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ON THE STATE OF THE TM 71 EXTENSOMETER MONITORING IN SLOVENIA: SEVEN YEARS OF MICRO-TECTONIC DISPLACEMENT MEASUREMENTS

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ABSTRACT

At the end of 2010 seven TM 71 extensometers, installed at or near the active faults in Slovenia, were in operation. Three of them are on the surface and four inside karst caves. The highest rates with stable sense of movements were observed on the Idrija fault. Average horizontal displacement rate was 0.24 mm/year. Short term rates were even greater and reached 0.54 mm/year. The Raša fault first experienced an uplift of the SW block of 0.16 mm/year, which was followed by a short-term down-slip of the same block at the rate of 0.37 mm/year. Later the sense of movement returned to uplift with a rate of 0.05 mm/year. The average horizontal displacement was 0.07 mm/year. The Kneža fault experienced very small average displacements (y=0.035 mm/year, z=0.03 mm/year and x=0.02 mm/year). Similar rates were observed in nearby Polog cave (y=0.015 mm/year, z=0.027 mm/year and x=0.016 mm/year), which is located close to the seismically active Ravne fault. For Kostanjevica cave, located near the Brežice fault, small average rates are characteristic (y=0.006 mm/year, z=0.017 mm/year and x=0.012 mm/year). In Postojna cave, located close to the Predjama fault, two monitoring sites are very stable with small tectonic movements, including general dextral horizontal movement of 0.05 mm from 2004 to 2010 (Postojna 1) and two significant short-term peaks of 0.08 mm (Postojna 1-y and Postojna 2-z).

KEYWORDS: geodynamics, TM 71 extensometer, micro-tectonic displacements, active faulting, Slovenia.

1. INTRODUCTION

The geotectonic position of Slovenia at the contact between the Adria microplate in the south and Eurasia plate in the north with moderate historic and recent seismicity, makes it a good place to study active tectonic deformations. For this reason the first four TM 71 extensometers, which measure three-dimensional (3D) displacements on cracks separating tectonic blocks, were installed in Slovenia in 2004. At the end of 2010 seven instruments were in operation. Monitoring sites were selected in the seismically active areas, in the vicinity of regionally important faults and inside representative outcrops within fault zones. Three monitoring sites are located on the surface within fault zones of active Dinaric faults in W Slovenia, and four monitoring sites are located inside karst caves close to known tectonic faults, three in W Slovenia and one in SE Slovenia.

Taking into consideration that karst in Slovenia represents 43 % of the area it is not unsurprising that all seven monitoring sites are situated in karst areas. The results of regular monitoring show interesting rates and sense of displacement, as discussed previously (Šebela and Gosar, 2005; Šebela, 2005; Gosar, 2007a; Gosar et al., 2007; Šebela et al., 2005; Šebela et al., 2008; Gosar et al., 2009; Šebela, 2009; Šebela et al., 2009; Šebela et al., 2010a; Šebela et al., 2010b). 3D monitoring of tectonic displacements is useful for proving the active character of individual faults, and together with the established rates of movements, is important for any seismic hazard study in the area.

In this paper an overview of seven-year 3D micro-displacement monitoring is presented for all seven sites that show active tectonic micro-movements.

2. GEOLOGICAL SETTING

Slovenia is situated at the border between the Adria microplate and Eurasia plate and is

Table 1 TM 71 monitoring sites in Slovenia.

No. (Fig.1)	**Monitoring site**	**Geological structure**	**Distance to important regional tectonic structure**	**Monitoring since**	**Above sea level (m)**
1~~a~~	Postojna 1	fault zone NW-SE	1 km south of Predjama fault	2004	560
1~~b~~	Postojna 2	fault zone NW-SE	1 km south of Predjama fault	2004	526
2	Učja	Idrija fault NW-SE	within Idrija fault zone	2004	420
3	Vremščica	Raša fault NW-SE	within Raša fault zone	2004	620
4	Zadlaz-Čadrg	Kneža fault NW-SE	within Kneža fault zone	2006	530
5	Polog cave	bedding plane	300 m south of Ravne fault NW-SE and 200 m above Julian Alps thrust	2008	735
6	Kostanjevica cave	fractured zone SW-NE	3 km south of Brežice fault	2008	175

characterized by complex and neotectonically active geological conditions. The studied area, which includes seven monitoring sites, is part of Adria microplate south of the Periadriatic lineament. Since the late Miocene to Pliocene paleomagnetic data indicates about 30° counter-clockwise rotation of the Adria microplate (Márton et al., 2003).

The Paleogene to recent thrust belts along the Adria margin include Dinaric thrust systems, the South- Alpine thrust system and Dinaric faults. The Dinaric thrust systems are post-Eocene, representing a NW-SE striking fold-and-thrust belt that can be followed from the Istra peninsula towards central Slovenia (Vrabec and Fodor, 2006) and that belongs to the External Dinarides.

The S- to SE-verging fold-and-thrust-belt of the Southern Alps formed in the Pontian. Dinaric faults cut and displace both Dinaric and South-Alpine fold-and-thrust structures. Many Dinaric faults, including the Idrija Fault, formed as dip-slip normal faults and were only later dextrally reactivated (Vrabec and Fodor, 2006).

A large part of regional deformation seems to be still concentrated on the Periadriatic lineament as a long-lived structural system, whereas the younger structures south of it, such as the Dinaric faults, have a comparatively minor role (Vrabec and Fodor, 2006). The GPS-based best-fitting angular velocity vector predicts actual convergence in the Dinarides at ≤ 5 mm/year (Weber et al., 2010). Recent seismicity observed in the vicinity of the Raša and Idrija faults is characterized by focal mechanisms that indicate the right-lateral strike-slip or reverse type of faulting (Poljak et al., 2000). Brežice fault in SE Slovenia was identified as a reverse fault on the southern limb of the Krško syncline, built up of several reverse faults and backthrusts (Verbič, 2005). The fault has SW-NE direction parallel to Mid-Hungarian zone (Márton et al., 2002). The northern branch of the Brežice fault is a neotectonic fault with sinistral horizontal movement and vertical reverse movement, with uplift of the SE block (Verbič, 2005).

3. METHODOLOGY AND MONITORING SITES

The description of use of TM 71 extensometers to monitor relative micro-displacements on cracks that separate tectonic blocks has been presented several times (Košťák, 1977, 1991; Košťák and Rybář, 1978; Stemberk et al., 2003; Košťák et al., 2007; Stemberk et al., 2010; Briestenský et al., 2010). The instrument measures the displacements in 3D (x, y and z) – displacement vector in two perpendicular planes (horizontal and vertical) and angular deviation (rotation). The sensitivity of the instrument is 0.0125 mm in all three space co-ordinates and 3.2 x 10^{-4} *rad* in angular deviations.

Monitoring of micro-displacements in Slovenia includes seven TM 71 instruments (Table 1). Three of them are located on the surface and four in karst caves (Fig. 1). The wider tectonic zones of six regionally important faults (Raša, Predjama, Idrija, Kneža, Ravne and Brežice faults) are included in the TM 71 monitoring net in Slovenia.

In November 2004 two TM 71 extensometers were installed on the surface, one on the Raša fault zone at the SE foot of Vremščica Mountain and the other on the Idrija fault in Učja valley. In November 2006 the third surficial instrument was set up on the Kneža fault (Zadlaz-Čadrg). All three instruments are installed on Dinaric-oriented (NW-SE) regionally important faults in W Slovenia.

In three karst caves (Postojna, Polog and Kostanjevica caves) four TM 71 instruments are installed. The monitoring of micro-tectonic displacements in Postojna cave started in May 2004 (Postojna 1) and in February 2004 (Postojna 2). Two instruments, 260 m apart, are installed on a Dinaric-oriented (NW-SE) fault zone, which is situated about 1 km northeast of the regionally important Dinaric-oriented Predjama fault and about 5 km south of the Idrija fault.

Polog cave is situated about 300 m south of the Ravne fault. An instrument is installed between two sliding limestone beds dipping towards the SE. Monitoring has taken place since June 2008.

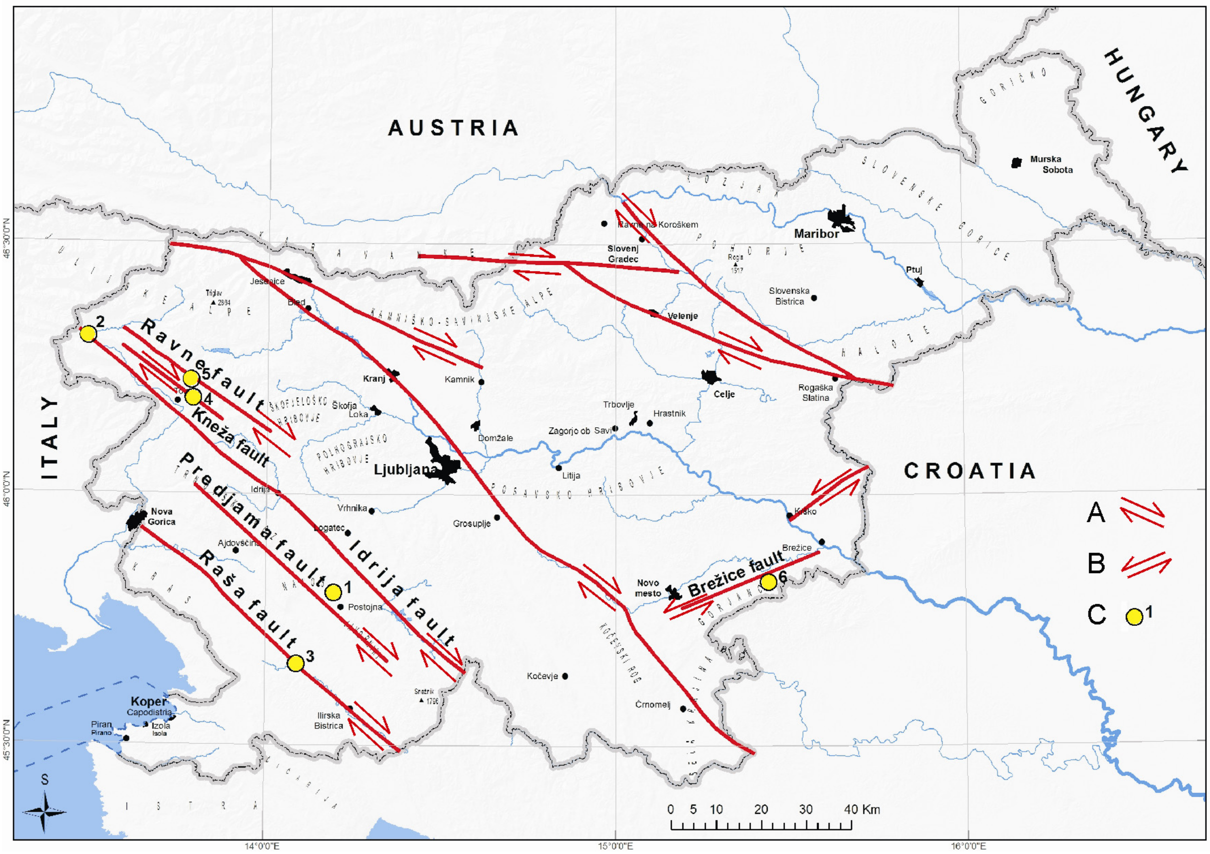


Fig. 1 TM 71 monitoring sites in Slovenia and most important faults. A – dextral horizontal movement along the fault, B – sinistral horizontal movement along the fault, C – monitoring sites (1-Postojna cave, 2-Učja, 3-Vremščica, 4-Zadlaz-Čadrg, 5-Polog cave, 6-Kostanjevica cave).

In Kostanjevica cave the TM 71 is installed within a NE-SW oriented fractured zone, which is situated about 3 km south from the main northern branch of parallel Brežice fault. Monitoring started in June 2008.

The graphs (Figs. 2, 4, 5, 6, 7, 8 and 9) represent the results of the movements in three dimensions, *x, y* and *z*, where +*x* represents compression of the observed fault (-*x* extension), +*y* represents sinistral horizontal movement (-*y* dextral) and *z* vertical movement.

4. RESULTS OF TM 71 MONITORING AND DISCUSSION

Idrija fault

The Idrija fault is the most important regional strike-slip fault in W Slovenia (Fig. 1). It extends from the Italian border near Bovec to Croatia in Gorski Kotar (N of Rijeka), having a total length of more than 120 km. The strongest historical earthquake in the region, the »Idrija« earthquake in 1511 with estimated magnitude of 6.8 and max. intensity X, is usually related to this fault (Ribarič, 1979), but its exact location and relation to the faults in the region are still debated (Fitzko et al., 2005). The second strongest known event, with magnitude 5.6, happened in 1926 (Šebela, 2010) at the SE part of the Idrija fault. However, recent seismicity in the vicinity of this fault is rather low (Živčić et al., 2011). Recently the seismicity was high on the Ravne fault (Zupančič et al., 2001; Gosar, 2007b), which runs parallel to the Idrija fault at a distance of 10 km to the NE.

In November 2004 we installed the TM 71 device in the NW part of the Idrija fault, where good exposure of the main fault zone was found in the Učja valley near Bovec. The whole fault zone is there more than 1 km wide and was divided into outer and inner fault zones by Čar and Pišljar (1993). The TM 71 instrument is installed on a prominent crack in the central part of the inner fault zone, which cuts the 50 m high wall of a canyon.

A clear trend of left-lateral horizontal displacements is characteristic for this monitoring site, with a small amount in the vertical axis. The rate of horizontal displacement is quite constant, being on average y=+0.24 mm/year during six years of observation (Fig. 2). In the first 10 months of measurements the displacement rate was even higher, being y=+0.54 mm/year. It was followed by an outlying measurement at the beginning of 2006.

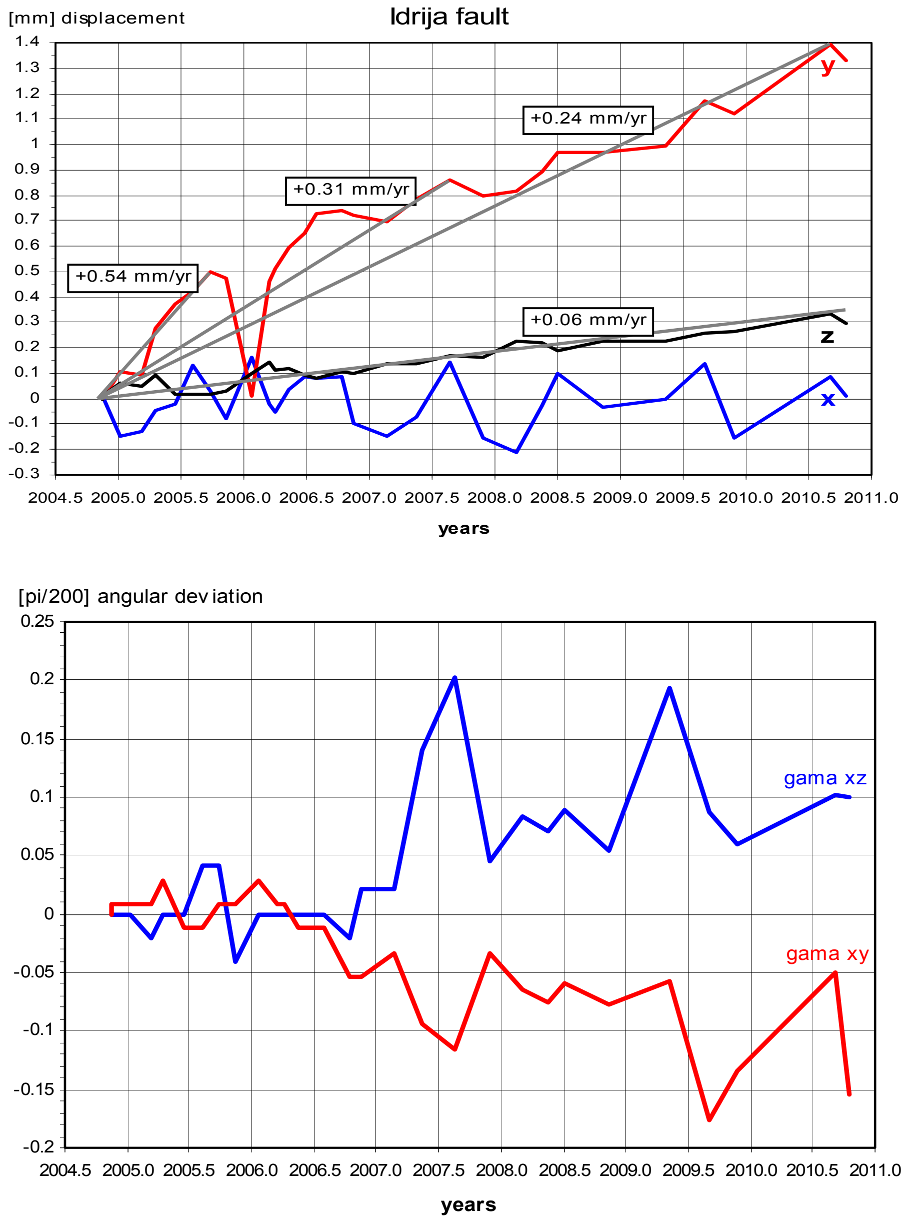


Fig. 2 Relative displacements (+*x* compression (-*x* extension), +*y* sinistral horizontal movement (-*y* dextral) and +*z* down-slip of SW block (-*z* uplift)) and angular deviation detected with a TM 71 extensometer for the Idrija fault (Učja).

This measurement was most probably caused by a mechanical impact on the instrument (fallen rock or ice), because the displacement completely recovered in the subsequent months. The average displacement rate for the first two and a half years of measurements is y=+0.31 mm/year. On the vertical z-axis the sense of displacement is also stable (down-slip of the SW block), with the average rate of z=+0.06 mm/year. The x-axis (opening or closing of the crack) shows only clear seasonal effects, which are in good correlation with recorded temperatures (Fig. 3). Also in this graph the outlying measurement at the beginning of 2006, already discussed above, is visible. In the six years of monitoring angular deviations on both planes were small, up to +0.1 pi/200 in the *xz* plane and up to -0.15 pi/200 in the *xy* plane. Two anomalies with greater amplitude occurred in mid-2007 and in mid-2009, but they were almost completely recovered later.

Relative movement between blocks shows left-lateral horizontal displacement with a minor down-slip component. This is an unexpected result, because the Idrija fault is usually considered as a dextral strike slip fault (Čar and Pišljar, 1993). There are clear

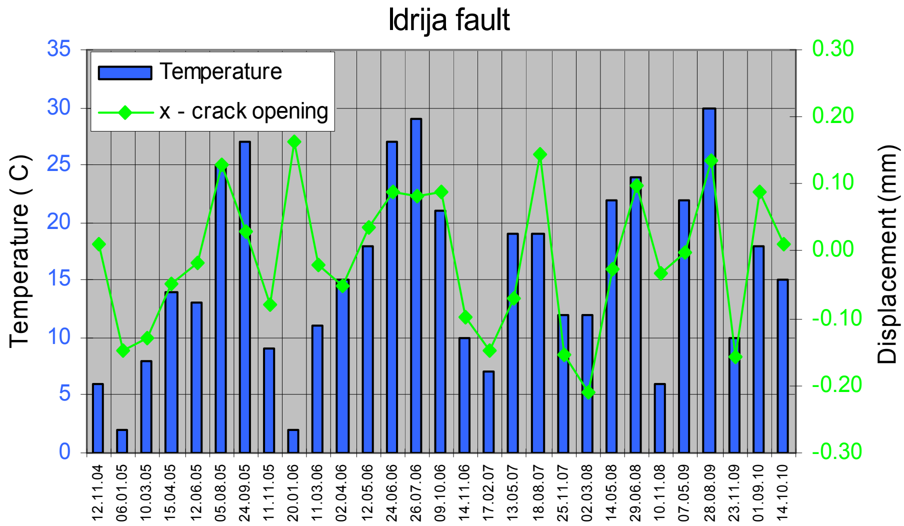


Fig. 3 Correlation between temperature variations and opening (-*x* extension) and closing (+*x* compression) of the crack at the Idrija fault (Učja) monitoring site.

geological evidences of dextral displacement during the geological history, but in recent times no direct proofs are available. Therefore the dextral strike-slip movement was mainly inferred from the orientation of the principal stress axis, which is oriented in the N-S direction, and from fault plane solutions of two stronger earthquakes that occurred on the parallel Ravne fault. Observed left-lateral displacement should therefore be explained by local permutation of stress direction inside the very complex fault zone (Kavčič, 2006). The observed slip rate of 0.24-0.54 mm/year is in agreement with regional rates of movement in W Slovenia established from GPS measurements (Vrabec et al., 2006), which are up to 2 mm/year. However, the GPS points were too sparse in this study to establish the sense of displacement along individual faults; only regional rates of movement can be determined. In any case longer observations and detailed tectonic mapping of the complex Idrija fault cross-section in the Učja valley are necessary to understand the relations between different cracks observed in outer and inner fault zones.

Raša fault

The Raša fault is located approximately 25 km SW of the Idrija fault. It can be clearly traced for a length of 50 km from N of Nova Gorica to the Snežnik thrust at Ilirska Bistrica (Fig. 1). The main surface expressions of this fault are the almost straight valley of the Raša River and the topography around Vremščica Mountain. The fault has a multiphase kinematic development, which is typical for most regional faults in the External Dinarides (Jurkovšek et al., 1996). The seismicity in the vicinity of the Raša fault is concentrated mainly in the Snežnik Mountain area at its SE termination. Hypocenters of the earthquakes in this area define a steeply NE dipping fault plane (Michelini et al., 1998).

We explored the whole trace of the Raša fault to find a suitable location for installation of a TM 71 extensometer. In spite of its clear expression in the topography there are very few good exposures. The best location was found at the foot of Vremščica Mountain on its SE side, near Košana. There are two abandoned quarries in the Upper Cretaceous limestone situated exactly at the fault trace. The lower one has been abandoned for more than 15 years and will remain closed. Therefore, it provides a suitable place for crack gauge measurements. The contact between Upper Cretaceous limestone to the NE and Palaeocene Kozina limestone to the SE (Buser et al., 1967) is exposed in this quarry, separated by the main fault zone, which is approximately 10 m wide. Therefore, it was not possible to install the instrument in the main fault plane, but we selected a parallel crack in the exposed wall of the quarry built of Cretaceous limestone. The measurements started in November 2004.

In the six years of monitoring the site established a clear reverse uplift of the hanging wall (SW) block and left-lateral displacement (Fig. 4). The average rate of vertical displacement is z=-0.06 mm/year, but both the rate and the sense of displacements change during this period. In the first nine months a displacement of z=-0.53 mm/year was recorded. Later, till mid-2007 the displacements preserved the sense, but the average rate of z=-0.16 mm/year is much smaller than before. From October 2007 to July 2008 the sense of vertical displacement changed (down-slip of SW block) and had a rate of z=+0.37 mm/year. From mid-2008 onwards the measured displacements are highly variable. The average rate in the last two and a half

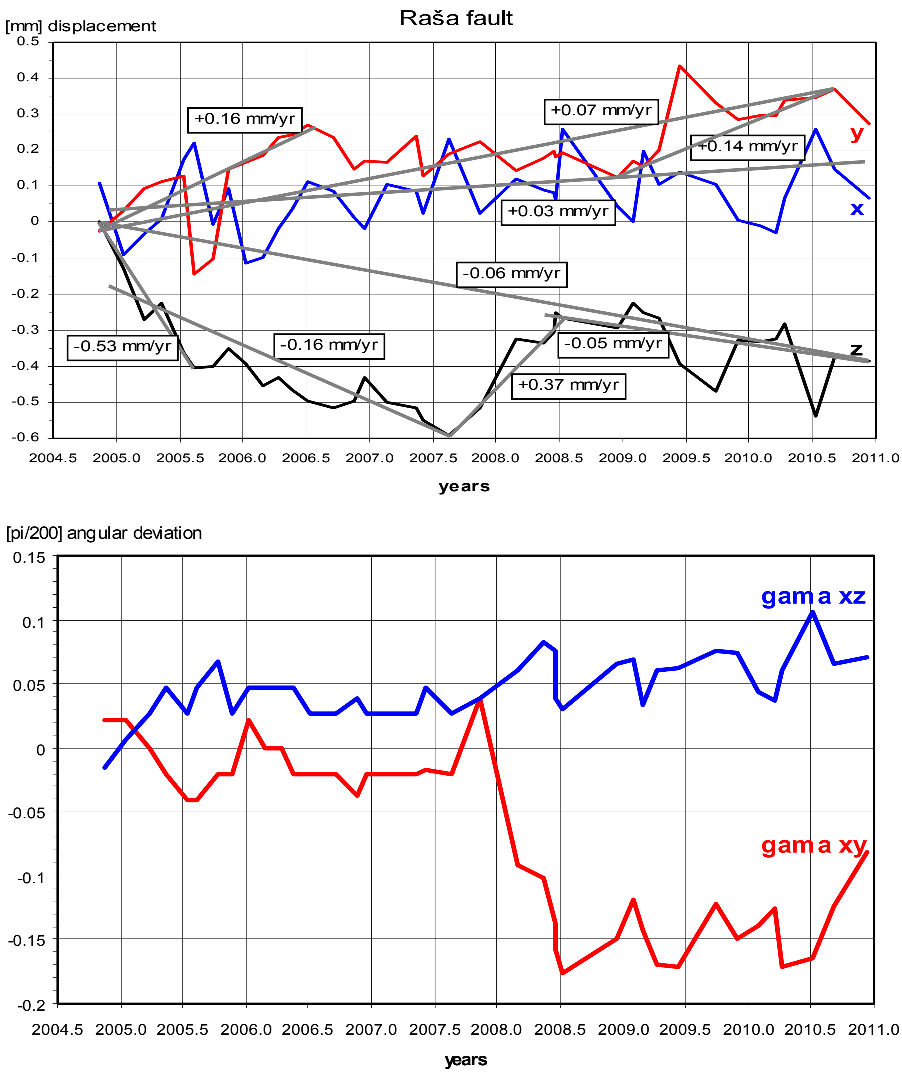


Fig. 4 Relative displacements (+x compression (-x extension), +y sinistral horizontal movement (-y dextral) and +z down-slip of SW block (-z uplift)) and angular deviation detected with a TM 71 extensometer for the Raša fault (Vremščica).

years is z=-0.05 mm/year. The average left-lateral displacement through six years is y=+0.07 mm/year. The short-term rate in the first year and a half is y=+0.16 mm/year. In the period from mid-2008 to the first quarter of 2009 no clear trend of displacements is visible in the horizontal axis. Later, till the end of 2010 the average left-lateral displacement is y=+0.14 mm/year. The x-axis (opening or closing of the crack) shows clear seasonal effects, which are in good correlation with recorded temperatures. Nevertheless, a gentle trend of crack opening with the rate of x=+0.03 mm/year can be deduced from the line fitted across the whole period of measurements. Although no clear trend in angular deviations was observed in the first three years of measurement, during the last three years a clear trend on the xy plane was developed with the amplitude of -0.15 pi/200.

The established oblique sense of displacement is only partly in agreement with geological and seismological observations. In comparison of our measurements with other data it must be considered that the TM 71 instrument was not installed on the main fault plane, but on one of the nearby parallel cracks within the fault zone. Local variation of the stress axis can therefore explain the observed differences. Focal mechanisms of some stronger earthquakes in the active zone of Snežnik Mountain, SE of the monitoring site, also indicate strike-slip and reverse movement (Poljak et al., 2000). On the other hand Jurkovšek et al. (1996) claimed that the fault has undergone multiphase development from reverse over gravitational to the final dextral strike-slip movement. From repeated geodetic levelling line measurements along the Sečovlje-Bled polygon (Rižnar et al., 2007) only the vertical component of relative displacement was revealed due to the limitation of the method. From this data set the area between the Divača and Raša faults shows a uniform uplift on the order

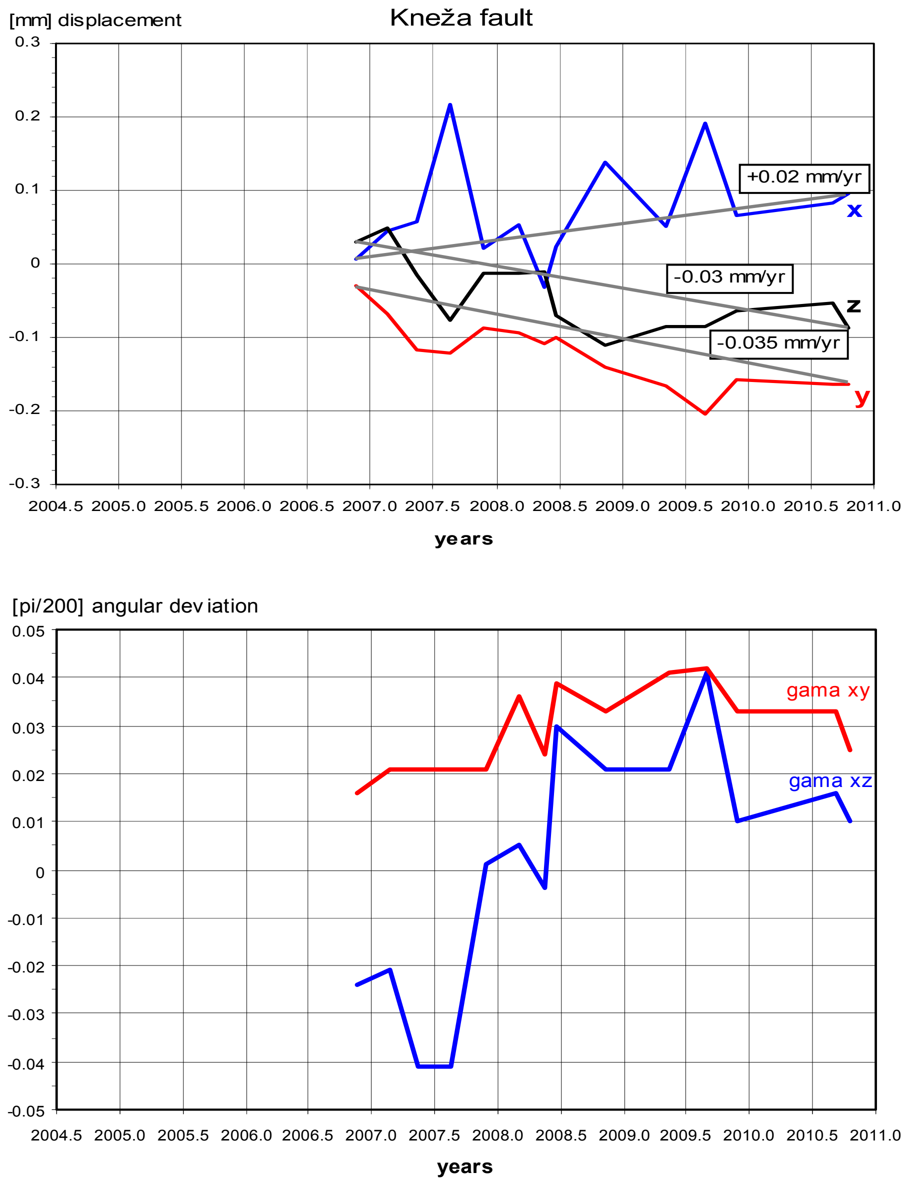


Fig. 5 Relative displacements (+*x* compression (-*x* extension), +*y* sinistral horizontal movement (-*y* dextral) and +*z* down-slip of SW block (-*z* uplift)) and angular deviation detected with a TM 71 extensometer for the Kneža fault (Zadlaz-Čadrg).

of 2 mm/year in relation to the reference point in Sečovlje, but close to the Raša fault anomalous values were obtained as low as 1 mm/year. For the area NE of the Raša fault the relative vertical uplift is again around 2 mm/year. Unfortunately, no 3D terrestic geodetic or GPS data are available in the area to compare the actual sense of the movement in three dimensions along this fault.

Kneža fault

The Kneža Fault is a dextral strike-slip fault located in the Julian Alps between the Idrija fault to the SW and Ravne fault to the NE (Fig. 1). It can be traced for at least 30 km between the Bovec basin in the NW and Idrijca valley and further to the SE. There are no direct proofs of activity of the Kneža fault, but the nearby Ravne fault was proved active (Zupančič et al., 2001; Kastelic et al., 2008) by two recent strong earthquakes, Mw=5.6 in 1998 and Mw=5.2 in 2004 (Gosar, 2007b). Despite careful inspection we did not find a suitable place to install a TM 71 extensometer on the Ravne fault, because it extends mainly across a high mountain area with difficult access. Therefore we decided to monitor the parallel Idrija and Kneža faults, which are both supposed to be active. On the Kneža fault the TM 71 device was installed in autumn 2006 near the village of Zadlaz-Čadrg at the contact of the highly fractured fault zone with adjacent compact rock.

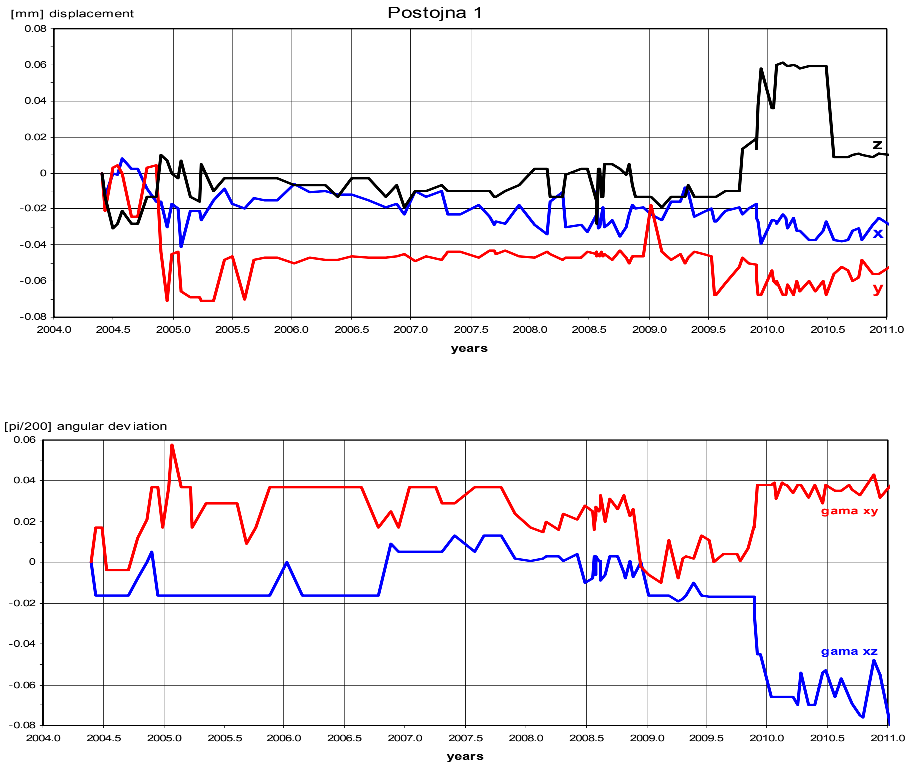


Fig. 6 Relative displacements (+*x* compression (-*x* extension), +*y* sinistral horizontal movement (-*y* dextral) and +*z* down-slip of NE block (-*z* uplift)) and angular deviation detected with a TM 71 extensometer for Postojna 1 (Postojna cave).

During four years of monitoring some clear trends of displacement were established along all three axes (Fig. 5). The average horizontal right-lateral displacement is y=-0.035 mm/year. The vertical axis shows an average displacement rate of z=-0.03 mm/year, which corresponds to the uplift of the SW block. The x-axis (opening or closing of the crack) shows clear seasonal effects, which correlate well with temperature variations, but long-term opening of the crack with a rate of x=+0.02 mm/year is also visible. Angular deviations are less clear, although some minor rotation is visible in the *xz* plane, which changed the sense during the first year. This can be explained by the consolidation of the material around the TM 71 anchor on its SW side, which is cemented in highly fractured fault zone.

The measured oblique displacement (dextral strike-slip with reverse component) is in agreement with the geological setting and sense of displacement established from fault-plane solutions for the two earthquakes on the Ravne fault (1998 and 2004) and the majority of their aftershocks. From the distribution of aftershock hypocenters around the Ravne fault (Ganas et al., 2008) it is highly probable that some of them occurred on the Kneža fault. The rate of displacements observed so far on the Kneža fault is considerably smaller than the rates established on the Idrija and Raša faults.

Postojna cave

The Dinaric-oriented (NW-SE) fault zone, which is parallel to the southern Predjama fault, has been monitored since 2004. At Postojna 1 the TM 71 is installed in the contact between the fault plane, representing the Velika Gora collapse chamber's northern wall, and a 2x2x1 m collapse block of limestone. The Postojna 2 site is an artificially enlarged narrow (1-1.5 m wide) natural cave passage. The movements obtained from two, 260 m distant, monitoring sites in the cave are small (Figs. 6 and 7), but there are some interesting peaks (maximum of 0.08 mm on both monitoring sites) and very stable periods with almost no movements (Postojna 1 and 2 *y*-axis from the end of 2005 to 2008), which supports the idea that we are monitoring real tectonic micro-displacements, excluding other causes such as influence of karst water oscillation or karst collapses.

Generally we detect dextral horizontal movement of -0.05 mm from 2004 to the end of 2010 for Postojna 1. More significant vertical movements at Postojna 1 started in October-December 2009, representing subsidence of the NE block for 0.07 mm. After June 2010 the *z*-axis returned back (uplift of the NE block) and remained at +0.01 mm. Within the *y*-axis at Postojna 1 the biggest movement of –0.08 mm (dextral horizontal movement) was registered from 10th November 2004 to 15th December

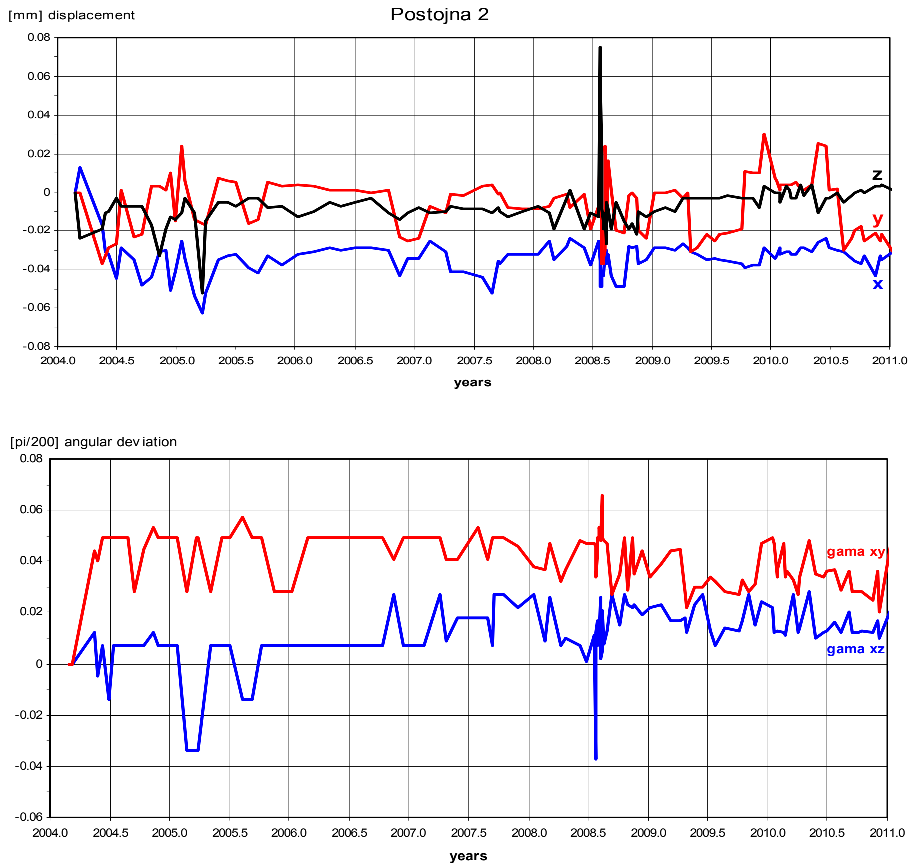


Fig. 7 Relative displacements (+*x* compression (-*x* extension), +*y* sinistral horizontal movement (-*y* dextral) and +*z* down-slip of NE block (-*z* uplift)) and angular deviation detected with a TM 71 extensometer for Postojna 2 (Postojna cave).

2004. The movements generally return back to the previous relative position.

At the end of 2010 the rotation on *xz*-axis at Postojna 1 reached -0.08 pi/200. The more expressed rotation started at the end of 2009.

The Postojna 2 site showed the highest movements between July and September 2008, with a horizontal movement of 0.06 mm maximum, changing from sinistral to dextral and returning back to the null position, and the best expressed peak on the *z*-axis of +0.08 mm (24-25th July 2008, uplift of the SW block). Over seven years Postojna 2 represents a very stable place with small general displacements.

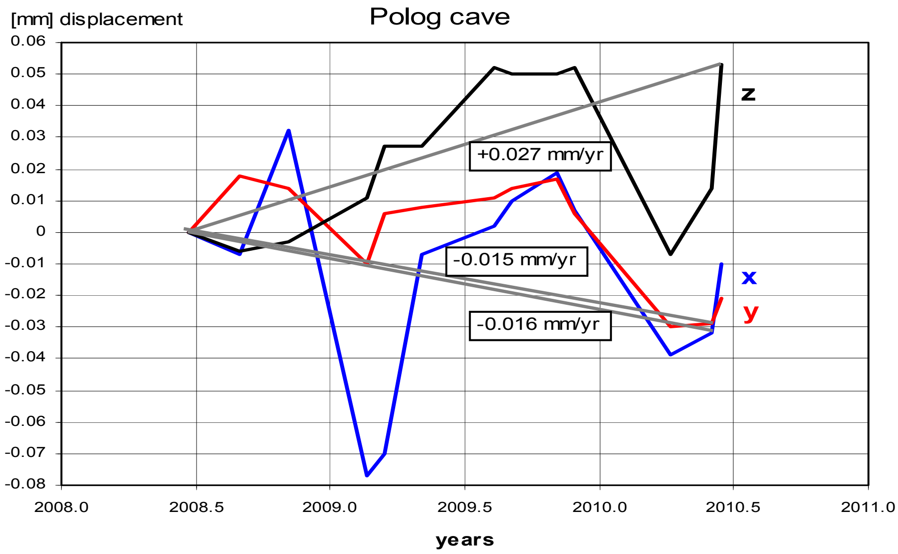
Although measuring the same fault zone the Postojna 1 and 2 sites present different behaviors (Gosar et al., 2007; Šebela, 1998; Šebela et al., 2009) due to the complex geological structure of the cave. Some remarkable peaks were explained as temporary changes in the Earth's crust stress field that can coincide with earthquakes (Gosar et al., 2009).

Polog cave

The cave's lower entrances are situated at 730 m above sea level on the eastern slope of the Krn Mountain (2,244 m). The cave's passages, being 10,800 m long and 704 m deep, are situated 250-800 m south of the Ravne fault. The TM 71 is placed between two tectonically displaced limestone beds dipping towards the SE at 40°, about 300 m south of the Ravne fault and about 50 m inside the cave from the NE lower entrance. The important regional structure of the Julian Alps thrust (SE-verging and parallel to the monitored bedding-plane) within the Southern Alps geotectonic unit (Poljak, 2000) can be found about 200 m below the monitoring site.

The average rates observed in Polog cave are *y*=-0.015 mm/year, *z*=+0.027 mm/year and *x*=-0.016 mm/year and represent general dextral horizontal movement, extension and subsidence of the SE block. The highest rates for vertical displacements representing subsidence of the SE block can be attributed to slope instability. Horizontal movements between bedding planes prove existence of tectonic deformations.

The highest displacement, -0.08 mm, was detected in the *x*-axis (Fig. 8) and represents horizontal opening between two limestone beds in the period from October 2008 to March 2009. From March to May 2009 the movement on the *x*-axis



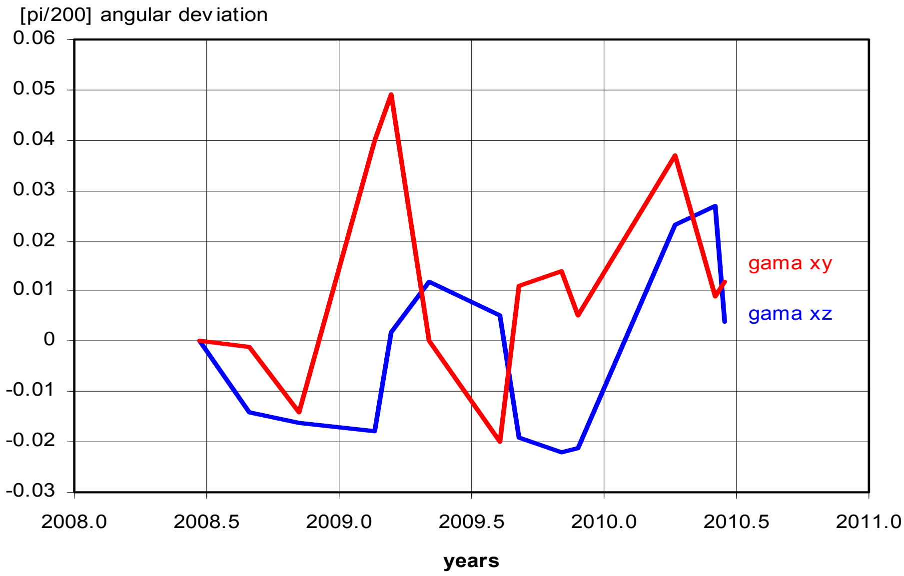


Fig. 8 Relative displacements (+*x* compression (-*x* extension), +*y* sinistral horizontal movement (-*y* dextral) and +*z* uplift of NW block (-*z* down-slip)) and angular deviation detected with a TM 71 extensometer for Polog cave.

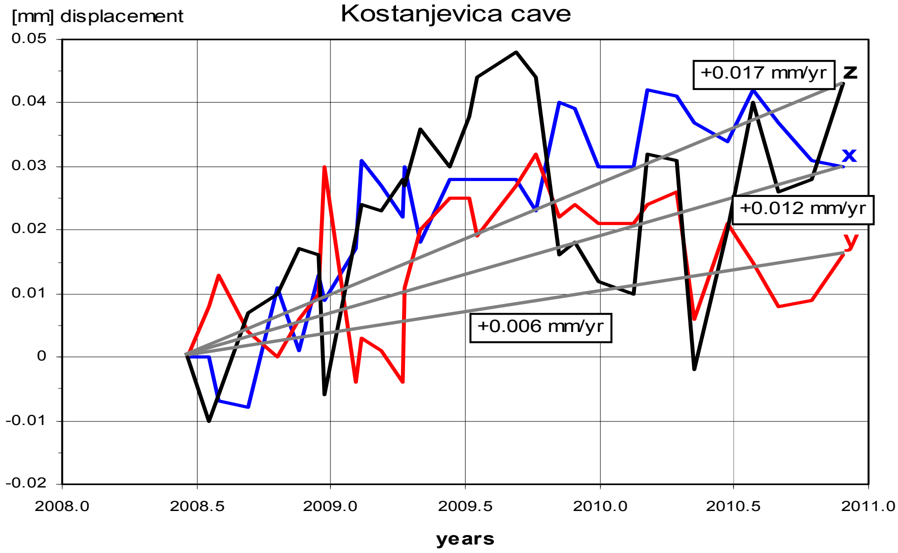
returned back to -0.02 mm. The observed displacement can be connected with temperature changes (2nd November 2008 = 6 °C and 17th February 2009 = 1 °C).

Gosar et al. (2009) proposed, according to the position of Polog cave south of the Ravne fault and above the thrust of Julian Alps, that the results of detected movements with TM 71 represent active deformations of the transition zone between both tectonically active zones.

Kostanjevica cave

The cave is the longest known cave (1,871 m long and 47 m deep) on the northern slope of the morphologically well expressed Gorjanci Mountains with a highest peak of 1,178 m. The cave entrance is at 170 m a.s.l. and above the monitoring site there is 70 m of limestone roof. The TM 71 instrument is installed 125 m inside the cave within a NE-SW oriented fractured zone that is dipping towards the NW at 80°. The monitored tectonic zone is situated about 3 km south of the main northern branch of the Brežice fault, which is determined as a neotectonic fault with sinistral horizontal movement and vertical reverse movement, uplift of the SE block (Verbič, 2005).

The movements are detected along all three axes with the highest trend for vertical movement along the *z*-axis at +0.017 mm/year, representing subsidence of the NW block and/or uplift of the SE block (Fig. 9), which is in accordance with Verbič (2005). Some sinistral horizontal movement (*y*=+0.006 mm/year)



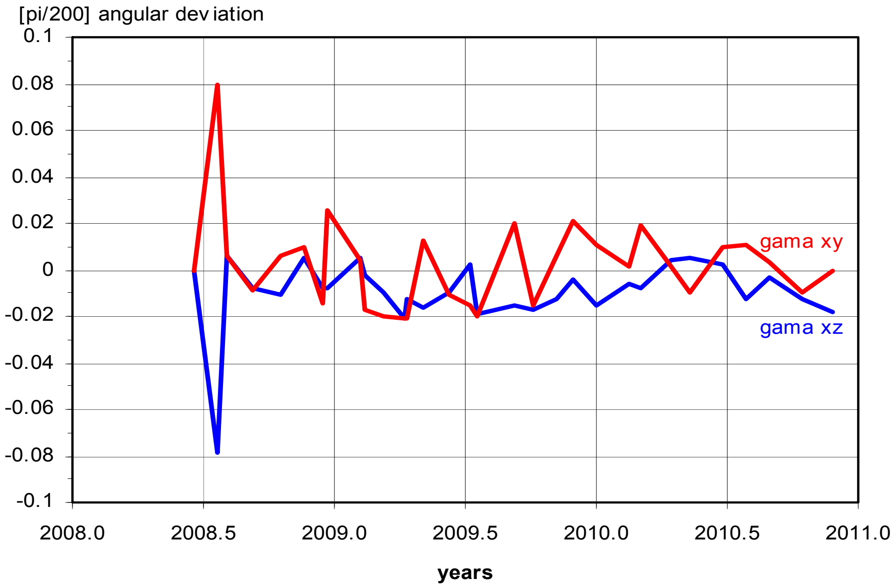


Fig. 9 Relative displacements (+*x* compression (-*x* extension), +*y* sinistral horizontal movement (-*y* dextral) and +*z* down-slip of NW block (-*z* uplift)) and angular deviation detected with a TM 71 extensometer for Kostanjevica cave.

and general extension (x=+0.012 mm/year) are presented as well. The highest trend in Kostanjevica cave was detected as vertical movement along the *z*-axis of +0.035 mm from June 2008 to May 2009, representing subsidence of the NW block and/or uplift of the SE block (Šebela et al., 2010b).

5. CONCLUSIONS

Micro-deformation monitoring with TM 71 instruments in Slovenia provides quantification of recent active tectonic deformations within the fault zones of five active faults located in W Slovenia and one in SE Slovenia. The highest rates with very stable sense of movements were observed on the Idrija fault, which is the most prominent strike-slip Dinaric fault in W Slovenia. The average horizontal displacement rate over six years was 0.24 mm/year. Short term rates were even greater and reached 0.54 mm/year. The Raša fault established first an uplift of the SW block at 0.16 mm/year, which was followed by a short term down-slip of the same block at the rate of 0.37 mm/year. Later the sense of movement returned to the uplift with a rate of 0.05 mm/year. The average horizontal displacement rate in six years of observation was 0.07 mm/year. The Kneža fault monitoring site established in four years of observation very small average displacement rates for all three components (y=0.035 mm/year,

z=0.03 mm/year and x=0.02 mm/year). Similar rates were observed during two years of monitoring at the nearby Polog cave monitoring site (y=0.015 mm/year, z=0.027 mm/year and x=0.016 mm/year), which is located close to the Ravne fault. For Kostanjevica cave located close to the Brežice fault very small average rates are characteristic (y=0.006 mm/year, z=0.017 mm/year and x=0.012 mm/year), but the fluctuation of values inside this period is high. Monitoring at two sites in Postojna cave has lasted for seven years. Both Postojna cave monitoring sites (Figs. 6 and 7) are very stable with small tectonic micro-movements, being general dextral horizontal movement of -0.05 mm from 2004 to 2010 (Postojna 1). There are two significant peaks of 0.08 mm (Postojna 1-y and Postojna 2-z). At the end of July 2008 the highest peak of +0.08 mm on the Postojna 2 z-axis (Fig. 7) was detected. The biggest movement of –0.08 mm (dextral horizontal movement) from 10 November, 2004 to 15 December, 2004 was registered at Postojna 1. The largest recent vertical movements at Postojna 1 started in October-December 2009, representing subsidence of the NE block by 0.07 mm. After June 2010 the z-axis returned back (uplift of the NE block) and remained at +0.01 mm. The subsidence of the NE block at Postojna 1 can be attributed to tectonic activity and not to instability of collapse blocks in the biggest collapse chamber in the cave.

No repeated geodetic measurements from areas of TM 71-monitored active faults are yet available for comparison. Therefore it would be very important in the future to supplement TM 71 measurements presented in this paper with detailed geodetic measurements as proposed by Placer and Koler (2007). Along supposed active faults new networks of triangulation points should be installed outside the fault zones and precise terrestic geodetic measurements repeated at regular intervals, which would enable establishment of 3D displacement along these faults, as it has already been done along the Orlica fault in SE Slovenia (Kogoj et al., 2004). This is very important because, by using TM 71 instruments, only displacement along individual cracks can be determined, but it is well known that the fault zones of major faults in Slovenia are very broad and composed of many parallel cracks. It is therefore necessary to derive the sense and the cumulative rate of displacement across the whole fault zone to characterize the fault for seismic hazard studies. Nonetheless, the observed displacement rates of up to 0.5 mm/year derived from TM 71 monitoring represent a significant step in this characterization.

In karst caves the obtained displacement rates by TM 71 are small but in general accordance with accepted regional structural geological movements. The highest movement rates along surface Idrija and Raša faults are not in the same direction as is generally accepted from earthquake focal mechanisms (Poljak et al., 2000). The TM 71 results within Idrija and Raša faults can present an inner segment within the more metres wide principal fault zone and in such sense also local rotations that are contrary to general displacement of the fault zone. Well-organized GPS net will add important data to the TM 71 measurements in Slovenia.

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