Acta Geodyn. Geomater., Vol. 8, No. 4 (164), 453–467, 2011

GEODYNAMIC REACTIONS TO RECENT TECTONIC EVENTS OBSERVED ON SELECTED SITES MONITORED IN SLOVAKIA

Ľubomír PETRO [1)]*, Blahoslav KOŠŤÁK [2)], Josef STEMBERK [2)] and Ján VLČKO [3)]

[1)] *State Geological Institute of Dionýz Štúr, Jesenského 8, 040 01 Košice, Slovak Republic*
[2)] *Institute of Rock Structure and Mechanics, Academy of Sciences of the Czech Republic, V Holešovičkách 41, 182 09 Prague, Czech Republic*
[3)] *Faculty of Natural Sciences, Comenius University, Mlynská dolina G, 842 15 Bratislava 4, Slovak Republic*
**Corresponding author's e-mail:* lubomir.petro@geology.sk

(*Received* June 2011, *accepted* October 2011)

ABSTRACT
Long-term geotechnical monitoring of crack and fissure movements in slope deformations, historical buildings, as well as underground objects in Slovakia, provided results that bear evidence of movement trends, as well as of present tectonic unrest. The results were subject to an analysis regarding anomalies in movements that would verify activity of a specific geodynamic process. Such a process was detected recently in the Bohemian Massif and evidenced even in other European countries, north as well as south of the Alps. The process began by a tectonic pressure pulse and followed by a phase of increased geotectonic activity. The search for signs identifying this process on the Slovak territory which belongs to a different geological unit than the Bohemian Massif was successful. This is further evidence that the process in question is of a very deep foundation. The investigations proved successful long-term outdoor operation of TM71 crack gauges working on the principal of mechanical interference between optical grids. A thirty year long record was even reached. A useful function of the gauge which allows for supplementary data about angular deviations in faults has been found useful in the analysis. The data indicate affinity of the process to a large global disturbance in the Earth crust.

KEYWORDS: finite pressure pulse, geodynamic monitoring, tectonic process, crack gauge, Slovakia, earthquake effect

1. INTRODUCTION

Engineering geology in former Czechoslovakia was busy with landsliding. A number of laboratories started research programmes which included long-term monitoring of block type slope deformations to check slope stability. A series of deformations proved to be active showing permanent slope movements and obtained data were used in stabilization projects and geotechnical decisions, as well as regional landslide susceptibility mapping. It was especially the problem of Slovakia where destructive landslides occurred and stability of faulted rock slopes were investigated consecutively. This is why one can find in Slovakia a number of geological objects and structures where documentation includes yearly long and detailed registration of displacements. The objects that were under special attention regarding the investigation reported in this paper are indicated in Figure 1.

Thanks to the use of a robust crack gauge TM71 registration covered crack and fault displacements in all the three space coordinates as well as angular deviations. Some investigations have fulfilled their main geotechnical purpose but a number of objects are continuously observed.

It was during the last decade when special observations in Bohemian Massif produced evidence of some specific geodynamic movements due to an unusual tectonic pressure pulse (Stemberk et al., 2010; Košťák et al., 2011). As investigations covering several distant regions in Europe proved also to show the said effects a project was introduced to check even such old long-term observation records from Slovakia (Petro et al., 2005) for a possible correlation with the geodynamical effects reported recently.

2. METHODS

Original investigations performed in the Bohemian Massif were based on the TM71 crack gauges. The same instrumentation was applied in Slovakia. The use of the same instrumentation in the both neighbouring territories is a positive precedent for possible correlation investigations.

TM71 crack gauges were well described within the papers reporting the earlier research that led to the verification of the main effect, a tectonic pressure pulse. Basic informationa about the instrument, as well as of its applications, can be found in Košťák (2006).

The most general setting for movement measurements is based on field selection of a representative crack or fissure which would characterize the object that is supposed to produce local deformation. Cracks or fissures between rock blocks were bridged over with the gauge installed to fill up the gap.

The instrument built up permanently into the structure operated on the basis of the mechanical interference on optical grids. The interference patterns that develop and characterize the movement are then registered and analyzed later in laboratory for micro-deformation data. Three coordinates *x*, *y*, *z* represent usually Δx as decrements or increments in the gap width, Δy in lateral displacement, Δz in relative subsidence.

In this way displacement graphs can be constructed and our research is oriented to anomalies that define special reactions caused tentatively by a tectonic pulse or other specific events. The same procedure is applied in the analysis of angular deviations which are defined in two planes: horizontal ($\Delta\gamma xy$) and vertical ($\Delta\gamma xz$). Such deviations are not commonly identified in movement observations but can be simply understood to define micro-rotations between the investigated blocks, either at horizontal or vertical planes, i.e. planes formed by lines *xy* or *yz*.

3. CORRELATIONS

Our test is going to inspect selected localities in Slovakia (Western Carpathians) for possible movement anomalies to be correlated with the specific effects in the Bohemian Massif.

As to the main effects in the Bohemian Massif these were described in the previous research oriented to tectonic fault movements. We refer to the result of a geotectonic research (Stemberk et al., 2010; Košťák et al., 2011). The principal effect was the pressure pulse. Its occurrence in the Bohemian Massif was dated to summer 2003 (August/September) when the peak effect struck the localities in the Krušné Hory Mts. as well as in the Sudeten Marginal Fault zone. Several observations have shown a process which developed signs preceding the peak effect and then even anomalies as after-effects. The pulse was the principal finding initiating a process. The pulse was then followed by a period of increased geodynamical activity which produced several local earthquakes and at most places ended in 2007.

Meanwhile, another important group of anomalies were registered. This effect was attributed to the catastrophic Sumatra earthquake from the end of December 2004. However, it could not be correlated exactly with the time of the epicentre quake. It was typical that the effect recognized in the anomalies of movement records came up in this case one to several months before the earthquake. Therefore, there was no intention to see the said anomalies as a direct reaction to the earthquake. Instead, the authors assume that the anomalies developed due to progressive deformations leading to the quake, representing precursors of it.

On the other hand even delayed reactions were observed, and exceptionally even reactions looking like almost immediate response to the quake. This is in short what was observed and reported from the Bohemian Massif.

Sites investigated in Slovakia represent very distant locations showing important movement anomalies, too. In our research we are interested in the time when such anomalies in the graphs displaying local movements appear and see possible correlation with the Bohemian Massif. To verify possible correlation we introduced several asterisks into the graphs which indicate timing of several most important events which represent resulting factors indicated in our previously published investigations (Stemberk et al., 2010; Košťák et al., 2011). The first factor is the aseismic tectonic pressure pulse of 2003. The second factor was pronounced with the occurrence of the Sumatra earthquake of December 2004. It is therefore mentioned as Sumatra quake, although we mean rather an observed anomalous movement of a gradual process of geodynamics culminating close to the time of this earthquake. The third factor is connected with disappearance of the increased geodynamics which followed the pulse. This ending as well as beginning of another period was dated to 2007. The reader then can easily see in any individual graph if an anomaly indicated at the Bohemian Massif also occurred at the particular Slovak locality or not, its character being advanced or delayed, and which anomaly was most pronounced.

The reactions or anomalies as to their magnitude will differ from place to place, which is obviously supposed to depend on the local geological setting and other local conditions. However, geological conditions are discussed only briefly since the previous research concluded that in geodynamics faulting is dominant over local geological structure conditions.

General trend of movement and movement magnitude are currently the most demanding data of the monitoring with a direct impact in geotechnical investigations. To get data like that was the main reason for the majority of monitoring projects followed in Slovakia. However, this aspect is not followed in our research. Here, however, we are going to investigate the anomalies which may be seen often as secondary phenomena if not negligible effects from the point of view of geotechnics. Nevertheless, such data are considered important to see geotectonic effects. Therefore, we will not pay attention principally to the magnitude of the reaction but rather to time when it appeared, which can be correlated with the effects originally reported in the Bohemian Massif, verified in the other parts in Europe and may be now possibly documented even in Western Carpathians.

4. OBSERVATIONS

Monitoring results are going to be presented with graphs. Selection of results has been oriented to show the most remarkable anomalies and trends which can be correlated with recent development in European geodynamics reported by Stemberk et al. (2010) and Košťák et al. (2011), as well as indicated in an earlier work of Košťák et al. (2007). For this purpose the observations can be thus considered as a specific extension of the earlier research to a different geological unit than originally, i.e. Western Carpathians. It is to be stressed that the monitoring in Slovakia to be exploited was not established for the geotectonic research but for a long-term geotechnical purpose exclusively. The long-term character of the observations is important, and the documentation bears signs of an unspecific random distribution in the Slovak territory.

To observe and correlate easily different geodynamic reactions and anomalies indicated in our graphs we have introduced specific signs into the graphs (Chapter 4): ⅄ - disturbance at the time of Iran and Turkey earthquakes 1997/9; ✦ - disturbance due to the tectonic pressure pulse of 2003; ★ - the occurrence of Sumatra earthquake by the end of 2004; ✧ - ultimate period when the increased geodynamics due to the pressure pulse ceased.

4.1. SLOVAK CASTLES

Historical castles in Slovakia are usually built on high hills or even cliffs. Many of them suffered fires in the past and after having been abandoned turned into ruins. Recent reconstruction projects called for engineering geological survey into stability conditions of their foundations and geological setting. Monitoring of crack movements provided useful geotechnical input data for such projects as well as for later stabilisation control.

4.1.1. ORAVA CASTLE

Orava Castle towering above the Orava River, the main northern tributary of the Váh River, is a dominant of NW Slovakia as a historical sovereign's residence administering locally the whole region. The castle was relatively well conserved but a lower part annexed to accommodate increasing administration suffered fracturing from unstable subsoil of weathered siltstone (Gross et al., 1994). The sliding plane of the slope deformation produced an open fracture in the corridor to a dungeon. This wall fracture was instrumented with a TM71 gauge in 1983 and monitored till now (Fig. 2). In this case rotation grids have not been yet introduced in monitoring.

Results of 29 years of observation covered the last periods of destructive sliding, slope reinforcement with the use of micro piles and anchoring (Fig. 2a), slow stabilization and finally more than 10 years of post-stabilization stage (Fig. 2b,c,d). Geotechnical results were then published (Košťák and Sikora, 2000). Searching the last period which was relatively calm (Fig. 2b, c, d) we revealed a single anomaly in micro-displacements x and y in 2003. Timing of the anomaly can be correlated with the tectonic pressure pulse registered in the Bohemian Massif.

4.1.2. STREČNO CASTLE

Historical ruins of Strečno Castle are rising above the Váh River near the town of Žilina. The ruins were conserved between 1977 and 1994. There is a high rock wall beneath the castle facing a highway with heavy traffic deep in the valley. The wall was anchored displaying a fracture situated above the highway up near the castle. Therefore, the fracture was decided to be monitored and a TM71 gauge was installed on it.

Results showing micro-deformations on the fracture between 1996 and 2010 proved a trend of slow and progressive opening (co-ordinate x) in the fracture (Fig. 3a). This is an important geotechnical finding but not in the scope of this paper. On the other hand, even y co-ordinate and micro-rotations (Fig. 3b) proved some low but important changes. Lateral movement y (Fig. 3a) showed a permanent shift in 2003/4 and angular displacements γxy and γxz produced smooth curves with turns in 1997, then in 2002/3, which lasted till 2007 (Fig. 3b). Timing of such movement correlates with the pressure pulse of 2003 followed by the phase of increased geodynamics that lasted up to 2007 as registered in the Bohemian Massif. The first noted turn in 1997 indicates a serious geodynamic disturbance in Europe due to earthquakes in Iran and Turkey (Košťák et al., 2007).

4.1.3. SPIŠ CASTLE

Spiš Castle was built and enlarged gradually from the beginning of the 12th century. The castle is said to be the second largest fortification complex in Slovakia and represents a central dominant ruin of the large Hornád Basin of Eastern Slovakia. The complex has been included into the World Heritage list of UNESCO in 1993.

Its buildings and fortifications have been situated on a hill formed by a travertine cupola dome resting on an unstable clayey sedimentary formation. The castle bedrock displays serious open cracks because the travertine cupola body has been disintegrated into a series of blocks dipping slowly into the underlying beds and spreading to the margins. Its deformation was thoroughly investigated including crack gauge monitoring (Vlčko et al., 1998). The monitoring provided important geotechnical data about the movements, which is out of the scope of this paper. Let us demonstrate rather some results showing anomalies from two TM71 gauges installed in the SE section of the castle (Figs. 4a, b). The point near the main castle gateway (TM1) indicated special short-term movements in co-ordinates y and z by the end of 2004 together with the angular deviations γxy and γxz which appeared simultaneously at TM2, farther on behind the gate (Fig. 4c). Another series of anomalies in micro-rotations appeared even earlier in 1997.

Evidently, the anomalies are delayed here as compared with Orava and Strečno castles and 1997 anomaly is a new one. In any case, the late 2004 anomaly has been also registered by the research in Bohemian Massif and considered as a post-pulse effect when even Sumatra earthquake occurred. A wider search reported even the year 1997 as anomalous.

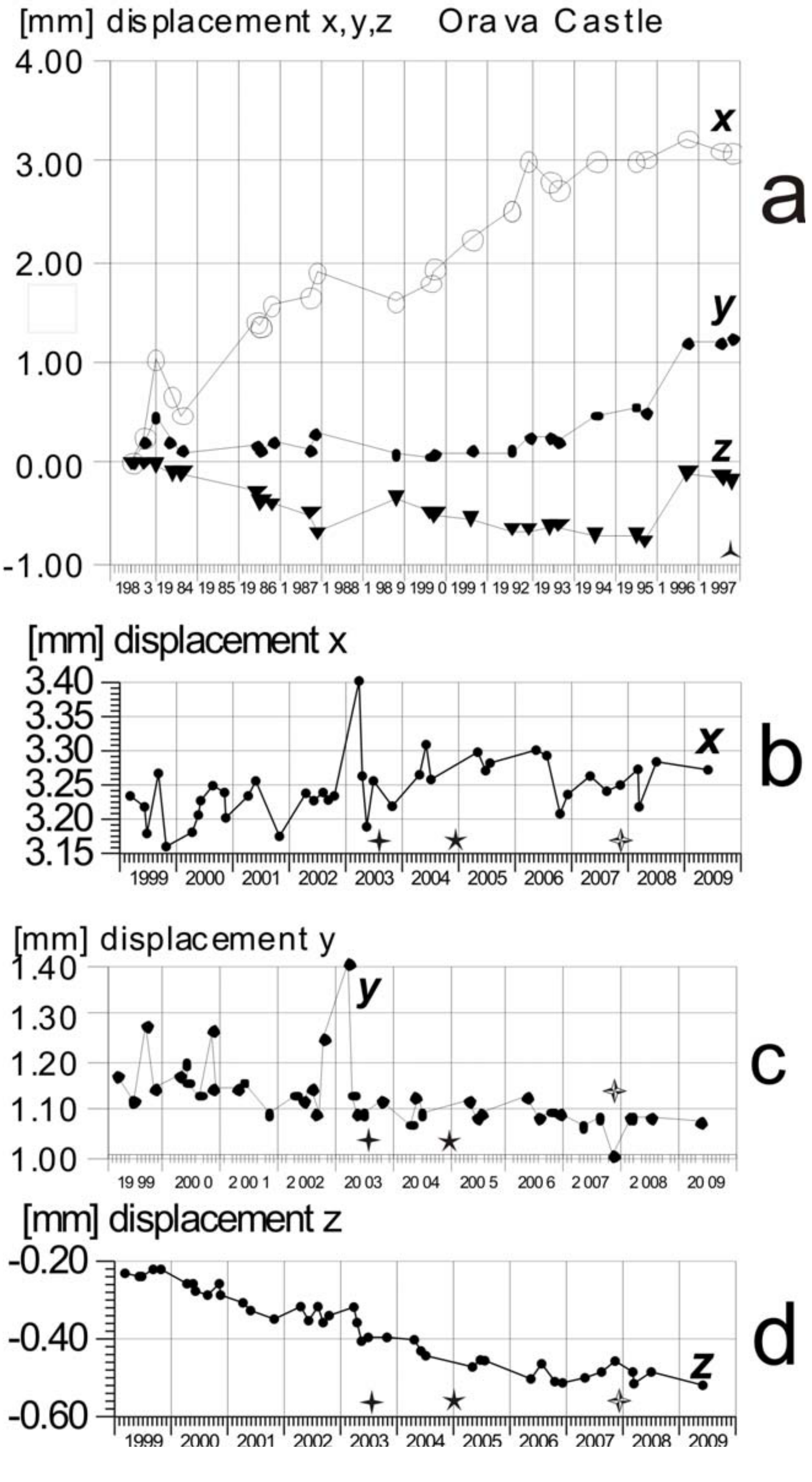

Fig. 2 Displacement records before (a) and after (b, c, d) stabilization measures at Orava Castle. Record (a) shows serious permanent movements from 1983 when the monitoring started. Serious instability has been confirmed in all the three co-ordinates *x,y,z*. Reconstruction took place between 1989 and 1993 reaching full effectiveness in 1999 as proved by movement deceleration (b,c,d) in *x,y* or even reversal in *z*, interpretable as anchoring effect of micro-piles. Nevertheless, in 2003 a single movement anomaly was recorded in *x* and *y*. This unusual anomaly coincides with the pressure pulse detected that time in the Bohemian |Massif.

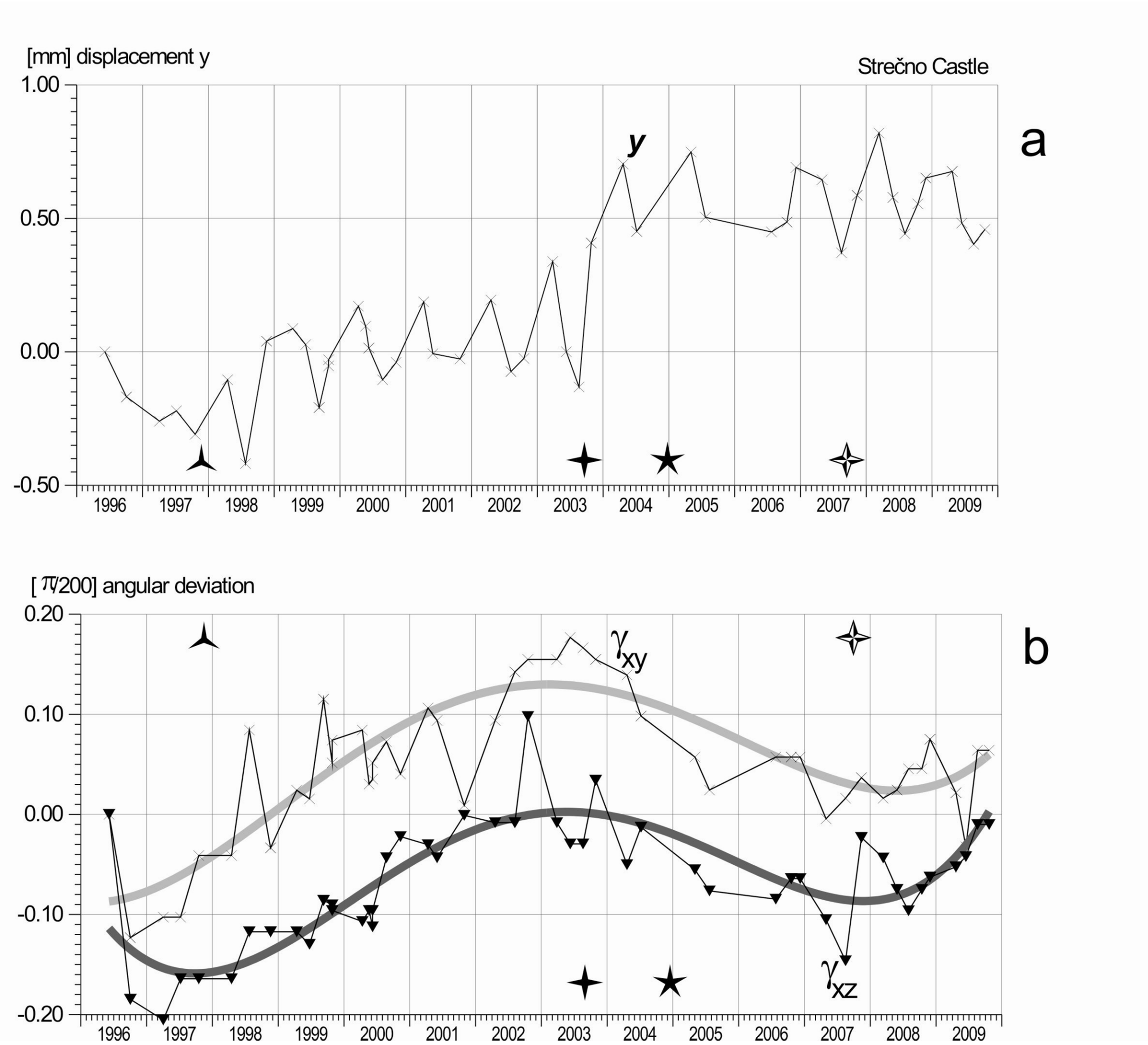

Fig. 3 Monitoring records from the rock wall fracture beneath the Strečno Castle showing lateral shift *y* (a) and micro-rotations γxy and γxz (b). The shift of 2003/4 and the progress in micro-rotations indicate the beginning and the end of an increased geodynamic phase registered earlier in the Bohemian Massif. (Polynomial fits of 4^{th} degree shown in (b).)

4.2. BLOCK-TYPE SLOPE MOVEMENTS

A special attention of engineering geologists was given to slope deformations of this type because they often affect very extensive areas. The main reason of investigations was to determine their recent moving activity, which is necessary for making decisions about their possible suitability for industrial development, their place in geological history or safety on tourist paths.

4.2.1. STENY (PAROHY) SITE

The site represents a part of crest section named Steny (Parohy) and is located between Mt Chleb and Mt Rozsutec (Malá Fatra Mts.). A vivid discussion started about the idea to accept this crest section as a possible area suffering from a mountainous process of crest splitting known from the Alps. Movement monitoring of a crest fissure initiated by A. Nemčok as early as in 1973 is continuing and brought positive results as to the active crest-slope movements and oriented to the Váh River Valley. A pertinent report about the locality and performed investigations is given recently in this issue (Briestenský et al., 2011).

It was in 1973 when an original gauge was installed here for observations to observe displacements *x, y, z*. Later in 1981 the gauge was supplemented with grids allowing registering micro-rotations γxz in a vertical plane *xz*. The new installation provided data with an unexpected development (Fig. 5). One can observe a rising parabolic development from 1983 to 2003 – 2007. Years 2008 – 2010 represent then a period of a change

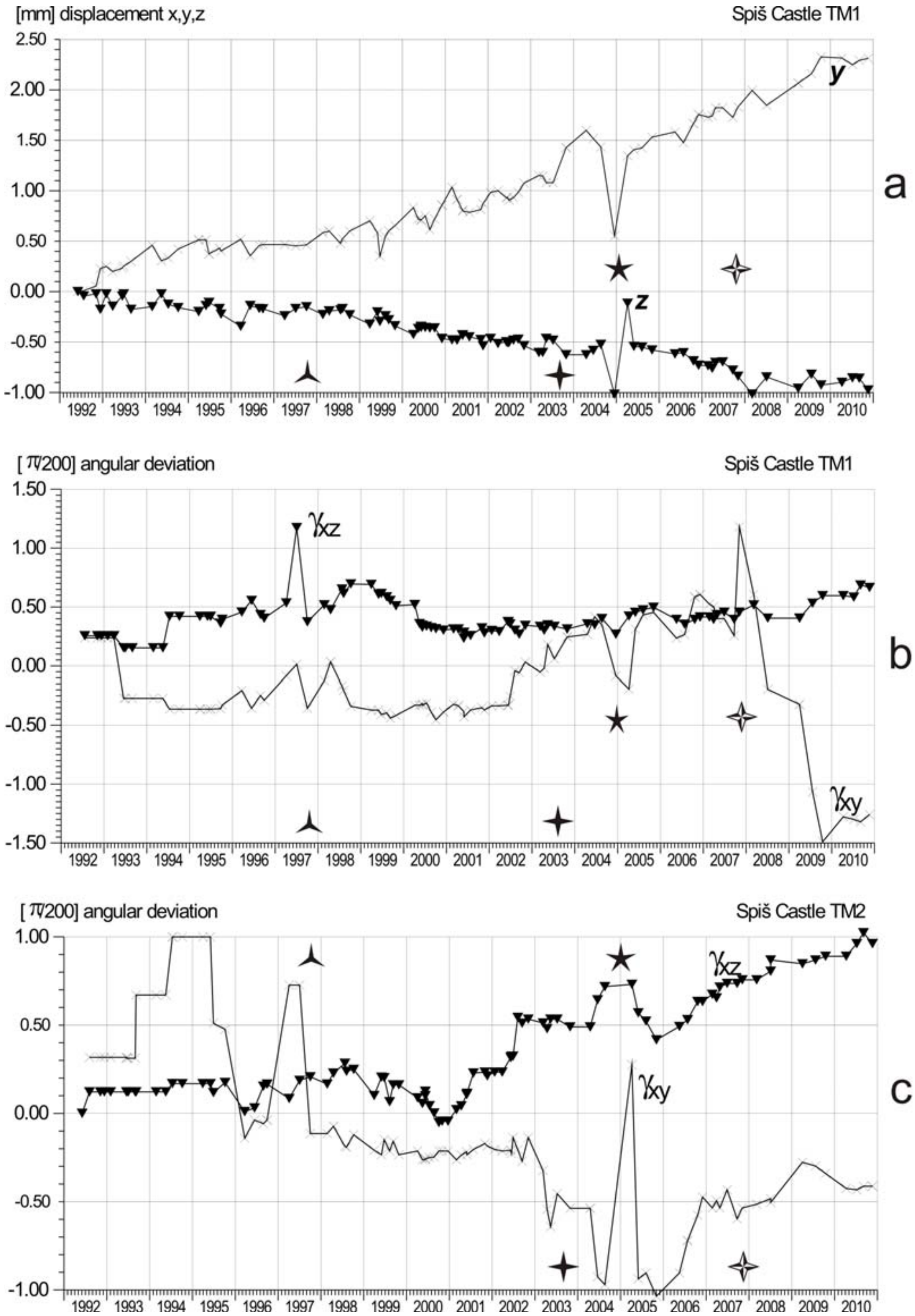

Fig. 4 Displacement and (b), (c) angular anomalies found at the Spiš Castle, at the measurement points TM1 and TM2. Anomalies appear in 1997 and 2004/5.

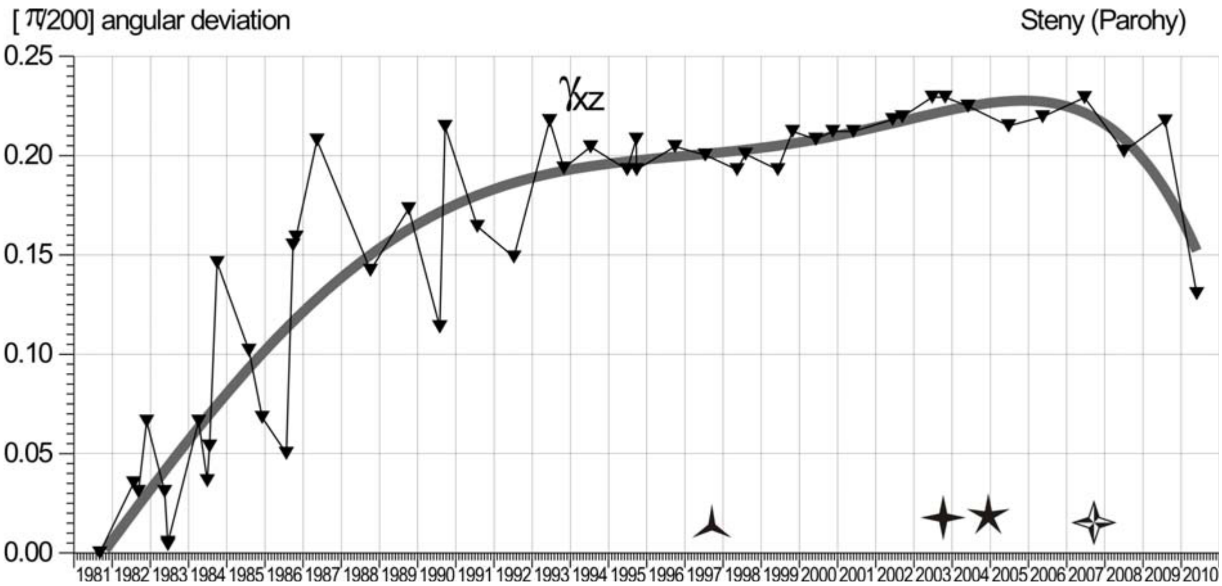

Fig. 5 Vertical micro-rotation *γxz* measured at Steny (Parohy) fissure site near the crest of the Malá Fatra Mts. Rotation development shows serious variation first, yet diminishing gradually along with a continuous deceleration. Eventually, a final turn from positive to negative values took place right in a short period 2003 - 2007. Later in 2010 a fast opposite rotation was indicated. Thus, the period of the change coincides with the period of increased geodynamics recorded in the Bohemian Massif, where it developed after the pressure pulse of 2003. (Polynomial fit of 8th degree shown in the graph.)

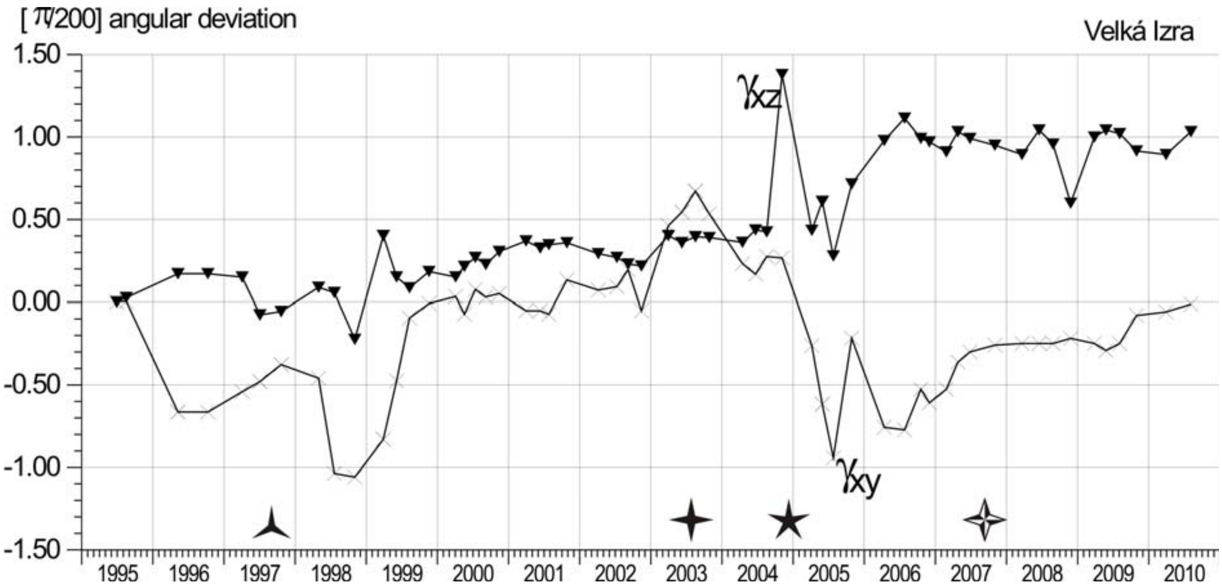

Fig. 6 Angular deviations *γxy* (horizontal) and *γxz* (vertical) recorded at the site of Velká Izra block-type slope deformation. Two anomalous periods can be recognized here: 1997 – 1999 and 2003 – 2005.

in the process, notably a deceleration or even a reversed tendency i.e. a turn to opposite rotation. Interpretation of the turn reads a change from a situation when the crack has shown a tendency of opening while going down to an opposite situation, i.e. a serious change of behaviour in the crack. Interesting enough, the period of the change coincides with the period of increased dynamics in the Bohemian Massif.

4.2.2. VELKÁ IZRA SITE

The monitoring site heavily forested and disturbed represents a huge block-type slope deformation. It is located in Eastern Slovakia. Main scarp of lateral spread is close to the Hungarian border, south of the town of Košice. The slope becomes steep here with volcanic rocks broken into block steps. Deep in a fissure a TM71 gauge was installed in 1995 to monitor movements and rotations.

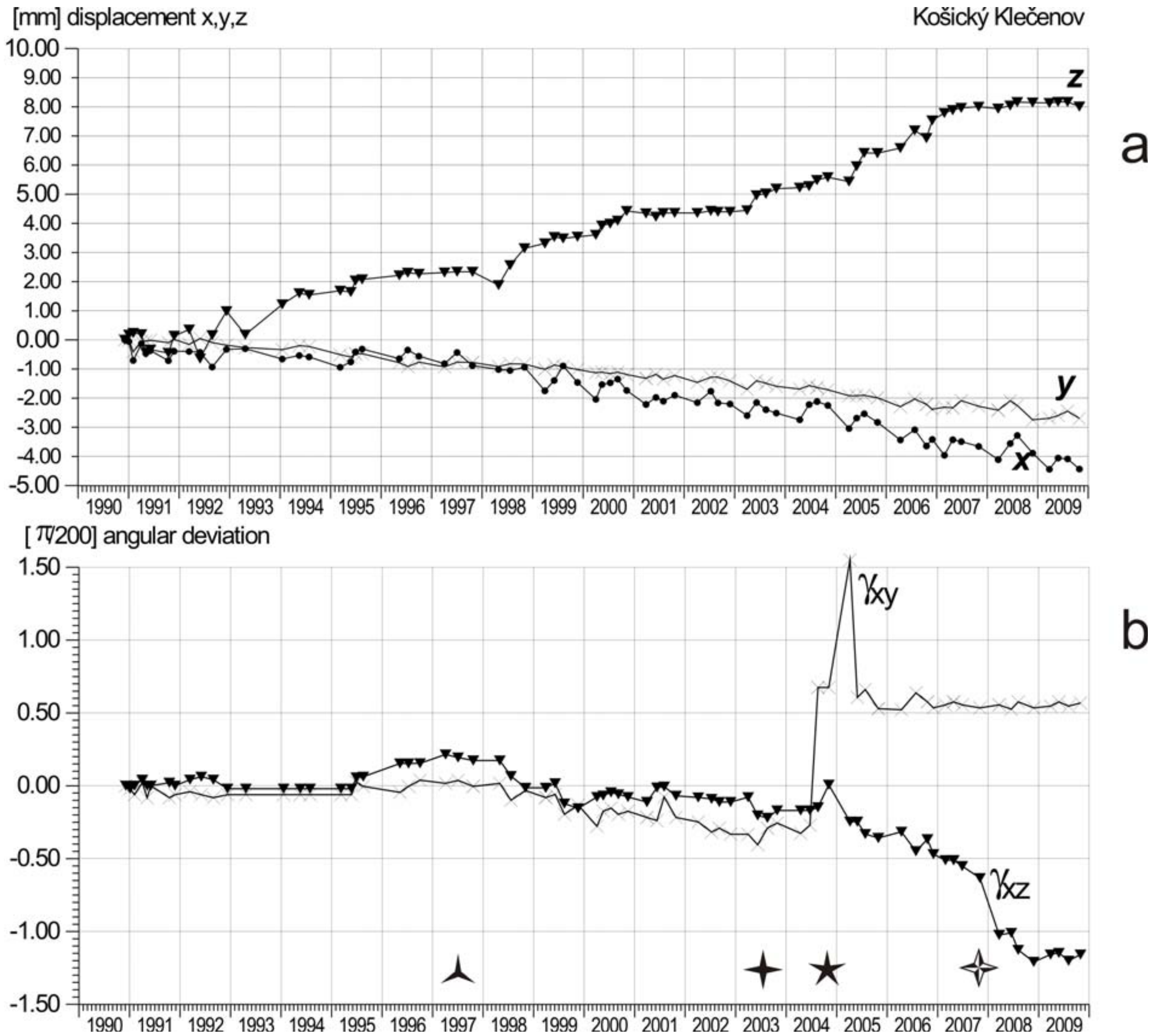

Fig. 7 Significant geotechnical effect of *x, y, z* in long-term movements (a), and tectonically conditioned angular deviations *γxy* (horizontal) and *γxz* (vertical) (b) recorded at the site of Košický Klečenov slope deformation. The conspicuous anomaly in the graph (b) displays an important earthquake precursor effect.

Movement trends were recorded here which identified active slope deformations. Rotations (Fig. 6) revealed two anomalous periods. The first one (1997 – 1999) was interpreted as a tectonic disturbance connected with Iran and Turkey (North-Anatolian Fault – Izmit) earthquakes (Košťák et al., 2007), and the second one (2003 – 2005) covers the period from the pressure pulse (2003) to Sumatra earthquake (2004/5).

4.2.3. KOŠICKÝ KLEČENOV SITE

This is a large slope deformation at a forested ground SE of the town of Košice (Eastern Slovakia). It displays some open and fresh looking cracks. Two cracks were instrumented with TM71 crack gauges which verified present slope movements. Figure 7a presents records of displacements and Figure 7b rotations.

The movement displayed by *x,y,z* which covers now 20 years of observation is almost stable and so productive that minor deviations from the stable rate are almost unidentifiable. However, the deviations due to tectonic development are well evident in rotations. The anomalies of 2004/5 are striking. *γxy* is sharply developed representing an acceleration moment for *γxz*. One can notice that the conspicuous anomaly in *γxy* originated as early as in August/November 2004, i.e. well before Zakopane earthquake (SE Poland, 30.11.2004; M=4.8), as well as before the Sumatra earthquake which took place on December 26, 2004. This fact excludes any idea that the anomaly has been produced by seismic vibrations of the mentioned earthquakes. It was rather a precursor and demonstrates validity of our earlier statements that the geodynamic process behind the movements that followed the pulse was aseismic.

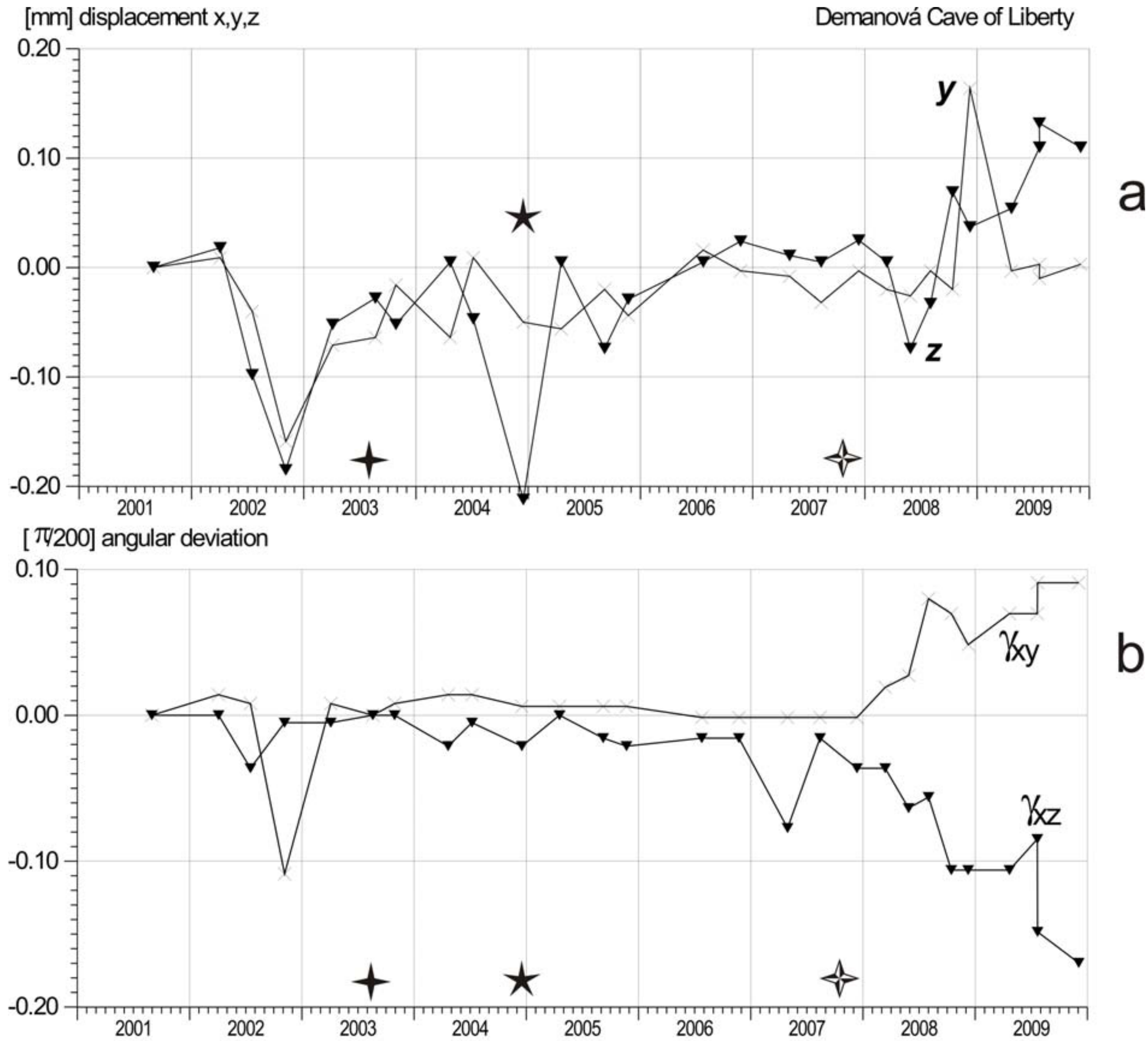

Fig. 8 Displacements *y* and *z* recorded in Demänová Cave of Liberty (a). Movements are quite low on the fault and produce individual reversible step-like displacements rather than a continual slipping. First two slips *z* and *y* of this type appear in 2002 and 2004 making thus a frame for the year of 2003 with the pulse occurrence. They were both negative in the first slip, negative/neutral in the second. Further slips of 2008/9 were negative/positive which means a different orientation of the resulting slip. They appear after the period of increased dynamics reported in the Bohemian Massif, framing its end. Angular deviations (b) signalize a period of rejuvenation of tectonic movements after 2007.

4.3. UNDERGROUND SITES

Underground measurements are clearly preferable regarding highly stable environmental conditions. In Slovakia underground crack gauging with the use of TM71 was applied relatively later than on landslides. Therefore we are not able to find records longer than of one decade. Dealing with movement monitoring in caves we have to count with interpretation of low order values. In spite of such difficulties several sites were instrumented and provided results which correlate well with data obtained by regional geological.

4.3.1. DEMÄNOVÁ CAVE OF LIBERTY

Demänová cave system is located in the Demänová Valley on the northern side of the Nízke Tatry Mts. The cave was formed in the Triassic lime-stones. The gauge is installed on a NW-SE oriented tectonic fault. Recorded displacements *y* and *z* displayed in Fig. 8a are better pronounced than *x* which is even lower and will not be displayed here.

On the cave fault one can observe a state of unrest rather than shifts. Only individual reversed step-like slips occur. A clear comprehension of the local process would need longer observation.

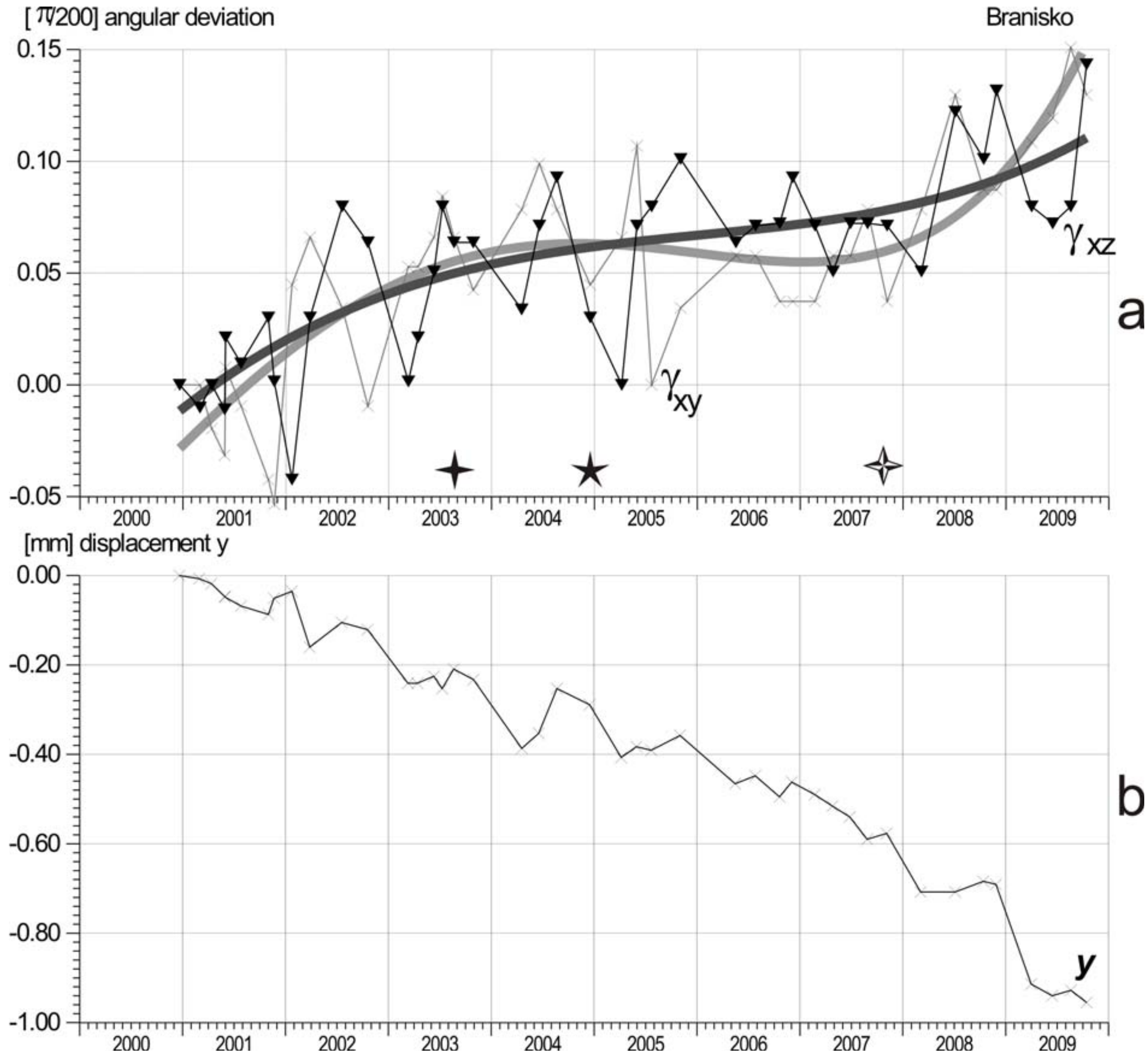

Fig. 9 Branisko tunnel site showing deceleration phase in the development of angular deviations on the local fault (a). The course is almost parallel in both vertical and horizontal rotations and shaped to an S-like curve leaving the 2003/2007 period almost stable. This is the incriminated period when the pulse and the phase that followed occurred. (Polynomial fits of 3rd degree shown in the graph.)
Important geotechnical displacements are found in *y* component (b).

However, the incriminated pulse period 2003 – 2007 may be expressed by suppressed movements. Moreover, the slips show changed orientation in time.

Angular deviations (Fig. 8b) may support a view that observations indicated a specific period of suppressed movements till 2008/7. They show anomalies in 2002 and then new accelerations beginning only with 2007. The year 2007 signalize a period of rejuvenation in tectonic movements.

A special attention should be paid to the peak that occurred by the end of 2004 in *z* co-ordinate (Fig. 8a). Formal interpretation would it classify as a result of Zakopané earthquake (SE Poland, 30.11.2004; M=4.8). This is a most prominent finding while the site is generally one of the most difficult sites for movement interpretation.

4.3.2. BRANISKO TUNNEL

The site is located inside the emergency highway tunnel which starts at the east end of the Hornád Basin (Eastern Slovakia) and continues through the Branisko Mts. to the east. The TM71 gauge is installed at the eastern part of the tunnel directly between footwall and hanging wall of a local fault. Ten years of observations proved micro-displacements.

Angular deviations γxy and γxz revealed progressive lines affected by seasonal variations (Fig. 9a). However, the course is showing clearly an almost parallel time development in both the rotations. An S-like shape of the time development shows progressive rotation before 2003 and after 2007 leaving the period in between almost stable. The central period coincides with the period of the pressure pulse with the post-pulse process.

The most prominent and geotechnically important is a long-term and progressive trend of shear displacements along the *y* axis, which proves a dextral tectonic movement on the investigated fault (Fig. 9b).

4.3.3. IPEĽ GALLERY

The site represents TM71 gauge measurement on the main fault found in the investigation gallery excavated for a projected pump storage power plant in Central Slovakia. The measurement began in August 2002 and observed displacements proved tectonic activity of the investigated fault quickly.

It is mainly vertical displacement, important from a geotechnical view, which is displayed in the co-ordinate *z* (Fig. 10a). This movement produced significant variation which can be correlated with the pulse (2003), the post-pulse (2004 Sumatra reactions), and the final development of the phase of increased geodynamics (the 2007 end).

The course of vertical rotation γxz (Fig. 10b) is also very expressive. We find an S-like shaped course rising during 2003, culminating at the break of 2004/5, and descending until March 2008. Later, a rising till now can be observed. One can state again that the central and descending period of the curve coincides with the period of the pressure pulse and the post-pulse process. The development correlates with that of Branisko and Strečno.

5. DISCUSSION

The inventory of movement characteristics recorded at the investigated Slovak geotechnical sites (Fig. 1) and important in the discussion concerning correlations is given in Table 1. Individual characteristics are related to the main events found and discussed in the earlier geotectonic research in the Bohemian Massif.

The first aspect which is to be well understood when discussing the observations presented here is the fact that the selection of the investigated objects covers a large territory (Fig. 1). We move from NW Slovakia represented by Orava Castle and Parohy in Malá Fatra Mts. through Central Slovakia (Strečno Castle, Demänová Cave of Liberty, Ipeľ, Spiš Castle), to Eastern Slovakia (Branisko, Košický Klečenov, and Velká Izra sites). This means also considerable difference in geological conditions and tectonic setting. We combine superficial measurements as well as underground ones. It is to see this territorial and vertical disposition when possible seismic effects might be seen behind observed anomalies. Minor effects of a short reach will be of little effectiveness therefore, impossible to produce anomalies to be correlated. Correlation or even coincidence of effects on such a large territory must have been based on a process from a deep and massive source.

The question of seismic effects is notoriously introduced into discussions. There are hundreds of seismic events registered every year in Slovakia. However, we cannot find even one strong enough to affect the bulk of so distant objects in Slovakia and simulate an effect like the indicated pressure pulse. This is to be said generally. On the other hand, we should consider individual quakes to affect objects within their perimeter. This may be the case of Zakopané earthquake (SE Poland, 30.11.2004; M=4.8), its epicentre lying close to the northern Slovak border line in High Tatra Mts. It was unusually intensive and reported as an unknown event in the area. Searching through our results we can find an anomalous vertical slip in Demänová (16. 12. 2004, z = - 0.22 mm; see Fig. 8). The slip was completely reversible and may be seen pertinent to the quake. A similar slip has been found at the Spiš TM1 site (16.12.2004, Δy = - 0.88 mm; Δz = - 0.50 mm; Fig. 4). This is probably the most critical case of the period in question and we have found none else effect of this kind and magnitude with the other sites. This effect occurring within the peak period of the Sumatra geodynamics would be obviously attributed to the local source near Zakopané rather than to the distant one, even if strong, like that of Sumatra. Besides, the observation of the incriminated slips at both the sites reported here - Demänová Cave and Spiš Castle, was made before the event of Sumatra but after Zakopané earthquakes. Therefore, from the point of view of our record, the two sites leave the question of priority open.

Nevertheless, a question can be raised, whether even this particular earthquake of Zakopané were not the result of the pulse process which is of a much larger radius. Are the two specific processes of movement really independent? There are indications supporting a view they are not. A detailed analysis of anomalies shows some peaks and micro-movements occurring in advance of earthquakes, as well as earthquakes occurring in later stages of increased dynamics. It contradicts general feeling about earthquakes as independent and initiating geodynamic factors. It is rather a progressive and aseismic geodynamic process that produce the earthquake. A closer argument about geodynamics as being primarily aseismic can be found in the 2010/11 publications of the authors. The authors realize however that this view is not accepted generally and it would take time for the audience of geosciences to allow for such a hypothesis. Although episodically active, local earthquakes can be seen hardly as a dominant factor in geodynamics of Slovakia.

There is another problem to be discussed regarding our reference to the Sumatra earthquake

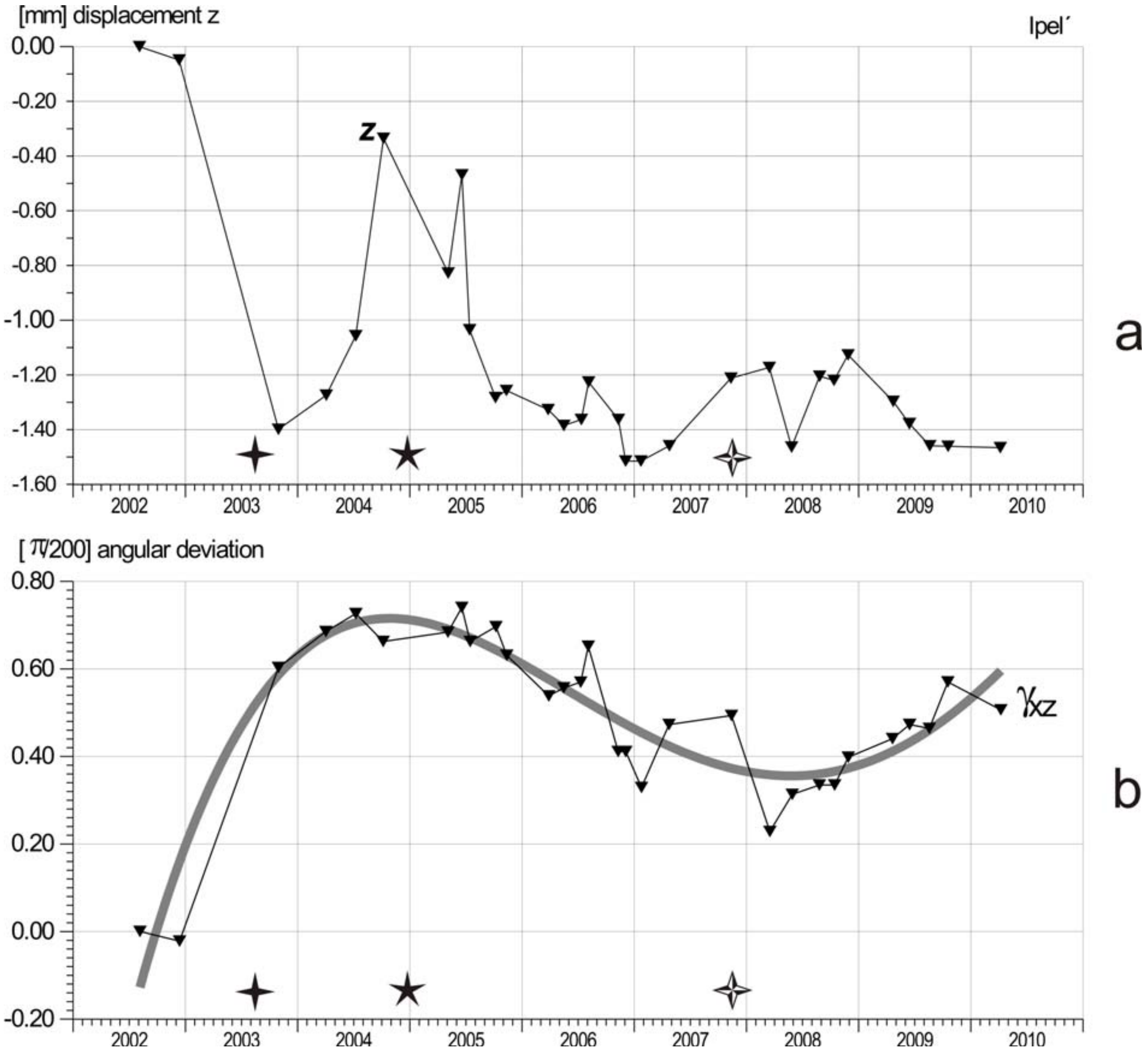

Fig. 10 Ipeľ gallery site showing development on the local fault with vertical movements *z* (a) and angular deviations *γxz* (b) on the local fault. Vertical movements in *z* component produced significant variations (a), and the course of *γxz* is S-like shaped (b). Early in 2003 vertical *z* component gets to two culminations points, first in autumn 2004, second in summer 2005, which correlates with the culmination in *γxz.* In the next development the course drops down to turn up again beginning March 2008. The period with the descending course coincides with all the important moments of the incriminated period when the tectonic pressure pulse and the phase of increased geodynamics occurred.
(Polynomial fit of 4th degree shown in the graph (b).)

(Sumatra 26. 12. 2004, M=9.0 and 7.5). The earthquake was catastrophic, as well as unique, well registered in Europe and globally, but in spite of that we cannot blame frontal vibrations due to its occurrence for any particular permanent macro-effect at so distant territory like Centrtal Europe. On the other hand we accept that a stress/strain transformation process in the crust which preceded and followed this magnificent and catastrophic earthquake, was probably effective in slow micro-tectonic displacements even in Europe. We find indication of such a process in observed micro-movements, i.e. in the anomalies. The best evidence of such a process may be reorientation in tilts registered by the end of 2004 in the Krušné Hory Mts., W Bohemia (Košťák et al., 2011).

As for the data reported in this paper it is specific that they were accepted with no respect to the tectonic and detailed geological setting. This follows interpretation of data from Bohemian Massif by Stemberk et al. (2008). Shortly, the factor of faulting is dominant over the factor of geological setting; also, reactions to the tectonic pressure pulse were found not only on tectonic faults but even on landslides where

Table 1 Inventory of characteristic movements at the investigated Slovak geotechnical sites. Important anomalies indicating the key factors found conjointly at the Bohemian Massif are specified as well as other characteristics that may be correlated with factors like major regional earthquakes.

	MOVEMENT CHARACTERISTICS 1992-2009								
	SLOVAK CASTLES			**SLOPE DEFORMATIONS**			**UNDERGROUND SITES**		
SITE	**Orava**	**Strečno**	**Spiš**	**Parohy**	**V.Izra**	**K.Klečenov**	**Demännová**	**Branisko**	**Ipel´**
⅄ - phase of Iran/Turkey earthquakes 1997/9	out of detection range -----------	y **ANOMALY**	γ_{xy}, γ_{xz} **ANOMALY**	γ_{xz} decelerate	γ_{xy}, γ_{xz} **ANOMALY**	z **ANOMALY**	----------	----------	----------
✦ pressure pulse Aug 2003	x,y (-3✦) **ANOMALY**	y,γ_{xz},γ_{xy} (-3✦) **ANOMALY**	γ_{xz} (-3✦) **ANOMALY**	////////////	γ_{xy} (✦) **ANOMALY**	////////////	////////////	γ_{xy} (✦) **DECELERATE**	z, γ_{xz} (✦3+) **ANOMALY**
★ Sumatra earthquake M=9,1 Dec 26/2004	----------	no anomaly observed ////////	y,z, γ_{xy} (-1★) **ANOMALY**	///////////	γ_{xz} (-1★) γ_{xy}(★+7) **ANOMALY**	γ_{xy} (-2★5+) **ANOMALY**	γ_{xz} (-1★) **ANOMALY**	γ_{xy} ; γ_{xz} (★3+) **ANOMALY**	z (-3★) **ANOMALY**
Zakopane PL SE, M=4.8 earthquake Nov 30/2004	----------	////////////	(+1)	////////////	distant	distant	(+1)	distant	distant
Vrbové SK W, M=3.6 earthquake Marz 13/2006	----------	///////////	///////////	///////////	distant	////////////	////////////	distant	distant
✧ increased geodynamic phase ending Nov 2007	----------	γ_{xz} (✧) **ANOMALY**	γ_{xy} (✧) **ANOMALY**	γ_{xz} (✧) decelerate	////////////	γ_{xz} (✧4+) **ANOMALY**	γ_{xy} , γ_{xz} z;y (✧+) **ANOMALY**	γ_{xy} (✧) **ACCELERATE**	γ_{xz} (✧5+) **ACCELERATE**
deceleration course	----------	✦2003/7✧ γ_{xy} ,γ_{xz} **S-like**	////////////	////////////	////////////	////////////	////////////	✦2003/7✧ γ_{xy} ; γ_{xz} **S-like**	✦2004/8✧ γ_{xz} **S-like**
Legend: γ_{xy} (-2★5+) ANOMALY read : component γ_{xy} (anomaly record 2 month before Sumatra earthquake and 5 month after)									

gravitation tectonics is dominant, as generally accepted (Orava Castle, Velká Izra, and Košický Klečenov).

It was not always anomalies in micro-displacements or micro-slips observed as peaks on the graphs which showed the correlation. We have introduced a series of graphs that show angular deviations or micro-rotations. Such effects can remind the function of geophysical tiltmeters. They are sensitive to elastic/plastic strain in the massif. Thus, the function of TM71 gauges is complex and it was specific to find some S-like curves in the graphs. See underground sites: Ipeľ and Branisko which have delimitated the period of increased or decreased geodynamics in their S-like course. A tectonic pulse may not always accelerate but even decelerate a geodynamical process. Counterparts of such periods are in pointed arch forms and steps (Košický Klečenov, Steny, Strečno and Demänová).

Reactions correlated with the geodynamics of the Sumatra earthquake have become often dominant among the anomalies (Spiš Castle), and often appear as precursors (Košický Klečenov, Velká Izra). They should be seen inherent in the tectonic process in question and therefore reactions of the pulse and that of the quake merge sometimes into one 2003/4/5 anomaly. Individually, we may find reactions (Strečno) which are due to an earlier (1997/9) tectonic process in Europe (Košťák et al., 2007).

6. CONCLUSIONS

The geodynamic process due to the tectonic pressure pulse of 2003 which was identified in Central, as well as in South Europe and reported by Stemberk et al. (2010); Košťák et al. (2011), has been evidenced also by movement monitoring on sites in Slovakia. It is specific that even sites of landslides evidenced such movements. Geotechnical projects can be well involved in such a research which supplies important information about present geodynamics in the region. Long-term monitoring is a necessary condition in it. Monitoring of micro-rotations (angular deviations) was found useful in detection of geodynamic events.

Observations are in agreement with the earlier research oriented to Bohemian Massif and the Mediterranean (Stemberk et al., 2010; Košťák et al., 2011) and fit in the geodynamic pattern in question. Thus, valuable supplementary information about the geodynamics of the Central Europe has been gained.

ACKNOWLEDGEMENTS

This research was carried out in frame of the international European Science Foundation action COST 625 "3D monitoring of active tectonic structures", supported by Czech Ministry of Education, project OC 625.10 during 2000/2006, as well as within the national project entitled "Partial monitoring system of geological factors of environment of the Slovak Republic – Neotectonic and seismic activity" (since 2006). The interpretation was done in the framework of the Czech Rep. grant projects GAČR 205/06/1828 "3D monitoring of micro-movements in the collision zone between African and Euro-Asian tectonic plates" during 2006/2008 and GAČR 205/09/2024 "Time-development analyses of micro-displacements in the collision zone between African and Euro-Asian plates". Latest data analysis has been supported also by the Czech Academy of Sciences (Projects S3012353 and IAA300120905, respectively).

REFERENCES

Briestenský, M., Košťák, B. and Stemberk, J.: 2011, Long-term slope failure monitoring in the region of the Core High Mountains (the Western Carpathians). Acta Geodyn. Geomater., 8, No. 4 (164), 405–414.

Gross, P. (Ed.), Filo, I., Halouzka, R., Haško, J., Havrila, M., Kováč, P., Maglay, J., Mello, J. and Nagy, A.: 1994, Geological map of southern and eastern part of Orava. Publ. by Geological Institute of D. Štúr, Bratislava.

Košťák, B.: 2006, Deformation effects in rock massifs and their long-term monitoring.- Quarterly Journal of Engineering Geology and Hydrogeology, 39, 249–258. Geological Society, London.

Košťák, B., Cacoń, S., Dobrev, N.D., Avramova-Tacheva, E., Fecker, E., Kopecký, J., Petro, L., Schweizer, R. and Nikonov.A.A.: 2007, Observations of tectonic microdisplacements in Europe in relation to the Iran 1997 and Turkey 1999 earthquakes.- Izvestiya - Physics of the Solid Earth, 43, No 6, 503–516, Pleiades Publ., Moscow.

Košťák, B. and Sikora, J.: 2000, Ověření účinnosti sanačních opatření na Oravském hradě (Verification of effectiveness of the remedy measures applied at the Orava Castle site). Geotechnika 3/2000, 8-10, Praha, (in Czech).

Košt'ák, B., Mrlina, J., Stemberk, J. and Chán, B.: 2011, Tectonic movements monitored in the Bohemian Massif. Journal of Geodynamics, 52(2011), 1, 34–44, doi: 10.1016/j.jog.2010.11.007

Petro, L., Polaščinová, E., Stercz, M. and Košťák, B.: 2005, Current results from 3-D monitoring of active faults in the Western Carpathians, Acta Geodyn. Geomater. 2, 1, (137), 37–43.

Stemberk, J., Briestenský, M. and Jurková, N.: 2008, Posuny na tektonických poruchách registrované ve vybraných jeskyních Českého masívu (Displacements on tectonic fractures registered in selected caves of Bohemian Massif). Speleofórum 27, 141–144, Praha, (in Czech).

Stemberk, J., Košt'ák, B. and Cacoń, S.: 2010, A tectonic pressure pulse and increased geodynamic activity recorded from the long-term monitoring of faults in Europe. Tectonophysics, 487, 1–12.

Vlčko, J., Petro, Ľ. and Košťák, B.: 1998, Monitorovanie pohybov skalných blokov na Spišskom hrade (Monitoring of slope movements on Spiš Castle). Proc. Conf. "Geológia a životné prostredie", Geologická služba SR, Bratislava, 102–104, (in Slovak)

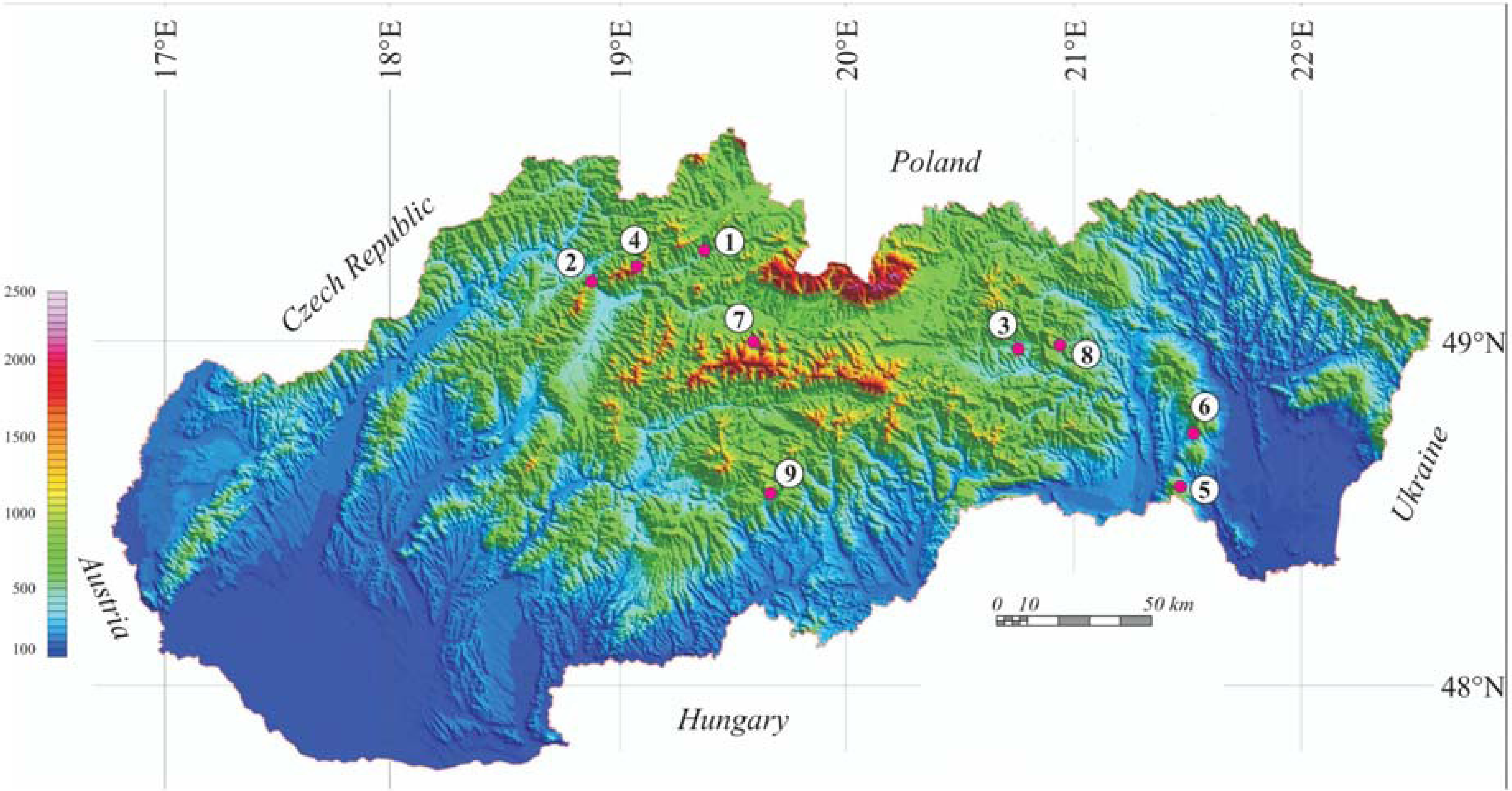

Fig. 1 Location of the Slovak monitoring sites reported in this paper. 1 – Orava Castle, 2 – Strečno Castle, 3 – Spiš Castle, 4 – Steny (Parohy), 5 – Veľká Izra, 6 – Košický Klečenov, 7 – Demänová Cave of Liberty, 8 – Branisko tunnel, 9 – Ipeľ tunnel.