

Rock displacement and thermal expansion study at historic heritage sites in Slovakia

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Abstract The paper discusses the results of the research devoted to the preservation of cultural heritage carried out within last two decades in Slovakia. The aim of the study depended on monitoring of selected castle rocks showing instability problems due to extremely slow displacements of creep character. Apart from traditional methods of investigation at one test site (Spis Castle), authors implemented in their work the study of thermal expansion of the rocks as a result of seasonal periodic temperature changes having potential influence on displacements and numerical modeling in order to understand better the landslide failure mechanism. The results obtained from all study sites confirmed that even slow movements have to be implemented into preservation and stabilization works in order to safeguard the sites of great historic value.

Keywords Rock slope stability · Displacement monitoring · Thermal dilation · Historic site

Introduction

A great number of medieval castle ruins (dating back mostly to the thirteenth century) located at steep ranging cliffs belongs to the typical landscape of Slovakia. Since

the beginning of the eighteenth century, the castles were loosing their primary defense function; many of them were destroyed by fire or during military actions and later abandoned. At present, the majority of the castles have the character of ruins. Some of them endanger the residents in nearby settlements or the traffic routes; others are located in dense forests, in places difficult to access. The latter being parts of nature reserves present a hazard mostly to individuals.

The majority of castle ruins are located in areas of flysch and neovolcanic uplands and core middle mountains at a height of 350–700 m.a.s.l. (Fig. 1). Due to intensive neotectonic movement of the West Carpathians in the periods of late Neogene and in the Quaternary, a complicated geologic-tectonic structure developed. This development resulted in the formation of a highly dissected relief and a climatic diversity of the territory. The effect of the climatic conditions is quite evident, manifesting sudden daily and seasonal temperature fluctuations ranging from -20 to $+20^{\circ}\text{C}$, the daily temperature fluctuations range from 10 – 15°C . The mean annual amount of precipitation varies between 600 and 800 mm. In this respect, the prolonged snow cover (100–140 days a year) is of great importance. The vertical climatic diversity and the variety in lithology control not only the exogenous processes like weathering, erosion, slope movements, etc., but also superficial sediment formation and groundwater conditions (Matula 1969).

The presence of overthrust tectonic units is a typical feature of the West Carpathians and has a substantial influence on the character and the rock mass heterogeneity of the castle rocks. A very frequent case is when soft rocks mostly claystones and marlstones are overlain by rigid limestone–dolomite units. Overthrust lines act, when affected by shear forces, as an important plain of weakness and potential shear plains. Such geological structure forms

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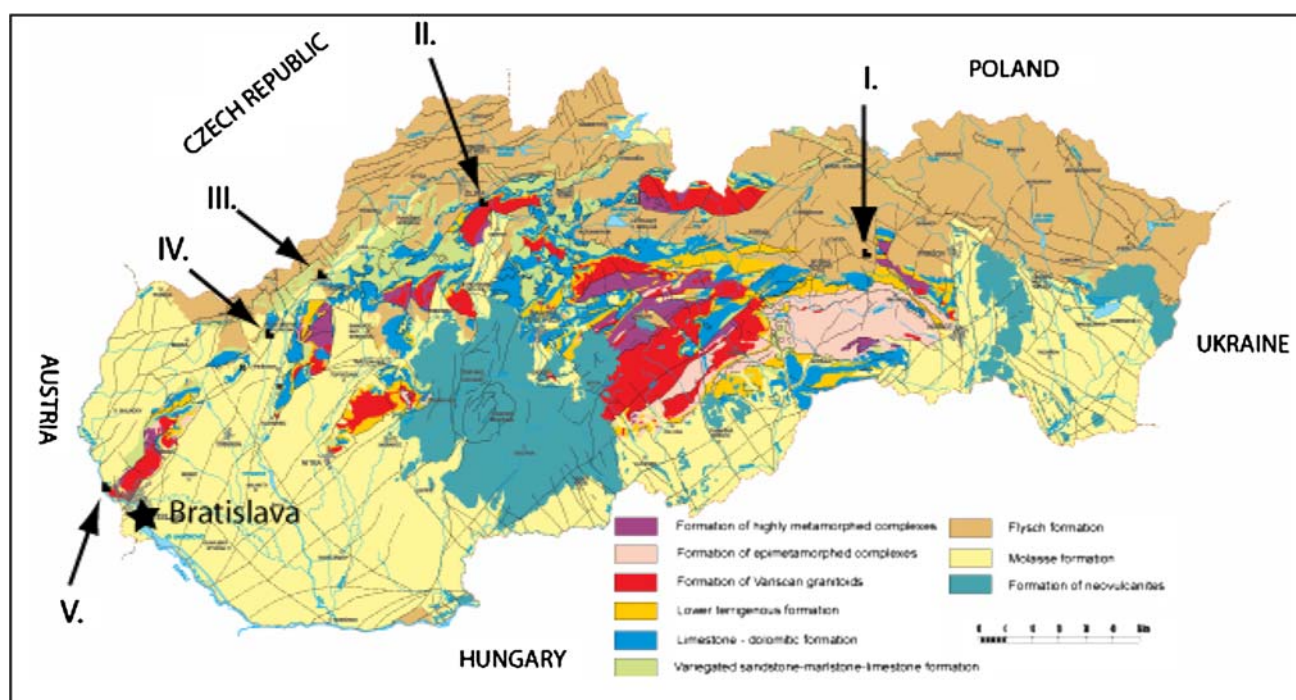


Fig. 1 Location of investigated sites in the regional geological map of Slovakia. *I* Spis Castle, *II* Strecno Castle, *III* Skalka Monastery, *IV* Čachtice Castle, *V* Devin Castle

favorable conditions for deep-seated creep deformations ridge loosening, block failures (block rifts and block fields), lateral spreading followed by rock toppling and rock falls (Poisel et al. 2005).

An investigation program sponsored by the Ministry of Environment in which about 40 most prominent castles or castle ruins were going to be investigated with the aim to recommend the remedial measures, and thus, to prevent their gradual disintegration both due to natural and man-made influence was set up and later on a successive project focusing on monitoring of the selected castle rocks showing instability problems was established. The paper presents some of the results of both projects.

Works and techniques employed

The preliminary stage of investigation carried out on a large regional basis, within a limited period of time, with low financial costs requires a cost-effective approach. The experience gained from previous studies and practical works aimed toward the protection and stabilization of historic sites proved that each historic site represents a completely different site of interest from geological, geo-technical, and historical point of view. This was the real reason why no standardized methods and techniques were applied and the survey was strictly focused at these priorities:

- to undertake an engineering geological study of all rock slopes and to determine in the rock mass and in the castle walls those sections which represent a potential source of instability,
- to recommend the appropriate stabilization measures in designated sections,
- to prepare graphic outputs easily understood by non-geologists, mostly experts dealing with historic building conservation, landscape architecture, etc.

The engineering geological survey was conducted largely by visual techniques mostly without drilling, applying traditional and special laboratory tests. The main accent was laid on engineering geological mapping and consequently engineering geological maps at a scale of 1:500 were prepared from each site. Further activities were focused on measuring the joint orientation, on location of past and active slope failures, rock falls, etc., on study of weathering processes in rock mass and rock material and on karst processes. Special attention was paid to the character of anthropogeneous sediments and their thickness, which is quite different from the thickness found there at the time of construction. These sediments act now as a source of active pressure on the castle ruins and when accompanied by other natural and man-made factors, they may cause serious damage.

Use was made of terrestrial photogrammetry for surveying and calculating joint orientation patterns in places difficult to access, as well as in places which have been

identified as potential sources of instability. Finally typical profiles from stereo pairs were drawn.

In the case of UNESCO World Heritage Site Spis Castle, distinct element modeling and thermal dilation studies were employed in order to determine the failure mechanism and thus potential risk to the castle.

Spis Castle

“The Spis Castle, a Natural Cultural Monument under the patrimony of UNESCO, represents the largest medieval fortification system in Central Europe”. The castle was founded in 1120. The historic development of it 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 continued.

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, which is underlain by Paleogene soft rocks formed by claystone and sandstone strata (flysch-like formation). The travertine body reaching more than 52 m 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° – $250^{\circ}/80^{\circ}$ – 90°) and joints striking approximately N–S dipping to the W (250° – $270^{\circ}/85^{\circ}$). The origin of the Temna jaskyna Cave is strongly bound to this system, as well. The destruction is the result of gravitational slope failures due to spreading of rigid travertines blocks on relatively plastic claystone strata. 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 and tilted cliffs reaching the height from 25 to 30 m, sloping at an inclination of 70° – 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 ($220^{\circ}/80^{\circ}$), which inhibited the total disintegration of the block field, followed by rock falls, toppling and tilting of huge cliffs of travertines (Vlcko 2004). The restoration works are slowly carried out since 1985, some objects are completed (Romanesque Palace, Chapel, Lower Courtyard), others are partly restored, but not completed. The castle rock was stabilized at NW and E part using rock bolts and anchors. The eastern part is still in the process of stabilization.

Monitoring

In 1980, three TM-71 type crack-gauges (TM-71-P1–P3) and in 1992 six additional were installed (TM-71-1–6). It should be noted that from a number of nine crack-gauges only four (TM-71-1, TM-71-2, TM-71-P1 and TM-71-P2) installed at the castle subgrade operate; the unexpected visitors demolished the rest (Fig. 2).

Significant displacement was observed in the southeast part of the Lower Courtyard near the castle entrance at a high travertine cliff called Perun's rock. Given past failures here, three monitoring locations were selected (Fig. 2): one (TM 71–2) in a 74-cm-wide tension crack outside the castle near the entrance to Podhradská jaskyna Cave and two (TM 71–1, TM 71-P1) on the opposite side of the cliff at Courtyard II.

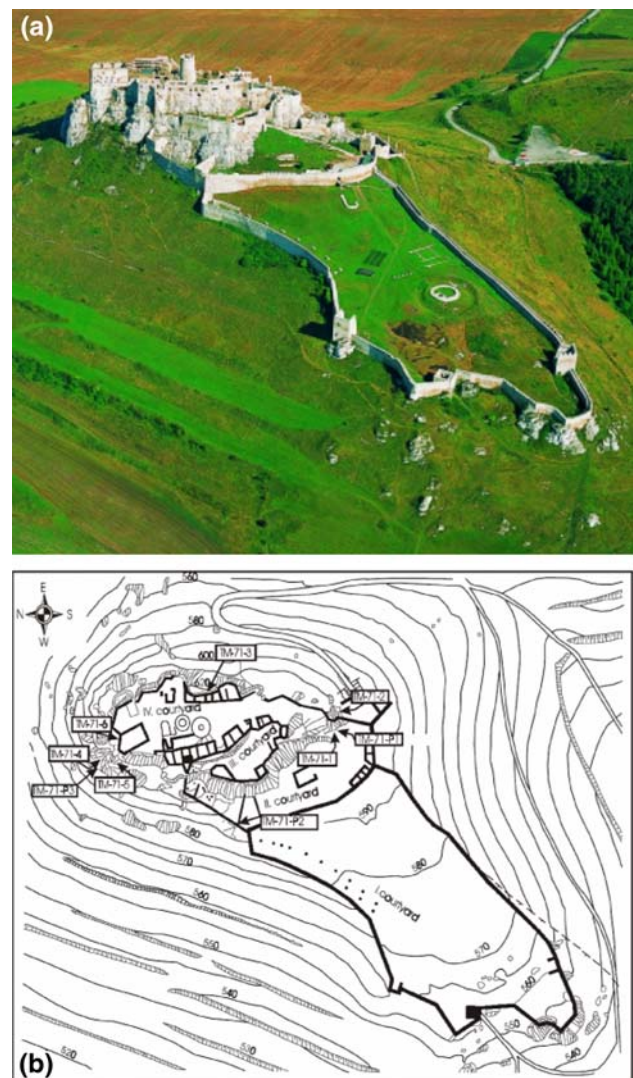


Fig. 2 Photograph (a) and the locations (b) of TM-71 crack-gauges at the Spis Castle

Data obtained from crack-gauge TM-71-2 indicate progressive crack closing (x -axis) of 2.3 mm for the period 1992–1994. Since then, and for the next 6 years, displacements oscillated about 2.5 mm as a function of the influence of seasonal temperature and precipitation. Since December 2000 there was a marked change in the rate of displacement. This is likely due to a large boulder which fell from the upper slope into the tension crack which is also the entrance of the Podhradská jaskyna Cave and thus formed a temporary barrier to further compression. The direct evidence for lateral pressure of Perun's rock was the progressive cracking of the boulder and the fissuring that began to occur in the repaired masonry walls. The latter effects required the eventual removal of the boulder from the open crack. Subsequent measurements confirmed an acceleration of the movements (1.0 mm) until the summer of 2006 when compression (closing of the crack) reached a maximum value of 3.98 mm for the whole monitoring period. The only exception to the trend of closing the crack occurred in spring 2002 and spring 2007 when abrupt extension (crack opening) was observed in response to “relaxation” of the opposite cliff. The recorded data confirm that boulder removal for the period of 2 years (2002–2004) accelerated the rate of displacement (approximately 1 mm per year), since that time the displacements correspond to the temperature oscillations except a short period in 2006 and 2007 (relatively rapid closing and opening with relative cumulative displacement of 0.7 mm). In y -axis the (horizontal shear) movement is relatively constant with the rate of 0.2 mm per year indicating the movement direction toward SW. In z -axis (vertical shear) the mean rate of displacement is about 0.25 mm per year and indicates the slip of the cliff. In Fig. 3a are shown the records obtained from crack-gauge TM 71-2 as well as the displacement 3D visualization of monitored block (Fig. 3b) within the period 1992–2008.

Data from the crack-gauge TM-71-P1 shown in Fig. 4 exhibit opening of the crack in the initial stage to an extent of 4.8 mm (max in 1997). Since that period, the inverse movement took place and the displacements show clear oscillation approx 0.5 mm per year with significant trend of compression (closing of the crack) in winter months and inverse displacements in summer months. The total closing of the crack since 1997 was estimated to 5.9 mm (0.59 mm per year). The trend in oscillation is since 2004 confirmed by an additional automatic crack-gauge Geocon 4.2 (crack-gauge lent with courtesy of GEOEXPERTS Ltd.)

Within y -axis until year 2001, very slow movement reaching 1.00 mm was recorded, since that period cyclic shear with forth and back movement was recorded. No significant movement in z -axis was recorded.

Based on monitoring records, we may estimate that the Perun's rock is tilting in the NW–SE direction. This

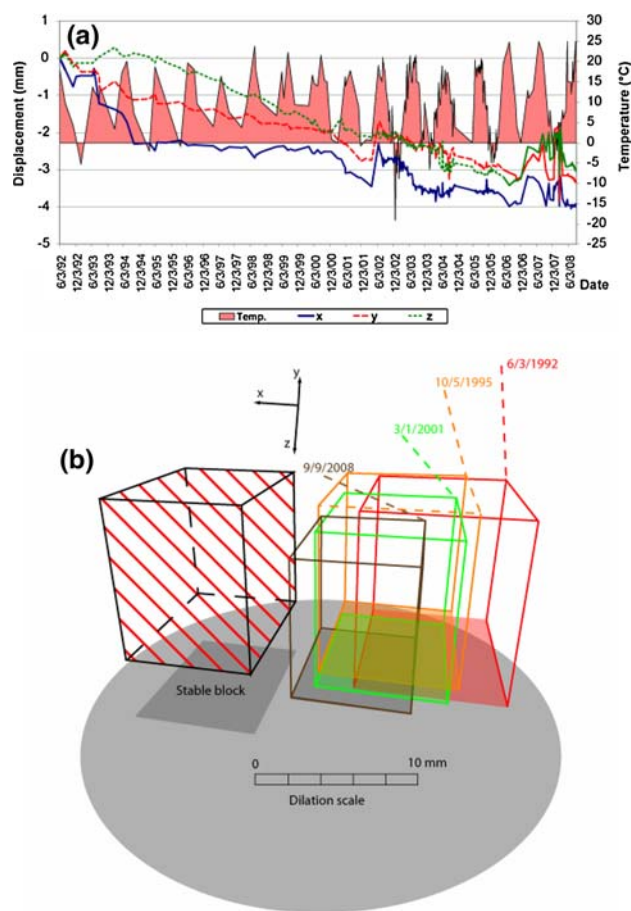


Fig. 3 **a** Records from crack-gauges TM-71-2 [x -direction = opening of the crack (positive values), closing (negative values); y -direction = horizontal shearing; z -direction = vertical shearing (down slip, positive values; uplift, negative values)]. **b** Displacement's 3D visualization within the period 1992–2008

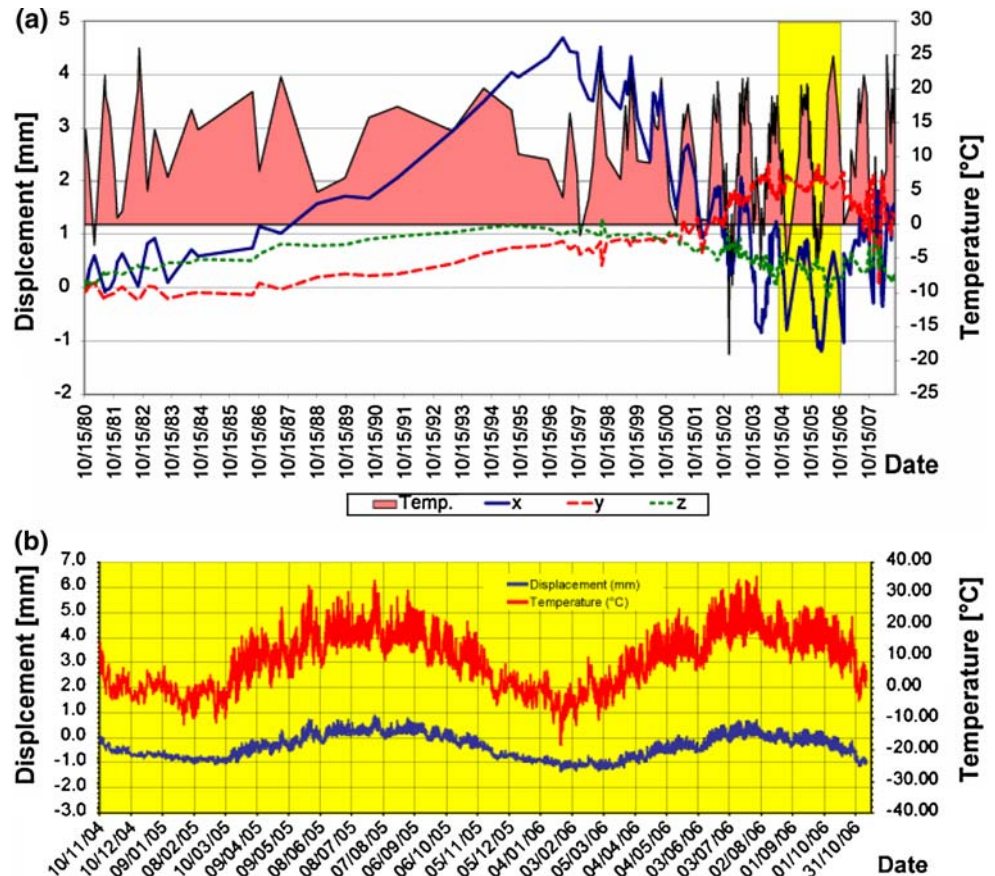
movement indicates the closing of both cracks, which are separating the cliff.

Thermal expansion study

The reliability and accuracy of monitored data recorded by any crack-gauge is based on the material temperature correction of the used device, thermal properties of the monitored rock body are generally not considered. For that reason, we included into our work the study on thermal characteristics of rocks, thus presenting a more realistic and correct view concerning monitoring data sets.

As far as the laboratory methodology is concerned, we followed the European Standards Proposal—“Natural stone test methods: Determination of the thermal expansion coefficient” which specifies methods to determine the linear thermal expansion coefficient of natural stone based on mechanical length-change measurements.

Fig. 4 Records from crack-gauges TM-71-P1 [x-direction = opening of the crack (positive values), closing (negative values); y-direction = horizontal shearing; z-direction = vertical shearing (down slip, positive values; uplift, negative values)]



The linear thermal characteristics are:

- Unitary expansion–relative dilation (ε)
- Linear thermal expansion coefficient (α)
- Thermal residual strain (L_r)

Unitary expansion–relative dilation (ε) expresses relative length change within certain temperature range and is expressed by the formula:

$$\varepsilon = \Delta L / L_i \text{ (mm m}^{-1}\text{)}$$

ΔL is the change of length of the sample between initial temperatures T_i and final experimental temperature T_{fin} .

L_i , initial sample length at the temperature T_i 20°C).

Linear thermal expansion coefficient (α) of rocks can be defined as unitary expansion of the sample–relative dilation (ε) related to the temperature interval $\Delta T = T_{fin} - T_i$,

$$\alpha = \frac{\varepsilon}{\Delta T}$$

and can also be expressed as:

$$\alpha = \frac{\Delta L}{L_i \Delta T}$$

Temperature **change** ΔT corresponds to the temperature range $\Delta T = T_{fin} - T_i$.

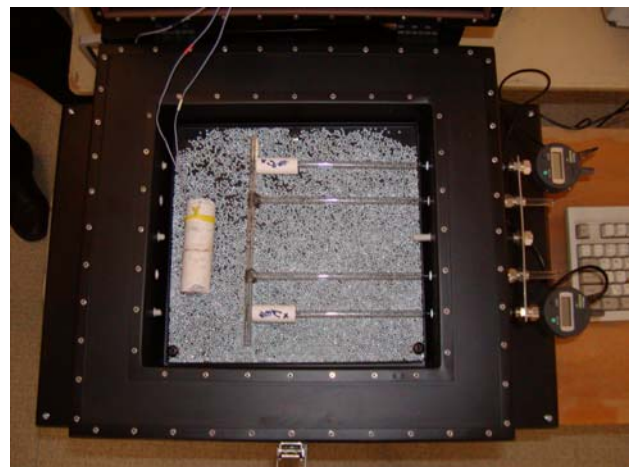


Fig. 5 Photo of the thermal dilatometric device VLAP 01

Apart from the temperature the thermal rock expansion properties depend on mineralogical composition, texture, structure and physical properties.

Thermal residual strain– ΔL_r , represents a measurable quantity corresponding to the destruction of the sample after heating/cooling treatment (Siegesmund et al. 2000, 2001; Kirschner et al. 2003). Thermal residual strain corresponds to the length increment of the sample length

before (L_i , initial sample length) and after experiment until in the heater/cooler chamber initial temperature (T_i) is fixed. Actually it represents a non-reversible sample length.

Thermal expansion tests were performed on travertine using a thermodilatometer **VLAP 01** especially constructed for these purposes with heater/cooler chamber capable of raising the temperature from (-20 ± 0.2) to $(+80 \pm 0.2)^\circ\text{C}$ at a rate of 0.1°C per min and maintaining temperatures within that range at least 2 h with an accuracy of at least $\pm 0.5^\circ\text{C}$ (Fig. 5). The apparatus is linked with datalogger in order to record the temperature and the length change of tested sample and to calculate linear thermal characteristics. Thermodilatometer VLAP 01 is capable of measuring thermal expansion on two samples simultaneously. The rock samples were of cylindrical shape 25×50 mm in size cut in three x -, y -, and z -axis orientations. A dummy sample corresponding to the same rock type with a thermocouple in its center regulates the

temperature and secures the identical experimental conditions for both rock samples.

Based on the outside temperature recordings, three thermal cycles corresponding to real seasonal temperature conditions were distinguished and subsequently laboratory tested using apparatus VLAP 01. These are as follows:

- Summer cycle with the temperature range from $+20$ to $+50^\circ\text{C}$,
- Winter cycle with the temperature range from -5 to -20°C ,
- Spring/autumn cycle with the temperature range from $+20$ to -5°C .

The results we gained maybe summarized as follows: the highest value of linear thermal expansion was observed on the samples corresponding to the y -axis direction with the mean α value $15.060 \times 10^{-6}^\circ\text{C}^{-1}$ and in the x -axis direction with the mean α value $13.310 \times 10^{-6}^\circ\text{C}^{-1}$.

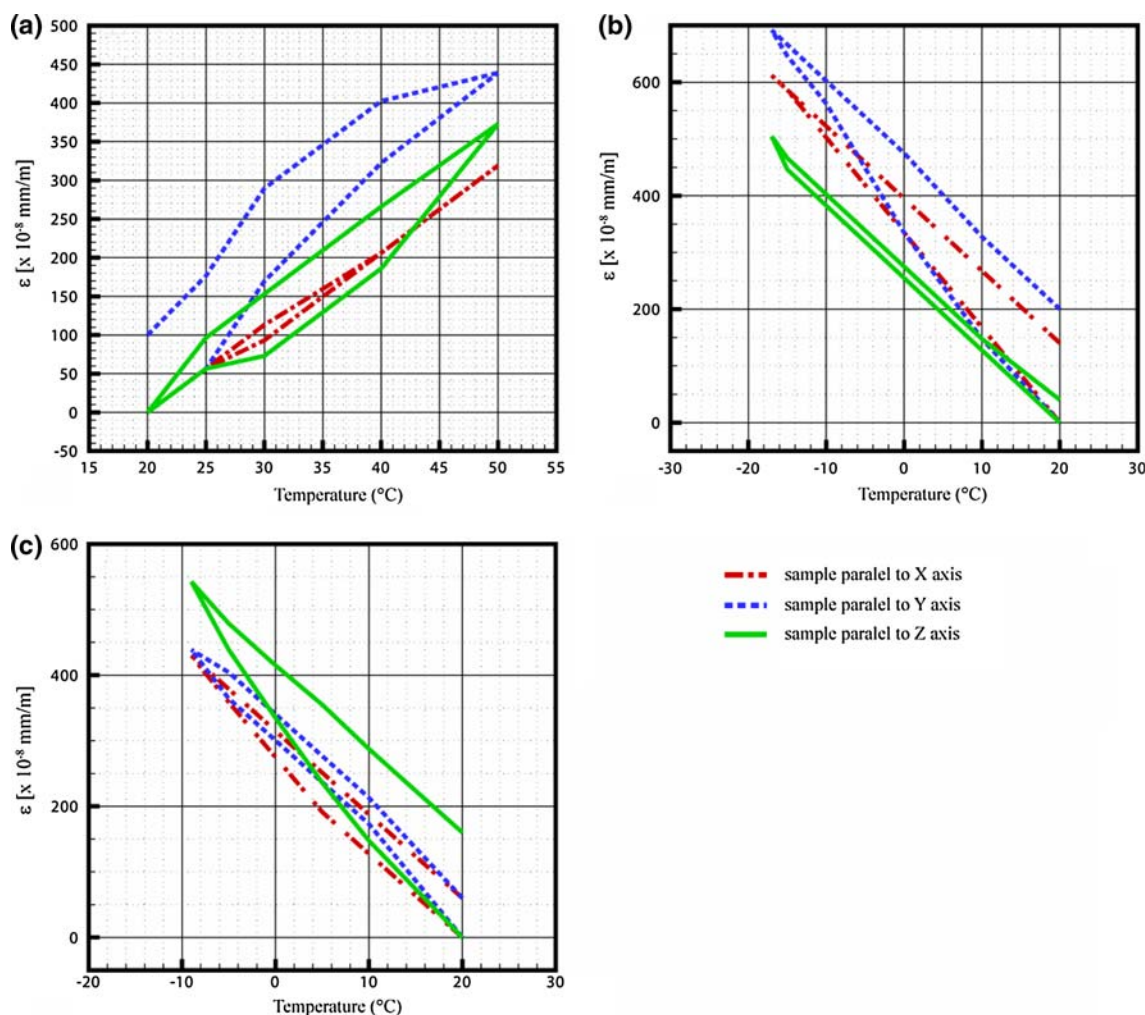
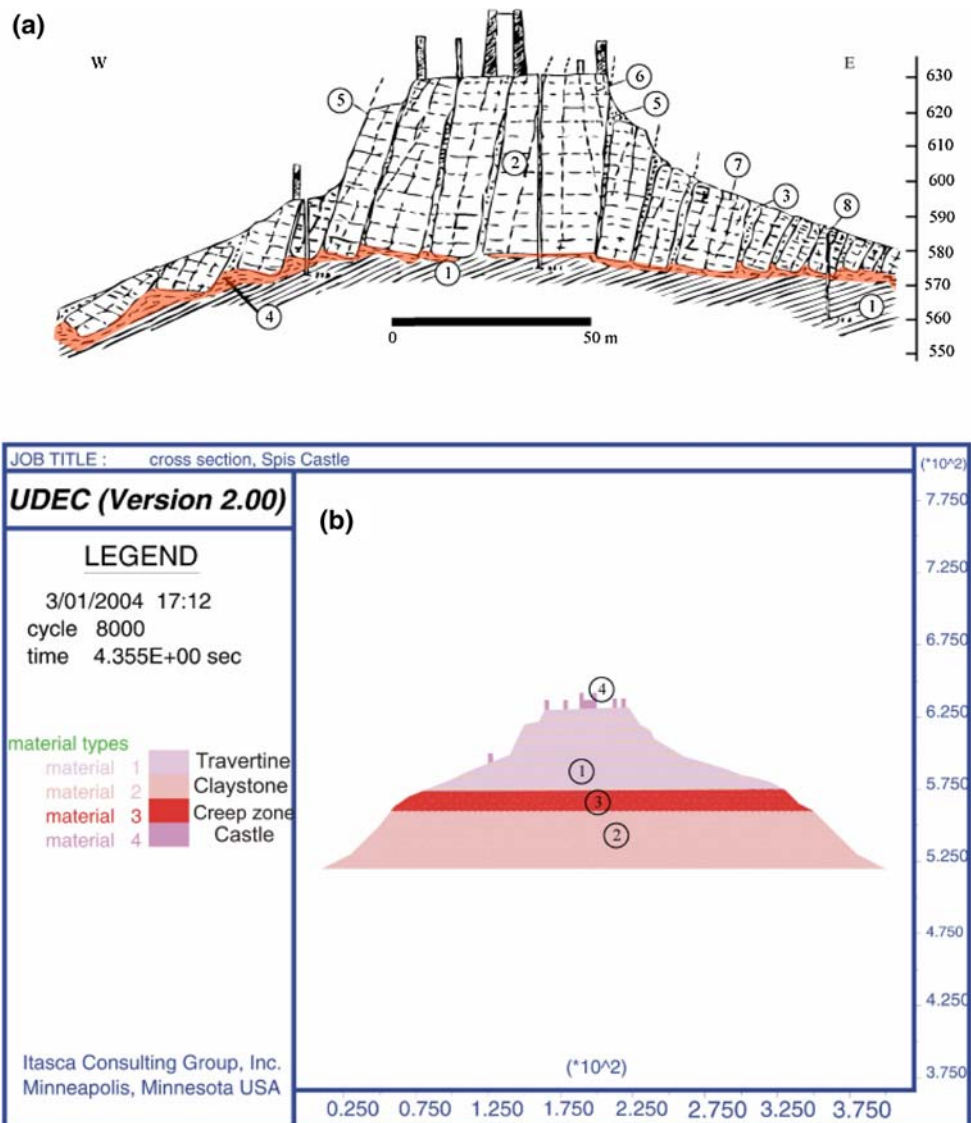


Fig. 6 Temperature dilations for summer (a), winter (b) and spring/autumn (c) season temperature ranges. Red line sample prepared in the direction of x -axis (parallel to bedding), blue sample prepared in

the direction of y -axis (parallel to bedding), green sample prepared in the direction of z -axis (perpendicular to bedding)

Fig. 7 Representative geological profile (a) and its numerical representation (b). **a** 1 Claystone with sandstone (Paleogene), 2 Travertine (Mio-Pliocene, Quarternary), 3 Debris (Quarternary), 4 Creep zone, 5 Fault lines, 6 Cracks, joints, 7 Bedding planes, 8 Boreholes. **b** 1 Travertine, 2 Claystone, 3 Creep zone, 4 Castle walls



Finally, the lowest mean α value was determined on samples with z -axis direction reaching $13.299 \times 10^{-6} \text{ } ^\circ\text{C}^{-1}$ (Fig. 6a–c).

The highest value of thermal residual strain (in some papers assigned as residual dilation) was observed in direction of y -axis with the mean value $\Delta L_r = 3.9 \times 10^{-6}$ m, following direction in z -axis with mean value $\Delta L_r = 1.5 \times 10^{-6}$ m and the lowest one was determined in direction of x -axis with mean value $\Delta L_r = 1.23 \times 10^{-6}$ m (Vlcko et al. 2005). The observed differences in thermal residual strain can be explained by means of the thermal anisotropy of the calcite grains in connection with the natural preferred orientation in travertine rocks.

Since the maximum temperature within rock mass reached the value of 35°C , it is possible to conclude that, the dilation effects triggered by temperature change at recent climatic conditions have small influence on the

monitoring records, but the thermal expansion is causing physical rock deterioration and acts as a potential trigger in time cumulative precursory stage of slope movements at Spis Castle. The thermal expansion results support the idea that the lateral spreading is the representative mode of failure confirmed by long-term monitoring as well as by the orientation of displacement vectors gained by numerical modeling.

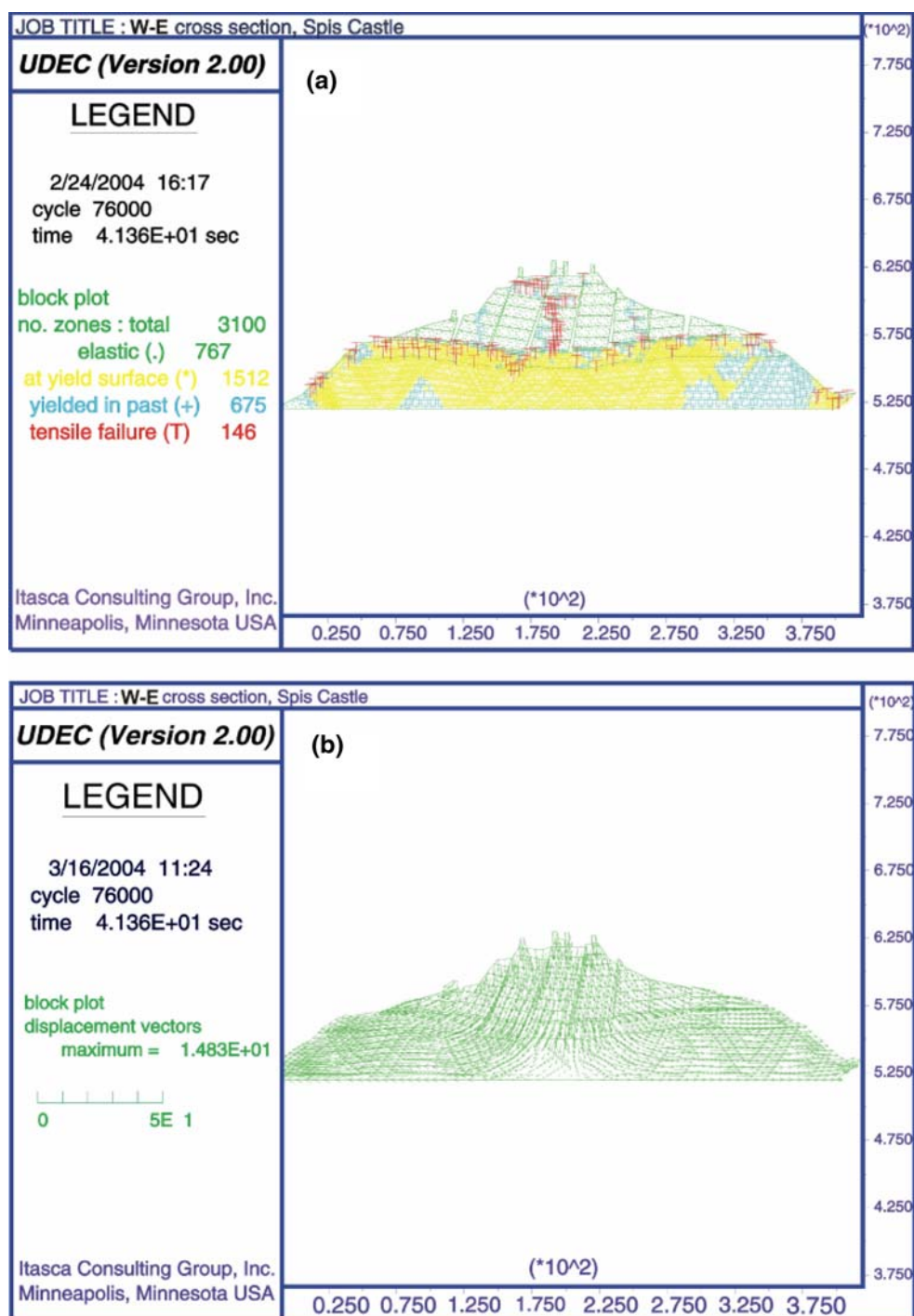
Numerical modeling study

The model has been analyzed using the Universal Distinct Element Code (UDEC, ITASCA 1993). This program simulates the mechanical behavior of the discontinuous medium represented as an assemblage of discrete blocks subjected to either static or dynamic loading. The main features of the code can be summarized as follows:

Table 1 Physical and mechanical parameters

Lithological type	ρ (kg m ⁻³)	σ_c (MPa)	E (GPa)	ν (-)
Travertine	2,500	63	56.6	0.19
Silty clay	1,850	10	17.0	0.35
Claystone	2,310	33	20.0	0.25

- 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;

Fig. 8 Developments of tension cracks (a) and block spreading indicated by the displacement vectors (b)

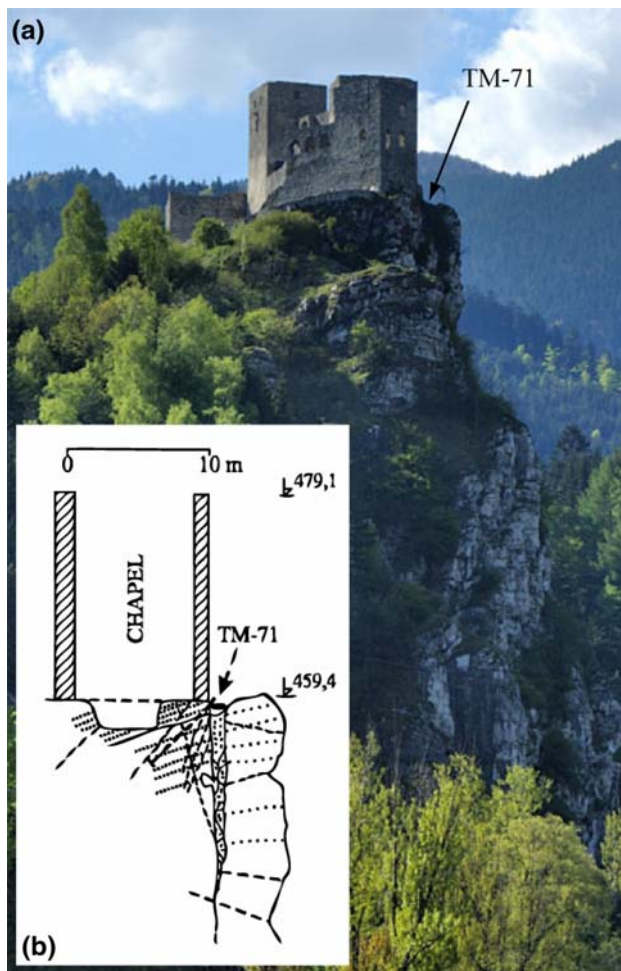


Fig. 9 Strecno Castle with typical cross-section showing the location of the crack-gauge TM71 in an open tension crack

- Several constitutive behavior 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-perfectly plastic when the Mohr–Coulomb failure envelope or tensile failures are reached. Travertine and bedrock 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.

In geotechnical terms, the stratigraphical sequence can be (schematically) represented as the superposition of a rigid travertine body over claystone strata, in the upper parts highly weathered. Numerical presentation of a representative geological profile is in Fig. 7a.

The stepwise modeling procedure we adopted (Baskova and Vlcko 2004) was based upon the back analysis comprising:

- Simulation of travertine sequences over the Paleogene rocks until the state of equilibrium (initial state of stress) was reached. The travertines were assumed as an ideal homogeneous rock body.
- 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.

UDEC model including assigned rock material properties is shown in Fig. 7b and physical and mechanical parameters as input data for modeling are summarized in Table 1.

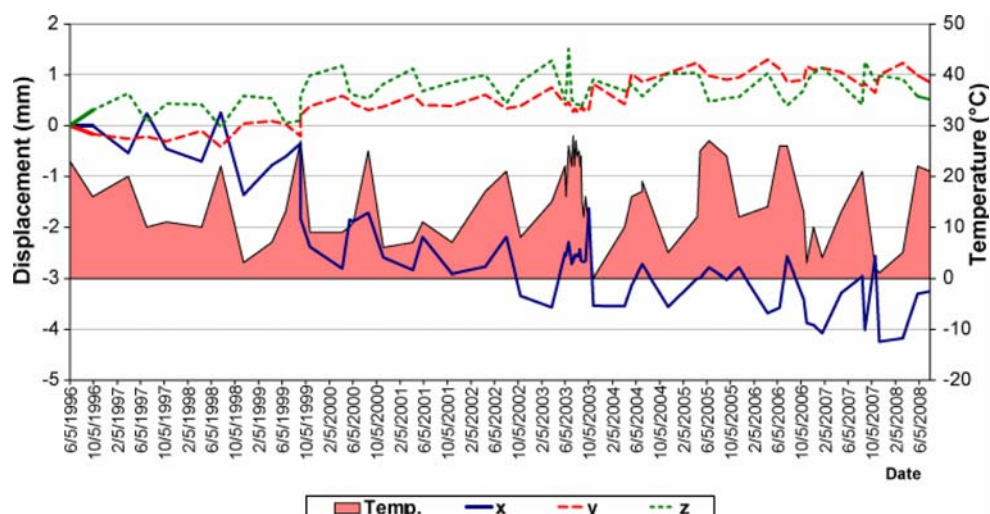
Numerical analysis confirmed that the instability of the travertine castle rock is related to significant shear strength reduction of the subgrade formation. The failure mechanism involves differential subsidence of the travertine cliffs into soft bedrock and formation of persistent tension cracks in the central part of castle rock. The development of tension cracks transmitted the strain to the castle walls and inhibited their rupture; in some places even collapse (Fig. 8a). On the marginal parts of the castle rock, the cliffs are toppled up-slope (western part), while in the eastern part these are toppled down-slope. Displacement vectors (Fig. 8b) indicate block spreading as a representative mode of failure, which is in accordance with the field study and monitoring results.

Strecno Castle

The original structure dates back to the thirteenth–fourteenth century, when the troops of King Leopold I pulled down the outer defense walls and destroyed several buildings. Since that time the castle was abandoned and became a ruin. The restoration works comprising rock bolts to secure the foundations, anchoring of non stable parts of the castle rock, filling in of cracks, screes and vegetation removal from the rock face, etc., started in 1978 and today the castle represents one of the best-preserved monuments in Slovakia.

The Strecno Castle is located in Malá Fatra Mts at a cliff reaching 103 m above the flood plain of Váh River (Fig. 9). The castle rock is formed by overthrust lithological formations of the Choc nappe consisting of various carbonate rocks mainly limestones of Gutenstein type as well as grey limestones with intercalations of dolomitic limestones and dolomites (Middle Triassic). The castle rock has a character of a fault zone with intense manifestation of cambering

Fig. 10 Records from crack-gauge TM 71 at Strecno Castle [x-direction = opening of the crack (positive values), closing (negative values); y-direction = horizontal shearing; z-direction = vertical shearing (down slip, positive values; uplift, negative values)]



(gravitational loosening). The potential danger of instability generally occurs at places where tectonically disintegrated and weathered dolomite rocks prevail and where a great number of overhangs gradually losing their stability developed. From the structural point of view the Eastern part of the castle rock where several castle objects were built upon unstable overhangs represents potential danger. The monitoring site has been placed beneath the chapel in open tension crack reaching the width 148 cm, which separates the castle rock body and a gravitationally separated huge cliff. Since 1996, 10-year measurements have confirmed the tendency to extension of the tension crack along x-axis resulting in slight cliff tilting towards ESE. The cyclic course of the records is corresponding to climate conditions. The total crack opening reached the value of 4.24 mm (Fig. 10). The sudden change in the displacements in 1999 is probably response to the activity in a nearby quarry.

Skalka Monastery

The Skalka Monastery, a well-known place of religious interest in Slovakia consists of six different buildings. In the most important building of the Monastery, Baroque chapel, serious failures and cracks in the chapel walls, which might be an evidence of deep-seated deformations were detected.

The Skalka Monastery is located near the city Trenčín in the Biele Karpaty Mts at a height of 250 m above sea level. The broader study area belongs to the contact zone of the Central West Carpathians formed predominantly by a granite core overthrust by Mesozoic carbonate rocks and the Pieniny Klippen Belt (outer zone) characterized by intensive folding and extreme tangential compression. Due to intensive neotectonic movements associated with

an uplift of the Biele Karpaty Mts as well as with a differentiated subsidence of the River Váh valley, a complicated geological-tectonic structure with a highly dissected relief developed (Fig. 11a, b). The Monastery is situated on a steep ranging cliff built by Cretaceous marly limestones with cherts. The limestones are rather massive, at places with bedding, grey in color. The discontinuities

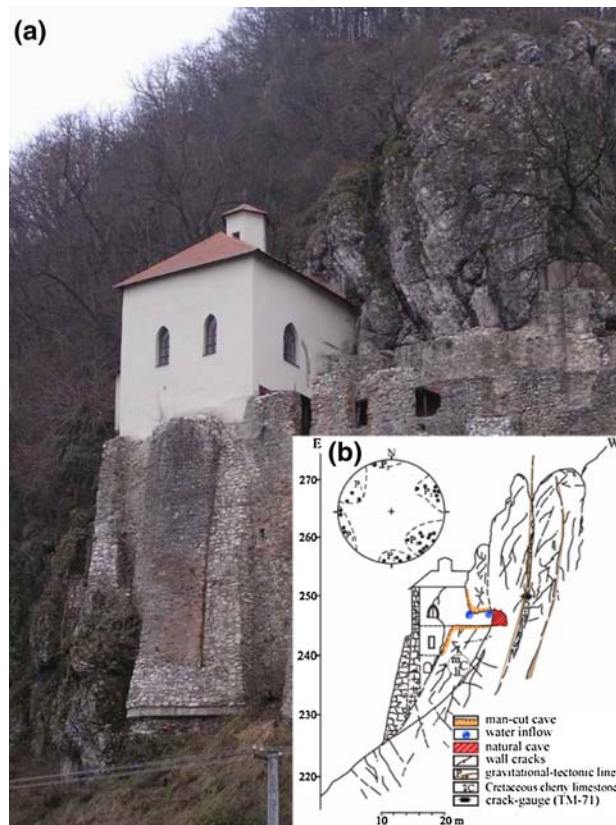


Fig. 11 a Photo of Skalka Monastery with the b cross-section with location of the TM-71 crack-gauge

Fig. 12 Records from TM 71 crack-gauge Skalka Monastery. [x-direction = opening of the crack (positive values), closing (negative values); y-direction = horizontal shearing; z-direction = vertical shearing (down slip, positive values; uplift, negative values)]

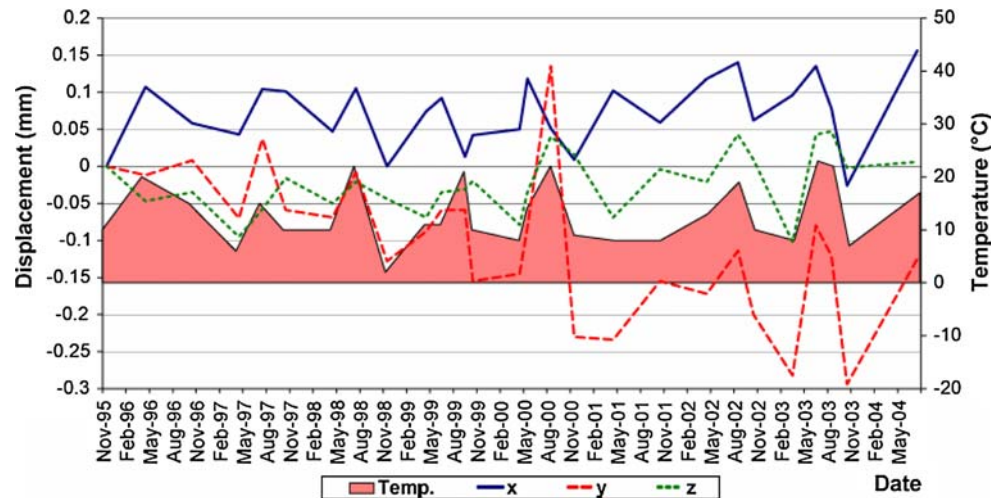
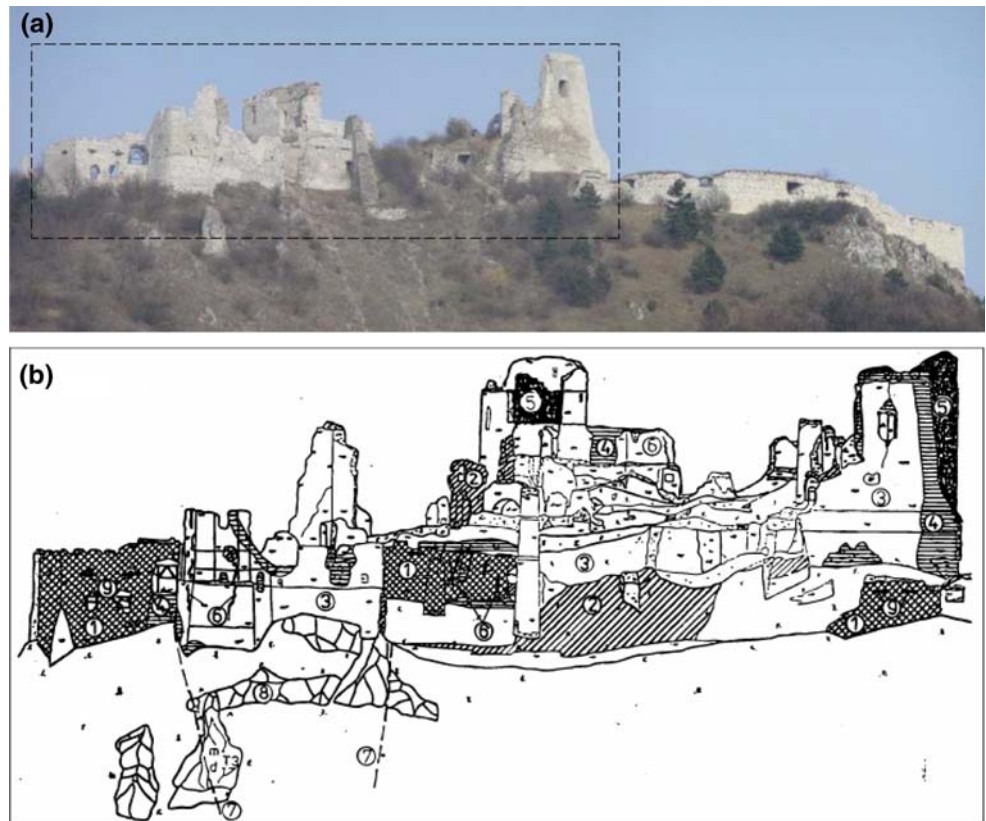


Fig. 13 a Čachtice Castle, b zoning of western walls at Čachtice Castle. Failures in the walls: 1 major, 2 moderate, 3 minor, 4 walls reconstructed in 1992, 5 fallen down walls, 6 open cracks, 7 faults, 8 Triassic dolomites, 9 supporting wooden beams



(gravitational-tectonic lines, cracks and joints) are in general widely spaced, persistent, open, karstified and unfilled, with a rough surface.

Along the prevailing gravitational-tectonic lines a cave developed, reaching 35 m in length and 4 m in width. At some places, the cave is man-cut and presents the only way of access to the chapel. Important gravitational-tectonic lines of N-S to NNE-SSW direction cut the bedrock beneath the northern part of the chapel and

caused open cracks in the walls. Since November 1995, a crack-gauge of the type TM-71 was installed in an open discontinuity (Fig. 12). The initial setting was carried out in November 1995. Since that time no distinct displacement was recorded, the crack-width proved to be constant and rock mass stable. A small displacement along the y-axis could indicate some tendency to horizontal slip. The total recorded displacement up to year 2006 is 0.29 mm.

Čachtice Castle

Failures of quite different origin brought about the destruction of the Čachtice Castle in Male Karpaty Mts (Fig. 13a). The castle rock is formed by Triassic dolomites (Hauptdolomite) in which the main discontinuities are the bedding planes. A constant dynamic process of loosening and damages associated with the collapse can be observed on the castle ruins. The main reason for this process is an active earth pressure of anthropogeneous fills of great thickness occurring at critical places. Calculation proved that the coefficient of earth pressure at rest reaches 80% of limiting state of equilibrium.

The western part of the castle ruin manifests signs of destruction illustrated in Fig. 13b. For restoration purposes, we have delineated in the western castle walls zoning units in terms of their physical state, where the highly endangered parts (1) are affected by active earth pressure of anthropogeneous fills and by the presence of bedding

planes (7) which have resulted in the formation of open cracks found in the castle walls (6). The stability of the castle walls (1) has been temporarily secured by means of supporting wooden beams. The zoning of the deterioration grade (physical state) of the castle objects has been carried out on all investigated castles in a similar way as in the case of Čachtice Castle: either with the use of photogrammetric photography or in a ground plan. The castle has not been restored yet.

Devin Castle

Located at the conflux of Danube and Morava Rivers the castle is one of the most important dominants of Slovakia with great cultural and historical importance. The castle is located on the 60 m high cliff composed mostly of carbonate conglomerates and breccias of middle Triassic and early Jurassic age. Structurally the cliff is rather complex

Fig. 14 Schematic view of the northern slope cliff of the Devin Castle showing the locations of automatic crack-gauges

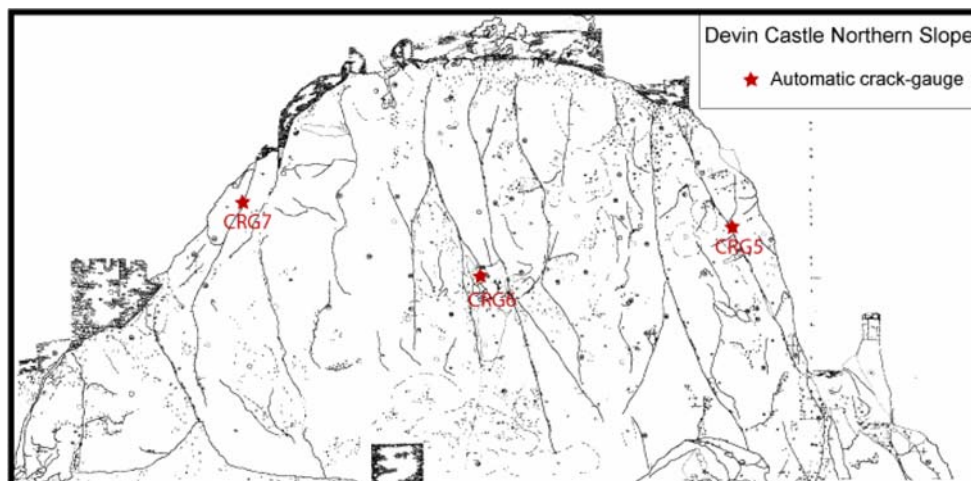


Fig. 15 Schematic view of the southern slope of the Devin Castle hill with the locations of automatic and portable crack-gauges measurements

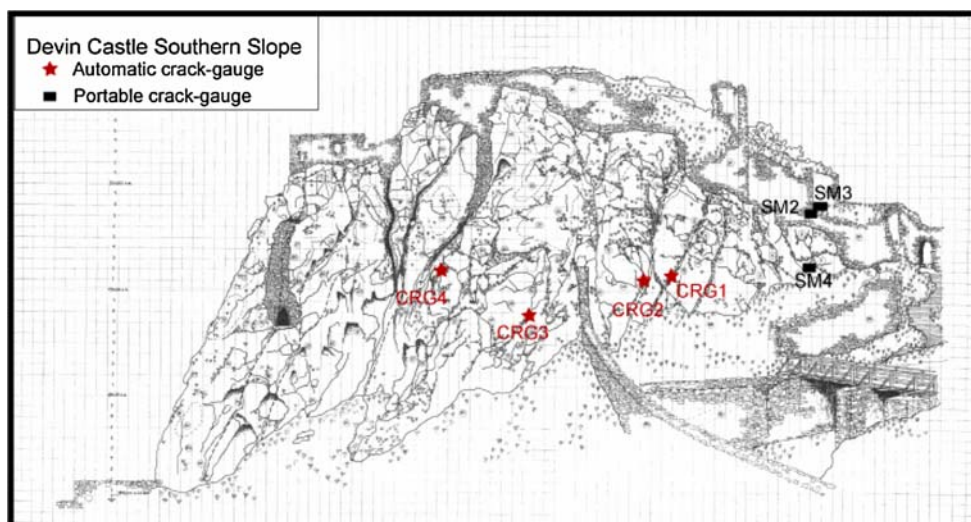


Fig. 16 Records from portable crack-gauge measurements SM2 and SM3 at Devin Castle in the period 2004–2007

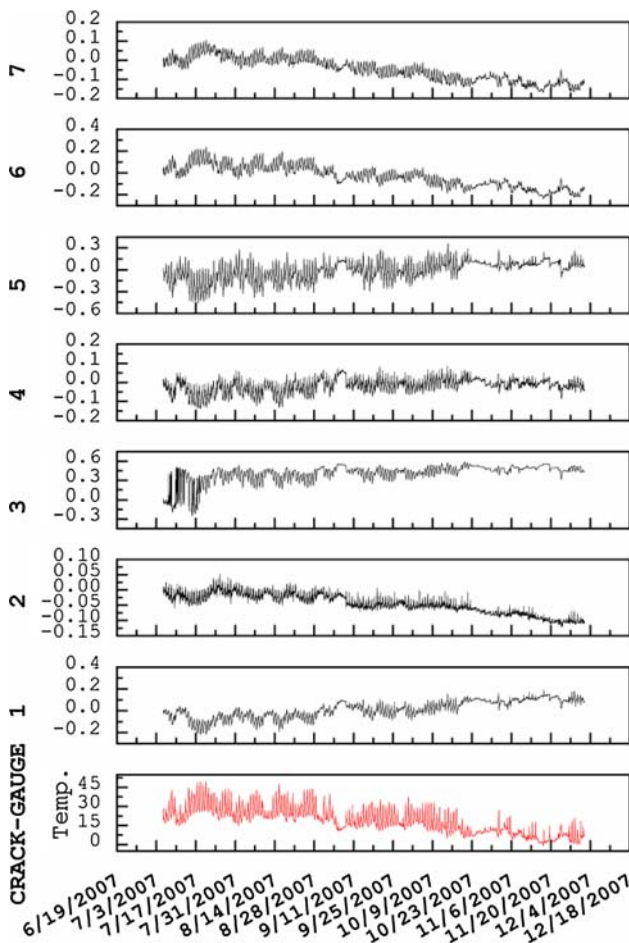
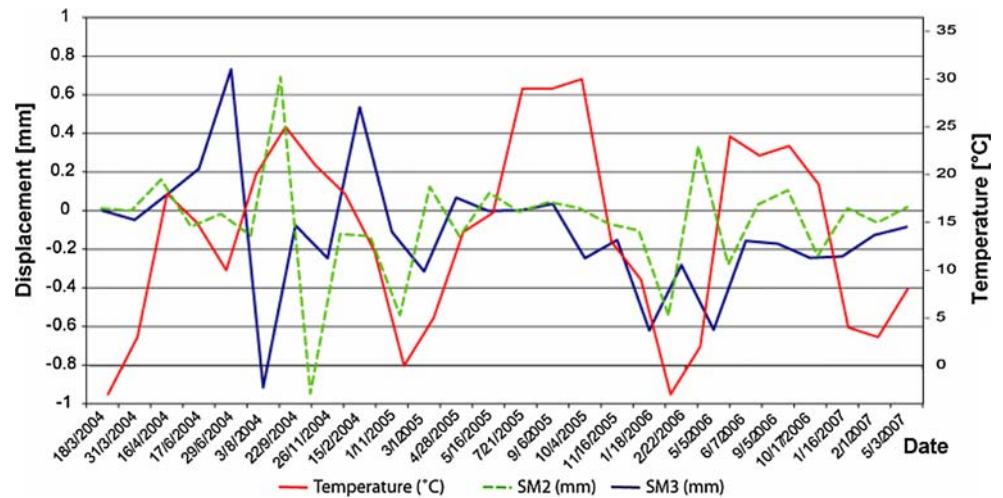


Fig. 17 Records from automatic crack-gauges CRG 1–7 located at the Devin Castle hill during the second half of the year 2007

controlled by discontinuities of first order oriented in the direction N–S, dipping at 70–85°, and older discontinuities of second order NE–SW, dipping at 80–89°. Stability of several rock blocks found mostly at the southern slope of

the Citadel is controlled mostly by the later type; however, dipping at gentler angles of 50°.

Several potentially unstable rock blocks were located on the northern slope of the castle (Fig. 14), as well as on the southern slope (Fig. 15) where automatic crack-gauges were installed. Regular monitoring of discontinuities started in 2004 using portable crack-gauges SM1–SM4, followed with fully autonomous monitoring system composed of inductive transducer crack-gauges located at seven potentially unstable blocks in 2005. The portable crack-gauges were installed on the castle wall near the staircase to the citadel. This wall, originally free-standing, was recently filled with fill material from the back side, which caused the origin of cracks due to active earth pressure. The monitoring records are shown in Fig. 16. Permanent displacements were recorded at the crack behind smaller block in the central part of the northern slope, where the automatic crack-gauge CRG 6 is installed. Recent results from other crack-gauges (Fig. 17) do not show any significant displacements deviating from usual temperature induced changes.

Conclusions

The safeguarding of the cultural and natural heritage is the priority of every nation. As shown in this paper, the causes and triggering factors of the damage to the medieval castles in Slovakia can be identified using engineering geological methods, with minimal or virtually no effect on castles or other historical structures itself. In case of Spis Castle, a monument under patrimony of UNESCO, the results gained during the study are of great value and are helpful in design of stabilization and preservation works. Further methods and techniques were used to investigate the possibility of the temperature changes as the triggering factor

of the slope movements. A similar approach was applied in the study of slope stability at Rocher de Valabres in France (Gunzburger et al. 2005).

In order to understand failure mechanism and ongoing processes in the subgrade of the structures, it is vital to employ the rock monitoring techniques, which can be of substantial help in proper selection of mitigation works in unstable slope cases.

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