Journal of Cultural Heritage 14 (2013) 359–364

Available online at
SciVerse ScienceDirect
www.sciencedirect.com

Elsevier Masson France
EM|consulte
www.em-consulte.com/en

Case study

# Key block theory application for rock slope stability analysis in the foundations of medieval castles in Slovakia

Vladimír Greif*, Ján Vlčko

*Department of Engineering Geology, Faculty of Natural Sciences, Comenius University in Bratislava, Mlynska Dolina G, Bratislava, Slovakia*

ARTICLE INFO

*Article history:*
Received 17 February 2012
Accepted 4 September 2012
Available online 1 October 2012

*Keywords:*
Castle rock slope
Factor of safety
Key block theory
Pseudo-static analysis

ABSTRACT

This research investigates the stability of rock slopes in the foundations of selected medieval castles in Slovakia. In the first phase, static analysis of the 45 selected medieval castle rock slopes was performed, where more than 12,000 potentially unstable blocks were analyzed and the factor of safety in static condition was calculated using the key block theory implemented in the Kbslope module of PTworkshop software. Based on results of the static stability analysis, a pseudo-static analysis was performed adopting the seismic acceleration in accordance with Slovak Technical Standards – Seismic actions on structures. This was implemented by calculating the vectors of horizontal force acting upon shear failure in the direction of the slope face with a zero vertical component. When non-finite and tapered blocks were ignored, the results proved that 14% of the 12,217 blocks investigated under static conditions could be considered unstable. This number increased to 23% under pseudo-static conditions, when seismic acceleration was implemented in the stability calculations. A detailed stability assessment of the Gymes Castle located in western Slovakia was carried out with delineation of blocks prone to rock sliding and proper stabilization methods, based on joint sets orientation measurements performed on the 3D point cloud generated by laser scanner.



## 1. Research aims

There are over 250 medieval castles, chateaus or fortified monasteries in Slovakia. Although many are in a state of ruin, the majority of these sites are protected by law as cultural heritage. This includes Spis Castle which is under the patrimony of UNESCO. Due to their primary defensive function and the mountainous landscape of Slovakia, the majority of medieval castles are built on the top of rock cliffs. Their long-term stability is influenced by the stability of the rock mass in the bedrock. In addition, there are several reports of rock blocks falling from the steep slopes and endangering visitors, as witnessed at Devin and Likava Castles. Here, the contribution of an engineering geologist dealing with rock slope stability is vital not only for safeguarding the historic structure itself, but also for visitor safety. Furthermore, due to the longevity of cultural monuments, rock slope stability problems must be solved, especially to limit seismic risk even in countries like Slovakia, where earthquake risk is relatively low. Therefore, seismic rock slope stability and factor of safety calculations were established for the bedrock of medieval castles in Slovakia. This work began on a regional scale, and covered rock features in 45 local castles where the stability of individual rock faces was described and evaluated in detail. The rock block stability was calculated for static and pseudo-static conditions in three dimensions using the key block theory.

## 2. Introduction

The accepted methods of assessing rock slope stability and calculating safety factors, as applied in natural rock outcrops or engineered man-made slopes, can be successfully applied to the natural rock slopes beneath cultural heritage site foundations. In recent years, vast emphasis on national pride instigated the reconstruction of historical sites in Slovakia, including the ruins of medieval castles. A set of 45 mostly medieval castle rock slopes were therefore selected for examination, and restoration where required (Fig. 1a). Each castle contained several rock faces with different slope orientation, and these were analyzed using the static and pseudo-static key block methods. A complete stability analysis of discontinuous rock slopes consists of the following three steps: (1) creation of the geometry of the block system isolated by discontinuities and rock face; (2) finding all potentially removable blocks and corresponding mechanisms causing failure and (3) the stability calculations [1]. Most previous static analysis research work on stability problems in discontinuous rock slopes focused only on details, such as the generation of the blocky rock mass [2,3]; determination of sliding modes and safety factors of sliding

* Corresponding author. Tel.: +421 2 602 96596.
*E-mail address:* greif@fns.uniba.sk (V. Greif).

1296-2074/$ – see front matter © 2012 Elsevier Masson SAS. All rights reserved.
http://dx.doi.org/10.1016/j.culher.2012.09.001

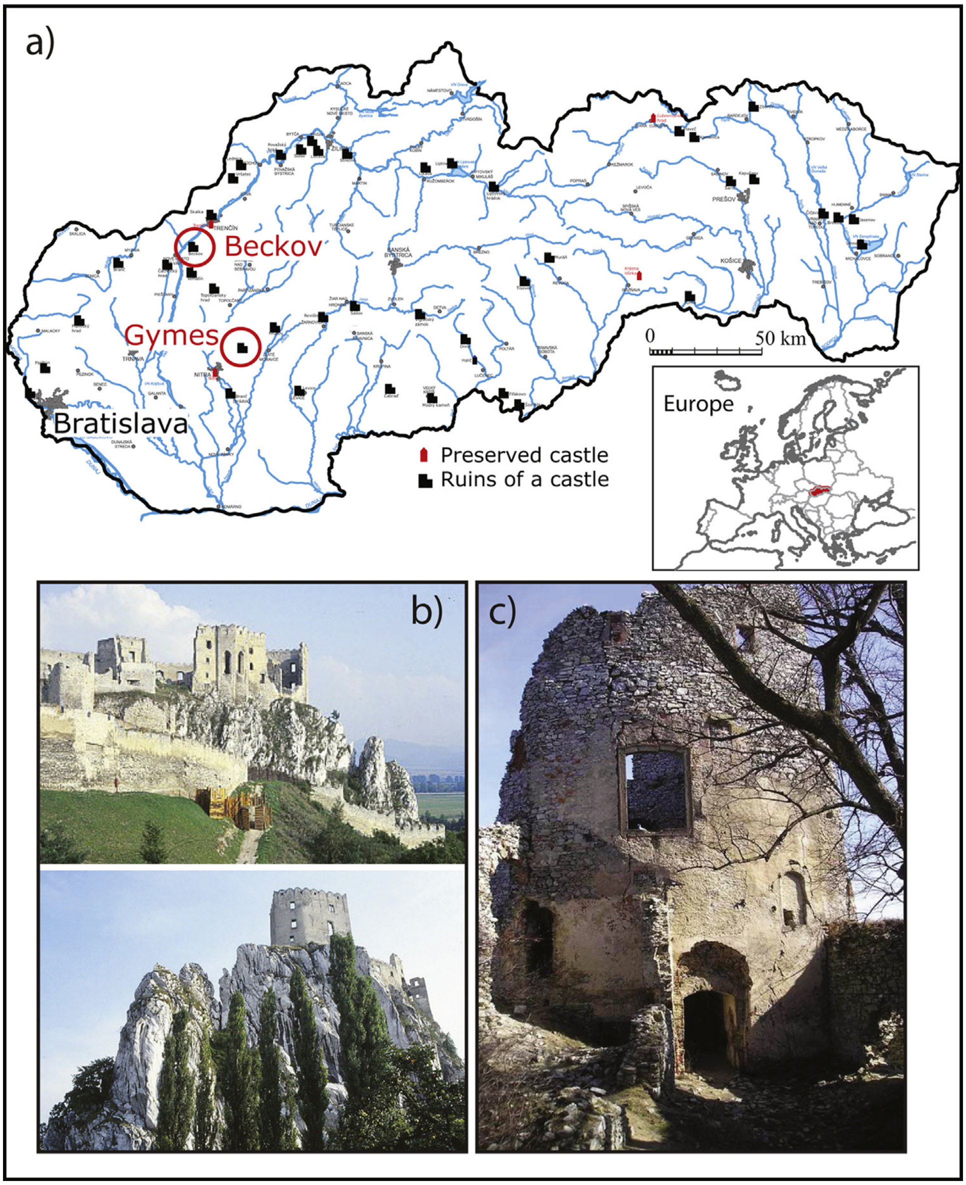


**Fig. 1.** Locations of the investigated castle rock slopes with highlighted castles referenced in the text (a) and photographs of the Beckov castle northern and southern views (b) and a view of St. Ignatius Chapel in the Gymes castle (c).

blocks [4,5]; the distinction between single and double plane sliding of blocks [6,7]; the assessment of kinematic feasibility, sliding and volumes of blocks by means of inclined stereographic projection [8] or through vector analysis [9], or based on graphic theory [10]. The block theory developed and continuously extended by Shi [11,12] and Mauldon and Goodman [13] can be considered a comprehensive procedure of static analysis for stability evaluation of discontinuous rock slopes. The power of the block theory lies in its simplification of a quite complicated analysis of discontinuous rock slopes to a step-by-step analysis [13]. Detailed fundamentals and proofs can be found in the text by Goodman and Shi [12].

## 3. Methods

In the first phase of this research, a static analysis of the 45 selected medieval castle rock slopes was performed. The necessary input data consisted of the joint sets orientations obtained from the engineering geological inventory of medieval castles of Slovakia, and also field mapping. With the exceptions of the joint friction angle which was selected from published data [5] and outcrop slope orientation determined in field investigation, all other input parameters were determined in the laboratory. Approximately 60% of the joints surveyed in the field lacked information on their spacing, so a default value of 1 m was set [5]. All this data was used to determine the potential failure mechanism and calculation of the safety factor using the 3D stability KbSlope software. The resulting factor of safety and the failure mechanism are summarized in Table 1, with an excerpt for the Beckov and Gymeš Castles presented in Fig. 1a and b.

Based on results of static stability analysis, a pseudo-static analysis in dry conditions was performed for the 45 castle rock slopes. The safety factor (FOS) was determined using the pseudo-static method, and it is presented with reference to the geometry and mechanical quantities in Fig. 2a, as:

$$FOS = \frac{cA + \left(W\cos\beta - F_h\sin\beta\right)\tan\phi}{\left(W\sin\beta + F_h\cos\beta\right)} \tag{1}$$