Use of Distinct Element Method in the Numerical Analysis of Slope Failure Mechanism Study at the Spis Castle

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Abstract: Spis Castle (Eastern Slovakia) is built on a travertine mound overlying the Paleogene soft rocks. The travertine castle rock represents an erosion remnant of an originally larger travertine's formation precipitated during the Miocene/Pliocene epoch. The physical and mechanical properties of travertines are strongly influenced by jointing, weathering and karstification. The travertine body of the castle rock is influenced by to lateral spreading. Slope failure mechanism using 2D numerical modelling (UDEC - professional code) have been analysed and investigated.

Key words: discontinuities, discrete element method, numerical modelling, travertine mound

Introduction

Earth sciences, particularly engineering geology, rock mechanics, and rock slope engineering, etc. belong to those disciplines from which the concept of distinct element method originated. The availability of numerical modelling techniques is sufficient for both continuum and discontinuum materials to be analysed with many advantages with respect to slope failure mechanism study. Distinct element models are appropriate to simulate the blocks as discontinuum materials either rigid or deformable and the weaker underlying layers as elastic - plastic continuum materials. Both 2D and 3D distinct element modelling techniques are available - UDEC and 3DEC (Itasca, 1993).

This paper explores the application of 2D distinct element models in studying slope failure mechanism at Spis Castle. Due to particular geological and geomorphologic features the Spis Castle is suffering from large-scale slope instability phenomena: in the travertine's cliff, due to jointing, karst processes, lateral spreading, topples and rock falls are the common landslide typologies while in the underlying Paleogene outcropping at the lower part of the castle rock are soil creep prevails.

Geological setting

On a travertine mound 200 m above the surrounding land, at the elevation of 634 m, there is one of the most precious cultural monuments in the Spis region that reigns over the Spis Basin - the Spis Castle. It represents the largest medieval fortification system in Central Europe (Fig.1). It was founded in 1120. The historic development of the castle was rather complicated showing traces of many historic epochs up to the Baroque. In 1780 the castle burnt out and since that time it was abandoned and the process of destruction caused both by the natural and man-made factors was going on.

Fig. 1 Location map

From a geological point of view the studied area is located in a zone referred to as Hornadska kotlina Basin (Eastern Slovakia). Spis Castle is built on a travertine mound (Fig. 2), which is underlain by Paleogene soft rocks formed by claystone and sandstone strata (flysh-like formation).

The travertine body reaching more than 52 meters in thickness reflects several features of destruction and is disturbed by a series of faults, cracks and joint systems. Two prevailing joint sets can be found: sub-vertical joints striking approximately NW to SE with a general dip to SW (dip direction/dip 220°-250°/80°-90°) and joints striking approximately N-S dipping to the W (250° to 270°/85°). In relation with orientation of main discontinuities two caves were developed Dark Cave (Temná jaskyňa) and Podhradie Cave (Podhradská jaskyňa; Fussgänger, 1985).

Lateral spreading caused by the subsidence of the strong upper travertine into the soft underlying claystone has fractured and separated the castle rock into several cliffs. The central part of the travertine rock is formed by a block rift (travertine cliffs separated by persistent tensional joints and cracks), the marginal parts of the castle rock are formed by a block field consisting of displaced

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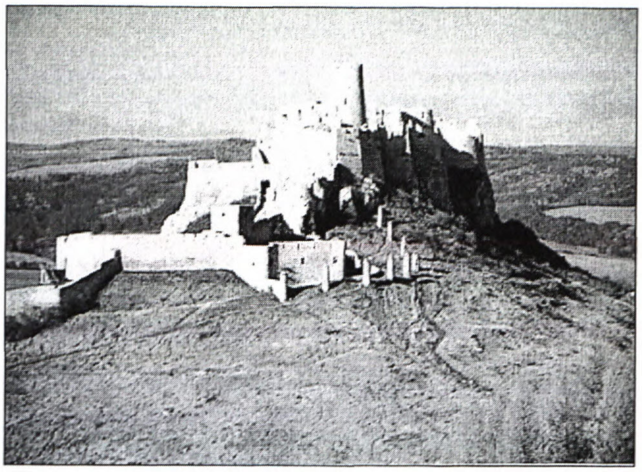

Fig. 2 Spis castle

and tilted cliffs reaching the height from 25 to 30 m, sloping at an inclination of 70° to 80°, in some places up to 90° with a number of overhangs. The absence of a block field in the SW part of the castle rock is due to the uplift of Palaeogene claystones along the fault line (220°/80°) which inhibited total disintegration of the block field, followed by rock falls, toppling and tilting of huge cliffs of travertines (Vlcko et al.1993, Vlcko 2002).

Numerical modelling

Based on the geological setting (Fig. 3) a simplified geo – mechanical model in accordance with the objectives of the analysis was considered. The upper part of the castle rock represented by travertines were assumed as rigid discontinuum medium, the underlain layers formed by Paleogene claystones as elastic-plastic medium, both following Mohr-Coulomb criterion. The contact zone between those two materials with different geomechanical behaviour is always represents the creep zone or the shear plane).

The UDEC program simulates the mechanical behaviour of the discontinuum medium represented as an assemblage of discrete blocks subjected to either static or dynamic loading. The main features of the code can by summarized as follows:

- The discontinuities are treated as boundary conditions between blocks; finite displacements along discontinuities and rotation of block are allowed;
- Blocks may be rigid or deformable; contacts are always deformable;
- The program recognizes new contact as the calculation proceeds;
- Several constitutive behaviour models following linear or non-linear laws are available for both joints and blocks;
- The program can simulate steady or transient fluid flow through the discontinuities.

As introduced in the UDEC code, vertical sides of the model have been assumed to move vertically only and the horizontal ones only horizontally. The rock material and the discontinuities are assumed elastic- plastic when the Mohr-Coulomb failure envelope or tensile failures are reached. Travertine and bedrocks rock have been assumed as fully deformable blocks and then discretized into finite difference triangular elements. The model ran over a number of iterations until the initial equilibrium conditions were attained.

A stepwise modelling procedure we adopted was based upon the back analysis comprised**:**

a) Simulation of travertine sequences over the Paleogene rocks until the state of equilibrium (initial state of stress) was determined. The travertines were assumed as an ideal homogeneous rock body.
b) Introduction of gradual decrease of bedrock material properties (weathering, softening) as well as gradual decrease of tensile strength along the joints in travertines (mainly joint normal stiffness and shear stiffness) were considered.

The physical and mechanical parameters as input data for modelling are summarized in Tab.1 (Baskova, Vlcko 2003). The resulting limit values reported in Tab.1 represent parameters determined by laboratory tests.

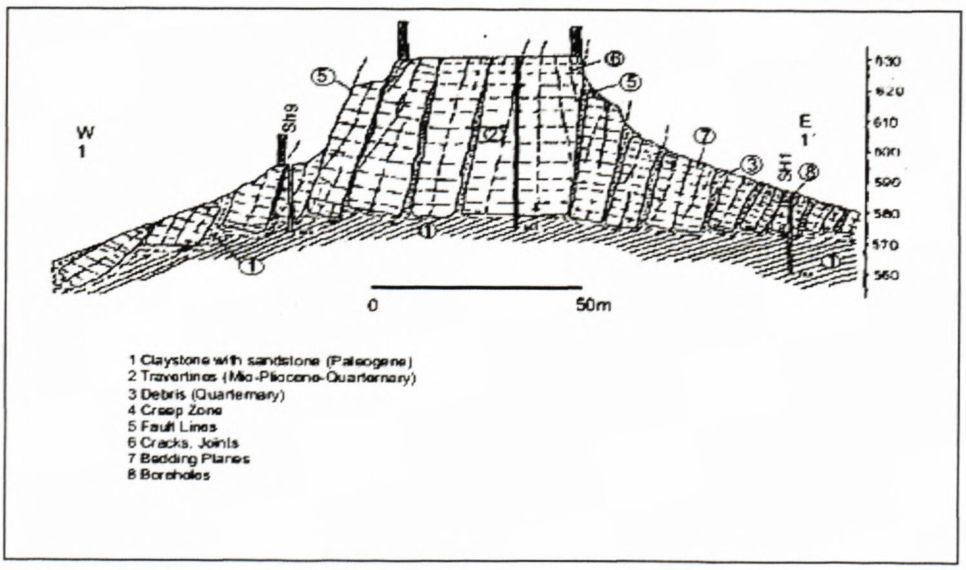

Fig. 3 Geological cross section after Malgot in Vlcko et al. 1993

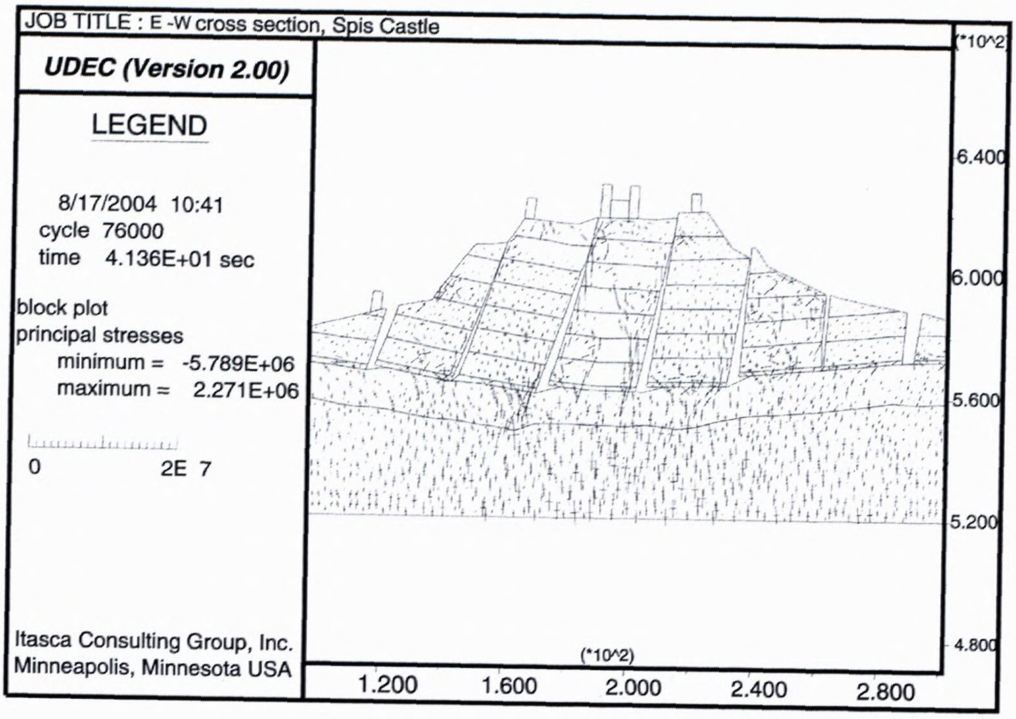

Fig. 4 Numerical analysis at Spis Castle - principal stresses

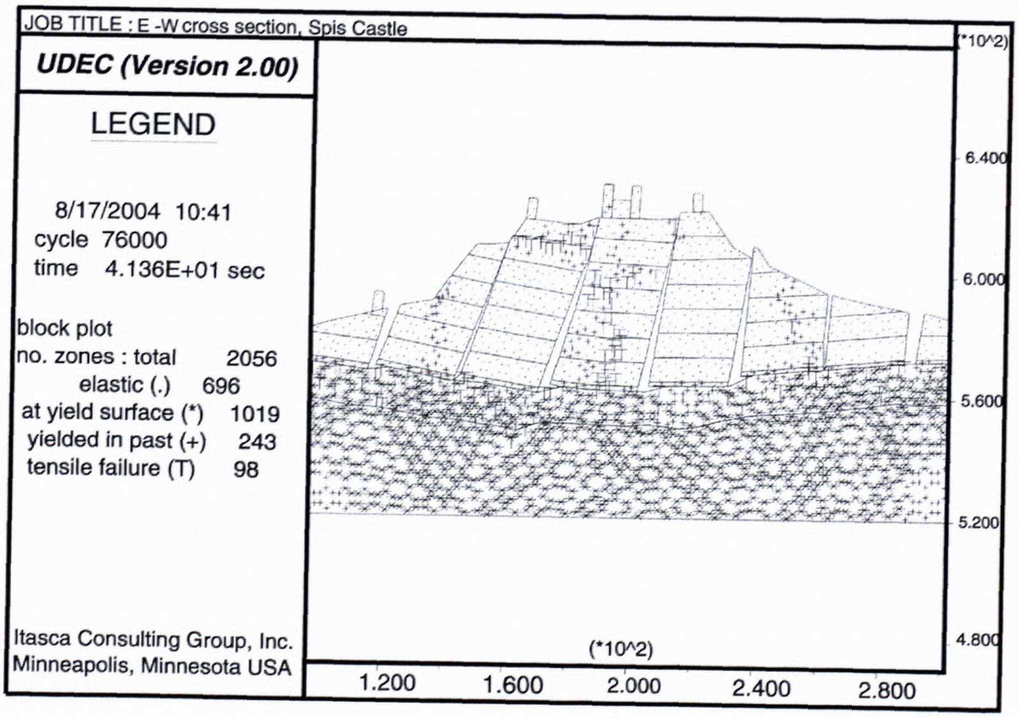

Fig. 5 Numerical analysis at Spis Castle - yielding zone and tensile fracture

Tab. 1 Physical and mechanical parameters of rocks use in numerical model (Baskova, Vlcko 2003)

Material	ρBulk density $(kg.m^{-3})$	ρ_c – Uniaxial strenght (MPa)	E – Young´s modulus $(MPa.10^3)$	νPoisson´s ratio
Travertine	*2500*	*63*	*56,6*	*0,19*
Contact zone (creep zone)	*1850*	*10*	*17,0*	*0,35*
Claystone	*2310*	*33*	*20,0*	*0,25*

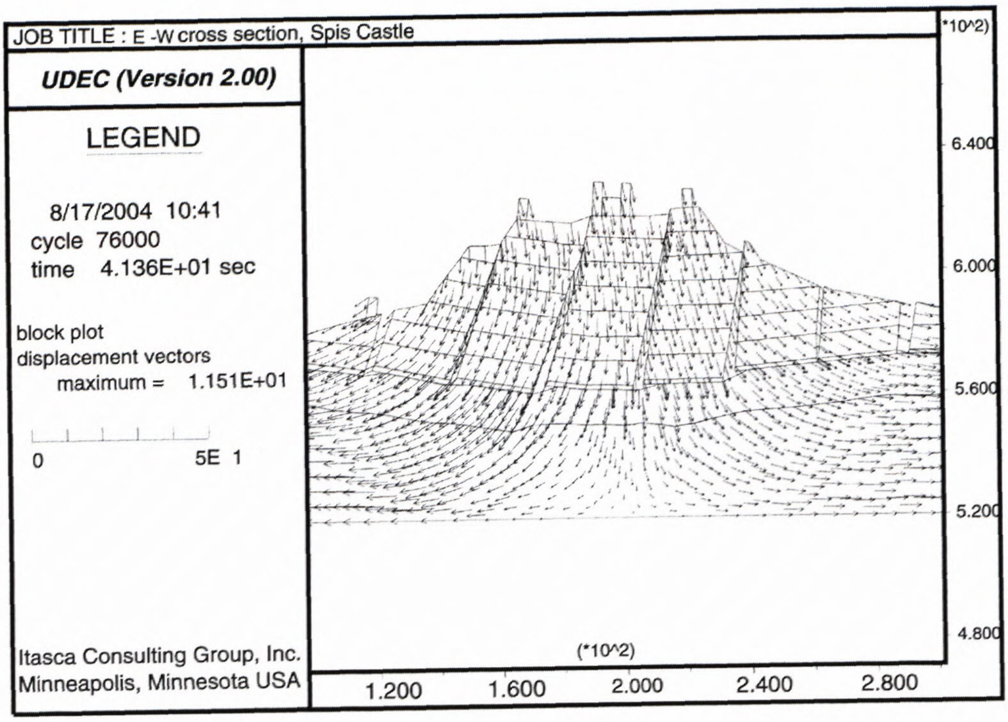

Fig. 6 Numerical analysis at Spis Castle – displacement vectors

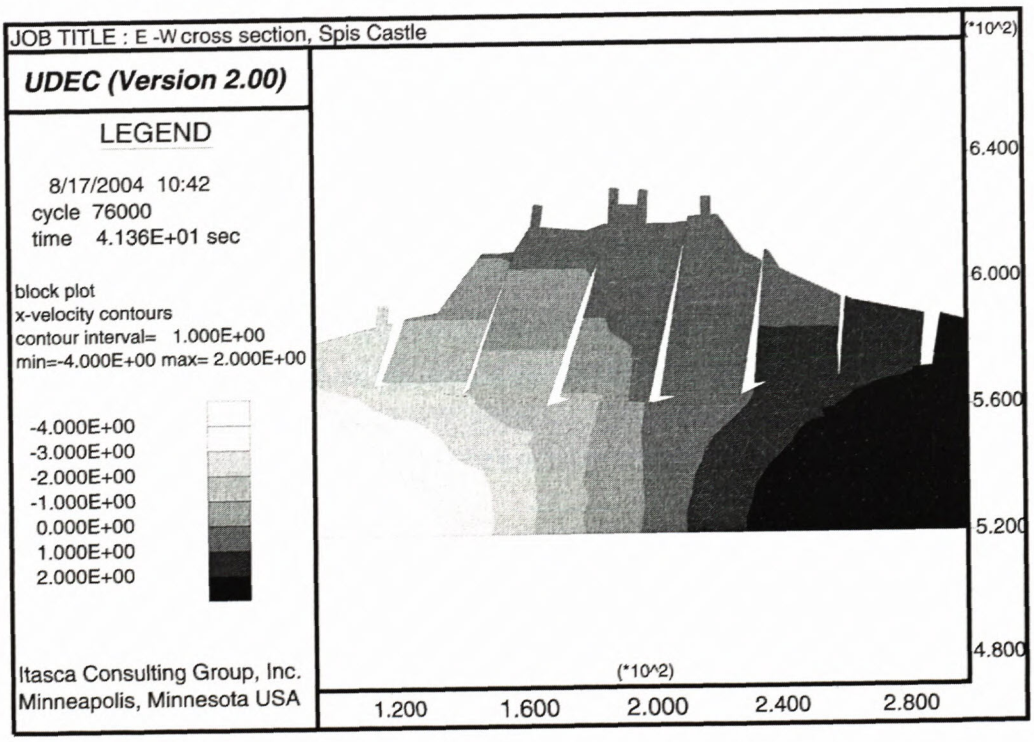

Fig. 7 Numerical analysis at Spis Castle – x- velocity contours (-4.0 mm.s^{-1} up to 2.0 mm.s^{-1})

Discussion

Discrete element method incorporates the main features required for slope failure mechanism analysis as it provides a realistic presentation of the rock mass under study and the use of deformable medium (travertine blocks) makes this method capable of reproducing the Spis castle rock deformation.

The results of the study confirmed the complexity of the phenomenon investigated and there are a number of details that emerge. Numerical analysis confirmed that the instability of travertine is related to significant shear strength reduction of the claystone formation. When the shear stress induced by the weight of travertine equals the diminishing shear strength (Fig. 4) and the strength of the claystone reaches the residual state, yielding zone and the

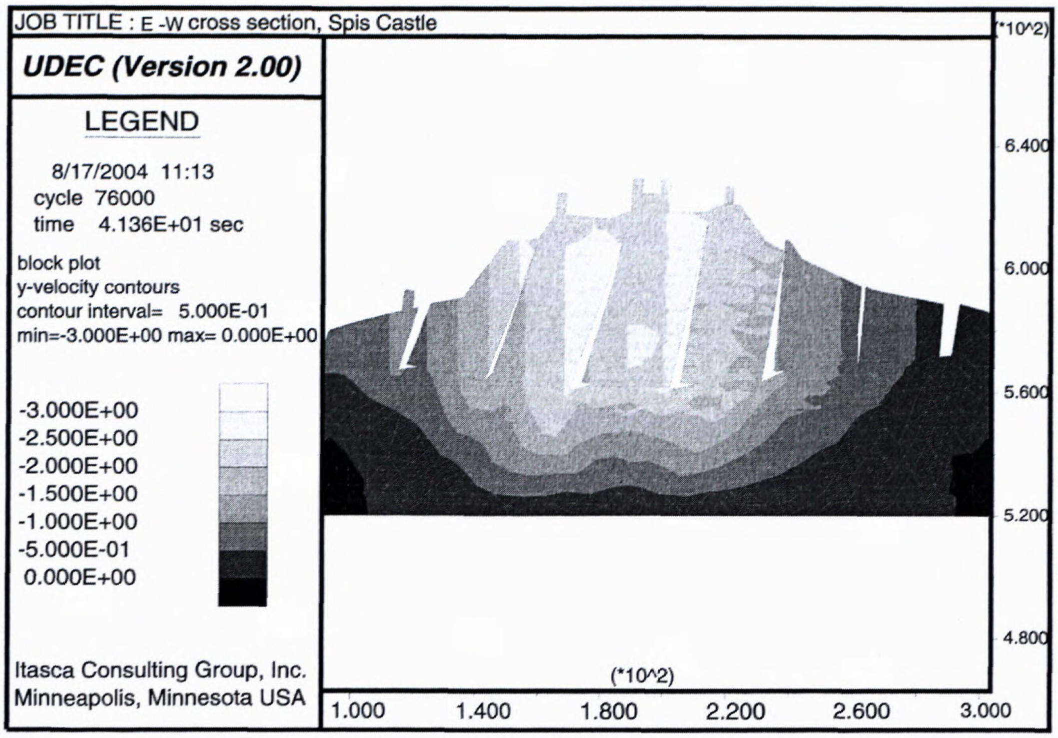

Fig. 8 Numerical analysis at Spis Castle – y - velocity contours (-3.0 $mm.s^{-1}$ up to 0.0 $mm.s^{-1}$)

failure surface start to develop and the travertine body is separating by subvertical persistent tensile fractures into several individualized blocks that starts to be unstable. At the western marginal part of the castle rock the cliffs are toppled up-slope while in the eastern part these are toppled down-slope. Along tensile fractures the strain is transmitted to the castle walls and inhibits their rupture, in some places even collapse (Fig. 5).

The slope failure mechanism is evident from the distribution of the displacement vectors (Fig. 6) as well as from the contours diagrams of velocity in x (Fig. 7) and y directions (Fig. 8).

Conclusion

To understand better landslide failure mechanism a numerical modelling can significantly contribute to the hazard/risk assessment for various purposes. The applicability in numerical modelling in rock slope engineering apart from material properties data almost entirely depends on the quality characteristics of the fracture system geometry, physical behaviour of individual fractures and the interaction between intersecting fractures.

The numerical modelling has a broad variety of applications in engineering geology (Greif et. al. 2001, 2002), rock and soil mechanics, structural engineering, etc. In case of Spis Castle, a monument under patrimony of UNESCO, the analysis confirmed the continual process of castle rock disintegration and the results we gained will be applied in design of stabilization and preservation works.

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