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Karst deformations due to environmental factors: evidences from the horizontal pendulums of Grotta Gigante, Italy

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ABSTRACT The aim of this work is to characterize the deformation of a natural cave induced by temperature variations and by the underground water flow. We consider the tilt recorded by two horizontal pendulums installed in the largest cave of the Italian Karst, the Grotta Gigante. The environmental factors we consider are temperature, rainfall and level and flow rate of the river Reka that feeds the underground Karstic waters. The tilt and temperature have a regular annual cycle, with period of 365 days, which is caused primarily by the thermo-elastic deformation. Semiannual periods are present but more than 10 times smaller. For rainfall and river level the semi-annual and annual oscillation have comparable amplitudes. The effect induced by the underground water flow consists in a tilting towards SW, that has a linear relation between maximum tilting and the integrated amount of water entering the Karst during the flood, with tilting coefficient $a = 10.7 \cdot 10^{-6}$ nrad/m^3. The minimum amount of water giving a tilt signal is $V_0 = 5.2 \cdot 10^6$ m^3.

Key words: Karst, north-eastern Italy, deformation, pendulum.

1. Introduction

The aim of this work is to quantify the tilting of the Grotta Gigante cave situated in the Trieste Karst (north-eastern Italy) due to environmental factors and the underground water discharge. The deformation of the cave is monitored by a couple of long-baseline horizontal pendulums, the first edition of which was installed in 1959 in occasion of the International Geophysical year (Marussi, 1960). The station belongs to the network of subsurface geodetic stations of the University of Trieste that includes two more stations, the Bus de la Genziana (Fregona, Treviso) and the Grotta Nuova of Villanova, Udine (Braitenberg, 1999; Braitenberg and Zadro, 1999). The locations of all stations can be examined on the homepage of the network (http://www2.units.it/geodin/).

The horizontal pendulums of the Grotta Gigante measure tilting, being sensitive to differential horizontal movements of the bottom and the vault of the cave. These differential movements are caused either by a rotation or by a shear-deformation of the cave. There are several known causes that make the cave deform, and the recorded tilt signal is the superposition of the different aspects, which are the long period tectonic deformations due to plate tectonic convergence of the Adria plate and the Eurasian plate, Earth's free oscillations, Earth's tides and the loading effects of the Adriatic Sea's tides, seismic waves, co-seismic effects but also presumably the atmospheric agents and hydrologic effects.

Studies conducted on more than 40 years of recordings, have allowed to identify most of these deformations and to estimate the entity of their influence (e.g., Zadro and Chiaruttini, 1975; Rossi and Zadro, 1996; Braitenberg, 1999; Braitenberg and Zadro, 1999, 2007; Zadro and Braitenberg, 1999; Braitenberg *et al*., 2001, 2006). In this work we want to identify the effects of the underground water and of the environmental parameters of temperature and pressure. Recent publications on the study of hydrologic effects on gravity and tilt include the works of Boy *et al*. (2009), Florsch *et al*. (2009) and Longuevergne *et al*. (2009). There has been recently a revival in the interest to the study of tilting induced by subsurface run-off in Karstic areas, as documented in the recent works of Tenze *et al*. (2010) and Grillo *et al*. (2011) for the Italian Karst and Gilli *et al*. (2009) for the Plateau of Calern (Alpes Maritimes, France). The time variation of water storage in a Karst system was investigated by Jacob *et al*. (2010) with repeated relative and absolute gravity measurements. The tilt induced by the hydrologic flow is due to a combination of deformation caused by the load of the water mass, poroelasticity (Kümpel, 1986; Weise *et al*., 1991; Jahr *et al*., 2008, 2009) and the deformation of crevices and cracks typical for a Karstic rock due to the temporary saturation with water (Gilli *et al*., 2009). First results from finite element modeling (Gilli *et al*., 2009) show that the loading alone is insufficient to generate the large observed tilt signals, and that the other two mechanisms are necessary to explain the observations, at least for what concerns the observation in the Maritime Alps (France). A side-product of the research relating geodetic observations as tilt and gravity to the underground water flow, is that the results can be used as an observational parameter to study the Karst hydrology. For the Trieste Karst one important question regards the ramification and depth of the underground river flow, which is still unknown to date.

Here we study the relation of the tilt observations to the amount of water entering the Karst system and that is observed flowing in the river Reka, which is the river that disappears in correspondence of the Skocjan caves (Slovenia) near the border between Italy and Slovenia and continues underground in the Italian Karst, until it emerges as the Timavo river at the base of the Karst close to the sea (Fig. 1). We use the observations of the level and flow rate of the river Reka accomplished by the Environment Agency of the Republic of Slovenia. The atmospheric factors we have considered are the data series of temperature and rainfall recorded by the meteorological station installed outside the Grotta Gigante of the Commissione Grotte "Eugenio Boegan".

2. Geographic, geomorphologic and geologic context

The classical Karst is an area of about 900 km^2, that extends across the border between Italy and Slovenia from the Trieste bay area to Postojna and Skocjan (Fig. 1). The Classical Karst is a vast area of a mature Karst system that has a well developed hydrostructure, characterized by a diffuse karstification that protrudes also below the sea level. The area is characterized by a large number of natural cavities and by a complex underground water flow. From a structural point of view, the Karst belongs to the Karst-Friulian carbonatic platform, the northern extension of the Adria plate. The whole platform is formed by three layers: Triassic limestone at the base, Eocenic limestone at the top (with a section up to 2000 m) and a third cover layer, Eocenic, formed by layers of flysch. The last two layers are placed in an anticlinal, slightly asymmetric position on a

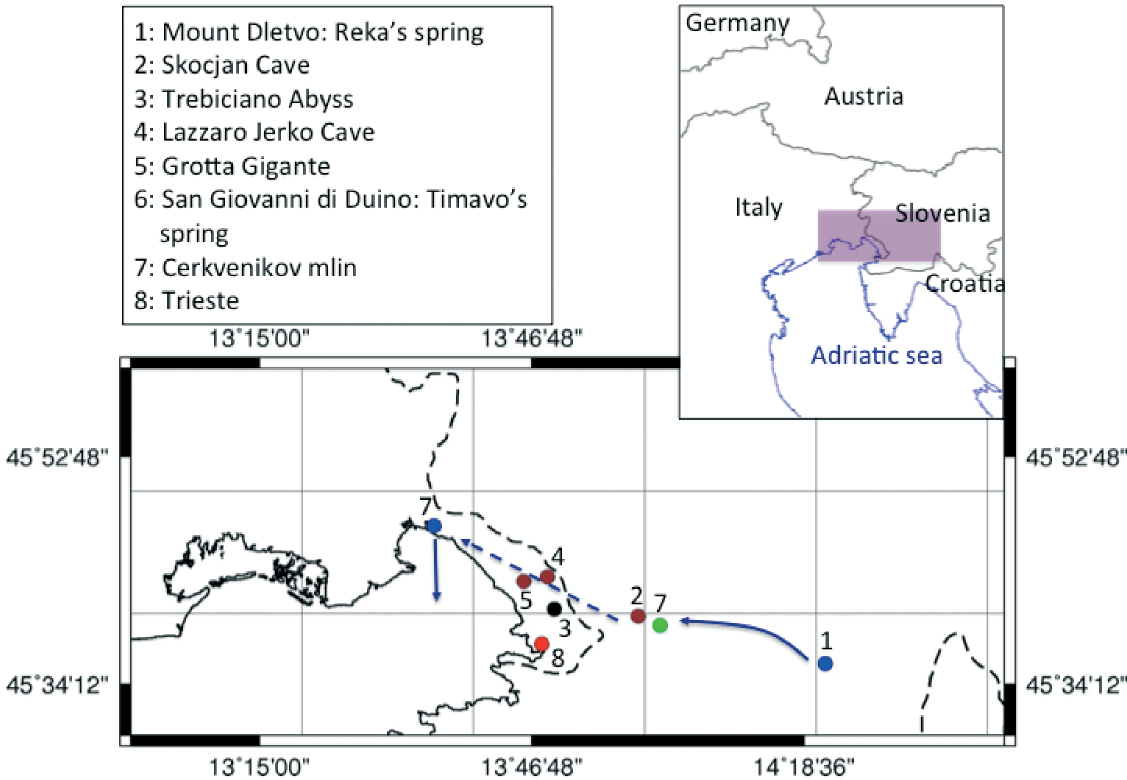

Fig. 1 - Schematic map with the sites mentioned in the paper: the Timavo's spring (1), Skocjan Cave (2), Trebiciano Abyss (3), Lazzaro Jerko Cave (4), Grotta Gigante (5), the Timavo's spring in San Giovanni di Duino (6), Cerkvenikov mlin station (7) and Trieste (8). The blue arrows represent the general trend of the water flows. The dashed line represents the state boundaries.

Dinaric NE-SW axis (Carulli and Cucchi, 1991; Bensi *et al.*, 2009). The south-western face of the anticline overlooks the Trieste Gulf delimiting the Karst highlands.

The river Reka, or Timavo in Italian, originates between Croatia and Slovenia, on the slope of Mount Dletvo. After 40 km, still on Slovenian territory, the river disappears in the big complex cave of Skocjan. The underground path is supposed to be 70-80 km long, with direction NW, and is composed by a very complex network of primary and secondary flows, with many changes of direction. For example, inside the Trebiciano Abyss the water flows from south to north, while on the bottom of the Lazzaro Jerko cave it flows from east to west (Cucchi *et al.*, 2001). At San Giovanni di Duino the river emerges from the foot of the Karst with the name of Timavo. Fig. 1 shows the locations of places and stations cited in the text.

3. The Grotta Gigante underground geodetic station, the surface meteorological station and the river Reka station

The Grotta Gigante cave, situated on the Trieste Karst, bears the Guinness Award for the greatest tourist cave in the world; the main room of the cave has an overall volume of 600,000 m^3,

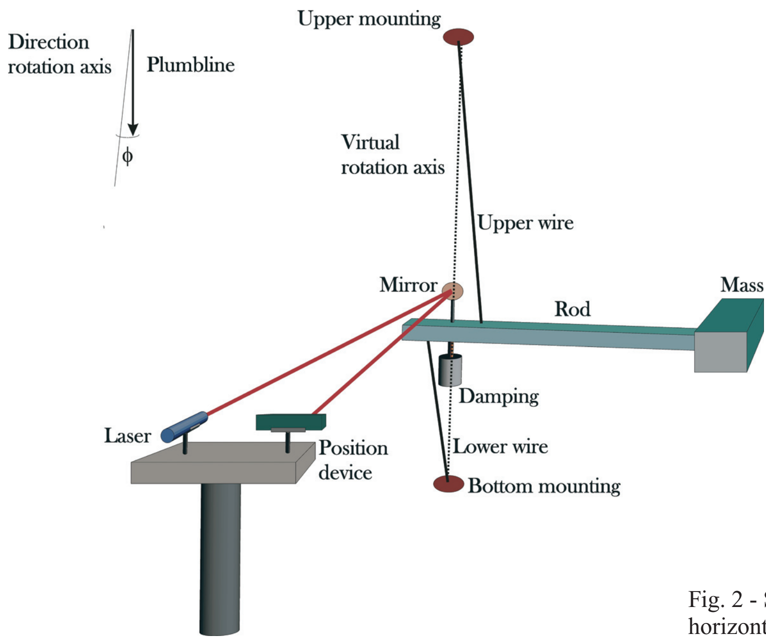

Fig. 2 - Schematic graph of the Grotta Gigante horizontal pendulums (Braitenberg, 2011).

the bottom of the cave is at 151 m above sea level, it has a length of 160 m, a width of 65 m and a height of 107 m. In 1959 Antonio Marussi exploited the height of the cave to build a couple of long-base tiltmeters of the horizontal pendulum type with Zöllner suspension (Zöllner, 1872; Marussi, 1960). The horizontal pendulums consist of a sub-horizontal pendulum arm suspended by an upper wire fixed at the vault of the cave and a lower wire fixed to the ground of the cave (Fig. 2). The distance between upper and lower mountings is 95 m and the period of oscillation of the pendulum in the horizontal plane is presently kept at 6 minutes (Marussi, 1960; Braitenberg, 1999; Braitenberg and Zadro, 1999; Zadro and Braitenberg, 1999). Horizontal shifts of the upper mounting in respect to the lower mounting of the pendulum (shear) and a tilt of the cave are recorded as a rotation of the beam in the horizontal plane around the rotation axis, which lies on the line connecting the upper and lower mounting points of the pendulum. The two pendulums record respectively the N-S and the E-W movements of the vault in respect to the bottom of the cave. The beam's movements are recorded by the reflection of a solid-state laser beam pointing on a mirror fixed to the pendulum arm. This reflection is recorded with a photo-sensitive device with a sampling of 30 values/s. Thanks to their dimension (95 m) and to the amount of the data series collected (from 1966 to today) these pendulums are worldwide unique instruments. Their length gives them a great stability reducing the noise level in respect to smaller scale tiltmeters installed at the same site. The meteorological station outside the Grotta Gigante cave is managed by the Commissione Grotte "E. Boegan" and has been active since Janaury 1, 1967, giving us continuous daily records of temperature and rain records. The measurement of the water level and flow rate of the river Reka is made by the Environment Agency of the Republic of Slovenia. The agency holds two stations on the river Reka, Cerkvenikov mlin, with a continuous data series from 1952 to present, and the station Skocjan, for the years 1957-1966. For our purpose the station Cerkvenikov mlin is ideal, as it covers an extensive time-series that coincides

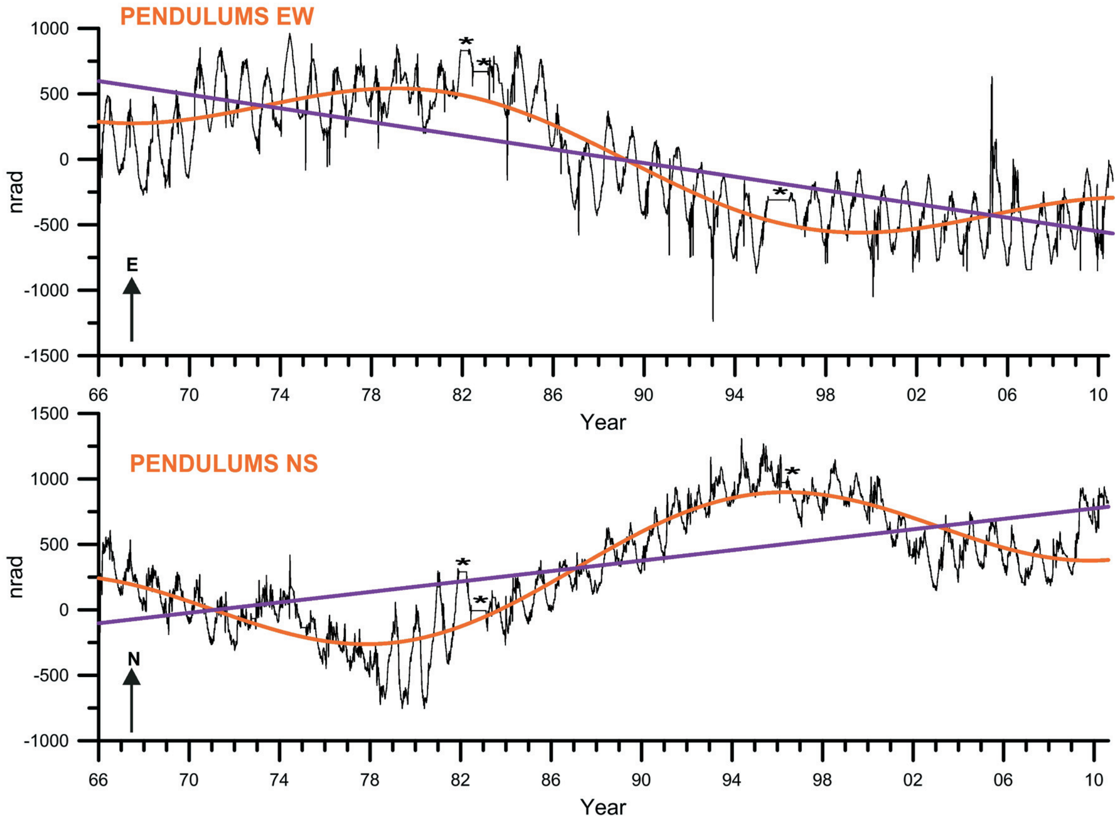

Fig. 3 -The data series of the two pendulum components of the Grotta Gigante station recorded from October 13, 1966 to March 22, 2011. Stars mark interruptions in the data acquisition.

with the one of the horizontal pendulums. Up to 1956, water level data were based on regular daily observations (staff-gauge, 1 observation per day, additional observations during high levels). From 1957 to 2006 the gauging station was equipped with a water level recorder (1957 – 1976 water level recorder "METRA"; 1976 – 1981 SEBA DELTA; 1981 – 2006 SEBA –OMEGA with pressure probe) and from 2004 with a data logger. Discharge data are derived from water level data with height-volume transformation according to a rating curve. The rating curve is based on discharge measurements with a current meter and lately (from 2005) with an acoustic Doppler current profiler (ADCP) or flow tracker ultrasonic velocimeter (321 discharge measurements between 1952 - 2011; precision ± 5%; 23 validated rating curves in 37 intervals). The daily water level data were then transformed to daily discharge data (personal communication Marjan Bat, Environment Agency of the Republic of Slovenia).

4. Presentation of geodetic, meteorological and hydrological observations

In this paragraph we present the observations we use for our study. Fig. 3 shows the data series of the two pendulum components recorded from October 13, 1966 to March 22, 2011. The

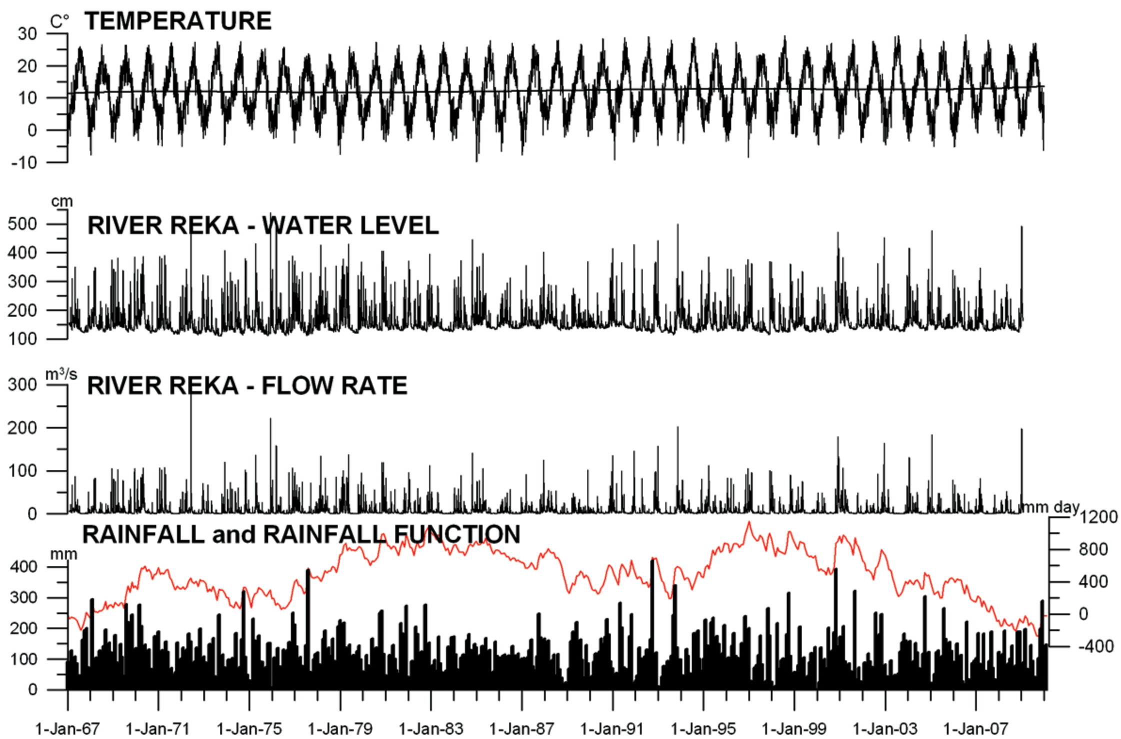

Fig. 4 - Graph of environmental parameters: rainfall and temperature recorded at the Borgo Grotta meteorologic station (Commisione Grotta "Eugenio Boegan" Soc. Alpina delle Giulie). Rainfall function (see text); level and flow rate for the river Reka at station Cerkvenikov mlin (Environment Agency of the Republic of Slovenia).

original hourly data were resampled at one value a day after applying an anti-aliasing low pass filter. The long period trend is formed by an oscillatory function with a period of 33 years and a linear drift, which have been determined by a least squares approach. The linear variation corresponds to an inclination with direction N57W with a rate of 27 nrad/a [for more details see Braitenberg *et al*. (2006)]. It is also possible to see a regular annual variation that will be analyzed in greater detail in the next chapter. Beyond the annual signal and the 33-year period oscillation there are other short-period or impulsive signals. These last signals will be shown to be generated by the underground water discharge.

In Fig. 4 the records of the daily temperature and the monthly rainfall observed at the surface above the Grotta Gigante cave, and the level and flow rate of the river Reka are shown. The continuous curve above the rainfall is the time integral of rainfall, to which the average rainfall-rate has been subtracted (111 mm/month). The rainfall function (Latynina *et al*., 1993; Zadro and Braitenberg, 1999) is an alternative way to present the precipitation variation, and has the advantage to be a continuous curve, same as the other quantities we analyze. The pressure and temperature show an evident yearly variation, which is not evident in the rainfall. The temperature and river level variations are stationary, and do not show an evident long-term variation. The rainfall shows some pluri-annual variation, which is emphasized in the integrated rainfall, with two

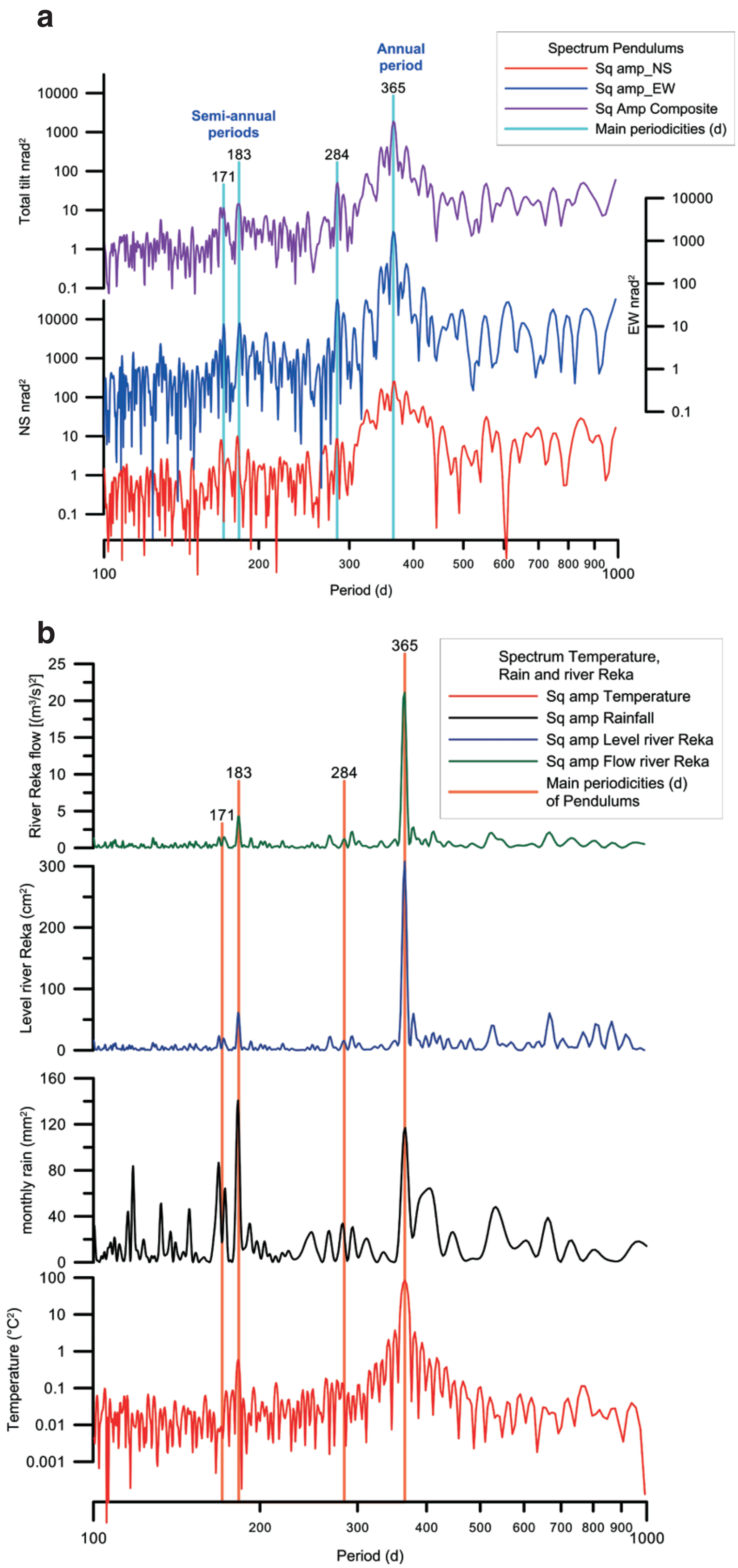

Fig. 5 - Squared amplitude spectrum of the tilt observations and the environmental parameters: a) spectrum of the two tilt components and total squared amplitude of tilt, the main spectral peaks that emerge on both components are marked with vertical lines and their respective periodicity (in days); b) squared amplitude spectrum of temperature, rainfall and river Reka. Notice that the scale for the spectrum of rainfall and river is linear. The main spectral peaks of the horizontal pendulums are marked with vertical lines and their respective periodicity (in days).

reductions in precipitation during the years 1973-1976 and 1989-1994.

In Fig. 4 we also present the time series of water level and flow rate of Reka river at station Cerkvenikov mlin used for our study. The characteristic variation is a fast level increase followed by an exponential decrease. The flood-events usually are contained in a time-interval of 20 days. The flow rate has a similar variation, covering 2 orders of magnitude, with a basic level of 2 m^3/s increasing to maximal values of 280 m^3/s during floods. One characteristic parameter which defines the flood is the total water that enters the Karst system and is defined by the time-integral of the river flow over the time interval of the

Table 1 - Results of the spectral analysis of temperature, rainfall, level of river Reka and tilting at Grotta Gigante station: periods of principal spectral components with amplitudes, phases, day in the year and dates corresponding to the maximum excursion.

	Period(d)	**Phase**	**Amplitude**	**Day of maximum**	**Date of maximum**
Temperature	183	257.7	0.77°C	52, 235	21 feb., 23 aug.
Temperature	365	158.8	9.1 °C	204	23 lug.
Rain	168	60.6	9.3 mm	140, 308	20 may, 4 nov.
Rain	173	70.1	8.0 mm	139, 312	19 may, 8 nov.
Rain	182	129.9	11.9 mm	117, 301	27 apr., 20 oct.
Rain	366	128.3	10.8 mm	236	24 aug.
Reka River level	169	80.0	5.1 cm	131, 300	11 may, 27 oct.
Reka River level	172	137.8	4.5 cm	106, 278	16 apr., 5 oct.
Reka River level	183	108.4	8.2 cm	128, 311	8 may, 7 nov.
Reka River level	365	-23.8	17.3 cm	24	24 jan.
Reka River flow rate	169	83.3	1.3 m^3/s.	129, 297	9 may, 24 oct..
Reka River flow rate	172	133.0	1.2 m^3/s.	108, 280	18 apr., 07.oct.
Reka River flow rate	183	108.7	2.2 m^3/s.	128, 311	08 may, 07 nov.
Reka River flow rate	365	-16.6	4.6 m^3/s.	17	17 gen.
Tilt composite	168	-	3.5 nrad	43, 211 EW 80, 248 NS	12 feb., 30 jul. tilt E 10 apr. 05 sept. N
Tilt composite	171	-	3.1 nrad	168, 339	17 apr., 05 dec. tilt SW
Tilt composite	183	-	4.0 nrad	20 , 203	20 jan., 22 jul. tilt SW
Tilt composite	365	-	42.2 nrad	85 266	26 mar. tilt NE 19 sept. tilt SW

flood. We will see further that this integrated quantity is proportional to the hydrologic tilting signal. Our goal being to quantify the inclination of the cave in correspondence of the floods, we select some major floods, during which the pendulums also are functioning. These events are marked with green color in Fig. 4.

5. Data analysis

Here we present the data analysis used in studying the environmental effects on the tilt. Our first analysis is concerned with finding the exact spectral components in the yearly variation of temperature, rainfall, water-flow and tilting. The subsequent analysis aims at quantifying the tilt-signal induced by the floods of the river Reka.

5.1. Spectral content of environmental parameters and tilt

In order to obtain a comparative analysis between meteorological and geodetic data, we have calculated the power spectrum of tilting, temperature, rainfall and water level of river Reka. We analyze the data over the time-interval from January 1, 1968 to December 31, 2008 and present the

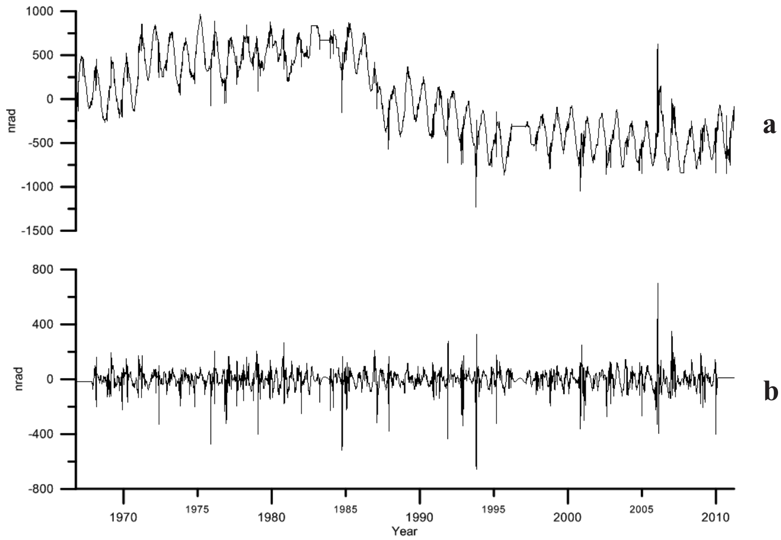

Fig. 6 - The E-W component before and after the signal processing for the time interval October 13, 1966 to March 22, 2011: a) original recording; b) the signal used for the study.

spectra in Fig. 5 for horizontal pendulums, temperature, rainfall, and the river Reka. Visual inspection of the spectra shows that the temperature variations are dominated by the annual variation that is over 10 times greater than the remainder of the spectrum. The horizontal pendulums have a pronounced annual spectral component as well, more than 10 times the spectrum at smaller periods, although in this case the maximum centered on the annual frequency is broader. The rainfall and river Reka have a very different characteristic, the entire spectrum being flatter, and allowing a linear amplitude scale. For rain the semi-annual periods have greater amplitude than the annual period. We summarize the amplitude, phase and period of the principal annual and semi-annual periods in Table 1. The phase is illustrated by adding the corresponding date of the year of the maximum of the oscillation. We find that the temperature presents an annual variation with an amplitude of 9.2°C, with maximum value on July 22 and minimum value on January 21. For the semi-annual period we obtain two maximal values during the year. The temperature has a single spectral peak at a period of 183 days. The tilt, rain and river level have three spectral peaks, near to 183, 172, and 168 days. The three periods have good agreement in the hydrologic and geodetic observations.

Of particular interest is the phase of the spectral components. We find that the pendulums' yearly maximum tilting towards SW happens on the 266th day of the year, which is 63 days after the temperature maximum annual variation. When considering the semi-annual periodicity of 183 days, though, tilt components have maxima near the months of January and July (towards SW), which lags about two months the hydrologic variations at the same periods.

5.2. The tilting of the cave during floods

In this section we analyze the tilt records and the level and water flow rate of the river Reka during a selection of floods. We consider the timeframe in which both data-types were available, which goes from January 1, 1968 to December 31, 2008. In order to isolate the deformations induced by the floods of the river on the pendulums' registrations, we had to clean the tilt-record

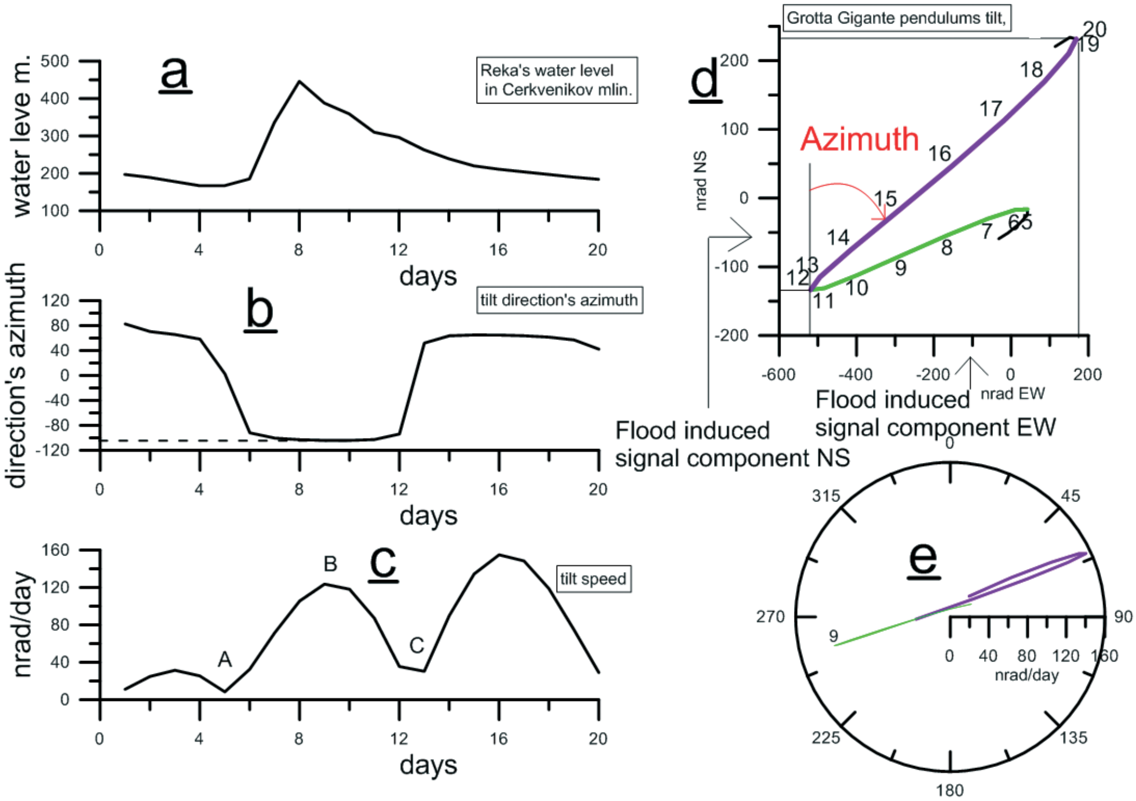

Fig. 7 - The plots used to characterize the deformation during a flood event. All the plots concern the 20 days covering the flood of October 2, 1984: a) flow rate of the river Reka recorded in Cerkvenikov mlin; b) azimuth of the tilt directions; c) tilt speed; d) pendulum total tilt with the two components plotted together; definition of the azimuth of the signal induced by the floods; e) tilt represented in a rose diagram plotted with the azimuth and the speed. The "outgoing" and the "return" signal are high-lighted in green and purple, respectively.

from all the other components (induced for instance by tectonic plate movement, earthquakes, temperature, etc.) through a specific process. In Fig. 6a the E-W pendulum component is shown for the time-interval from October 13, 1966 to March 22, 2011. The annual component and a slower variation (the sinusoid of 33 years and a linear variation described above) are evident. To neutralize these two components, and isolate the rapid hydrologic signal, we first removed the linear variation and the long period sinusoid, which removes the trend and shifted all the values around zero. Then, to remove the annual periodicity, we used a low pass filter to cut all the frequencies with periodicities higher than 300 days. Fig. 6b shows the signal, without the disturbing components, used to find the correlation of tilt with water level, subject of this chapter.

After these operations, we start to evaluate direction, speed and amplitude of the signal during the days of the floods. In total we have selected 11 floods, and we select a time window of 20 days which covers the flood. The peak flood is chosen to coincide with the 8th day of the time window. All the plots in Fig. 7 represent the flood event of October 2, 1984. At the top left (Fig. 7a) the variation of water level flow rate of the river Reka is shown, in the same figure below, the plots in Figs. 7b and 7c represent respectively the azimuth and the speed of the tilt, at the top right, Fig. 7d

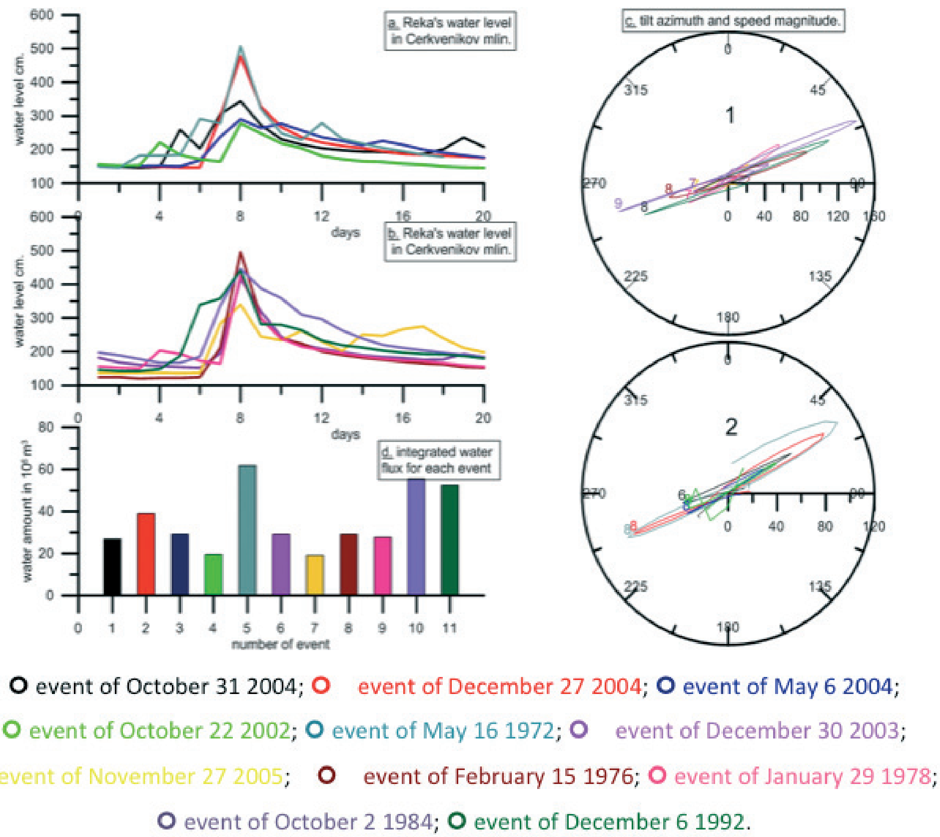

Fig. 8 - Summary of the deformation during eleven selected floods: a) water level of river Reka in Cerkvenikov mlin for flood numbers 1-5; b) same as a) for floods 6-11; c) rose diagram representing the azimuth of the tilt and the magnitude of the speed plotted together. Upper graph (1) for flood numbers 1-5, lower graph (2) for floods 6-11; d) value of the integrated water flux for all considered events.

shows the movement of tilt, lastly Fig. 7e shows the azimuth and the speed of tilt together in a rose diagram. Fig. 7d shows the composite movement of tilt where the E-W and N-S components are used for the X and Y axes, respectively. The numbers on the curve on Figs. 7d and 7e indicate the sequential days of the flood. The first day of the sequence (day 1) matches the beginning of the time series we have extracted corresponding to the flood event. We define the direction of the tilt with the value of the azimuth, the angle counted clockwise from north, during the different phases of the flood induced movement (Fig. 7d). The magnitude of the vector is equal to the tilt's speed counted in nrad per day.

As shown in Fig. 7, the complete signal induced by the flood is characterized by specific phases in correlation to the river flow. The overall signal can be divided in two phases: the "outgoing signal" (green line in Figs. 7d and 7e) and the "return signal" (purple in Figs. 7d and 7e). During the first phase the signal moves towards SW (day 6). As confirmed by the plot, the speed is minimal in the turning points (day 5, point A in Fig. 7c) and the direction changes drastically (sharp drop between the 4th and 6th day shown in the direction plot). After that (second phase and begin of the "outgoing

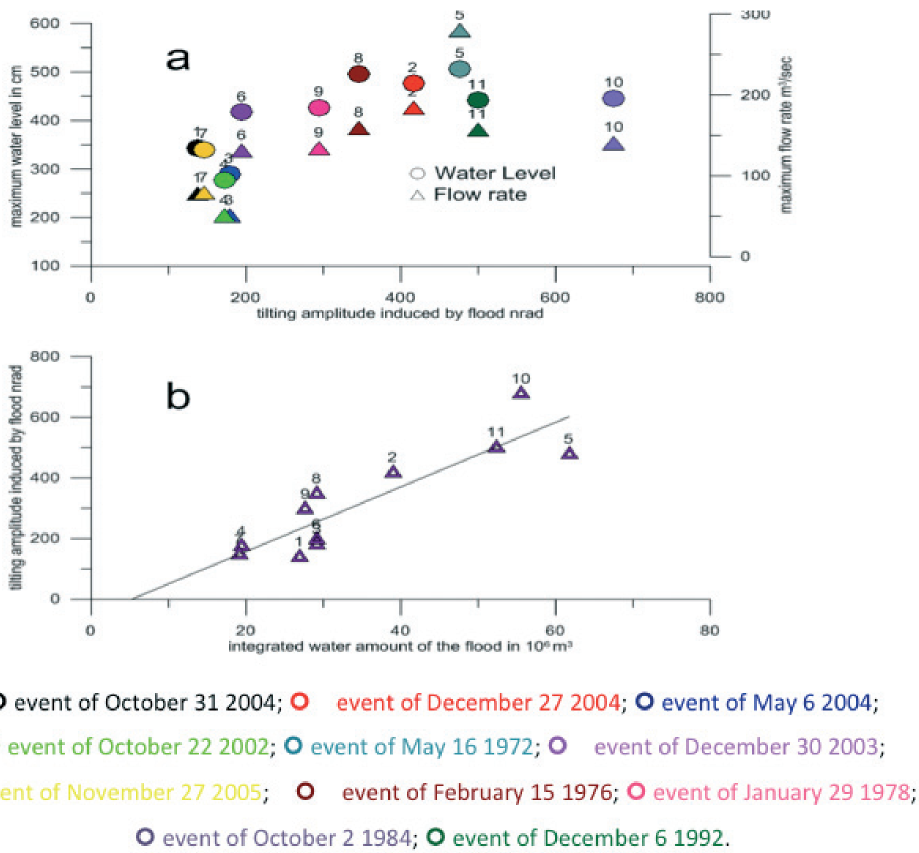

Fig. 9 - The relation between the tilting amplitude recorded in the Grotta Gigante and the floods in terms of a) water level and flow rate and b) integrated water flux recorded at Cerkvenikov mlin; in (b) the linear regression is also shown.

signal") the direction does not change from the 6th to 9th day, but the speed increases. This phase ends with the maximum speed point (point B in the speed plot Fig. 7c, also point 9 in Fig. 7e). The third phase, from the 9th to the 13th day, is characterized by a constant direction, almost the same as in the previous phase, and by a decrease of speed. The direction remains approximately the same until a specific day (in this case the 13th) when the tilt's speed is minimum and the signal changes to the direction N65E (point C in the speed plot Fig. 7c). The fourth and last phase begins from an abrupt change of direction, which defines the end of the "outgoing signal". In the clearest signals the tilting direction during the "return" phase is almost the same as during the "outgoing" phase, there is only a change of verse. In fact, we have called this phase "return signal" because the signal returns to the previous tilt position.

As clearly demonstrated, the tilt-speed increases during the flood, and then gradually abandons the direction because the water has no longer effect on the tilt. In the tilt plot (at the top right in Fig. 7d) we highlight how to define the value of amplitude of the flood signal. The signal often presents a clear difference between the amplitude of the "outgoing signal" and the "return signal", therefore we have measured both of them for each event.

We have repeated the above analysis for all the floods marked green in the Fig. 4, and have superposed the resulting tilting time sequences in Fig. 8. The superposition of the different events highlights the consistency in the time evolution of the deformation induced by the flood.

The characteristic signal defined above is repeated in the same pattern, maintaining the SW tilting of the pendulums and successive recovery. The floods we have selected have been taken from a time interval of 40 years, therefore demonstrating that in these last four decades the water flow during floods has taken the same pathway, as it induces the same geodetic deformation.

Finally, we calculate the time integral of the flow rate over the time interval of the floods and compare this value with the maximum tilting induced by the flood. In Fig. 9a the maximum value of water level and of flood rate are plotted against the maximum tilting. We find that for some events (for instance events 4, 3, 11, 10) the proportionality between water and tilting fails. The proportionality is greatly enhanced if we plot the maximum tilting against the integrated flood rate, this being the total amount of water that influences the instruments. As demonstrated in Fig. 9b, the tilting is proportional to the integrated water volume that entered the Karst system. We interpolate the values linearly, and obtain the following relation, where g_{tilt} is the maximum tilting induced by the flood, V the integrated volume of water entering the Karst during the flood, a the linear coefficient and c a second parameter:

$$g_{tilt} = a\,V + c. \qquad (1)$$

We find the values a =10.7·10^{-6} nrad/m^3 and c =-55.5 nrad. The parameter c is the intercept in the linear Eq. (1) and tells us that the minimum amount of water volume necessary to deform the cave is V_0=5.2·10^6 m^3; the coefficient a tells us that the tilting amounts to 10.7·10^{-6} nrad for 1 m^3 of water flowing into the Karst.

6. Discussion and conclusions

The goal of the present work was to quantify the deformation of a natural cave induced by the environmental factors of temperature, rainfall and water flow. The atmospheric pressure was not considered here, as it was shown in previous works to have a much smaller effect compared to temperature and the hydrologic agents (e.g., Braitenberg *et al*., 2006). The physical link between temperature and deformation is due to the thermal expansion of rocks and the consequent thermal stresses to which the rock fabric responds by a volume deformation. The yearly surface temperature variation penetrates into the Earth by thermal conductivity, leading to yearly temperature variations with exponentially decreasing amplitude and increasing phase lag with depth. Adopting the equations of Turcotte and Schubert (2002) and assuming a value for thermal diffusivity of K=5·10^{-6} m^2/s which could be representative of a limestone with crevasses and air-filled voids (Turcotte and Schubert, 2002), the yearly surface variation with amplitude of 9.2°C would lead to a variation of 1.2°C , time shifted by 64 days at a depth of 14 m. This is the time-shift we find for the annual variation of the tilting of the cave, which is the compound effect of an annual temperature variation that is maximal at the surface and decays at greater depths, and would indicate that the deformation is equivalent to that of the superior part of the cave, considering that the cave is 105 m high. Since the temperature variation inside the cave is affected by air currents, the above estimate is only indicative as it does not take into account the convective air currents inside the cave which alter the predictions from a purely conductive heat model. The convective contribution shifts the depth at which the surface temperature has an effect to greater depths and reduces the phase-shift. In any case, with the purely conductive model we obtain an equivalent depth that corresponds to the expected temperature variations in the rocks casing the cave and corresponding to the observed phase shift of the deformation. The geodetic deformation and the temperature variation have in common that the yearly variation is a very strong signal, that emerges more than 10 times above the remainder of the spectral energies. This is not the case for the hydrologic parameters as rain, river level, and river flow rate, where the annual signal is smaller or not too much greater (factor two to three) than the semi-annual signal. The geodetic signal has in common with the hydrologic signal, that the semi-annual variation is split into more than one spectral peak, at the periods of 183, 172 and 168 days. The peaks at the periods of 172 and 168 days are absent in the temperature variation, and are thus distinctive of the hydrologic influence. Beyond the mere coincidence of spectral energies deduced from the spectral analysis, the one to one coincidence of a characteristic deformation in correspondence with the floods of the river Reka is a proof of the fact that the hydrology induces a deformation of the cave. We deduce from the results that the yearly deformation of the cave is dominated by the thermal deformation, whereas at the semi-annual variation and at periods of a few days to 20 days the deformation has a greater hydrologic origin with respect to the thermal influence. The hydrologic and thermal deformations are superimposed to the other deformations of tectonic origin like free oscillations, seismic waves, co-seismic deformations and long period tectonic deformations.

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