard within the West Coast, i.e. Batilimanskiy landslide area (Erysh & Salomatin, 1999). The boundaries of the site coincide with the boundaries of Laspinsky tectonic block and with boundaries of the hydrogeological district of the same name, which allows detailing the study direction. The area of the district is 10.7 km^2. And it is located between latitudes 44°26′1″ N and 44°24′4″ N and longitudes 33°40′2″ E and 33°44′10″ E. Here are about 30 units of landslides with different genesis. Most of the part is represented by landslides of technogenic origin, appeared within the car and trolleybus routes as a result of construction and repair works. Also, the landslides of erosive origin are common within this area. The laws of development of the landslides of abrasion origin were not considered.

The results of calculating the weighting coefficients for each class in order to build a static model are shown in Table 1.

Based on Table 1, the weights calculated for various factors can vary within different bands. However, the maximum value of the weighting factors within the specified factors determine the parameter, which is most conducive to formation and activation of landslides.

Based on the weighting factor values determined for classes allocated within the human factor (distance from the transport network), a high degree of influence of the latter on the widespread development process should be noted. The range of the weighting factor totals on the resulting mapping model (Fig. 2) varies between –9.70 and +5.67.

The sequence of determining the spatial distribution of the stability index

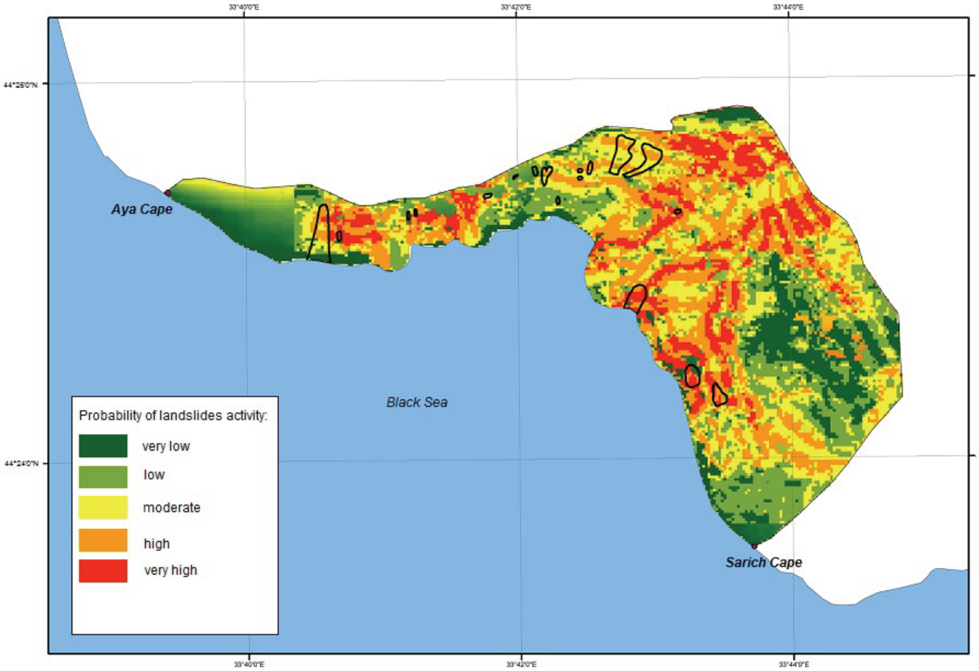


FIGURE 2. Schematic map of landslide activity probability, compiled on the basis of factor analysis by weight factors (Batilimanskiy landslide site)

using SINMAP module is as follows: initially a humidity index prevalence model is created on the basis of DEM. This procedure is similar to the hydrogeological analysis performed in ArcMap software environment using special tools such as "Flow direction", "Flow accumulation", "Basin" commands contained in the "Spatial Analyst Tools" block. Each pixel is assigned a value of the flow direction and accumulation for the purpose of delineating the hydrological basins (Virajh Dias & Gunathilake, 2014). Then, using the data from the attribute table of area zoning by physical-mechanical and hydrogeological parameters, as well as wetness index prevalence maps, a stability index prevalence map is created using SINMAP tools. The model resulting from application of the mapping method by stability index (Fig. 3) is a schematic diagram of zoning the study landslide area of the South Coast of Crimea by the landslide hazard degree.

The analysis of parameter combinations affecting the interaction of shear and restraining forces on the slope, with seasonal periodicity, is the basis of the interim landslide process activity forecast.

Conclusions

As a result of the study, the main factors creating favorable conditions for development and activation of the modern landslides is identified. The latter should include the geomorphological (slope angle and exposure, capacity of the ultimate relief-forming rocks, determined

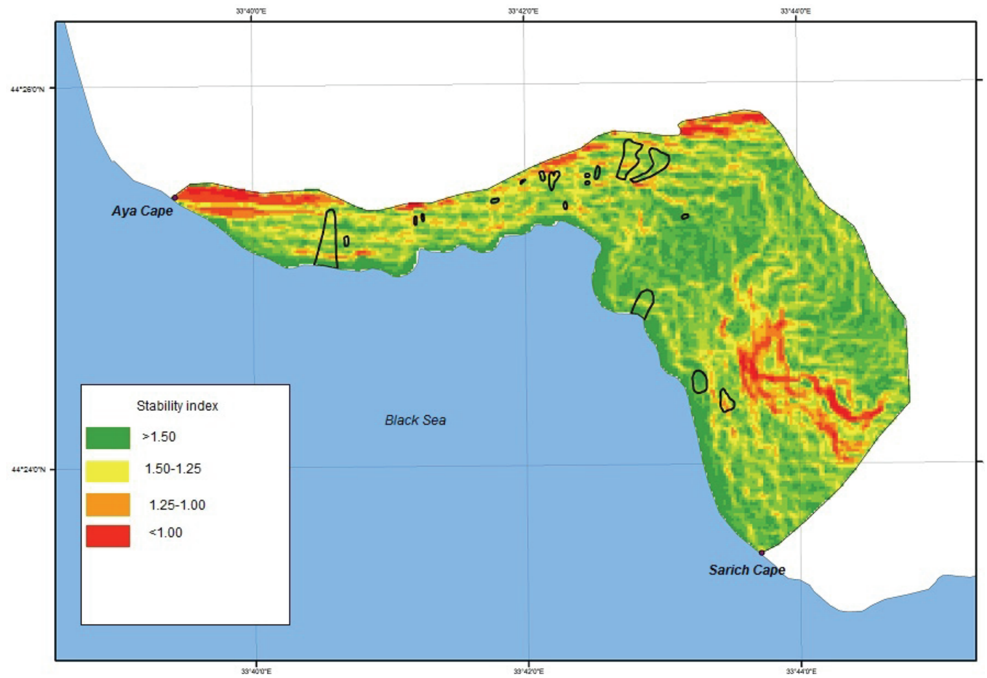


FIGURE 3. Schematic map of the landslide activity probability on the basis of stability index prevalence (Batilimanskiy landslide site)

by position of the modern erosion basis), tectonic (close to tectonic faults of the regional level), as well as man-made (dynamic impact of the transport).

Analysis of the static mapping model, reflecting the regional spatial patterns of the landslide process distribution, led to the following conclusions. Most of the study area (60%) features a low probability of landslide occurrence. At the same time, the range of values corresponding to the high probability of landslide manifestation covers the majority of the mapped landslides, falling within 20% of the total area of Batilimanskiy area. In general, the location of 15 of 18 landslides was predicted using the resulting model.

Statistical analysis of the dynamic model characterizing the stability index prevalence was carried out using the tools of simulating the modeling results based on SINMAP module platform. It was revealed that 20% of the area features an adverse range of stability index values ($SI < 1.2$). It should also be noted that according to the resulting model, more than 25% of the registered landslides of erosion and anthropogenic genesis are prevalent within the slopes identified as unsustainable and quasi stable as a result of simulation.

A joint analysis of the models constructed for the purpose of zoning the South Coast of Crimea by the degree of landslide hazard and reflecting the spatial features of the process shows a sufficient degree of their reliability given the used set of factors.

Recapitulation

The South Coast of Crimea is characterized as the most highly affected by landslide processes compared to other engineering-geological objects of the peninsula. On the other hand, the existing methods for predicting and assessing landslide hazard created for this area as a result of years of research are insufficiently adapted to modern requirements of engineering geology.

The purpose of the study is to develop and test a relevant method for integrated regional prediction of landslides. In this paper, landslide hazard prediction is understood to be a sequential analysis of assessment of spatial and temporal regularities of landslide development.

In the course of the study an analysis of regional factors determining the predisposition of certain areas to landslides and influencing the dynamics of their development was carried out. In order to identify spatial and temporal peculiarities of landslide development a static model and a dynamic model were built, together describing the nature of the process. The creation of the static model is based on calculation of the weighting coefficient as a degree of impact of each of the factors considered. The dynamic model was built using GIS tools. It shows the distribution of the indirect indicator of landslide activity – the slope stability index.

As result of research, two models, that consider the influence of certain factors on the landslides' activity, were developed. The statistical analysis of the obtained models demonstrated a sufficient degree of their reliability under the applied set of factors

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Summary

Application of a complex assessment of landslide hazards in mountain regions. The main regional factors of occurrence and activation of landslides within the mountain region were examined. As a result of study of recommendations made by experts, geologists, and gap analysis of existing methods of forecasting the landslide process, an algorithm of comprehensive assessment of landslide hazard areas based on the construction of models in a GIS environment was proposed. These models describe the spatial patterns of landslides. All factors determining the tendency of the studies area to the landslide process development were divided into actual factors, reflecting the regional peculiarities of the territory and forming the landslide-prone slopes (static model), as well as triggering factors, initiating the landslide process and determining its activity (dynamic model). The first cartographic model was built, showing the distribution of the deterministic indirect indicator of landslide hazard, i.e. stability index.

Author's address:
Kateryna E. Boyko
Taras Shevchenko National University of Kiev
Institute of Geology
Department of Hydrogeology and Engineering Geology
90 St. Vasylkivska, Kiev, 03022
Ukraine
e-mail: boyko_ekateruna@ukr.net