Measurement and Analysis of Cyclic Deformations and Movements of the TV Tower in Sopron

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Key words: building, deformation, movements, tiltmeter, tower.

SUMMARY

Monitoring the movements and deformations of buildings, industrial objects and other constructions is of great importance because their damage may endanger human life and can cause environmental catastrophes. The movements and deformation of a building depend among others on its own construction, local ground motions, on the variation of environmental parameters and is influenced by the ordinary use e. g. variation of loading of the walls, etc.

The main object of the present research was the investigation of the coupling between building and ground movements regarding to the safety of dangerous industrial objects. Results can contribute to the planning of more stable, reliable and motion-proof constructions and eventually to forecast damages.

To get insight into the mechanical coupling between a building and its close vicinity the TV tower in Sopron was chosen. High towers move due to strong wind or could change their centre of gravity caused by heating and dilatation while the sun radiates onto the walls of the tower and is going around it. The movements of the tower are transmitted to the ground and therefore the coupling between ground and building can be investigated in a broad period range, from "high" frequencies (0.01 ... 10 Hz) down to periods of years. During the investigations some remote earthquakes were also recorded and so the swings of the tower caused by the earthquake waves could be investigated.

Two borehole tiltmeters of type Applied Geomechanics Inc., model 722A with a resolution of 0.1 μrad were used for the measurements. One of the tiltmeters was installed on the concrete basement of the 176 m high TV tower and the other one in a 3.6 m deep borehole drilled in metamorphic rock at about 90 m distance from the tower.

The recorded, continuous data series has a length of about two years. In the paper the measuring methods and results of the data analysis are described.

The measuring and analysis methods are suitable for the assessment of the health and earthquake risk of very high buildings and large objects.

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1. INTRODUCTION

Monitoring the movements of dangerous industrial objects, high buildings, bridges, etc. meets a rising interest because the damage of such structures can cause environmental accidents. The movements and deformations of objects may be influenced by different geodynamical processes as tectonic movements, earthquakes or local phenomena e.g. landslides, rock slides, ground settlements or mudflows. Therefore the investigation of the interaction between ground and building motion is very important, too. Results of the investigations of the connection between the ground and building movements can be used to the planning of more stable, reliable and motion-proof constructions, to the assessment of health and safety of objects and eventually to forecast damages. Especially these investigations contributes to assessment of the earthquake risk of dangerous objects.

The Geodetic and Geophysical Research Institute of the Hungarian Academy of Sciences has experience in global and local geodynamical measurements as earth tides (Mentes 2001) tectonic movements (Mentes 2002, 2003) and landslides (Mentes 2004). The local geodynamical measurements were carried out in the frame of a scientific and technical co-operation between the Geodetic and Geophysical Research Institute of the Hungarian Academy of Sciences and the Section of Applied Geophysics at the Geological Institute of the University of Bonn. The connection between ground tilts and ground water level variations (Kümpel et al. 2001) and the one between building and ground motions were investigated by means of borehole tiltmeters. The preliminary results of the later investigation were published by Mentes and Fabian (2001).

For the investigation of the connection between ground and building motions the TV tower in Sopron was chosen because high towers are moved by strong wind or by changing their centre of gravity due to the dilatation caused by sunshine while the sun is going around the tower. The movements of the tower are transmitted to the ground and therefore the coupling between ground and building can be investigated from “high” frequencies (0.01 ... 10 Hz) to periods of years. In the case of normal buildings this connection can be investigated by means of very week microseismic swingings and during earthquakes occuring luckily rarely for such investigations.

2. INSTALLATION OF THE INSTRUMENTS

Figure 1 shows the map of the vicinity of the TV tower at the top of Mt. Dalos (394 m) in Sopron, Hungary. The TV tower is a 176 m high concrete building with a deep cemented foundation in gneiss. A borehole of 3.6 m depth was drilled in south-west direction about 90 m apart the tower for installation of a borehole tiltmeter to monitor ground tilts. The borehole has a diameter of about 0.3 m with a PVC pipe casing coupled to the surrounding formation by concrete (Fig. 2a). The tiltmeter is fixed by tampered quartz sand inside the pipe to obtain a stable, strong coupling to the ground. The top of the pipe is thermally insulated and sealed. The trunk placed in the ground contains the datalogger and batteries. The tower's tilt is being observed by a borehole tiltmeter installed in an iron pipe placed on the concrete foundation of the tower (Fig. 2b). The iron pipe is welded to a rigid bottom plate which is a rectangular triangle with footscrews at the vertexes for adjusting the instrument. For the sake of high stability and low frictional movements there are balls under the tips of the footscrews. The balls are placed in sockets on the concrete foundation of the tower. By this experimental solution both the tower and the ground motions are measured by comparable instrumental set-ups.

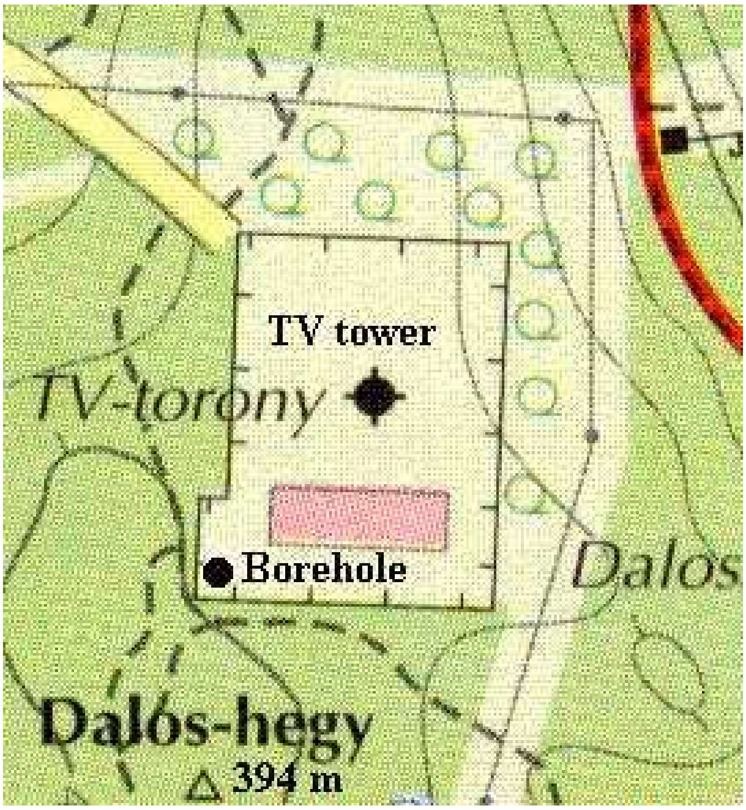

Fig. 1: Site of measurements

The tilt measurements have been carried out by means of dual-axis borehole tiltmeters Model 722A made by Applied Geomechanics Inc. (AGI), Santa Cruz, California. This tiltmeter consists of a cylindrical stainless steel body containing two orthogonal electrolytic precision tilt sensors, amplifiers and signal filters for each of them and a temperature sensor. The tiltmeter is connected to the data logger via submersible steel-reinforced cable and an external switch box.

The main parameters of the tiltmeter Model 722A are:

High gain mode:

Measuring range: ± 800 µrad
Resolution: ± 0,1 µrad ≅ ± 0,02 sec of arc
Scale factor: 0,1 µrad/mV

Low gain mode:

Measuring range: ± 2000 µrad
Resolution: ± 1 µrad ≅ ± 0,2 sec of arc
Scale factor: 1 µrad/mV

Temperature output: 0,1 °C/mV
Power supply: ±12 V
Power consumption: 11 mA (from +12 V) 6 mA (from -12 V)

Dimensions of the tiltmeter: ∅ 54 mm x 850 mm
Temperature range: -25 °C - +70 °C

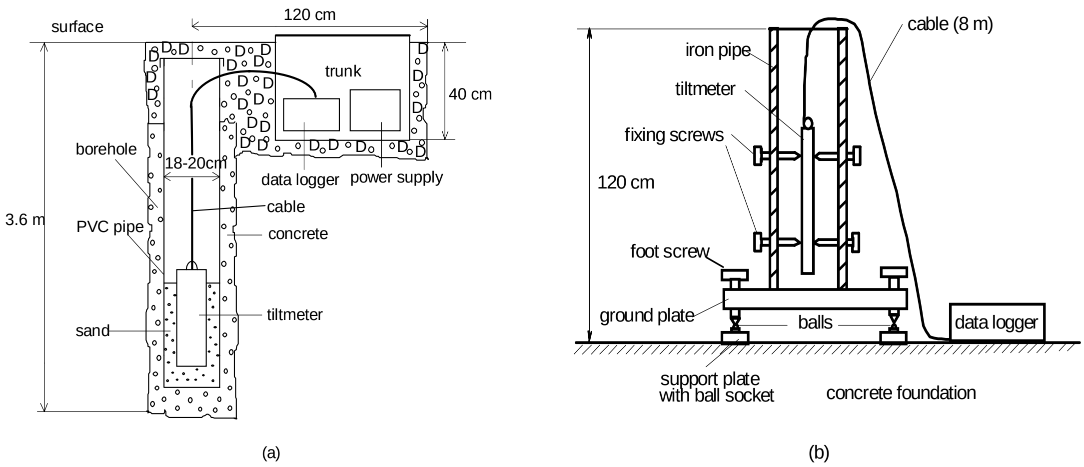

Fig. 2: Installation of the tiltmeters in the borehole (a) and in the TV tower (b)

3. RESULTS OF THE LONG-TERM MEASUREMENTS

Figure 3 shows raw data recorded from 04.11.1999 to 05.07.2001. X_T, Y_T and T_T sign the values of the X and Y components and the temperature of the tiltmeter at the TV tower, X_B, Y_B and T_B the corresponding values of the instrument in the borehole. The data were collected with a sampling rate of 1 data/hour. Both tiltmeters were installed so that their Y directions were parallel and corresponded the North direction.

To obtain the long term variations the data were filtered by a low pass polynomial filter of the 9 order. The frequencies higher than 1/day were cut. Figure 4 shows the filtered data. The period of the variations is one year. The variation of the ground temperature is slightly less than the one of the instrument in the TV tower and it has a time lag to the temperature in the tower because of its better thermal insulation. In Figure 4 long-term correlations between the temperatures and tilts seem to be obvious.

From the raw data a linear trend was also calculated to get an idea about the direction of the continuous tilting of the tower and the one of the ground. All time series show an individual linear long-term trend during the observation interval: X_T = -39 µrad/year, Y_T = -36 µrad/year, T_T = 1.18 °C/year, X_B = -1.5 µrad/year, Y_B = -5 µrad/year T_B = 0.19 °C/year. The long-term trend of the tilts have the same directions. According to the topography of the Mt. Dalos in surroundings of the TV tower, one part of the ground tilts may be of tectonic origin. The tilts may be in connection with the rising of the Alps because the Mt. Dalos belongs to the mountain chain of Alps. The other part of the tilt trend may be in connection with the trend of the temperature. For a more reliable interpretation of the trend longer data series are necessary.

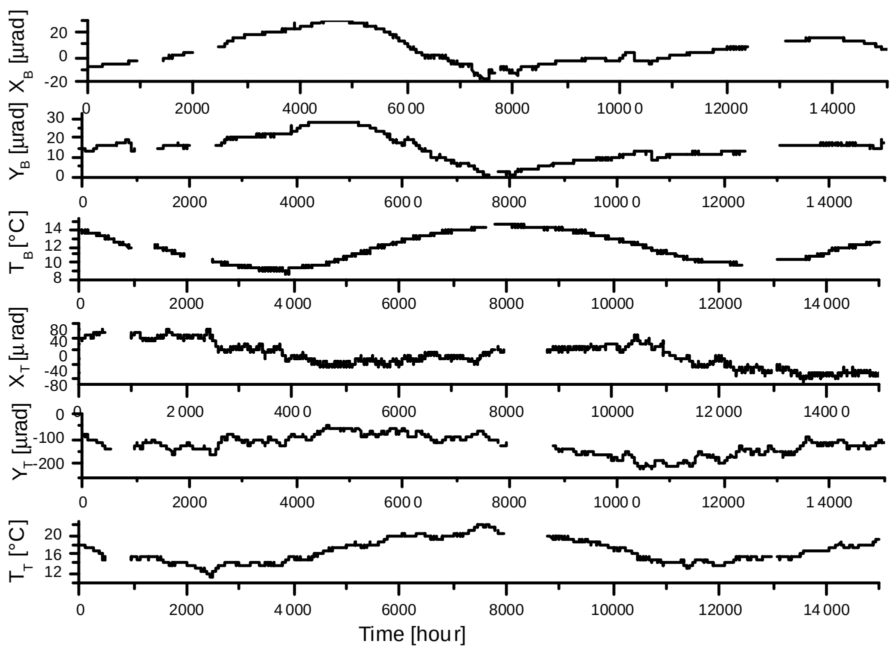

Fig. 3: Raw data recorded from 11.04.1999 to 05.07.2001

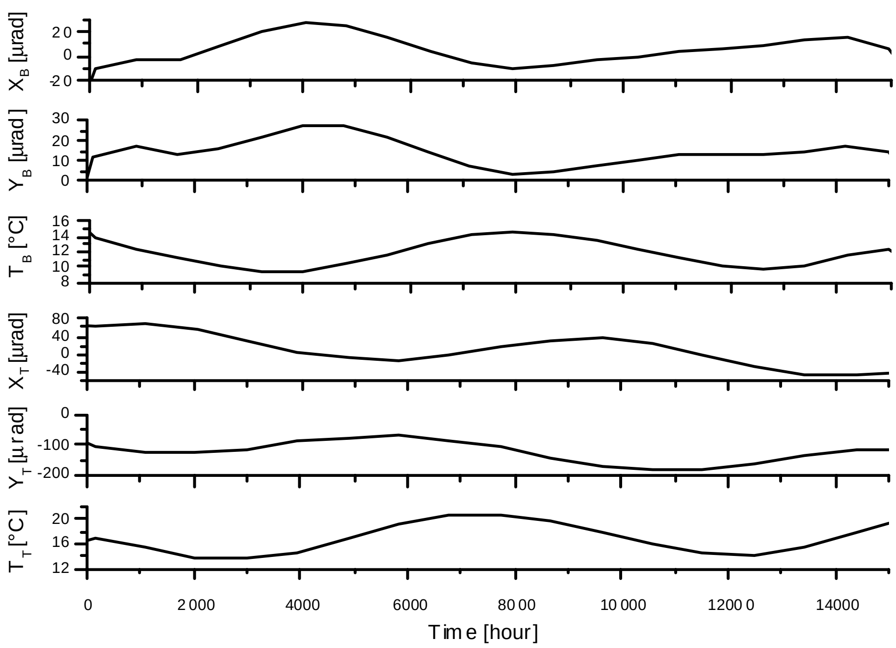

Fig. 4: Filtered data recorded from 04.11.1999 to 05.07.2001

The movements of the tower and the surrounding ground are better seen in a plot tilt Y against tilt X. Figure 5 shows the movements of the tower and the ground. The tilt of the tower is much more disturbed by short periodic variations than the one of the ground.

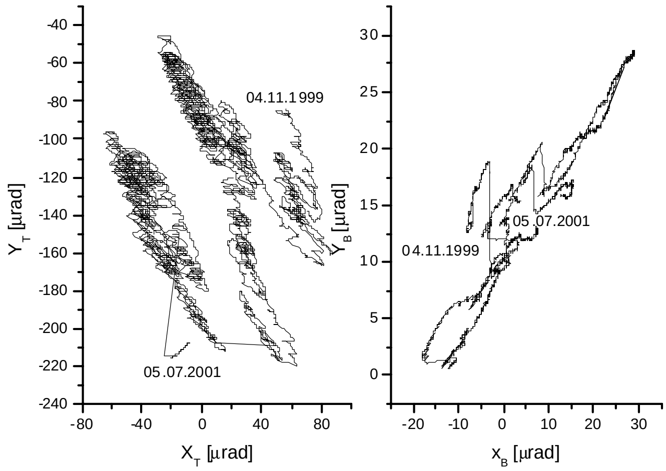

Fig. 5: The movements of the TV tower and the ground

To study the short periodic movements a polynomial of 9 order was fitted to the raw data and this polynomial was subtracted from the original data. Figure 6 shows the residual curves which represent the short periodic variations. To get the dominant frequencies of the variations the residual signals were Fourier-transformed. The amplitude spectra are shown in Fig. 7. Diurnal and semidiurnal periods appear both in the tower and ground tilt signals. The presence of the diurnal signals is obvious in the tilt signals because the temperature variation has a daily period. The appearance of the semidiurnal signals is slightly surprising. Because the tiltmeters are sensitive enough to sense Earth tides in a borehole drilled in gneiss, the characteristic frequencies of the spectra were compared with the tidal frequencies. Our institute has a geodynamical observatory in Sopronbánfalva some kilometers far from the TV tower. In this observatory extensometric measurements are carried out for observation of the Earth tides and tectonic movements. So we could use theoretical and practical data for the comparison. The diurnal signal K_1 has a much higher amplitude than the usual K_1 tidal component because the thermal effect gains this signal. The obtained frequency of this component 0.04175 1/hour = 1.002 1/day coincides with the theoretical one: 1.002737909 1/day (Melchior 1978, Mentes 2001). The frequencies of the M_2 and S_2 are 1.93224 1/day and 1.99944 1/day and the theoretical ones are 1.932273616 1/day and 2.0000 1/day respectively. This coincidence prove that the obtained dominant frequencies are of tidal origin. It is interesting to note that the tidal wave M_2 disappears at the tower tilts. The reason of this is not jet known.

The ratio of the tower and ground tilt amplitudes in X direction is about 28 at both frequencies. The same ratio in Y direction is about 16 in the case of the diurnal signals and about 1 in the case of the semidiurnal signals. Maybe the structure of the ground causes these differences.

The diurnal and semidiurnal variations of the recorded temperatures are very small which proves also that the semidiurnal frequencies are of tidal origin.

Figure 8 shows the raw signals from 23.08.2000 to 25.08.2000. The tower has a typical tilt with a daily period. A reason could be the variation of the towers centre of gravity due to the relative motion of the sun. The side of the tower towards the sun has a much larger thermal expansion than the opposite one, therefore the centre of gravity moves always oppositely to the sun and the tower tilts. The sun goes from east to west while the tower tilts from west to east. In Figure 8 the simultaneous tilt of the ground is also given. Figure 9 shows the short periodic movements of the tower and the ground plotted tilt Y against tilt X at the period given in Fig. 8. The magnitude of the ground movements is much smaller than the one of the tower and it is less regular.

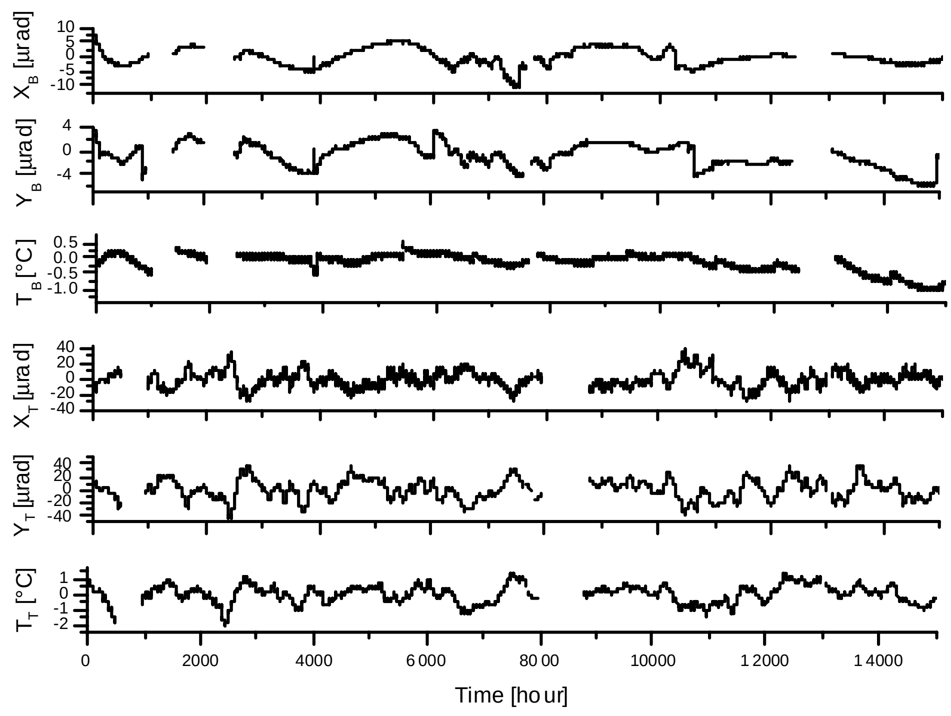

Fig. 6: Short periodic tilt variations from 04.11.1999 to 05.07.2001

4. RESULTS OF THE HIGH-FREQUENCY MEASUREMENTS

In autumn 1999 the two tiltmeters were connected to one high resoluting datalogger to sample the output signals over time spans of some hours with rates of up to 10 Hz simultaneously. With this special set-up we observed tiltsignals, while the TV tower was exposed to strong wind and also the transmission of seismic waves from distant earthquakes.

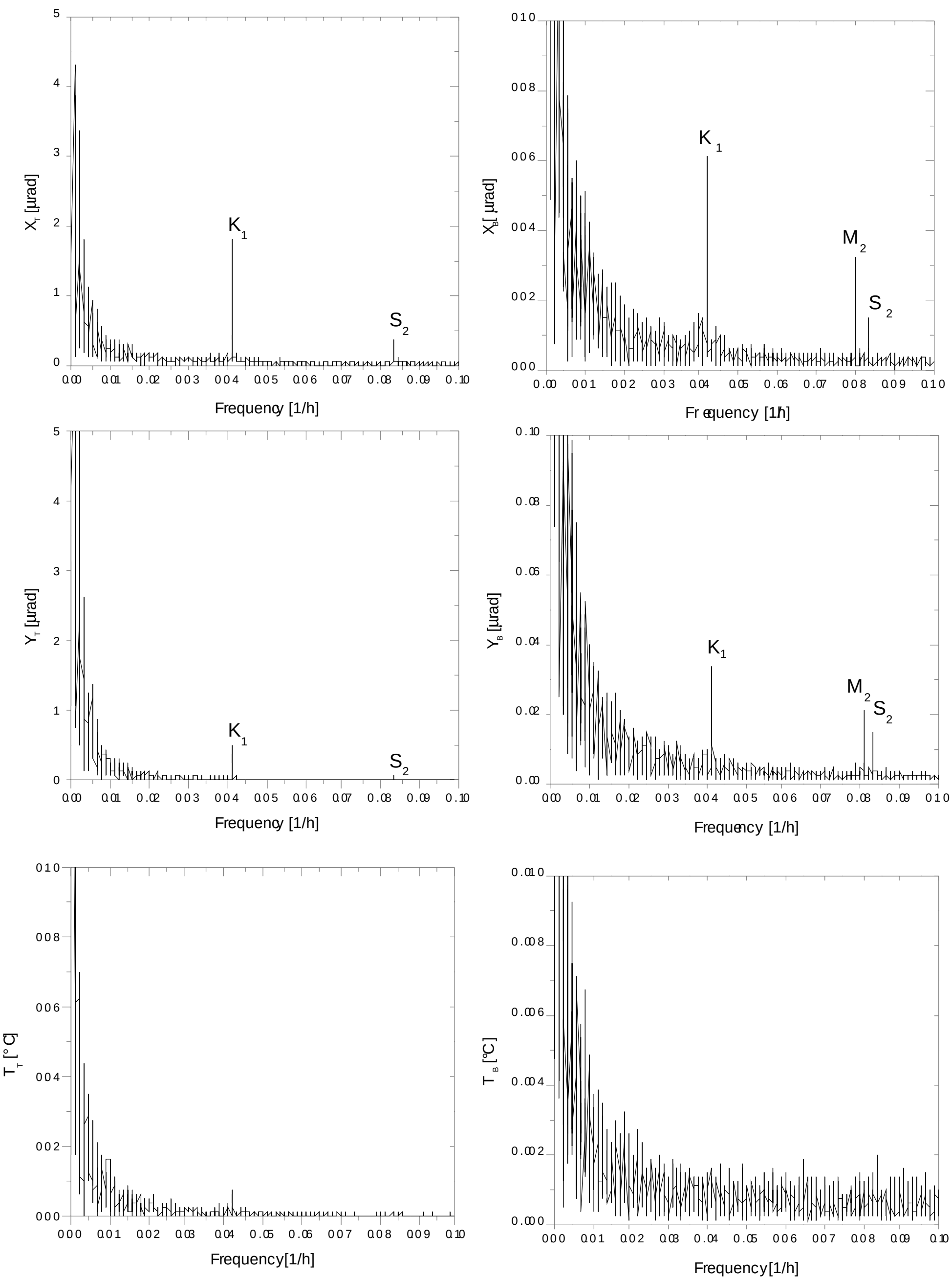

Fig. 7: Amplitude spectra of the residual signals

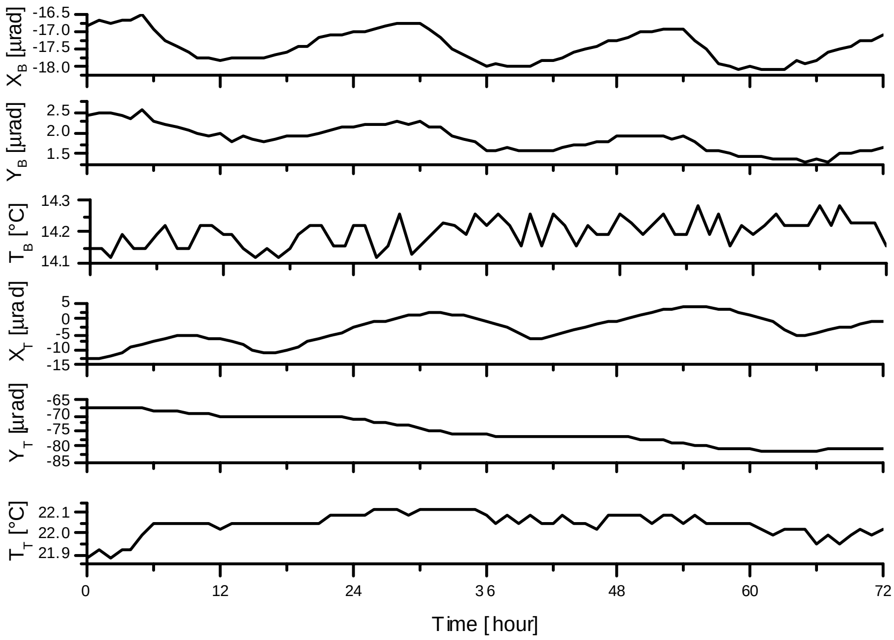

Fig. 8: Raw data from 23.08.2000 to 25.08.2000

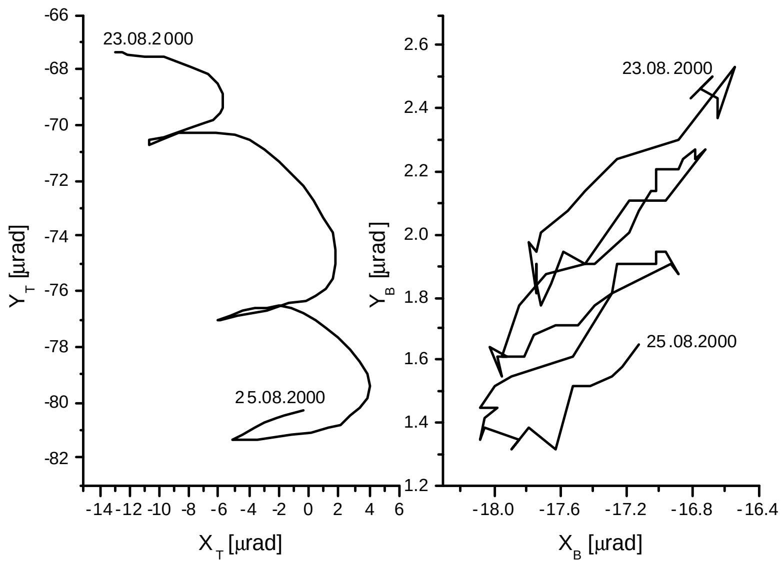

Fig. 9: Short periodic movements of the tower and the ground

Figure 10 shows the time series and the corresponding amplitude spectra for the data measured during a period of strong wind. The spectra were calculated with a Hanning window after filtering with a low-cut at 12 min. In Figure 10a the tilt amplitudes measured at the TV tower are two to four times larger than the amplitudes of the signals from the borehole. This could be caused by high frequency shaking or vibrating of the tower particularly with eigenfrequencies what may be forced by the wind. But these motions are not well transmitted to the ground i.e. to the borehole position. The spectra provide a better insight on this assumptions. In Figure 10b three significant lines at 3 sec (0.333 Hz), 0.7 sec (1.43 Hz) and 0.43 sec (2.32 Hz) are in the spectra of the data from the tower but these lines are very weak or absent in the other two spectra. Additionally the noise level is some times higher for the tilt signals from the tower, which could be caused by forced motions different from the eigenfrequencies.

Figure 11 shows the passage of seismic waves from a distant earthquake. In Figure 11a the time series with an arrow mark for the origin time of an earthquake in Oaxaca, Mexico with magnitude $m_B = 6.6$. After approximately 14 min the first seismic signal arrived at the site followed by clear wave trains in the time series of all tiltmeter components. The corresponding spectra of all tilt components show a broad band of strong amplitudes in the range between 10 s and 100 s, which is typical for distant earthquakes. The three spectral lines of Figure 10b are present too, but somewhat weaker.

5. CONCLUSIONS

The long-term data show a continuous trend in the motions of the TV tower and the borehole in a similar manner. This could be caused by a slow deformation or motion of the whole site. The trend is superposed by an one year-cycle in all components, which is also present in the temperature data of both instruments. On the time scale of days there could be motions of the centre of gravity of the tower associated to heating and dilatation of the tower due to radiation of the sun. This motions seem to lead to a deformation of the towers nearby surrounding underground so that the tiltmeter in the borehole moves in opposite Y-direction to the building.

The appearance of tidal frequencies in the high resolution tilt data give a possibility to control the health of large objects (e.g. very high buildings, long bridges, etc.) in special cases because they are well defined input signals. The change of the response of the object can be used to assess the health of the object.

High frequency measurements reveal aspects due to short period motions of the TV tower, their transmission through the underground and insight associated with the passage of seismic waves. Motions or better said vibrations of the tower with periods shorter than a few seconds, possibly with eigenfrequencies seem to be poorly transferred to the ground. On the other hand seismic waves caused by distant earthquakes are very well observed in both positions, in the TV tower and in the borehole. So ground motions of periods between 10 s and 100 s being typical for distant earthquakes are well transferred between the tower and its underground. That shows, the tower is well coupled to its ground in this period range. Such measurements can be used to assess the seismic risk of large objects.

Continuing these measurements, especially with a third instrument at a higher position in the TV tower and a fourth one in an other borehole, should yield additional important data.

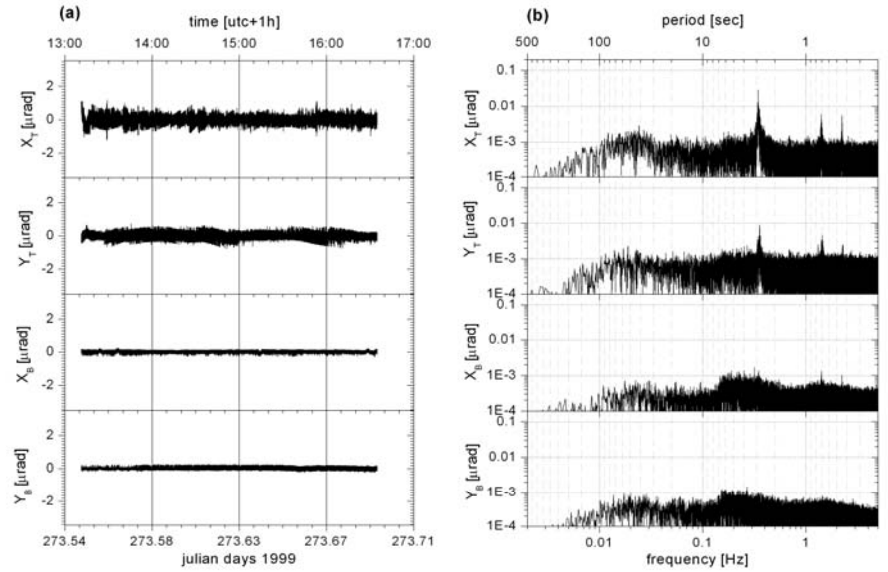

Fig. 10: High frequency measurements of tilt data (a) and corresponding amplitude spectra (b) during a period of strong wind

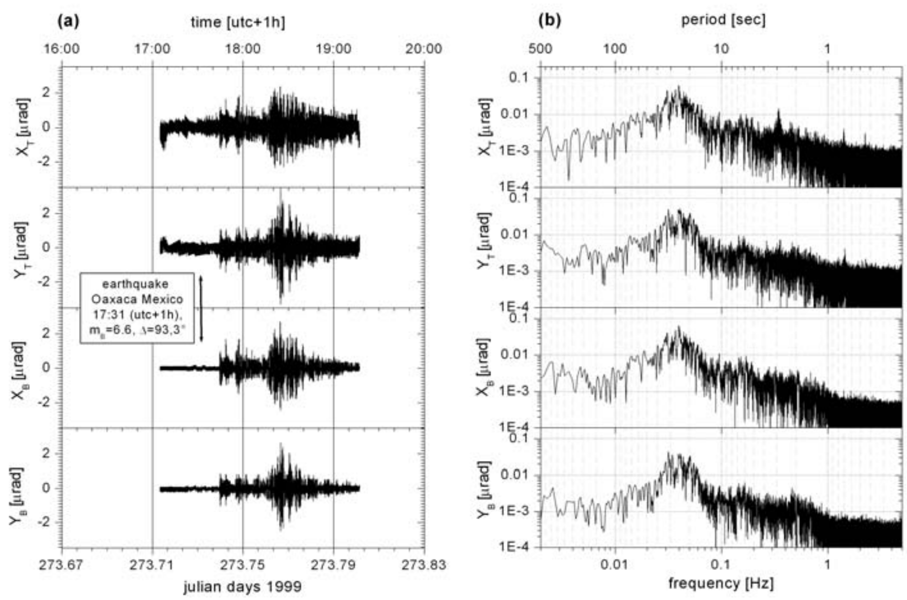

Fig. 11: High frequency measurements of tilt data (a) and corresponding amplitude spectra (b) during the passage of seismic waves from a distant earthquake

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BIOGRAPHICAL NOTES

Gyula Mentes, born in 1950.
1971: Graduated: from the Kandó Kálmán College of Technology and Electricity
1977: Graduate from Budapest University of Technology
Profession: Electrical engineer
Since 1971: Employed at the Geodetic and Geophysical Research Institute of the Hungarian Academy of Sciences (GGRI)
1971 -1977: Electrical engineering
1977 – 1987: Scientific co-worker, Head of Electrical Laboratory
1986: Candidate of Sciences (PhD)

1987 - 1999: Senior member, Head of the Department of Instrument Development
1989: Academic Prize in Earth tides research
1991 – 2002: half time assistant professor at the University of West-Hungary in Sopron
1992 -1994: Lecturer at the University of Technology in Vienna
1999: Prize “Széchenyi Professor Scholarship”
2000: Doctor of the Hungarian Academy
Since 2000: Scientific advisor at the GGRI, Head of the Geodetic Main Department
Since 2003: Half time professor at the University of West-Hungary in Sopron

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Global and local geodynamics: Earth tide research, tectonic movements, landslides, atmospheric tide.
Investigation of local effects: connection between ground water level and ground tilt, connection between ground and building motions
Development of instruments for Earth tide monitoring: horizontal pendulum, quartz tube extensometers, hydrostatic tiltmeters, calibration of instruments, automation of data recording
Development of data processing methods, data interpretation
Engineering Geodesy: Investigation of deformations and movements of structures and objects
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