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RISK MANAGEMENT OF KOPRIVLEN LANDSLIDES

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Abstract: *The present paper provides detailed results from the implementation of project RISKLIDES in the framework of European Territorial Cooperation Programme "Greece-Bulgaria 2007-2013". The study shows the geological and hydrogeological features, as we as the risk mitigation strategy, and risk management of two landslides, developed in Miocene-Pliocene sediments next to Koprivlen village, Gotse Delchev municipality, Blagoevgrad region, SW Bulgaria. A detailed characteristic of the area has been made, including data for the seismic situation, water table, and seasonal rain values. Fieldwork included sample collecting, low-scale geological mapping, and core boring. Laboratory analyses were performed on the collected samples for mineralogical phase identification as well as for rock and soil strength. As a result, detailed low-scale 3D GIS maps of the landslides were produced. A landslide risk management and mitigation strategy is provided for the prevention of the development of Koprivlen landslides.*

УПРАВЛЕНИЕ НА РИСКА НА СВЛАЧИЩЕ КОПРИВЛЕН

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Резюме: *Настоящата работа описва в детайли резултати от изпълнението на проект RISKLIDES в рамките на Европейската програма за териториално сътрудничество „Гърция-България 2007-2013“. Изследването предоставя геоложки и хидрогеоложки особености и стратегия за управление на риска на две свлачища в Миоцен-Плиоценски седименти в близост до село Копривлен, община Гоце Делчев, Благоевградска област, ЮЗ България. Направена е детайлна характеристика на района с данни за сеизмичната ситуация, нивото на подземните води и стойности на сезонните валежи. Теренните работи включват пробоотбор, геоложко картиране в мащаб 1:500, както и ядково сондиране. На събраните проби е направена минераложка фазова идентификация, както и тестове за здравина и якост на почвите.В резултат е произведен детайлен 3D GIS модел на свлачищата. Представена е стратегия за предотвратяване и управление на риска от развитието на свлачищата до Копривлен.*

Introduction

Landslides occur in different forms, from individual rock falls to large creep failures depending on site conditions and the type of the triggering event (earthquake, precipitation, erosion, excavation etc) [1-3]. Based on their characteristics (number, timing, location, size, mobility etc.), landslides can have significant consequences such as casualties, property damage or socioeconomic impacts, which constitute the "hazard" and the "vulnerability" of people, structures and infrastructure that exist or live in the potentially affected area [4-5]. Natural occurrence landslides can be provoked by a single or combined action of water, earthquakes and volcanoes. The effects of landslides triggered by natural causes vary widely and depend on factors such as slope steepness, shape of terrain, soil type, underlying geology etc. [6]. The change of the drainage patterns the destabilization of the slopes and the vegetation removal are human activities that are related to landslides occurrence.

Project RISKLIDES (RISK management of natural and anthropogenic landsLIDES in the Greek-Bulgarian cross-border area) carried the assessment and management of landslide risk caused by natural or anthropogenic causes in the area adjacent to the road line Lailias-Serres-Kato Nevrokopi- Koprivlen-Gotse Delchev-Bansko, covering a total road length of 160 km, from which 92 km in the Greek and 68 km to Bulgarian territory (Fig. 1).

Slope stability of roads is crucial in areas with rugged terrain. Different gravitational processes occur continuously and their mechanism and dynamics are determined by geological and geomorphological conditions, and the current destabilizing factors such as weathering, precipitation, erosion, contemporary tectonic movements, and earthquakes. Technogenic influence also plays an important role in slope stability. In many cases, the technogenic influence determines the occurrence or accelerates the activation of landslide and rockfall processes. The problems of various civil constructions resulting from activation of gravitational processes are large and the activities carried out in the slopes are regulated in order to reduce the risk and prevent the occurrence and activation of landslide and rockfall processes.

Several landslides have been established during the project and here we present a detailed geological and hydrogeological characteristic, as well as a risk mitigation strategy, and risk management of two landslides close to Koprivlen village, Blagoevgrad region, SW Bulgaria.

Fig. 1. Map of the area, concerning RISKLIDES project. Point 48 marks the landslides at Koprivlen

The landslides near Koprivlen are exposed in the southern parts of the village (point 48 – Figure 1). They are a two step-like developed bodies located to the northeast and northwest of benchmark 561.43 m. The central points of both landslides have coordinates as follows: 41 31 12.2/023 47 27.0 (for the northeast body) and 41 37 08.1/23 47 16.1 (for the southwest body), referred later as Koprivlen-1 (p. 48-1) and Koprivlen-2 (p. 48-2) (Figure 2).

According to the Geological Map of Bulgaria in scale 1:50 000, map sheets Hadjidimovo and Ilinden [7-8] and the carried out additional field investigations in scale 1:500 the landslides are developed in sediments of the conglomerate and sandstone formation aged Late Miocene-Pliocene. In the vicinity of Koprivlen village they are presented by sandstones, sandy siltstones, and clays. The sandstones are weakly bound and in some places pass into sands. They are medium- to thick-layered small- and medium-grained. The clays expose as separate layers and lens-like bodies with thickness from couple of centimetres to couple of meters. They are light grey, grey-greenish and brown in colour. Typically they contain siltstone admixtures.

The beds of the sandstones, siltstones, and clays are sub-horizontal or weakly dipping to the south. This dip is inconstant and is considered as an undulating part of the generally horizontal layers. From regional geological point of view the exposures nearby Koprivlen village are part of the southern periphery of the Mesta Depression and the Gotse Delchev graben separated from the marbles of the Pirin Lithotectonic Metamorphous Unit through a fault striking at 140°. The latter is post-Neogene in age according to its manifestations. This is a normal fault with north-eastern footwall. According to our investigations the fault is the main tectonic reason for the formation of a number of smaller landslides between the villages of Novo Lyaski and Koprivlen. Well expressed morphological steps have been formed along some satellite failures breaks as one of them divides the two landslides at bench mark 563.43 m.

Morphostructurally, the landslides at Koprivlen village fall in the southern periphery of the Gotse Delchev basin separated from the Pirin morphostrucutal Unit by a fault striking at 140°. The lay in the area of the landslide is hilly-plain with altitude ranging from 530-585 m. The landslides are developed in Neogene sediments presented by sandstones, limy siltstones and clays as their slope surface is inclined towards Mesta River. This surface is subjected to sheet and channel erosion, intensively manifested nearby the villages of Sadovo and Novo Lyaski. The areas of the landslides, superimposed over satellite image are shown in Figures 3 and 4.

Fig. 2. The two landslides near Koprivlen, Google maps orthophoto

Fig. 3. Area of Koprivlen-1 landslide, superimposed GIS layer over a Google maps orthophoto

Fig. 4. Area of Koprivlen-2 landslide, superimposed GIS layer over a Google maps orthophoto

Materials and methods

Electrotomography

The electrotomographic methods are applicable for defining the depth of ore body's deposits and water-saturated horizons. Most of the landslide surfaces of rupture are water-saturated and therefore, easily separable. In order to define the depth and the inclination of this surface a portable generator of 400 V tension current and high accuracy measurement equipment with digital indication and the necessary appliances have been used. The electrotomographic methods require interpretation of the curves obtained by data of the vertical electrical boring performed at each 5 m along the investigated profile. A dipole-plus scheme is applied (length of dipole 10 m). The quantitative interpretation of the curves is made by a program of practically proved merits. In order to investigate the landslides profiles of 100-120 m have been constituted. The measurements reach up to 80 m in depth which is enough for the assigned task.

Field surveys

Field surveys included borehole drillings and sampling. Field survey took place in mid-August, 2012. It is expressed in: terrain view and mapping of 3 landslides and 3 rockfalls; drilling of 9 exploratory boreholes with a diameter of 127 mm and a total length of 120 m with drilling equipment URB 2A2, on dry way and short trips (by 0.30 to 0.40 m). At each landslide 3 boreholes have been made in the slope profile; visual description and sampling of drilled lithological strata; clarification of hydro geological conditions.

Laboratory tests

Laboratory tests of 37 soil samples have been made by Soil mechanics laboratory of "Ecology and Geology" Ltd. in accordance with the standards and regulations in the country. Laboratory tests of 12 rock samples were carried out by the Geological Institute of the Bulgarian Academy of Sciences.

Slope Stability Analysis and Risk Mitigation Strategy

The main aim of this stage is to develop a geotechnical projects to improve slope stability and to prevent landslide activation based on results from engineering geological studies and additional detailed considerations about considered landslides. To achieve this goal the following tasks have been performed:

- Preparation of 2D geomechanical model of each of the three landslides, including determining the location of the most possible slip surface, groundwater level, verification of computing values of physico-mechanical properties of soils;
- Determination of the factor of safety (Fs) of landslides in different conditions - actual slope stability, slope stability after uprising of groundwater level, slope stability during an earthquake, slope stability in heavy traffic and a combination of relevant factors;
- Following the geotechnical slope stability analysis adequate preventive measures and/or structures have been designed to increase slope stability and to prevent activation of the recorded landslides.

All field and laboratory data were processed and presented in a final engineering geological report including drawings of engineering profiles as well obtained computational values of engineering geological layers. Design values of physical and mechanical properties have been determined from laboratory tests data, and they have been reduced by correction coefficients according to Ordinance № 12/03.07.2001. The method of Janbu in "effective stress" has been used. Several options have been considered - stability of the slopes in the natural state with deep groundwater levels, after rising of groundwater levels and earthquake influence. Software program Slope W has been used. Factors of safety for more than 1,000 slip surfaces have been calculated and most adequate of them have been selected.

Results and Discussion

From electrotomography data, the two step-like bodies developed in Neogene sediments have been separated in the landslide nearby Koprivlen village. They are characterized through longitudinal to the body geophysical electrical profiles, 120 m in length. The profiles directions are 70° and 65° for the northeast and the southwest part, respectively. Three-dimensional models of the landslides are shown on Figures 5 and 6.

Koprivlen-1 landslide is cut by the road and fastened by gabions. The main geomorphological data for it are presented in the tabular data base. A longitudinal profile of 120 m length and 70° azimuth has been constructed to investigate this part of the landslide positioned between the road and the benchmark 563.43. The measurement base station has been situated at a point with coordinates 41 31 12.2/023 47 27.0. According to the data of the performed electric resistance measurements the surface of rupture is registered along the boundary of a thick water-saturated sandy bed and the deposited beneath clays. The sandy bed is characterized by electric resistances of 20-50 Ω/m, while the clays have 4-15 Ω/m. Judging by the measured resistances a wedging of the clayey layer is observed in the northeast part of the profile leaving further on only the sands.

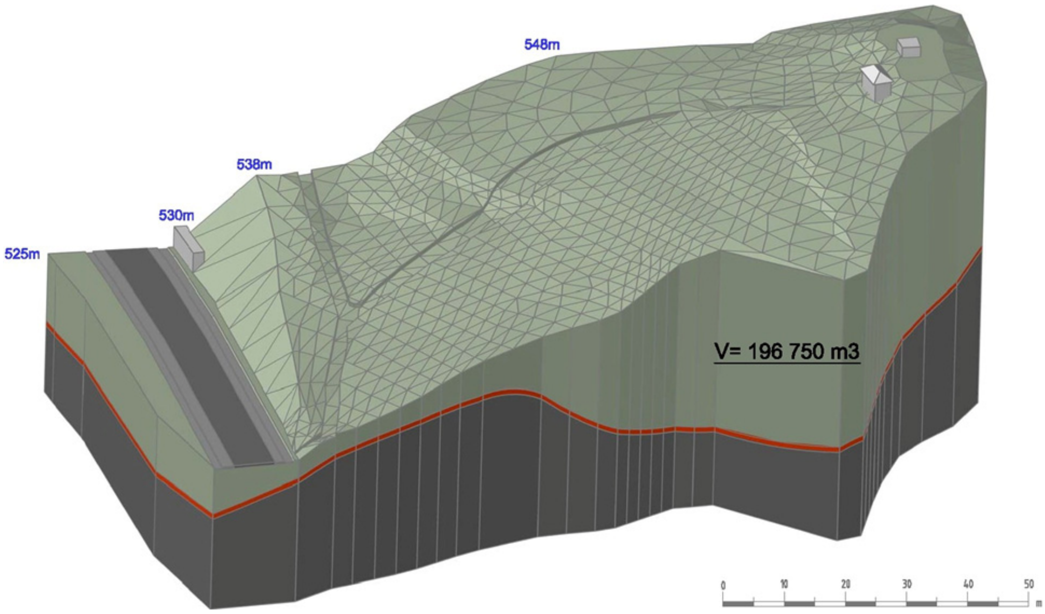

Fig. 5. 3D model of landslide Koprivlen-1, scale in meters

The geophysical profile of Koprivlen-2 landslide is revealing the form and the depth of localization of the surface of rupture. At the base point of measurement the surface of rupture is about 30 m in depth. In the north-eastern part (nearby the road-bed) it lays closer to the surface – 5-7 m. In the south western part it is approximately 30-35 m in depth.

According to the measurements the surface of rupture is developed along the boundary of water-saturated in its base sandy bed overlaying a clayey bed of about 10-12 m thickness.

The clayey bed is clearly marked by the low values of the electric resistance of 4-1 Ω/m. The resistance of the sands is between 15-50 Ω/m. The rupture starts in the south-western part of the profile where the surface of rupture rises outside. In the base station of measurements it is registered at about 15 m in depth and gradually increases in the north-eastern part of the profile.

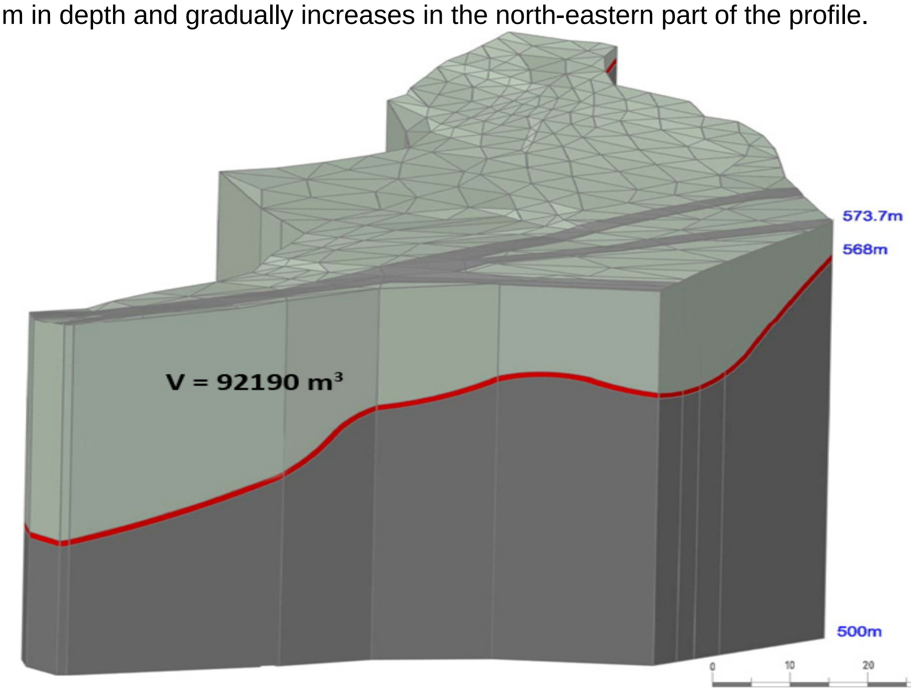

Fig. 6. 3D model of landslide Koprivlen-1, scale in meters

Hydrogeological conditions

The types of groundwater within the studied landslides are porous, phreatic to low pressure. Their depth of embedding is variable and depends on the filtration properties of the soil, geomorphological conditions, recharge zones and drainage. Groundwater levels are set at different depths to the terrain:

Table 1. Groundwater depth and hydraulic gradient of Koprivlen landslides

Landslide	Groundwater depth, m	Hydraulic gradient
Koprivlen-1	7.00-9.80	0.15
Koprivlen-2	8.30-14.00	0.17

Drilling studies were conducted after a prolonged dry period. It is expected that during wet periods groundwater levels will rise by 1.0 to 2.0 m. Groundwater flows followed slopes, but they aren't parallel to them. Paleogene and Neogene sediments within investigated landslides are too clayey and has low filtration properties and low water abundance. Relatively aquifers are sand and gravel layers. They are drained in erosion decreases in relief and small springs are formed.

Geological Environment

The landslides are cirque-shaped and the main reason for their occurence is the post-Neogene activation of the fault separating the south periphery of the Mesta Depression and the Gotse Delchev graben from the marbles of the Pirin Lithotectonic Unit. The main (initial) landslide process is during the Pleistocene when the depth of the slid masses is about 20 m in the upper part to 40 m in the lower part of the landslide body and the length from the initial landslide bevel to the lowest part of the body exceeds 350 m.

According to their geological and tectonic characteristics the landslides are consequent – the slipping occurs along a separating surface between heterogeneous beds and along interlayers without cracks. According to the mechanism of the landslide process it is detrusive – it starts from the upper part of the slope as the slid earth masses form "landslide domes" as a result of the above applied pressure. According to the depth of the surface of rupture it is characterized as a deep-seated one.

Neotectonic movements along the boundary fault during the Pleistocene have given rise to the formation of two step-like landslide bodies in the initial landslide – a lower one with coordinates 413112.2/0234727.0 and an upper one with coordinates 413708.1/234716.1. Starting from the Lower Holocene both landslides have been subjected to a number of activations manifested by secondary landslide bevels separating small "landslide domes". The bevels' height varies from 1.5 to 2-3 m.

The reasons for activation of the landslide processes are complex: neotectonic movements along the boundary fault between the Neogene sediments and the marbles of the Pirin lithotectonic Unit, combined with oversaturation of the slipping surface by abundant rainfalls and by the water-main system equipment (pouring of water from reservoirs, the presence and utilization of irrigation waters, etc.). An important reason for cutting of the lower landslide body is the setting of the road-bed for border checkpoint "Ilinden". This cutting activates the landslides and endangers the road through a bevel reaching 17 m. The landslide supporting by fastening this bevel through gabions is only a temporary and ineffective measure in the attempt to preserve the road.

Engineering geology

1. Landslide Koprivlen-1

The study paid particular attention to shallow landslides within the ancient landslide (Table 2). Three engineering geological layers are divided, which are characterized by laboratory tests data.

A. Layer 1 - Medium to coarse sand (N1-2). Layer 1 has relatively limited distribution. It reveals on the terrain in the borehole 1 (BH 1) and BH 2 as well in depth in the intervals from 11.7 to 15.0 m in BH 1; 11.4 to 12.0 m – BH 2. It is represented by grey to yellow brown medium to coarse sand, medium dense to weak sandstone with some gravels. Layer 1 has the following physico-mechanical parameters:

- Bulk density - 1,99 g/cm^3
- Void ratio - 0,55
- Angle of internal friction (residual) - 31,4°
- Cohesion (residual) - 2,7 kPa

B. Layer 2 - Silty sandy clay (N1-2). The layer is established in all boreholes at various depths. The thickness of the individual layers vary between 1.0 to 2.6 m, increasing downhill. The biggest overall thickness is 6.7 m and it is established in BH 3. The layer is made of brown to variegated stiff to firm sandy silty clay. Physical and mechanical properties of this layer are within following limits:

- Bulk density - 1,83 – 1,94 g/cm^3
- Consistency index - 0,71 – 1,97
- Void ratio - 0,59 – 0,69
- Angle of internal friction (residual) - 22,3°
- Cohesion (residual) - 18,7 kPa

C. Layer 3 - Clayey sand (N1-2). The layer occupies a large part of the incision. It is represented by grey, grey-yellow to brown clayey sand with thin layers of stiff to firm clay. Physical and mechanical parameters are within the boundaries:

- Bulk density 1,78 – 2,21 g/cm^3
- Consistency index 0,78 – 2,45
- Void ratio 0,33 – 0,74
- Angle of internal friction (residual) 22,8 – 24,7°
- Cohesion (residual) 8,0 – 9,3 kPa

Slope stability calculations are summarized in Table 2 and Figure 7

Table 2. Factors of safety in different conditions of the slope for Koprivlen-1

Condition of the slope	Slip surface No	Factor of safety, Fs
Dry slope	508	1.854
High ground water table	426	1.272
High ground table + earthquake	438	0.923

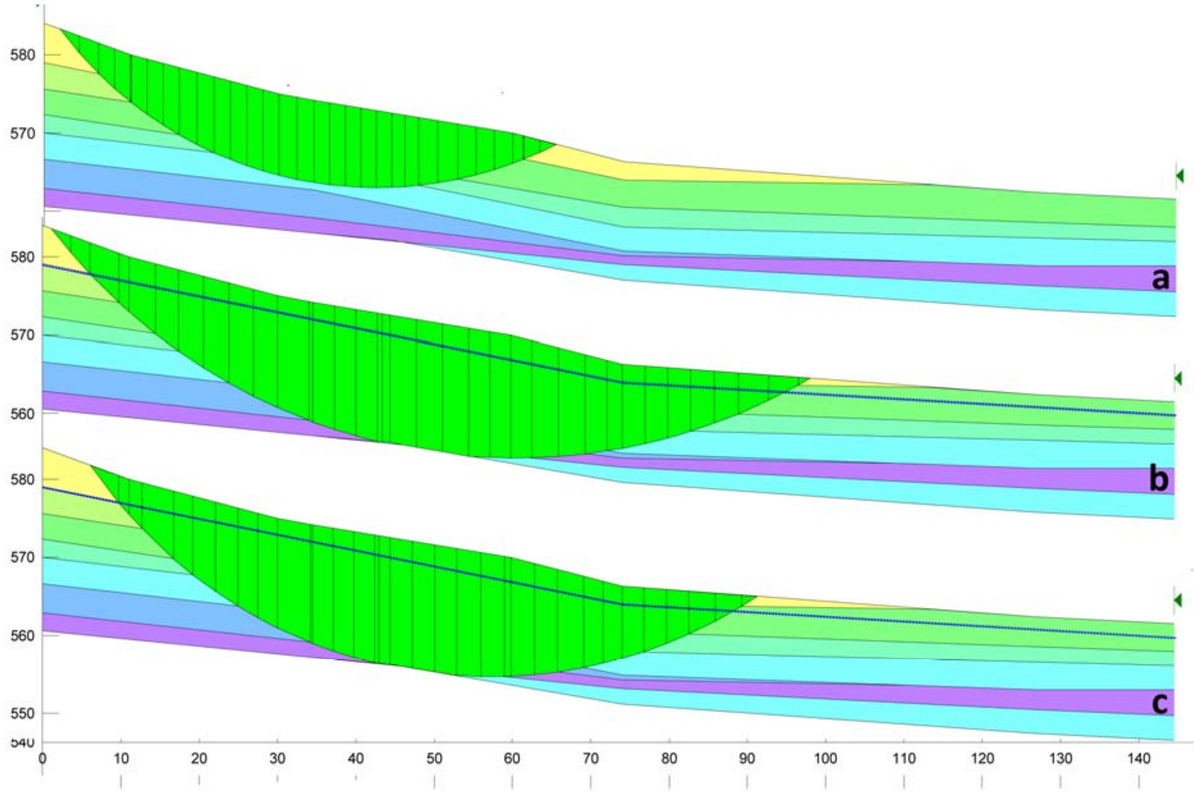

Fig. 7. Different load conditions for Koprivlen-1 landslide: dry (a), high ground water table (b), and High ground water table + earthquake (c). Scale in meters

In the current slope morphology both with deep groundwater table located under slip surface and with shallow groundwater the factors of safety are significantly above 1. Only in the case of combination between shallow groundwater levels and prognostic earthquake of VIII degree landslide Koprivlen 1 goes into unstable state. Since the landslide Koprivlen-1 is located up the hill, at a considerable distance from the road and do not endanger capital construction, it isn't necessary to conduct special reinforcement activities. Surface-panelled drainage ditches only can be applied to protect slope from penetration of surface waters into the landslide body.

2. Landslide Koprivlen-2

The landslide is located at the bottom of the hill just above the road. The base of the slope has been cut by a deep road pit. To increase retention forces in the heel of the trench retaining wall of gabions has been constructed. Data from exploratory drillings and laboratory data are used to divide three engineering geological layers.

A. Layer 1 - Medium to coarse sand (N1-2). Layer 1 has relatively limited distribution. It is established in borehole 4 (BH 4), just below the ground and in the range from 12.8 to 15.0 m, and in the BH5 - in the range from 3.3 to 5.1 m. Layer 1 is represented by grey to yellow brown medium to coarse sand, medium dense to slightly cemented sandstone with some gravels. Layer 1 has the following physico-mechanical parameters:

- Bulk density 1,91 g/cm^3
- Void ratio 0,61
- Angle of internal friction (residual) 32,6°
- Cohesion (residual) 1,3 kPa

B. Layer 2 - Silty sandy clay (N1-2). Layer 2 is found in all boreholes and takes up most of the section. It is made of grey-yellow to variegated silty sandy clay in stiff consistency, with thin sandy layers. Physical and mechanical parameters are within the limits:

- Bulk density 1,82 – 2,14 g/cm^3
- Consistency index 0,72 – 2,12
- Void ratio 0,39 – 0,71
- Angle of internal friction (residual) 24,2°
- Cohesion (residual) 16 kPa

C. Layer 3 - Clayey sand (N1-2). Layer 3 is encountered in layer 2. It is represented by gray clayey sand with thin layers or with alteration of brown stiff clay. Layer 3 is characterised with the following physical and mechanical properties:

- Bulk density 1,81 – 2,05 g/cm^3
- Consistency index 1,09 – 1,83
- Void ratio 0,48 – 0,73
- Angle of internal friction (residual) 23,7°
- Cohesion (residual) 6,7 kPa

Slope stability calculations are summarized in Table 3 and Figure 8

Table 3. Factors of safety in different conditions of the slope for Koprivlen-2

Condition of the slope	Slip surface No	Factor of safety, Fs
Dry slope	157	1.278
High ground water table	233	1.044
High ground table + earthquake	252	0.802

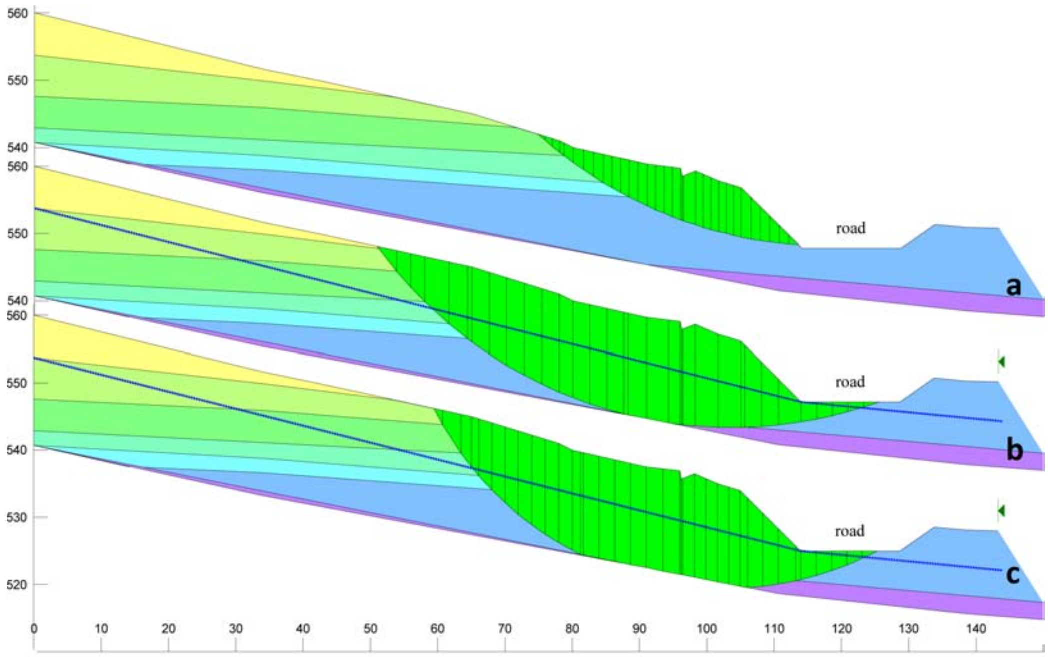

Fig. 8. Different load conditions for Koprivlen-2 landslide: dry (a), high ground water table (b), and High ground water table + earthquake (c). Scale in meters

In the initial state with deeply located underground water, table slope resistance is higher than the legally required levels. Upon elevation of groundwater the slope passes into a state close to the limit equilibrium. During the prognostic earthquake of VIII degree factor of safety drops significantly and lower part of the landslide passes in a unstable situation which real threatens with strong deformation and breaking the road in this area.

Landslide Koprivlen-2 lacks quality drainage. This includes urgent restoration of the surface ditch, which is seriously compromised by erosion runoff. Next, the slope should be strengthened. There are two options according to the author's opinion:

1. Continuation of existing section of flexible retaining wall of gabions. This retaining wall consists of four rows of gabions and the side height could be reduced stepwise. The existing wall of 22 m should be extended to about 72 m (Figures 9 and 10)

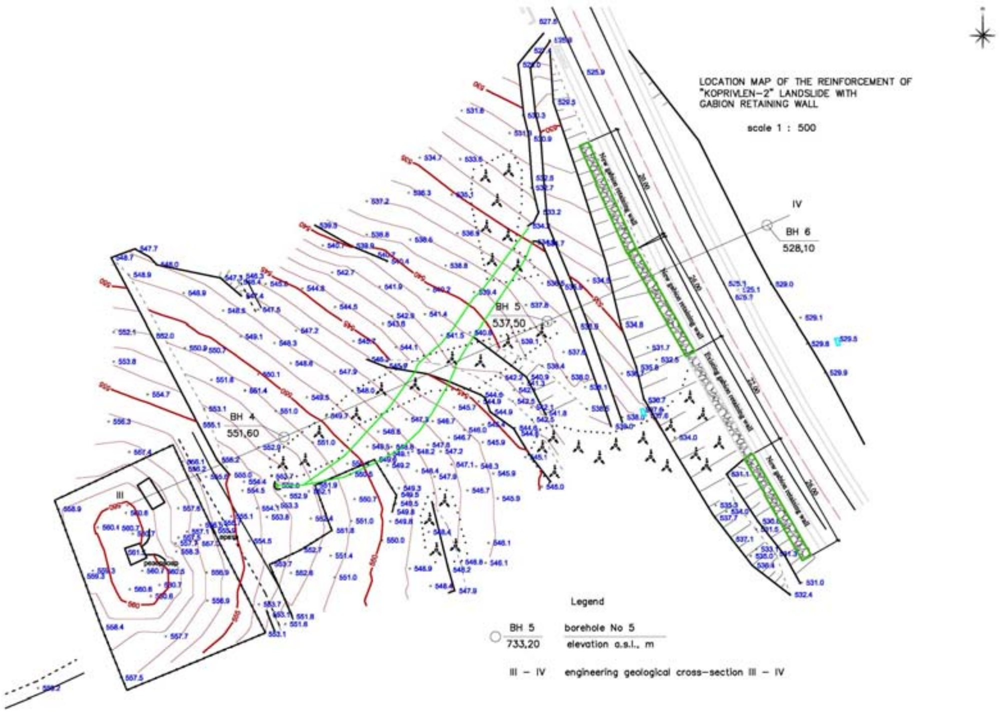

Fig. 9. Reinforcement of Koprivlen-2 with gabions

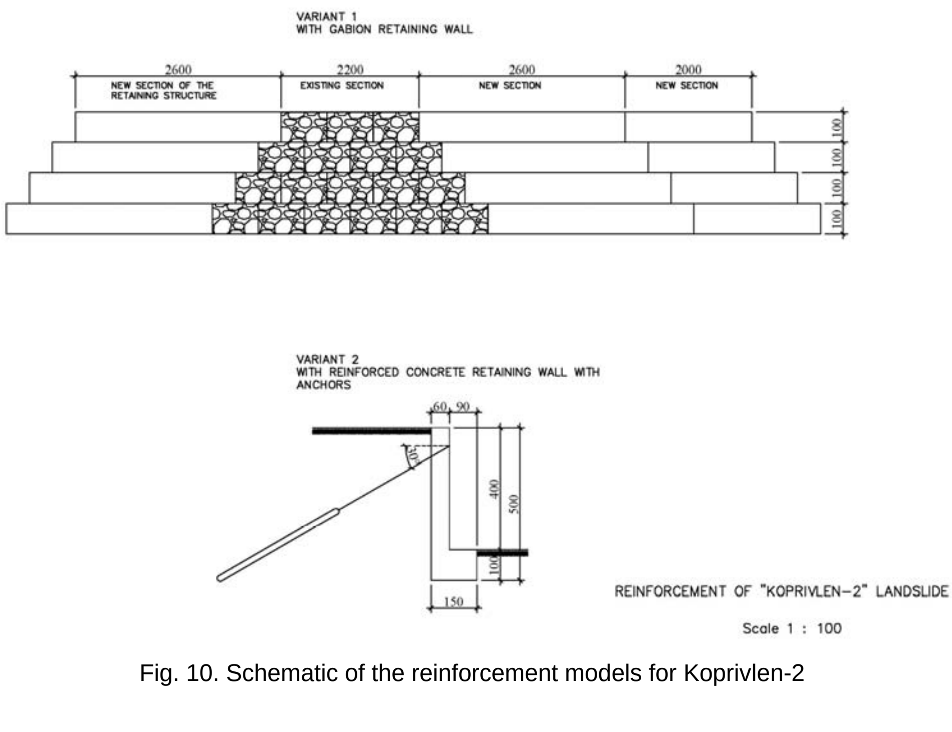

Fig. 10. Schematic of the reinforcement models for Koprivlen-2

2. Strengthening of the slope with reinforced concrete anchored retaining wall using injection anchors with dr = 0,2 m and lr = 4,0 m under 300. In this way all checks on sliding and overturning are satisfied (Figures 10 and 11)

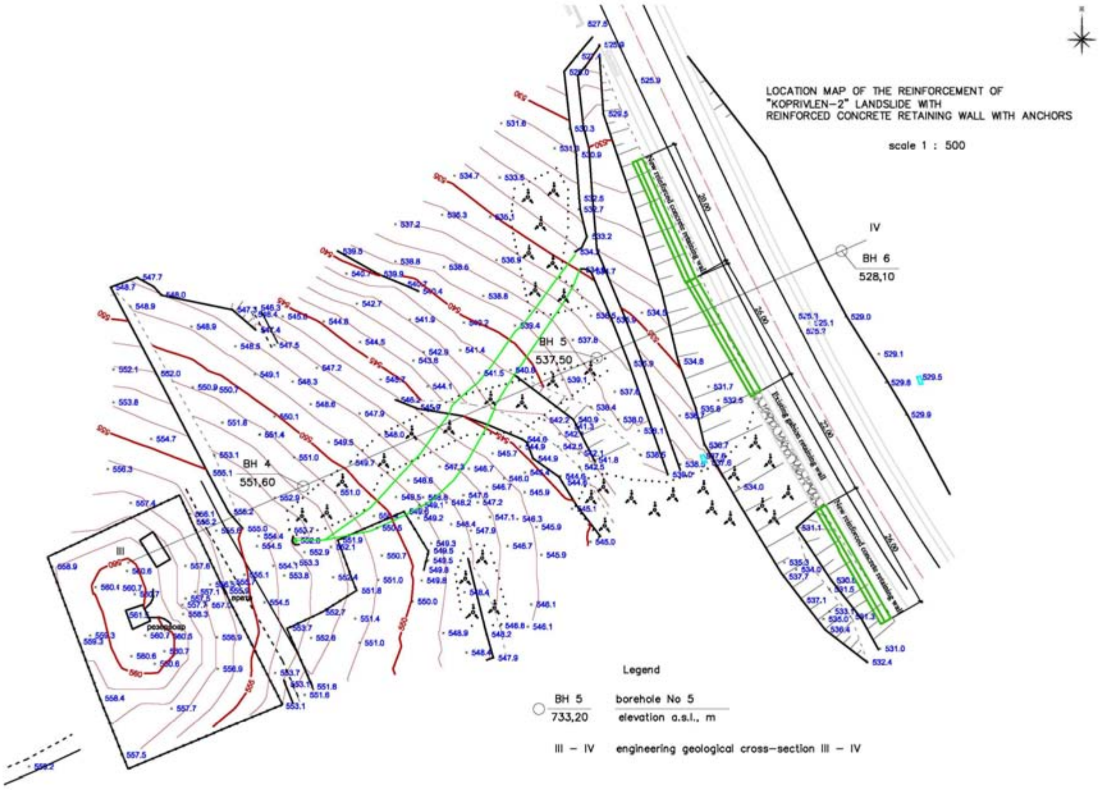

Fig. 9. Reinforcement of Koprivlen-2 with concrete retaining wall with anchors

Conclusions

The collected data and materials have been successfully implemented in RISKLIDES project. The results have been described in detail in several work report packages. Combination of high ground water table + earthquake puts the slope in an unstable environment. Adequate preventive measures and retaining structures have been developed to increase slope stability and to avoid activation of recorded landslides based on geotechnical slope stability analysis.

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