THE APPLICATION OF NON-DESTRUCTIVE METHODS TO ASSESS THE STABILITY OF THE NATIONAL NATURE MONUMENT OF THE PRAVČICKÁ BRÁNA ROCK ARCH, CZECH REPUBLIC

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ABSTRACT

The study contains the results of non-destructive research of the Pravčická Brána Rock Arch which focuses on the structure and natural dynamics of this rock formation and its current level of stability. The main results include a description of the block fabric of the rock body and the nature of the contact zone between the arch beam and the southern pillar, discovery of relatively fresh secondary fissures and identification of zones with weakened strength within the sandstone massif. Also the local hydrodynamic regime was determined by a combination of geophysical methods. Long-term monitoring has demonstrated slow and irreversible body movements and reversible quasi-cyclical movements associated with changes in temperature on a scale of days up to years. The collected information was used to develop a structural deformation model of the arch body, including a description of the nature of the disintegration. The work was designed to fully respect the protective conditions of the site, to facilitate future follow-up activities and to monitor any possible negative changes in the rock massif.

Keywords: cretaceous sandstones, rock arch, stability, geophysical methods, displacement monitoring

1. Introduction

The current form of the rugged sandstone relief of the Bohemian Switzerland National Park (BSNP – location on Figure 1) has resulted from long-term dynamic development (Vařilová and Zvelebil 2007) which has taken place within the full range of spatial and time scales and has affected the massive block sandstones of the Late Cretaceous age, which are part of the Bohemian Cretaceous Basin (BCB). The study site, i.e. the Pravčická Brána Rock Arch (PBRA), is found at the top of a ridge in the area of rocks called Křídelní stěny. Reaching a height of 16 m and length of 26.5 m, the formation represents a mature form of sandstone arches and a natural monument of European significance (Vařilová and Belisová 2010). Due to its geometry and exposure it is currently threatened not only by the stress posed by its own weight but also by extreme microclimatic factors, which act not only in the form of dynamic effects of volumetric changes but also as a driving force of physical and chemical weathering (see Vařilová et al. 2011a, 2011b; Navrátil et al. 2013). The geological and tectonic patterns of the rock body together with the effects of the microclimate are fully manifested in a gradual degradation of the sandstone material and a deterioration of physico-mechanical parameters of the rock. The key parts include the rock arch itself and its contact with both supporting pillars.

Consequently, the formation has been a subject of professional interest since the early 1990s, mainly in terms of determining the most suitable protective conditions and evaluating its lifespan. The initial evaluation of the stability of the rock body, however, was based only on a short-term data series of monitoring and a low level of knowledge of the exact geometry and structure of the formation (Zvelebil et al. 2002). In addition, the threat to the local rock massif from salt weathering processes, which have either been indirectly caused or their action intensified by anthropogenic effects, has been an issue examined over recent decades (Soukupová et al. 2002; Schweigstillová et al. 2009; Vařilová et al. 2011b).

Knowledge of the rock fabric and the weakness level of the actual rock massif form a basis for the assessment of the current condition and a plan for the optimal management and protection of this natural monument. Due to legal protective restrictions, geological and geotechnical investigation using common deep boreholes or standard rock sampling for laboratory testing cannot be conducted. Therefore, non-destructive methods of investigation had to be applied to document the condition of the rock arch, in particular to identify areas of discontinuity and inhomogeneity in the rock massif and to study the level of sandstone weathering. Regular monitoring and geophysical measurement are rigorous and non-invasive methods of describing the basic structure of the rock massif and

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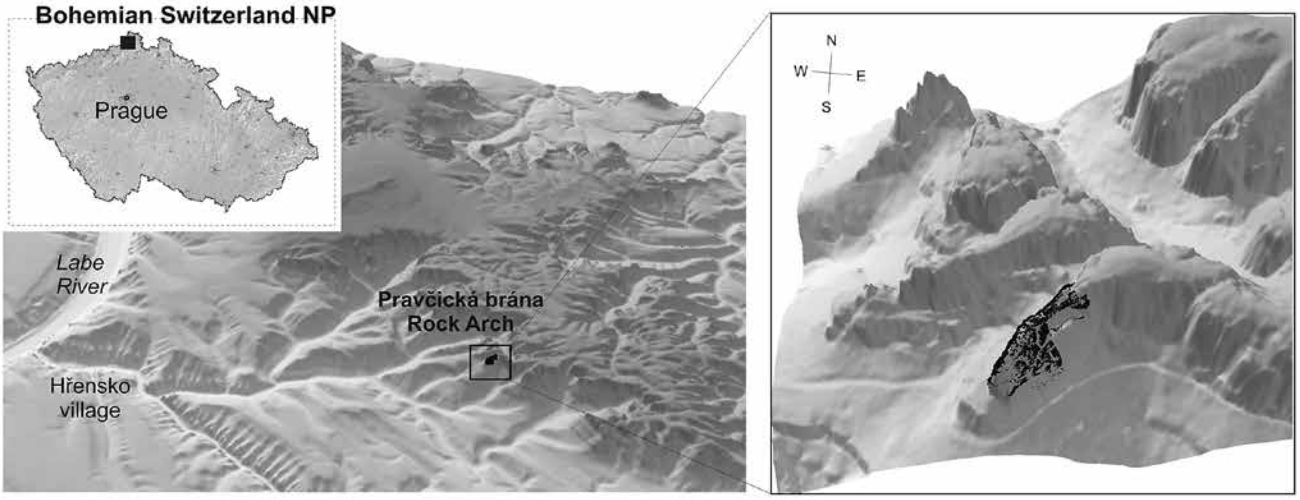

Fig. 1 Location of the Bohemian Switzerland National Park within the Czech Republic, digital model of the PBRA terrain and its surroundings (Technical University of Dresden; NASA (SRTM) – provided by the BSNP Administration).

its stability and can also be used to perform long-term monitoring of its alterations.

2. Description of the studied locality

The Pravčická Brána Rock Arch (PBRA) along with the rock towers in its surroundings are built up of Mesozoic sediments (forming part of the Bohemian Cretaceous Basin – the Jizera Formation, Middle to Upper Turonian age – e.g. Čech et al. 1980; Härtel et al. 2007). Relatively massive quartzose sandstones with fracturing in distant spacings along with the formation of basal planes show typical rectangular jointing. The rocks show subhorizontal bedding with quasi-cyclical variable granularity (from fine-grained sandstones at the base of the cycle passing into medium-grained and then coarse-grained sandstones to conglomerates – e.g. Uličný et al. 2009).

The PBRA is formed from the base of the original rock wall by gradual deepening of a double-faced overhang at the base of the present-day rock arch. The rock opening was then probably extended by blocks and flakes falling out along bow-shaped exfoliation fissures, supported by concurrent erosion and weathering processes to reach its present-day appearance. The ceiling of the PBRA is presently relatively thin (its width at the narrowest point is 7.5 m and the thickness of the cross-beam is a mere 2.5 m), its axis is NE–SW oriented and it is formed by a slab of fine-grained to medium-grained sandstone with conglomerate layers. The selective weathering of less solid layers has given rise to the characteristic horizontal structure (accentuated by gradual deepening of ledges – Figure 2). The most distinctive structure is the horizontal layer (L0), at a height of 17.5 m, which is built from a weaker conglomerate layer and forms a visual boundary between the cross-beam and the southern pillar.

The diagonal structure of the rock ridge is represented by sub-vertical joints following a predominantly NW–SE (locally also NNW– SSE) trend, which not only separate the narrow rock cliff into the individual sub-parts, but also influence the circulation of seepage water (sandstone percolates) in the rock body. The most distinct open joint

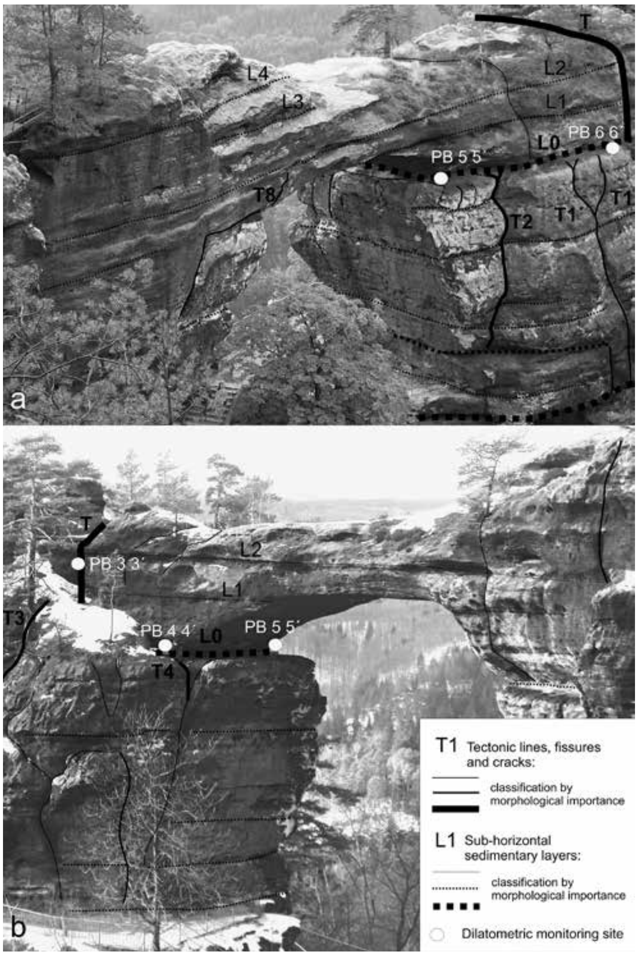

Fig. 2 View of the Pravčická Brána Rock Arch from the north (upper photo) and view from the east (lower photo) showing the positions of the morphology. The marked height levels correspond with the lithology of the arch body (L0, L1–L4), the main tectonic structures (T, T1–T4) and the dilatometric monitoring sites.

passing the body at the point of termination of the southern end of the rock arch cross-beam is also the formal end point of the investigation activities (marked T in Figure 2).

3. Methodology of data measurement and processing

3.1 Geophysical investigation

The status and the fabric of the rock massif as a whole were characterised by several independent geophysical parameters that complement each other. The geophysical investigation focused on the potentially hazardous parts and points of instability, with attention given to the arch block structure to verify lines of the main joints and identify new failures and any inhomogeneity within the rock massif, and to the southern pillar exhibiting a worn surface with special regard to the method of drainage and any intense salt weathering displayed. Combined geophysical methods, i.e. repeated georadar and seismic measurements, resistivity tomography profiling (ERT) and dipole electromagnetic profiling (DEMP) were selected for the investigation (Table 1).

The first georadar profiling conducted at the end of 2002 (Svoboda 2002) is considered the zero point of the geophysical monitoring of the rock body. In the second, main phase of the investigation in 2008 (conducted by G IMPULS Praha, Beneš 2008), the georadar measurements were repeated and refined, and also seismic methods were applied; in 2009 the methods applied so far were complemented by DEMP measurements (conducted by KOLEJ CONSULT & servis, Frolka et al. 2009).

Tab. 1 List of the geophysical methods applied during the non-destructive investigation of the Pravčická Brána Rock Arch.

Geophysical method	Purpose of application at the Pravčická Brána Rock Arch
Ground penetrating radar (GPR)	Identifications (orientation and character) of the course of the main bedding planes, open joints and fissures.
Seismic tomography (ERT)	Description of the state of stress and geomechanical state of the rock massif.
Dipole electromagnetic profiling (DEMP)	To indicate changes in lithology of the rocks, distribution and changes in moisture or the level of rock failure.

The condition of the entire PBRA body was assessed on the basis of measurements conducted on profiles running across the cross-beam and both pillars (the complete profile grid of the cross-beam is shown in colour appendix Figure II). The basic profile of the cross-beam used for all of the methods applied is situated in the longitudinal axis of the rock arch.

Georadar (ground penetrating radar/GPR) measurements using a SIR 20 radar manufactured by GSSI (USA) were conducted on the profiles at the top of the rock arch cross-beam. Conversion of the radar signal arrival time to the depth of the reflection boundary was done using the estimated value of dielectric constant $\varepsilon = 6$ (relative permittivity was determined by calculating the zones of known beam thickness). The error in the determination of depths caused by using estimated dielectric constant values should not exceed ±15% (more in Beneš 2008). The radar measurements were conducted using a 400 MHz antenna, penetration depth was approx. 10 m. The measurement was performed in both longitudinal (4 vertical profiles, P1 through P4) and transverse directions (13 vertical profiles, K4 through K19 – colour appendix Figure II) with a measurement density of approx. 40 scans per 1 m of the profile. During detailed processing of the georadar data, direct conversion of the time record to depth record was made according to the 2D velocity model, by which the error in determining depths of the individual boundaries was substantially reduced to less than 5% (more in Hubatka 2009).

Seismic measurements (tomography) were conducted using ABEM Terraloc Mk 6 (Sweden) apparatus. The seismic sensors (geophones) were placed on the profile along the cross-beam in regular spacings of 1 m. The seismic impulses were excited using a seismic hammer. The blow points were placed on the cross-beam between the geophones, on the fall line profile on the margin of the rock pillars and along the base of the pillars. The layout plan of the geophones and excitement points is shown in colour appendix Figure II.

Dipole electromagnetic profiling (DEMP) using CM-031 apparatus was conducted on 3 lateral profiles on the top of the rock arch cross-beam (spacings of 2 m between the profiles and measuring pitch of 2 m), 8 vertical profiles from the western part of the rock body (profiles D10–D17) and 6 vertical profiles from the eastern part of the rock arch (profiles D18–D23) with a measuring pitch of 1 m (colour appendix Figure II). Two measurements with a maximal and a 50% depth of penetration were performed at one point (reduction of the reach was achieved by turning the apparatus 90°). The measurements on the D1 and D2 profiles were conducted at the time of variable saturation of the rock body and were repeated under different microclimatic conditions (i.e. after a very dry summer, during 3 successive days with different rainfall intensities).

3.2 Monitoring of deformation behaviour

Long-term monitoring of the relative displacement of the PBRA was carried out using a combination of all of the methods applied throughout the BSNP as part of rock collapse prevention schemes (e.g. Zvelebil et al. 2005). Monitoring in the form of manual measurements (using a portable rod dilatometer) has been conducted since 1993 on 6 key sites along selected rock fractures in the PBRA body (i.e. 10 measuring points – Figure 7). An automatic remote monitoring system with online data transfer, containing 12 metering sensors with dilatation and temperature readings being carried out every 5 minutes, was also between 2006 and the middle of 2010. In addition to displacement, changes in air temperature were also measured at the study site.

The data were statistically analysed to identify not only long-term trends of irreversible movement of rock blocks but also to describe the daily and seasonal behaviour of the sandstone massif in detail which is represented by irregular reversible cycles. The time series of movements and temperatures were not only evaluated using time-tested standard qualitatively-empirical methods (e.g. Zvelebil 1995) but new procedures were used, as well. Based on the theory of complex systems these were successfully used until very recently in the field for monitoring sandstone blocks in the Děčín region (more in Zvelebil et al. 2005; Vařilová et al. 2011c).

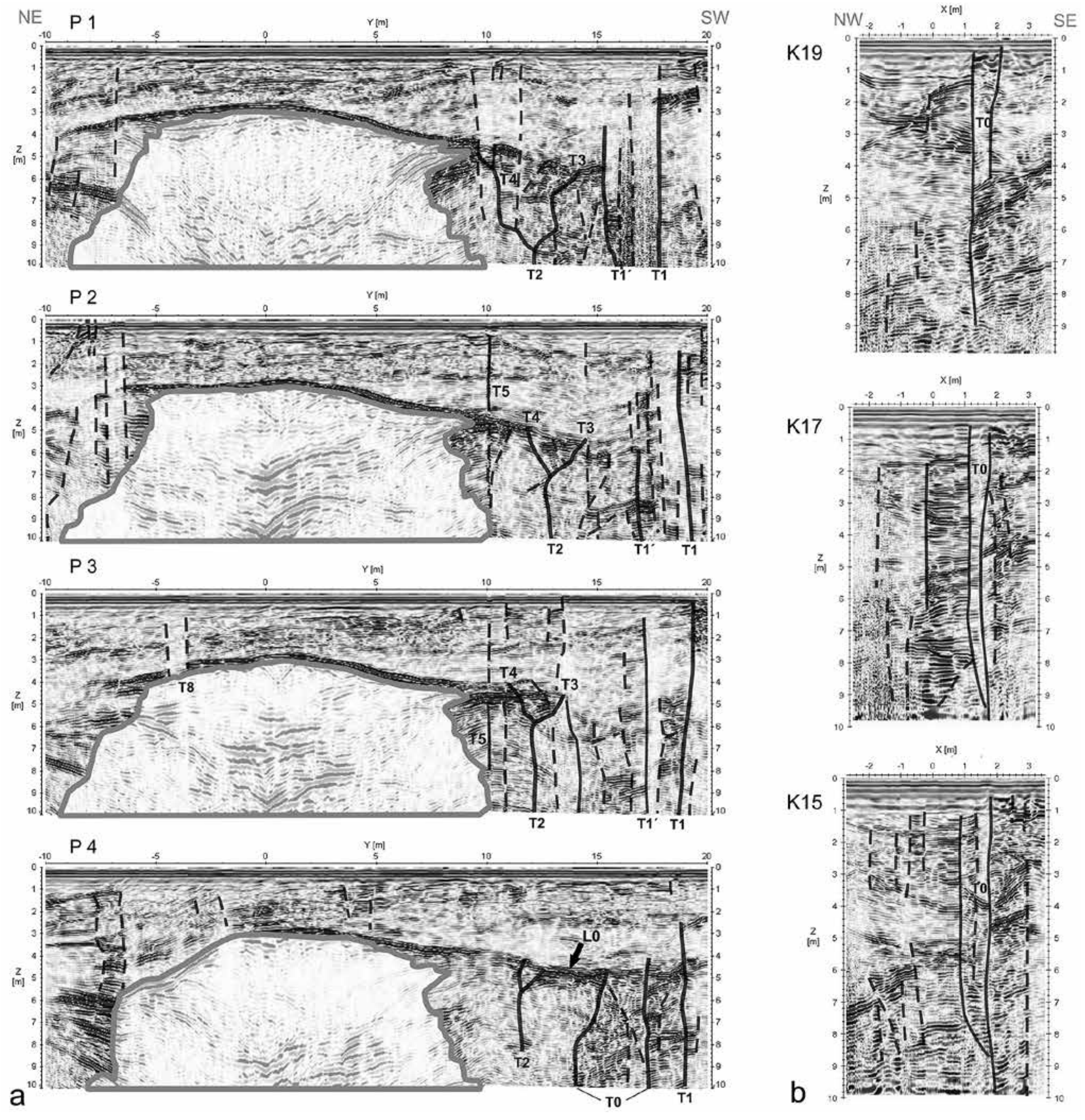

Fig. 3 Interpretation of the tectonic lines and fissures in a) lengthwise GPR sections (P1–P4), b) diagonal GPR sections (K19, K17, K15). The course of the horizontal reflection boundary (corresponding with the lithological structure) is deformed by not respecting the relief shape (topographic correction of the real terrain is not applied). The major joints were situated in places of interruption or termination of the reflexion boundaries (marked with a solid line), secondary assumed joints are interpreted in places of frequency changes (marked with a dashed line).

4. The results and interpretation

4.1 Massif fabric and strength distribution

Distribution of joints define the inner block structure of the sandstone massif and present the basic predisposition affecting the instability of local rocks (Vařilová and Zvelebil 2007). From the horizontal georadar cross-sections it is evident that the extent of failures of the rock massif differs at different depth levels. The sandstone gets substantially homogenized with increasing depth (downwards the joints close up and the rocks are less disturbed). Detected joints in the southern pillar can be considered open. No direct interconnection of the visible joints on the eastern and western walls is noticeable. Nevertheless, it is possible to delimitate three major (T0, T2, T4) and several minor joints in the individual vertical cross-sections, which mutually correlate in the area and delimitate the individual rock blocks (Figure 4). We consider the occurrence of the joint separating the triangular block in the southern pillar to be crucial (T2 in Figure 3a, Figure 4, observed from depths of 5 m, bifurcating into joints T3 and T4). Using a georadar, zones of secondary disintegration were found within the PBRA in areas where they had not been expected, with the most intense disruption and severe loosening of the rock identified in the area of the southern pillar, at a depth corresponding to the zone of contact with the arch beam (represented by a less-resistant conglomerate layer L0 – Figure 2). From the longitudinal radar cross-sections it is evident that L0 is not continuous within the entire face as originally hypothesized (Zvelebil et al. 2002). The disintegration of horizontal layer L0 is noticeable especially in the western part of the rock arch (on profile P4 in Figure 3a); in further cross-sections (P3, P2, P1) the subhorizontal face terminates near joint T3, failing to continue further southwards.

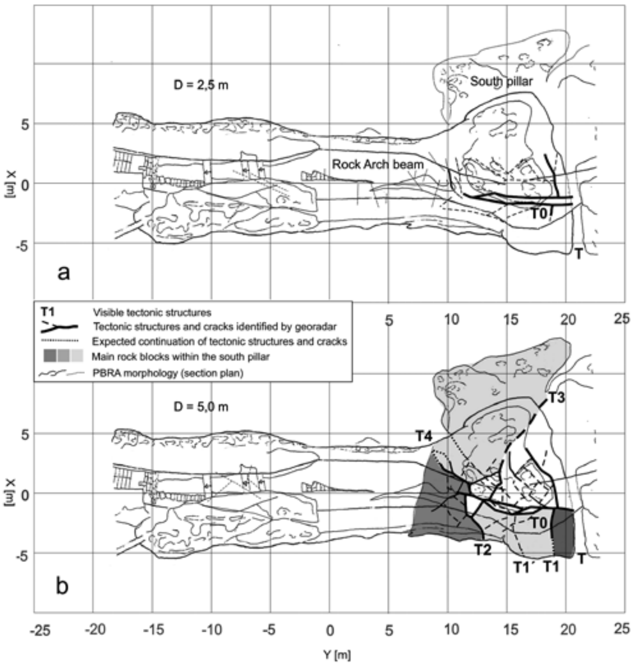

Fig. 4 Areal correlation of the course of the joint system in horizontal (ground plan) cross-sections in two depth levels from the cross-beam surface (2.5 metres/A – 5.0 metres/B) with the introduced visualization of real joints and with an indication of the main rock blocks of the pillar at the level of the horizontally trending layer.

The discovery of sub-vertical fissures in the southern pillar as well as in the arch beam itself is of essential importance. The open lengthwise joint running throughout the beam in its southern half (marked T0 in Figure 3b, observed within the depth range from 1 to 9 m) and the entirely fresh sub-vertical fissure (6 years old at most) in the beam, that presents an additional rainfall infiltration zone, were assessed to be of the highest significance (in colour appendix Figure III the most distinctive disturbance is marked T5). Another newly identified lengthwise fissure passes through almost the whole of the rock beam (marked T7 in colour appendix Figure III) and follows the direct course of the T0 continuation (and could become continued disturbing at the axial joint). The fissure on the ceiling of the arch beam first observed in 1992 is a subsurface rupture and takes up a third of its whole thickness (marked T8 in Figure 2 and colour appendix Figure III). Due to the fact that the rock arch cross-beam zone is very thin in places, even minor fissures could play a crucial role in the future development of the PBRA.

The geophysical data demonstrate also the curved interfaces at the contact of the cross-beam with both pillars. This may indicate the preparation of the next phase of the rock arch development through gradual falling away along arch exfoliation (this development is partly indicated only in the seismic tomographic cross-section – see red zone on colour appendix Figure IV).

The seismic method also verified the zones of rock massif weakening at the places where intensive weathering processes on the rock surface were already earlier visually documented (Zvelebil et al. 2002; Vařilová et al. 2011b), with the most marked ones being on the northern side of the southern pillar and also in the topmost layer of the northern pillar. Seismic measurements demonstrated areas of significant weakening in the interior of the rock mass along the arch vault (seismic velocities decreased to a value of 500 m/s, representing sand and clay based on the standards). The triangular part of the southern pillar presents not only a separate block bounded by continuous fissures but also the place of the deepest material weakening. The body of the arch also generally exhibits a relatively low seismic velocity that does not exceed 2500 m/s, which points to the sandstone being affected by weathering, as is further suggested by very low strength values (according to the classification of Deere and Miller 1966) found by sporadic laboratory testing: average uniaxial compression strength reached only 0.9 MPa in a samples of intensive weathered sandstone, 2.78 MPa in a sample of typical sandstone and 6.6 MPa for relatively fresh rock. Moreover, a comparison of the georadar measurement results from 2002 and 2008 shows that physical alterations have occurred in the cross-beam body indicating the advanced weathering of the subsurface part of the PBRA. The most significant alterations can be observed at the bottom part of the arch and along the contact zone of arch beam with the southern pillar (colour appendix Figure III).

Inside the arch body there is a redistribution of stress due to progressive disintegration and weakening of individual portions of the rock massif through weathering, which is an important finding from the perspective of stability compared with the processes of near-surface weathering that take place mostly in the form of flaking, spalling and granular disintegration.

The distribution of moisture identified using DEMP is a result of intensive infiltration and local drainage of the entire rock body. The measured specific conductivity values range between 7 and 9.8 mS/m. The data show that specific conductivity values increase towards the centre of the rock massif, the highest saturation was identified directly at the base of the southern pillar (above the less permeable layer of fine-grained sandstone). The repeated measurements on the D1 and D2 profiles (colour appendix Figure II) document a high water absorption capacity shown by porous sandstones and also indicate very rapidly changing rock saturation with percolating solutions (i.e. rapid evaporation and drying of the rock due to extreme exposure of the rock arch – more in Vařilová et al. 2011 a, b). At the time of intensive rainfall, the conductivity in the cross-beam increases to reach almost triple the value (i.e. 23 mS/m) compared to 8 mS/m measured on the same profiles the next day. Precipitation solutes firstly infiltrates into the top rock layer and then preferentially "trickles down" the slightly inclined rock arch cross-beam in a southward direction. Here the sandstone percolates sub-vertically infiltrates along several secondary inhomogeneities into the interior of the rock massif. Distribution of moisture within the PBRA is generally influenced by the existence of sub-vertical fissures and micro fissures that serve as preferential pathways of gravitational infiltration of rainfall and melting water under a gradual weakening of the surroundings (Young et al. 2009; Vařilová et al. 2011a).

4.2 Structural – deformation model

The identified block structure of the rock body allows long-term trends of the relative movement of the PBRA to be better explained, as demonstrated by the monitoring conducted between 1993 and 2010 (Zvelebil et al. 2002). The results of long-term monitoring have shown that both quasi-cyclic (reversible) movements and slow irreversible deformations were observed (Table 2 and Figure 5).

Reversible movements of the PBRA include a hierarchical system of partial quasi-cycles: 20, 15, and 10–11-year cycles; standard annual cycle; daily, and quarter-daily (8 hourly) and 2.5 daily (60 hourly) cycles. Most cycles can be causally linked to volume reactions of sandstone massif, depending on fluctuations in air temperature (or even tidal variations of gravity), or cycles of solar activity (sunspot cycles). The total irreversible deformation identified by long-term monitoring pertains (in comparison with other hazardous BSNP localities) to minor movements which do not poise a direct danger

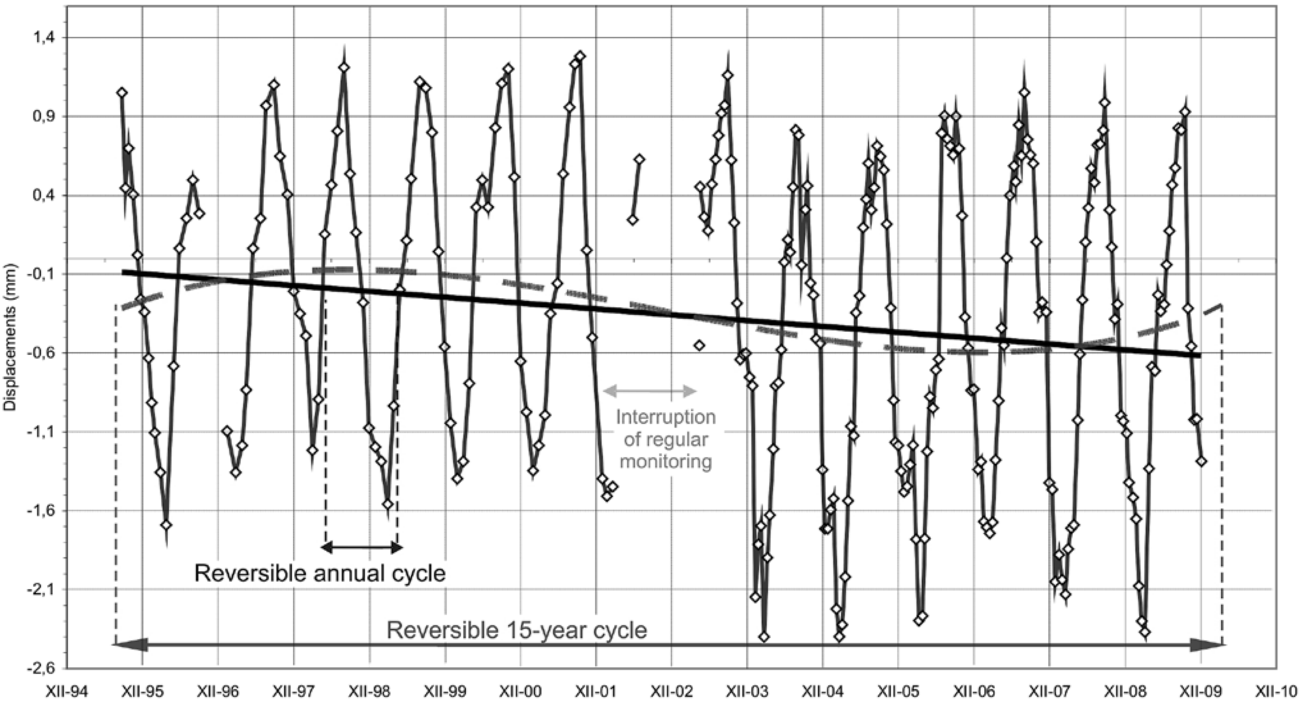

Fig. 5 Graph of relative movements – data from manual measurements: Displacements at site PB 5 (average amplitude for whole monitored period amounts to 2.81 mm), with the annual and 15 year interspersed reversible cycle. Long-term irreversible trend of deformation is represented by the very slow closing of the measured crack (the black linear connecting line of trend more than 0.5 mm/15 years).

to the PBRA body (Table 2). Nevertheless, the data provide very important information about the kinematics of reversible and irreversible movements (the dependence of these on the exposure and microclimatic conditions was also assessed).

More processes should be added to the initial model of the quasi-cyclic loading of the arch top beam i.e. bending up with parallel longitudinal arching due to the action of changes in volume of rock in a north-south direction (Zvelebil et al. 2002). The eastern and the western parts of the PBRA body behave differently both in terms of reversible and irreversible deformation. The effects of external temperature changes (specifically the influence of insolation) produce not only flexural stress but

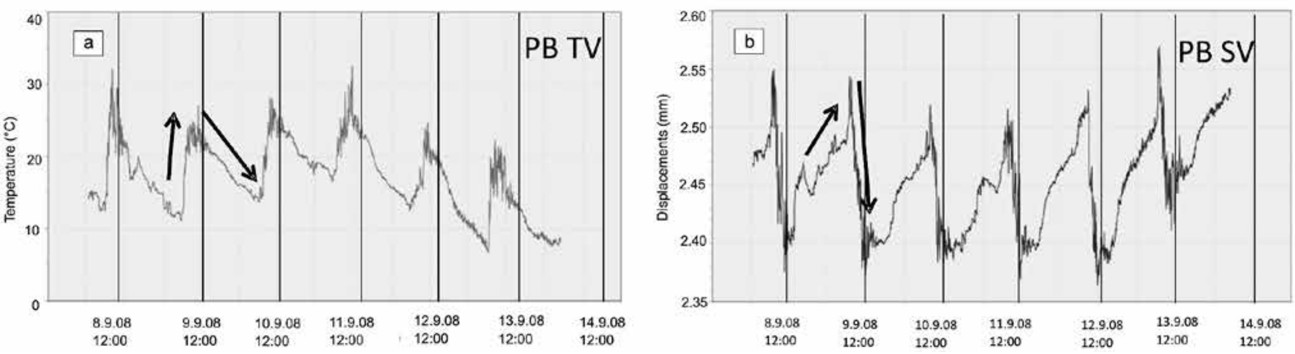

Fig. 6 a) Daily changes of temperature (a) and daily quasi-cycles of deformation (b) of the rock arch beam (example of an automatic monitoring data, from the sunny period 2008, site PB V on the east).

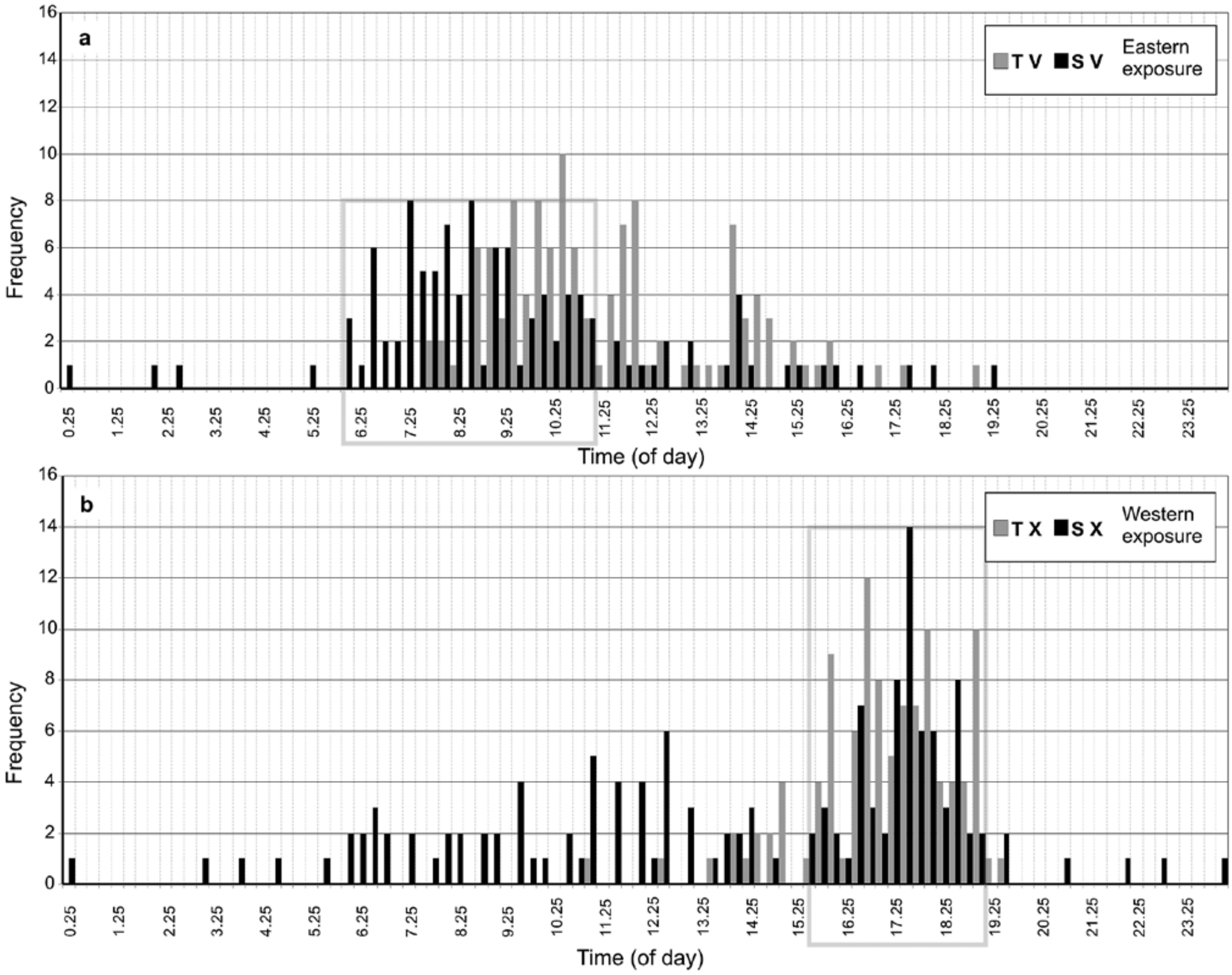

Fig. 6 b) Histogram showing the time-distribution of maximum temperature changes (T) and maximum displacement (S) during the daily quasi-cycles at site PB V and PB X (both oblique oriented measurement points). There is a difference between reaching the maximum of displacements on the east and on the west side of the arch beam depending on insolation effect (the maximum was reached between 6.00–11.00 a.m. on the east as distinct from 15.30–19.00 p.m. on the west). Transmission of partial deformation across the rock massive (from east to west and the other way around) was identified also with using automatic monitoring data.

partly also uneven sideways strain and torsion stress on the beam (the behaviour of the arch is displayed on Figure 7, example of daily quasi-cycles is on Figure 6a,b). When repeated many times daily, along with seasonal stress-strain pulses (due to temperature fluctuations), it leads to the gradual reduction of strength in the stressed parts of the sandstone rock mass, as well as to the accumulation of micro-deformations.

Higher seasonal amplitude of the movement was also detected on the western side of the beam compared to the eastern side (Table 2), which corresponds to the interpretation of the georadar data, showing only partial passability of the contact zone, i.e. not involving the entire area, as envisaged under the original interpretation by Zvelebil et al. 2002. The spatial asymmetry, as reflected in macro scales of long-term monitoring has also shown an irreversible long-term collapse of the western side of the arch beam, while a slow sub-horizontal displacement towards the south prevails on the eastern side (site PB 3′, PB 4′ in Table 2 and on Figure 7). To the west, the arch beam has completely separated from the southern pillar, with any unevenness being crushed and broken off the surface due to movement along the contact area. In addition, there is associated intense weathering of the near-surface parts of the massif. As the separation is not yet complete to the east, movement in the zone above L0 is of a mixed, elastic-plastic nature. Therefore there is an obvious and very slow cutting and gradual formation of continuous horizontal bedding of joint L0 throughout the area. This fact increases the importance of the sub-vertical joint T0, which is very probably a secondary crack produced additionally as a linear element, along which there is likely an offset of the stress between the two sides of the beam, each of which acting in a different manner. In terms of the future development of the arch, the direction of this axial joint is of particular importance, as well as its progress in response to changes in stress within the massif.

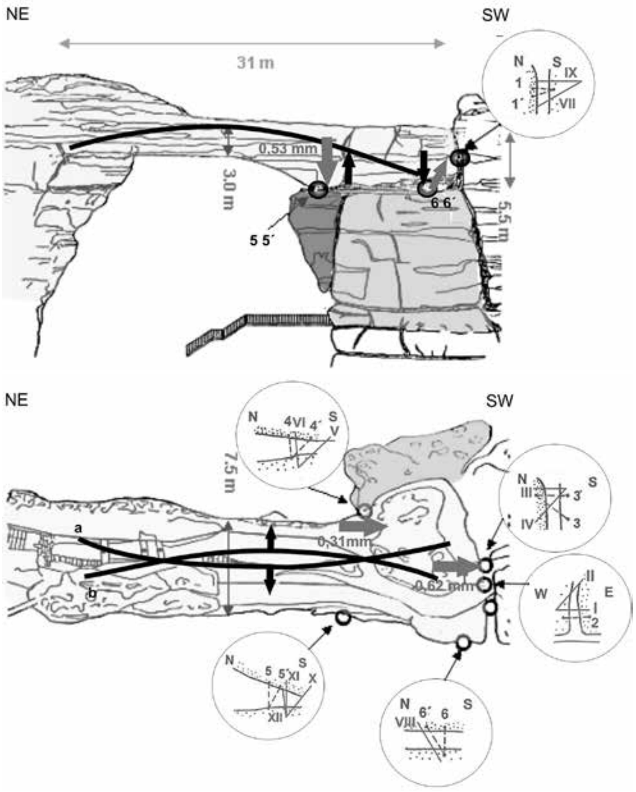

Fig. 7 Model of kinematics of reversible and irreversible movements of the PBRA: View from the west (above) and a top view of the arch beam (below) with highlighted dimensions of the rock body and locations of each measurement point during automatic (Roman numerals) and manual (Arabic numerals) monitoring. The arrow indicates the direction of observed deformation: irreversible movements are marked with grey colour while reversible thermal dilatations and ways of quasi-cyclic stress of the body are marked with black colour (lines marked a, b represent the torsion during daily quasi-cycles according to insolation).

Irreversible restriction of the passable joint T and especially the decline of the arch at the point of the cliff leads to a very slow flattening, which may cause a reduction in the future efficacy of the vault effect and a higher

Tab. 2 Irreversible deformation and average season amplitude of PBRA monitored sites (calculated by nonlinear visual analysis of data from dilatometric measurement). The categorization of displacement (as per Zvelebil 1995) includes the ambiguity of the relative trend of movement influenced by several years of reversible cycles.

Monitoring site	Direction of measurement	Period of measurement (years)	Total deformation (mm)	Categorization of displacement	Average season amplitude of reversible movements / 15 years (mm)	Interspersed reversible mega-cycles (years)
PB 1	horizontal	16.5	−0.08	standstill	1.33	–
PB 1′	oblique	16.5	**−0.20**	minor	0.87	modest 10 (11) years
PB 2	horizontal	16.5	−0.15	standstill	0.97	modest 11 years
PB 3	oblique	16.5	−0.20	standstill – minor	2.35	modest 20 years
PB 3′	horizontal	16.5	**−0.62**	minor	2.15	15 years
PB 4	vertical	16.5	−0.02	standstill	1.81	modest 20 years
PB 4′	oblique	16.5	**−0.31**	minor	1.61	modest 20 years
PB 5	vertical	14.5	**−0.53**	minor	**2.81**	15 years
PB 5′	oblique	14.5	+0.03	standstill	1.97	modest 15 years
PB 6	vertical – oblique	14.5	+0.17	standstill – minor	0.95	modest 15 years

tensile-bending load. Moreover, the daily and seasonal strain-stress pulses (causes by temperature fluctuations) lead to a gradual reduction of strength in strained parts of the rock massif (e.g. Glamheden and Lindblom 2002; Vlčko et al. 2009a, 2009b; Brček et al. 2010) and cumulative folding of micro deformations.

5. Discussion

Detailed investigation and long-term monitoring of selected processes were carried out using a set of non-destructive, in-situ methods. A combination of them provides basic information about the PBRA body such as its behaviour, characteristics of the rock massif, intensity and distribution of weathering. The results of the investigation confirmed the appropriateness of selected methods in this non-standard locality (within the study of macro-measures as per Turkington and Paradise 2005). The partially limiting factor of the geophysical methods used is particularly the non-standard morphological structure of the rock body (alternatively surface unevenness at the place of profiling). The highest informative value are the data acquired repeatedly by the georadar, complemented by the results of the methods of seismic tomography. Further monitoring needs to adhere to the defined unchanging conditions, technical parameters and the position of all measured profiles. In the summarized assessment of the acquired data it is also necessary to take into account the season and the period of the conducted measurements due to the fact that the level of applicability of the geophysical methods may be affected by extreme climatic effects (especially rainfall levels).

The local hydrodynamic regime (rapid changes in rock massif saturation with percolate solutions, infiltration and accumulation areas), which is of crucial importance to the correct assessment of the intensity and distribution of salt efflorescence and the associated processes of the chemical weathering of the rock body (Zvelebil et al. 2002; Vařilová et al. 2011a, 2011b), was identified by using the non-standard method of DEMP. Commonly used methods to identify moisture distribution, like resistivity tomography profiling (ERT) (e.g. Matsukura and Takahashi 1999; Beauvais et al. 2004; Sass 2005; Sass and Viles 2006; or Mol and Viles, 2010), unfortunately did not produce exploitable results due to several complications (primarily the impossibility to fix the electrodes using the standard technique, i.e. drilling boreholes, together with the less permeable surface of the rock crust). In order to refine the interpretation of the results of the DEMP method, it would be profitable to perform complementary measurements at the time of the minimal saturation of the rock massif with solutions and, on the contrary, at the time of the maximal saturation with water, in order to acquire limit values for the studied locality.

Data from the automatic monitoring system describe the detailed behaviour of the arch body and help to understand quasi-cyclic reactions of the rock massif However, operation of the system is very expensive and it occasionally malfunction able, in addition it produces a very large volume of data sets which requires their exact processing. This is why it is recommended to continue particularly with the dilatometric monitoring without interruption in order to obtain a database with a time-invariable quantitative shape. Long-lasting quasi-cycles of movement is necessary to take into account when evaluating the data, because their influence can distort long-term reversible trend of deformation, particularly in the case of shorter measurement time (examples are just points PB 2 and PB 3 – compare with Zvelebil et al. 2002). The distinctive response of the rock mass to temperature changes (during season and daily quasi-cycles) have been confirmed at the PBRA body. In this case is not possible to use standard monitoring data evaluation and warning thresholds applied throughout the BSNP. The existing collection of monitoring sites needs to be complemented with additional locations in light of the rock block displacements. The possible decline of the triangular block in the southern pillar together with the shear displacement on the axial joint T0 are important for the development of the arch and potential risk to it. In future it will also be necessary to continue to focus on the general geometry and structure in the inner parts of the arch beam (especially the extension of existing fissures/cracks and progradation of weathering zones), with special attention to the character of the contact zone between the beam and the southern pillar, together with the distribution of strength within the rock massif.

The acquired information on the structure of the PBRA will allow in the future to perform long-term monitoring of the condition of the rock arch and will significantly help to prepare more accurate interpretation of the long-term monitoring of the rock body movements, then produce an updated geomechanical model and prepare a prediction of the future development of the rock arch body. The actual degree of instability of the arch or rather the necessity of potential technical measures, will be determined from planned parametric sensitivity studies (Young et al. 2009), in which the input strength properties will be defined by tensile and compressive stress (Hoek and Brown 1980) with the model of distribution of the axial load (Heyman 1982) determining the overall tension along the opening gate. Nevertheless in the case of the PBRA, other factors such as existing fissures and cracks, weathering along weakened zones, and anticipated shear zones are also crucial for its continued stability. More detailed analysis (considering the combination of several forms of sandstone massif disruption, the non-standard morphology and complicated inner fabric, hydrodynamic conditions and variable strength parameters) will require advanced numerical methods (Stead et al. 2001); the different variation of PBRA stability collapse can be simulated for example by numerical analysis (finite and distinct element methods – e.g. Ohnishi et al. 1993).

6. Conclusion

The completed comprehensive research applied basic geophysical exploration together with long-term monitoring of movements in the rock massif. The research results have refined knowledge of the inner structure of the arch body, the kinematics of reversible and irreversible movements (their dependence on exposure and microclimatic conditions was also assessed) and knowledge of the distribution and growth of parts affected by weathering processes. The investigation was designed to fully respect the protective conditions of the given locality and to allow in the future repeated measurements and thus monitor over time any other potential negative alterations in the rock arch massif.

The results of this study helped to understand the complexity of the system of deterioration of the sandstone massif and to better understand the natural dynamics of the specific rock formation. The results also provide valuable information about the actual status of the PBRA. New stability risks were discovered associated with intense tectonic and secondary brittle impairment of the rock massif and involvement of episodic aquifers. By using geophysical methods, it was possible to define the local hydrodynamic regime of the rock arch body and identify sub-vertical sub-zones of infiltration (passing through the bedding). This demonstrated selective weathering in the PBRA body that so far had not been considered, one that not only causes damage to the near-surface parts but also weakens the strength of the internal parts of the massif, significantly influencing the overall stability of the object.

The collected information was used to create a structural deformation model of the arch body, including a description of the patterns of disintegration found. The model is to become an essential basis for subsequent geomechanical modelling of the arch stability and development. The gained knowledge will thus become not only an essential basis for management planning and designing the most suitable stability and security measures in the study area, but it can also be applied to similar small-scale protected areas and used for drafting master plans of field protection of the sandstone relief within the studied region, and hence also in the greater area of the rock formations throughout the BCB.

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RÉSUMÉ

Využití nedestruktivních metod k posouzení stability Národní přírodní památky Pravčická brána

Práce obsahuje výsledky nedestruktivního průzkumu Pravčické brány, který byl zaměřen na poznání vnitřní stavby tohoto skalního útvaru, jeho přirozené dynamiky a zejména pak posouzení současné úrovně stability. Ke studiu bylo použito kombinace geofyzikálních metod (opakovaného měření georadarem, seismiky, odporové tomografie a dipólového elektromagnetické profilování/DEMP) spolu s dlouhodobým kontrolním sledováním deformačního chování brány. Realizovaný průzkum byl koncipován tak, aby plně respektoval ochranné podmínky dané lokality, bylo na něj možné v budoucnu navázat a sledovat případné negativní změny v horninovém masivu. K hlavním výsledkům náleží popis blokové stavby tělesa a charakteru kontaktní zóny mezi trámcem brány a jižním pilířem, objevení relativně čerstvých sekundárních trhlin a identifikace pevnostně oslabených zón uvnitř pískovcového masivu. Popsán byl rovněž režim jeho přirozeného odvodňování. Dlouhodobým sledováním byly prokázány pomalé nevratné pohyby skalní brány a vratné kvazi-cyklické pohyby související s teplotními změnami v měřítkách dnů až let. Bylo zjištěno rozdílné chování východní a západní strany trámce a potvrzeno jeho obloukovité ohýbání, obohacené navíc o nerovnoměrné namáhání torzí a smykem. Ze získaných informací byl vytvořen strukturně-deformační model Pravčické brány (včetně popisu charakteru porušování). Výsledky poskytují cenné informace o současném stavu významného skalního objektu, napomohly k rozpoznání potenciálně rizikových partií a budou využity nejenom pro účely modelace budoucího vývoje, ale také pro případný návrh nejvhodnějších sanačních opatření.