Structural control, causes and mechanisms of a rockfall event in the valley of Krushuna Waterfalls, North-Central Bulgaria

Структурен контрол, механизми и причини за възникване на срутище в района на „Крушунски водопади“, Централна Северна България

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Introduction

The Krushuna Waterfalls Valley is a famous tourist destination in Bulgaria, visited annually by more than 200 000 tourists including a large number of foreigners. On the 6th November 2015 a rockfall in that valley, caused two fatalities. The present research aims at analysing of the rockfall hazard in the Krushuna Waterfalls area and studying the mechanism of the 6th November rock mass collapse.

Geological setting

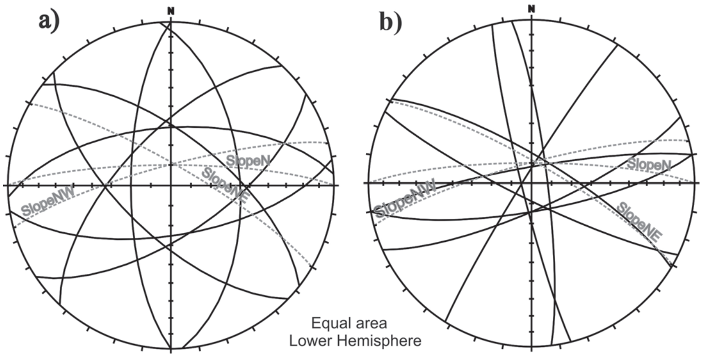
National park “Maarata” is located in the NW section of Sevlievo-Preslav swell, which is a part of the Centralbalkan-Forebalkan Zone. The rocks in the park belong to the Lower Cretaceous (Aptian) Devetashka Formation, part of the Lovech Urgonian Group. The formation consists of thick (up to several tens of meters) layers of limestone with intercalations of sand- and clay-rich limestones and marls. The limestones are strongly affected by karst processes. Due to their lower permeability, the thinner clay rich layers are more resistant to the karstification. The Lower Cretaceous sequence in the area is covered by Quaternary sediments of alluvial, diluvial and karst origin. The latter form a spectacular travertine edifice, in which Krushuna Waterfalls were formed. The travertine edifice comprises several layers of rather competent material (plant remnants incrusted by $CaCO_3$) separated by thin layers of finely laminated karst sediments mostly composed of non-lithified sand and clay ± organic matter. The travertine edifice rests on a relatively flat (shallowly dipping to north) surface, representing approximately the top of a 1–2 m thick clay-rich limestone to marl layer from the Devetashka Formation.

Results

For the travertine rockfall analysis, we have performed a detail study of four different sections in the Krushuna Waterfalls Valley. A combined approach included geological mapping, geotechnical mapping, structural analysis and stereographic simulations of the rock mass stability characteristics. Structural analysis and simulations are based on field observations and kinematic characteristics of the studied discontinuities, observed in the travertine.

At the location of the rockfall from 6th November 2015 (study section 1), we have mapped a system of joints which by kinematics, geometry, morphology and spatial relationships were classified as shear and extension (tension) joints. The stereographic simulations showed that the shear joints system includes four pairs of structures. Each of the pairs is characterised by an angle of about 60° between the opposite dipping sets which corresponds to the development of conjugated shear joints. These structures are rather discrete, with a minor opening. Often the shear joints are filled and sealed by carbonate material. In some places, a reactivation of the welded surfaces was noted, indicating the simultaneous joints formation and carbonate precipitation. Four sets of steep to subvertical joints developed along the bisector plane of the conjugated shear joints. These were interpreted as extensional structures (tension joints). The spatial distribution and the orientation of the four synkinematic sets of shear and tension joints from the observed system correspond to the orientation and geometry of the steep slopes geometry and rock faces in the travertine massif (Fig. 1).

The structural analysis and data simulations for study sections 2, 3 and 4 showed identical results. In



Shear joint sets (a):	Extension joint sets (b):
129/66/NE	121/77/NE
134/66/SW	116/82/SW
56/65/SE	66/77/SE
43/65/NW	32/86/NW
81/65/SSE	80/76/SSE
87/62/NNW	80/82/NNW
86/55/E	173/83/E
0/70/W	167/86/S

Fig. 1. Stereographic plots of joints from the rockfall area: *a,* large circles representing the maximum values in the orientation of shear joints; *b*, extension joints. The dashed large circles represent the orientation of the rock slopes.

section 2 a system of five conjugated shear joint sets and five extension joint sets was defined. Similarly as in section 1, their strike coincides with the strike of the steep rock slopes. In section 3, the system of joints is presented by two conjugated shear joint sets and two tension joint sets. Study section 4 is located in the nearby Green Rock Waterfall Valley. There, the joint system shows similar characteristics and relationships with the slope geometry and orientation of the cliff faces. We determined two conjugated shear joint sets and respectively two sets of extension joints.

Discussion and conclusions

The analysis and interpretation of the collected structural data from the area imply that the major factors for the rockfall hazard in this region are the lithological and structural features of the rock mass. The characteristic features of the discontinuities at the location of the rock collapse from 6th November show that they are spatially distributed and form several groups. Stability characteristics of the rock slopes and the mechanisms of the occurred deformation are strongly related to the orientation, morphology and infill of the different joint sets as well as the lithology of the rock mass. Along all studied section in the valley, we found a direct link of the orientation of the shear and extensional joint sets with the orientation of the steep travertine slopes. Considering that the joints developed in a rock with no older discontinuities, we can assume that their orientation and geometry are controlled by the applied stress field. The young (recent) travertine massif is clearly unaffected by a differential tectonic stress, and therefore the joints developed in a stress field, controlled by the gravity and lithostatic forces. In this kinematic framework, by definition, the maximum compressive stress tends to parallel the dip direction and the angle of the slopes in the valley, which implies that the maximum stress axis (σ_1) is subparallel and to the travertine rock slopes, the minimum stress axis (σ_3) is perpendicular to the rock faces, and σ_2 remains subhorizontal.

In summary, the structure of the travertine edifice in the area of the present research is presented by several layers of travertine, separated by thin layers of karst sediments and 8 joint sets, including 4 subsystems, which trend matches the strike of the rock slopes in the valley. The mechanisms of the occurred deformation are predetermined by the relationships between the different joint sets and the rock slope geometry. The gently north-dipping clay rich layer, on which the travertine edifice was deposited, further contributed to the rock slope failures. The geotechnical analysis determined that the controlling mechanisms of the rock slope failure were plane sliding and wedge sliding. Subvertical tension joints and shear joints dipping in the direction of the slope bounded the large blocks that collapsed and also acted as sliding surfaces. The oppositely or obliquely dipping sets of joints as well as the karst sediments contributed to separating the blocks from the travertine rock mass. The research in the Krushuna Waterfalls Valley showed that the formation of travertine is an ongoing process. On the other hand, the whole valley bears evidence of paleo and more recent rockfall events. The hazard analysis clearly indicates that the risk of future, unpredictable in the time, rockfalls in the area is very high. In order to secure a safety tourist environment without any artificial alteration of the travertine edifice, a close monitoring of the joints development in the whole valley is highly recommended. Safety measures to prevent visitor access to certain rock-walls shall be also implemented.

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