Hydrologically induced deformations obtained from active tectonic micro-displacement monitoring in karst

Hidrološko povzročene deformacije na krasu zaznane s pomočjo monitoringa mikro-premikov aktivne tektonike

Uroš Novak [*]

Abstract

Active tectonic deformations via micro-displacements measurements with TM extensometers in Slovenian caves have been continuously monitored since 2004, and is still an undergoing project. Currently there are 12 instruments installed all over Slovenia, 11 of them are situated in karstic areas, positioned either on the surface or in the caves. In order to properly analyze active tectonic micro-displacements one must exclude the effects of fluctuating atmospheric temperatures on the instrument and the hydrological effect. The scope of the paper is to evaluate the potential hydrological transient noticed in the Postojna cave monitoring site.

Povzetek

Deformacije aktivne tektonike, ki se opazujejo s pomočjo merjenja mikro premikov z TM ekstenzometri v slovenskih jamah se redno spremlja že od leta 2004. Trenutno je v Sloveniji nameščeno 12 instrumentov, 11 od njih se nahaja na kraških področjih, bodisi v jamah ali na površju. Za potrebe zanesljive analize aktivnih tektonskih mikro premikov je treba izključiti vplive nihajoče atmosferske temperature na instrument in hidrološko induciranih premikov. Namen raziskave je analiza potencialnih hidroloških tranzientov (prehodnih sprememb) opaženih v mikro premikih beleženih v Postojnski jami.

Ključne besede: TM 72 ekstenzometer, hidrološki tranzient, mikro premiki, aktivna tektonika, Dinaridi, Postojnska jama.

Keywords: TM 72 extensometer, hydrological transient, micro-displacements, active tectonics, Dinarides, Postojna cave.

Introduction and methods

The micro-displacement monitoring site of Postojna cave lies in a tectonically active area. Situated between two active major regional Dinaric faults, Idrija Fault and Predjama Fault, the area is highly karstified, and therefore a subject of many geoscientific studies including hydrogeological ones. Postojna cave has a multitude of different speleothem forms, some amongst them are deformed or broken speleothems, amongst them possibly deformed by tectonic and seismic activity (Šebela, 2008).

In an effort to characterize and quantify tectonic fault deformations associated with the activity of the western part of the Dinaric fault system, TM71 extensometers were installed, within the Postojna cave. TM extensometers are instruments that measure micro-displacements in geological discontinuities, such as fractures, faults and other geological structures. In Postojna cave they are installed in faults that have a Dinaric (NW-SE) strike

[*] ZRC SAZU Inštitut za raziskovanje krasa, Titov trg 2, 6230 Postojna; Univerza v Novi Gorici, Vipavska 13, 5000 Nova Gorica

(Šebela et al., 2021). Large tectonic transient signals were observed that coincided with the local earthquake activity in the years, 2009-2010 and 2014-2015 (Vičič et al., 2019). Recently, the older, manual, TM71 instruments with sporadic recording intervals were all substituted with a newer semi-automatic instrument model, TM72; with a recording interval of 24 hours. At the moment there are 4 monitoring sites in Postojna cave (Figure 1).

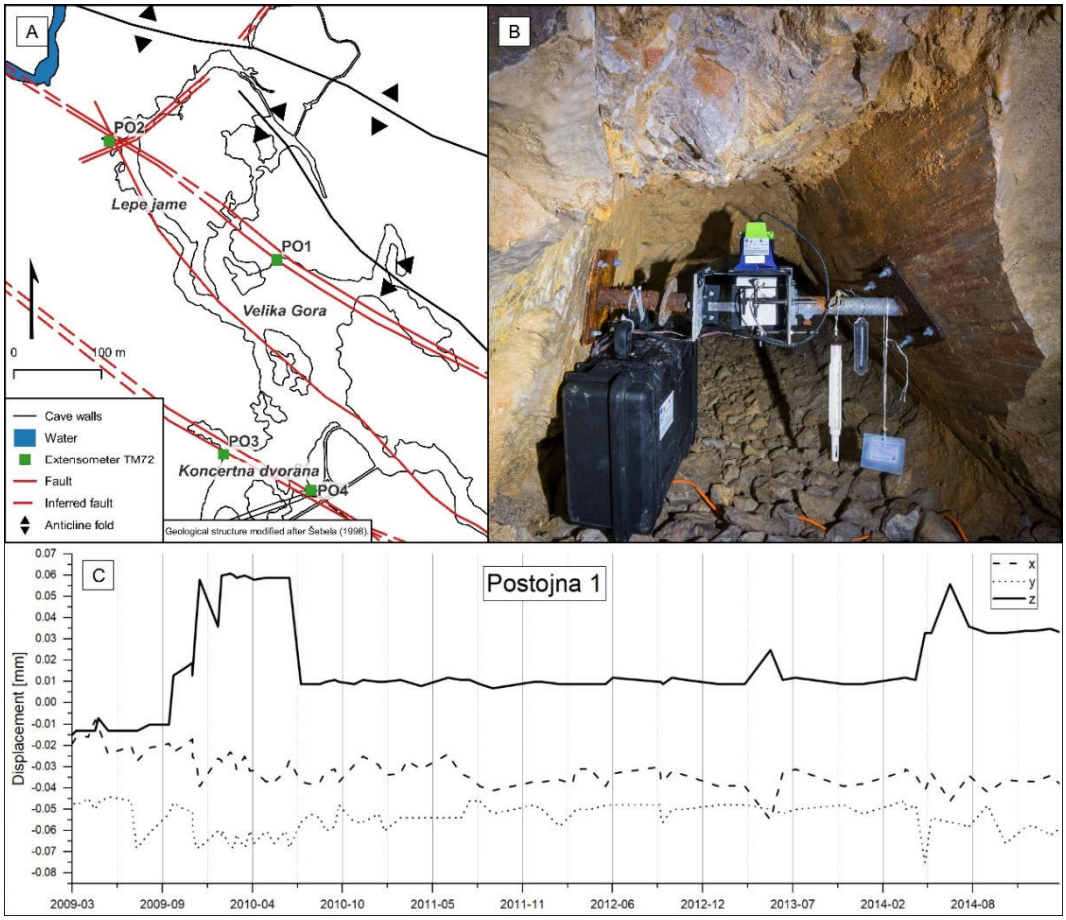

Figure 1 – A: The location of monitoring sites within the Postojna cave system. B: TM-72 extensometer in the cave. C: Vertical micro-displacements in Postojna cave, from 2008 to 2015, showing displacement peaks coinciding with earthquake swarming in the area.

Earth's surface displacements are caused by several tectonic and nontectonic processes (Dong et al., 2002). The identification of nontectonic transient signals is of the highest importance when transient tectonic deformations are expected to be smaller or of the same magnitude as hydrological deformations (Serpelloni et al., 2018), especially in very karstified regions with high precipitation and underground water oscillations, as are NW Dinarides. Additionally, TM extensometers are susceptible to atmospheric temperature fluctuations. Both phenomena may enable misinterpretation of the micro-displacements as tectonic.

The most imperative step of analyzing TM extensometer micro-displacements is to cancel out any processes that cause displacements which could be interpreted as tectonic deformations. In areas with low to moderate seismicity and strain rates as are in NW Dinarides, such noise can mask the tectonic signals. Consequently, seasonal or diurnal atmospheric temperature fluctuations, even in so-called stable cave climates, that may cause thermal expansion of the instruments metal parts, must be excluded.

At micro scale the influence of rainfall on crustal deformations has been described using tilt and strain meters as well as pendulums (Serpelloni et al., 2018; Braintenberg et al., 2019). Recently, GPS data has enabled to differentiate between long-term and transient tectonic deformations, horizontal and vertical displacements related to rainfall (infill) in karstic areas. The hydrological transient deformations can be explained by natural pressure changes attributed to variable water levels within the vertical fractures and cavities of the karst systems aquifer (Serpelloni et al., 2018; Braintenberg et al., 2019).

Postojna cave has permanent hydrological monitoring sites, in this study the Pivka river site at the entrance to the cave was used; making the cave system a suitable test site, to assess if the karstic aquifer fluctuations influence TM extensometer micro-displacement measurements.

Results and discussion

From 2002 Postojna cave TM extensometers recorded 2 major micro-displacement events that were in fact tectonic transient signals. Signals that coincide with two local earthquake activities, that were earthquake swarms or swarm-like activities. The first one, that lasted from the end of 2009 to 2011 called Postojna swarm attributed to the activity of Predjama fault with, 3000 detected events and with the largest event of M_L 3.5 (Vičič et al., 2019). The Postojna swarming event generated a 70 µm vertical displacement in the TM 71 extensometer record (Figure 1). The second one, in the summer of 2017, called Selce swarm, attributed to the Selce fault, lasted only 6 days and had 274 events, with the largest event M_L (Vičič et al., 2019). Selce swarm generated a 44 µm vertical displacement in the TM 71 extensometer record (Figure 1).

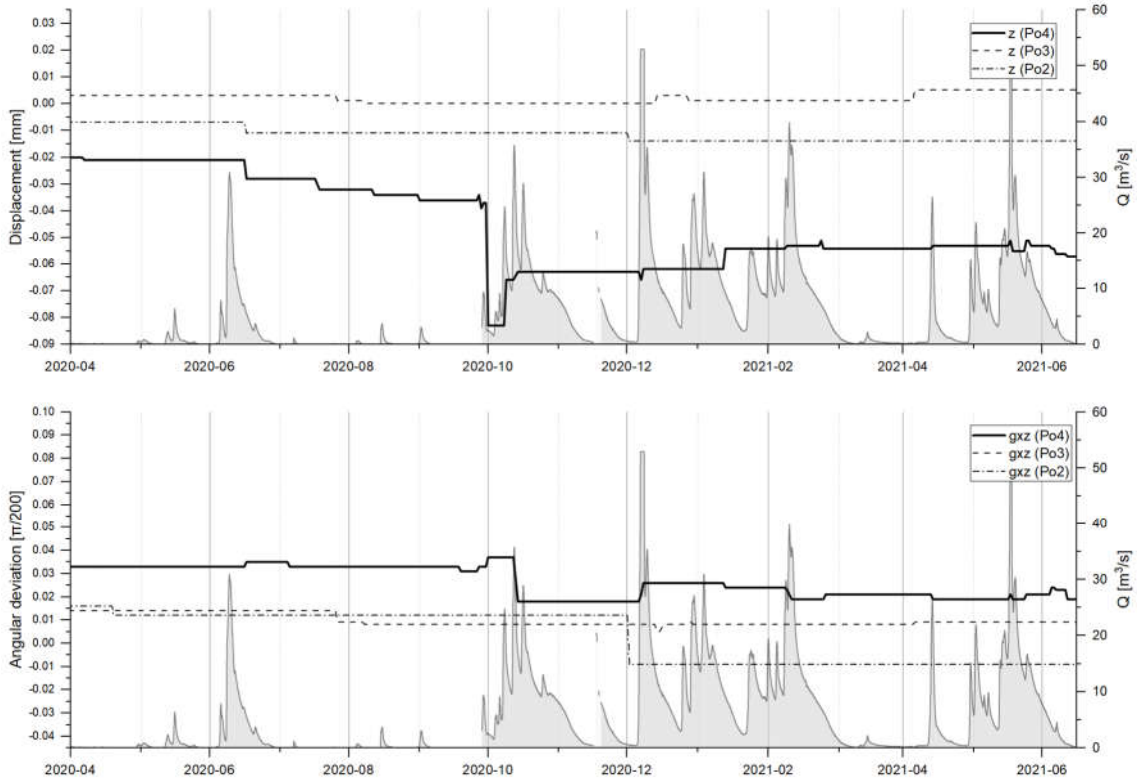

Figure 2 –Vertical micro-displacements in Postojna cave, from 2020 to 2021, with volumetric flow rate of Pivka at the entrance to Postojna cave.

Recording rates at that time were sporadic, because the recording was manual, with intervals stretching from days to months. From 2020 to 2021, the TM72 extensometers with the recording rate of 24h, recorded a tectonic micro-displacement event, larger than two preceding seismic swarming events, a vertical displacement of 83 μm. Presumably being aseismic in nature, at present.

With the recording rate of 24h the instruments reveal transient deformations that are shorter than weeks or months, revealing more short term micro-displacements. Two out of four instruments recorded displacement signals, that coincide with high water events. The most prominent event happened in December of 2020 that lasted for 3 days, with the peak volume flow of 54 m^3/s into the cave system on 8. 12. 2020. Three instruments almost simultaneously recorded a vertical displacement of 3-4 μm and horizontally 5 μm around the day of the peak of the flooding. One instrument of aforementioned ones recorded multiple such signals that coincide with flooding (Figure 2). Comparable hydrological events with coinciding displacements are mostly smaller. However, one event has the same inflow into the cave as the most prominent event, with smaller vertical displacements and no recorded displacements on the other instruments. The signals typically last for just few days. Some hydrological displacement never rebound to the same absolute displacement value, as it was prior to the flooding event. Inferring that there is a continuous tectonic displacement going on, simultaneously with the hydrological transient.

Lately hydrological observations - signals started being analyzed in GPS measurements as it is important to accurately measure secular geodetic velocities and to properly infer tectonic deformation transients in slowly deforming regions (Serpelloni et al., 2018). Said research of hydrologically induced karst deformations on GPS measurements was carried out in the Adria-Eurasia plate boundary zone, Southern Alps and NW-Dinarides. They observed GPS ground displacements driven by hydrological processes that are acting at different spatial and temporal scales. Besides common seasonal hydrological displacements, they found evidence of rainfall induced deformations with amplitudes and orientations controlled by structural features in karst terrains. Even movements in opposite directions and reversing movement in time. Suggesting a series of extensional-compressional strain periods with different amplitudes through time.

A more recent compound study of Braintenberg (2019) comprised of an analysis of karstic hydrological measurements, GPS and tilt meters (pendulum) on the Kras plateau. Demonstrated a correlation between underground flood events and terrain uplift; tilting, vertical and lateral displacements.

Hydrological transient (flooding events) GPS displacements from aforementioned studies were in the scale of few mm, up to 3.5 mm. Displacements associated with high water flooding events in Postojna cave are in the scale of few microns, up to 6 μm, smaller than signals recorded with GPS. GPS measures the bulk deformation displacements of a certain terrain volume, however normally extensometers measure displacements in discontinuities within said massifs, (fractures, faults, bedding plans) which are basically 2D elements.

The different instruments within Postojna cave site, react differently or even don't react to high water flooding event, probably due to the complex network of conduits and fractures in a karstic aquifer and the sequent inhomogeneous distribution of the water masses during the recharge process

Conclusions

Instruments in Postojna cave recorded micro-displacement signals that coincide with high water flooding events (hydrological transients). The displacements may perhaps be

hydrologically induced, to definitely confirm that more displacement records are still needed.

Nevertheless, if the recorded hydrological transients are smaller than tectonic signals, it is crucial to take in account hydrologically transient deformations besides fluctuating atmospheric temperatures when interpreting TM extensometer micro-displacement. For the reason that we don't over interpret the role of active tectonics in micro-displacements records. Additionally, these findings may contribute to future hydrological research and to deformations (tectonics, geodesy, etc.) in karst terrains, especially in understanding the relationship of deformations due to the infilling of karstic aquifers.

The study is carried out within the framework of the Karst Research Programme (P6-0119), a PhD thesis (2020-2024), all financially supported by the Slovenian Research Agency and the project operation "Development of research infrastructure for the international competitiveness of the Slovenian RRI space - RI-SI-EPOS" and EC Horizon 2020 project EPOS SP.

Literature

Dong, D., Fang, P., Bock, Y., Cheng, M., & Miyazaki, S. (2002). Anatomy of apparent seasonal variations from GPS-derived site position time series. Journal of Geophysical Research, 107(B4), 2075. https://doi.org/10.1029/2001JB000573

Braitenberg, C., Pivetta, T., Barbolla, D.F., et al. (2019). Terrain uplift due to natural hydrologic overpressure in karstic conduits. Sci Rep 9, 3934. https://doi.org/10.1038/s41598-019-38814-1

Serpelloni, E., Pintori, F., Gualandi, A., Scoccimarro, E., Cavaliere, A., Anderlini, L., et al. (2018). Hydrologically induced karst deformation: Insights from GPS measurements in the Adria-Eurasia plate boundary zone. Journal of Geophysical Research: Solid Earth, 123, 4413– 4430. https://doi.org/10.1002/2017JB015252

Šebela, S. (1998). Tectonic structure of Postojnska jama cave system. ZRC Publishing, Ljubljana. https://doi.org/10.3986/961618265X

Šebela, S. (2008). Broken speleothems as indicators of tectonic movements. Acta Carsologica 37, 51–62.

Šebela, S., Stemberk, J. & Briestenský, M. (2021). Micro-displacement monitoring in caves at the Southern Alps–Dinarides–Southwestern Pannonian Basin junction. Bull Eng. Geol. Environ. 80, 7591–7611. https://doi.org/10.1007/s10064-021-02382-4

Vičič, B. Aoudia, A., Javed, F., Foroutan, M., Costa, G. (2019). Geometry and mechanics of the active fault system in western Slovenia 2019. Geophysical Journal International, Volume 217, 3, 1755–1766. https://doi.org/10.1093/gji/ggz118