INVESTIGATION OF THE DEFORMATION AND MOVEMENTS OF OBJECTS CAUSED BY EARTH TIDES[1]

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Abstract: The investigation of the stability of large objects, such as towers, buildings, bridges, etc. without disturbing the function of the object plays a very important role. This paper deals with the problem how Earth tide waves can be used as exciting signals for this investigation. Two large objects, the TV tower and the church Kecske in Sopron (Hungary) were chosen for tidal measurements. The results prove that tidal signals can be detected and under special circumstances these signals can be used for health monitoring of large objects. Tidal monitoring on the object and in the surrounding ground gives an opportunity to investigate the connection between the ground and the object which plays a very important role both in assessment of the stability and in assessment of the earthquake risk of the object.

1. Introduction

The interest in the ability to monitor a structure and detect damage at the earliest stage is pervasive throughout all industries. The market demand for monitoring systems for identification of structural damage is the strongest in the civil construction sector. The motives are the increasing number and age of structures and at the same time the reduction of budgets available for inspection and maintenance. Currently used damage detection methods are visual or localized ones using different approaches. All techniques require a priori knowledge of the location of the damage and its area must be accessible. The need for quantitative, global damage detection methods applicable to complex structures has led to research methods using detection of changes in structural vibration characteristics. The method is based on the fact that the damage will alter the measured dynamic response of the object due to changes in stiffness, mass or energy dissipation. Although this assumption appears simple, its application posses major technical challenges, especially related to the application to real civil engineering structures. Differentiation between damage effects and environmental influences is also a major research subject in the next feature.

For health monitoring of objects, to detect damages dynamic testing has recently been carried out by inducing vibrations artificially. This impact test, as the name implies, consist of disturbing the structure from its quiescent condition by a single impulse, and monitoring the resulting response with accelerometers. These tests are quick and simple to execute, and are usually adequate for obtaining the in-situ vibration properties of relatively simple structures but they are not suitable for damage detection of the whole object. These impact tests cannot

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be carried out without disturbing the function of the object which is a fundamental requirement against health monitoring of structures. Therefore we investigated how natural exciting effects, e.g. wind, sunshine, earthquakes, micro-seismic activity, ambient vibrations can be used for these purposes. At the TV tower in Sopron we monitored the movements and the deformations of the tower due to wind blasts, apparent motion of the Sun and remote earthquakes. The measurements were made in co-operation with the Geological Institute of the Bonn University and the results are described in [1].

A very important research task of the next decades will be the assessment of the vulnerability and safety of existing structures to the loads from natural hazards as earthquakes, landslides, rock slides, ground settlements, mudflows, strong winds, etc. For these purposes not only the measurement of object motion and deformation but also the simultaneous monitoring of ground motions in the vicinity of the object is necessary. The knowledge of the connection between object and ground plays a very important role for earthquake risk assessment and planning of more stable, reliable and motion-proof constructions.

Because of the stability of large objects strongly depends on the quality of the ground in the vicinity of the object and the connection between the ground and the object, therefore the relation between ground water level variations and ground tilts and the interaction between ground and object motions were investigated in a close co-operation with the Geological Institute of the Bonn University [1, 2]. During a bridge test the ground motion was monitored and the connection between bridge load and ground motion investigated. This research was carried out in co-operation with the Institute for Geodesy of the University of Technology, Bratislava [3].

Earth tide is a phenomenon which causes the viscous-elastic deformation of the solid Earth due to the gravitational attraction of the Moon, the Sun and planets. This attraction varies with time and with the path of these celestial bodies causing a periodic deformation of the entire Earth. The tidal deformation of the Earth can be calculated a priori from the movements and data of celestial bodies. The tidal forces cause the deviations of the vertical with an amplitude of approximately $2 \cdot 10^{-7}$ radian, the variation of the intensity of gravity with an amplitude of $2.4 \cdot 10^{-7}$ m/sec^2, and a relative extension of about 10^{-8} between two points on the Earth's surface. The variations of these quantities can be usually measured by high resolution tiltmeters, gravimeters and extensometers in very stable underground observatories built in bedrock [4].

High buildings, large objects can be directly influenced by tidal forces or they move following ground motions due to tidal forces. In some special cases these tidal movements and deformations can be measured, so tidal waves can be used as input signals for the investigation of object movements and deformations. The change of the object response can be used for the health assessment of structures. Simultaneous recording of object and ground motions contributes to the study of the interaction between ground and object motion, to the determination of the transfer function of the ground and therefore to earthquake risk assessment of the objects.

Simultaneous tidal observations on the TV-tower in Sopron and in its surroundings were carried out to study how tidal waves can be used for structural health monitoring. The tidal waves could be detected both in the tower and in the ground deformations. The measurements were repeated at the church Kecske in the downtown of Sopron under more noisy circumstances than in the case of the TV-tower. The tidal waves were also detected.

The tidal phenomena are briefly described below and the results of the measurements are given thereafter.

2. Earth tides

Every point on the surface of the Earth is subject to the force of gravity due to the Newtonian attraction of the whole mass of the Earth and to the centrifugal force due to the rotation of the Earth. To understand the tide of the solid Earth let us see the Earth-Moon system. The Earth and Moon behave as a two-body system, rotating about a common centre of mass. The Earth rotates eccentrically about this so-called bary-centre which is within the Earth and lies about 4700 km from its centre. The centrifugal forces are directed parallel to a line joining the centres of the Earth and the Moon and have the same magnitude. The gravitational force will not be the same at all points on the Earth'surface, because they are not at the same distance from the Moon. Points nearest the Moon will experience a greater gravitational pull from the Moon than those on the opposite side of the Earth. Moreover, the direction of the Moon's gravitational pull at all points will be directed towards its centre, so it will not be exactly parallel to the direction of the centrifugal forces, except along the line joining the centres of the Earth and the Moon. The resultant of the two forces is known as the tide-producing force. The gravitational force exerted by the Moon at the Earth's centre is exactly equal and opposite to the centrifugal force there, so the tide-producing force at the centre of the Earth is zero. Figure 1a shows the centrifugal ($\bar{a}_o$), the gravitational ($\bar{a}_P$) and the resultant tide-producing ($\bar{b} = \bar{a}_P - \bar{a}_o$) accelerations, in accordance with the forces. Figure 1b shows the resultant tidal accelerations (forces) on the whole Earth's surface and the deformation of the Earth due to tidal forces caused by the Moon.

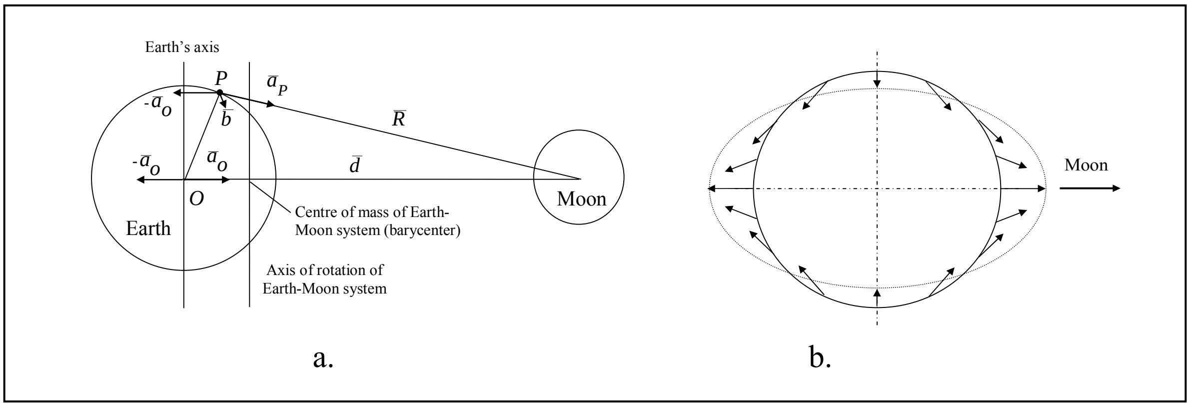

Figure 1: Definition of tidal acceleration (a), Tide-producing forces and deformation of the Earth (b)

The centrifugal force acts in the same direction all over the Earth, e.g. away from the Moon. Moreover, on the side of the Earth away from the Moon, the gravitational attraction due to the Moon is less than it is on the side of the Earth facing the Moon. The resultant tide-producing force acts away from the Moon at points opposite to the Moon. That is why there is a tidal bulge away from the Moon and towards it. Because the two bulges maintain their positions relative to the Moon, they travel around the world at the same rate but in the opposite direction as the Earth rotates about its axis. Therefore, there are two high and two low tides during each day at any point on the Earth's surface.

Because the Moon revolves about the Earth-Moon centre of mass once every 27.3 days, in the same direction as the Earth rotates about its own axis (24 hours). The period of the Earth rotation relative to the Moon, the lunar day is 24 hours 50 minutes. The interval between successive high (low) tides is about 12 hours 25 minutes. The period of a high and low tide is so 6 hours 12.5 minutes.

The Moon's orbit is not in the plane of the Earth's Equator (as it was supposed above), but is inclined to it. The angle between the plane of the Equator and the plane of the Moon's orbit, the declination of the orbit of the Moon is 28.5°. As a consequence of this declination the successive tides are not equal.

The Moon has an elliptical orbit and the Earth is at one of the foci. The consequent variation in distance from Earth to Moon results in corresponding variations in tide. The Moon's elliptical orbit precesses, i. e. it rotates with a period of 18.6 years. During this precession the variation of the angle between the lunar orbit and the ecliptic has a magnitude of 5°. Since the plane of the Earth's Equator is at an angle of 23.4° to the plane of the ecliptic, the maximum declination of the Moon ranges from 18.4° (23.4°-5°) to 28.4° (23.4°+5°), during the course of the 18.6 years precession cycle. This period of 18.6 year can be detected in long-term tidal records.

Like the Moon, the Sun also produces tractive forces and two tidal bulges. The Sun has an enormously greater mass, but it is much further from the Earth than the Moon, so its tide producing force is about 0.46 that of the Moon. The two solar tides sweep westwards around the Earth as it spins toward the east. The solar tide has a semidiurnal period of 12 hours. As the relative heights of the two lunar tides are influenced by the declination of the Moon, so there are diurnal inequalities in the solar components due to the Sun's declination (23.4°).

The regular changes in the declinations of the Sun and Moon, and their cyclical variations in position with respect to the Earth, produce very many harmonic constituents, each of which contributes to the tide at any time and place on the Earth. Besides the Moon and the Sun the influence of the nearby planets of our solar system also generates tidal accelerations on the Earth. To take all of these influences into account it is better to introduce the scalar tidal potential instead of the vectorial tidal acceleration in order to enable an expansion of the tidal potential into scalar spherical harmonics. This will allow us the separation of the tidal potential into latitude, and time/longitude dependent terms, and the spectral representation of the tidal potential by a tidal potential catalogue. The tidal acceleration vector is by definition the gradient of the tidal potential:

$$\bar{b} = grad\,V = \frac{\partial V}{\partial \bar{r}} \tag{1}$$

The tidal potential can be expanded into a series of Legendre polynomials:

$$V = \frac{GM}{d} \sum_{l=2}^{\infty} \left(\frac{r}{d} \right)^l P_l \left(\cos \Psi \right), \tag{2}$$

where G the Newtonian gravitational constant, M the mass, d the distance of the celestial (disturbing) body, r the radius from the geocentre to the observation point, P_l is the Legendre polynomial of order l and ψ is the geocentric zenith angle of the external body at point A. In the geocentre ($r = 0$) $V = 0$.

Because the relation r/d is about $1.6 \cdot 10^{-2}$ for the Moon and about $4 \cdot 10^{-5}$ for the Sun, the series expansion (2) converges rapidly. For the most accurate tidal potential catalogues, $l_{\max} = 6$ for the Moon, $l_{\max} = 3$ for the Sun and $l_{\max} = 2$ for the planets are used. The largest contribution to the tidal potential results from degree 2 with about 98% of V.

The geocentric zenith angle ψ can be expressed by the geocentric spherical coordinates of the station and the of the celestial body:

$$\cos\psi = \cos\theta\cos\Theta_b + \sin\theta\sin\Theta_b\cos(\lambda - \Lambda_b), \tag{3}$$

where θ the geocentric spherical polar distance of the station, λ the geocentric spherical longitude of the station, θ_b the geocentric spherical polar distance of the celestial body, Λ_b the geocentric spherical longitude of the celestial body.

Eq. (3) enables us the expansion of the Legendre polynomials into fully normalized spherical harmonics $\overline{P}_{l,m}$:

$$P_l(\cos\psi) = \frac{1}{2l+1}\sum_{m=0}^{l}\overline{P}_{l,m}(\cos\theta)\cdot\overline{P}_{l,m}(\cos\Theta_b)\cdot\cos(m\lambda - m\Lambda_b) \tag{4}$$

with l degree and m order. These spherical harmonics and their derivatives (with respect to θ) can be computed to high degree and order from recursion formulas [3]. The tidal potential on the Earth exerted by a celestial body is calculated inserting (4) into (2). In these equations d, Θ_b, Λ_b, are time dependent. Because of the latitude dependence of the spherical harmonics, the amplitudes of the tidal waves are latitude dependent: the long-periodic tidal waves have a maximum at the poles, the diurnal tides have a maximum at ±45° latitude, the semidiurnal tides have a maximum at the equator. In Table 1. the symbols, the periods and the amplitudes (relative to that of the M_2) of some principal tidal constituents are summarized. A more detailed description of the solid Earth tide is given e.g. by Melchior [5].

Name of tidal components		Symbol	Period in solar hours	Amplitude relative to M_2 ($M_2 = 100$)
Semi-diurnal	Principal lunar	M_2	12.42	100
	Principal solar	S_2	12.00	46.6
	Large lunar elliptic	N_2	12.66	19.2
	Luni-solar	K_2	11.97	12.7
Diurnal	Luni-solar	K_1	23.93	58.4
	Principal lunar	O_1	25.82	41.5
	Principal solar	P_1	24.07	19.4
Long-periodic	Lunar fortnightly	M_f	327.86	17.2
	Lunar monthly	M_m	661.30	9.1

Table 1. Some principal tidal constituents

Earth tide observations of high accuracy can only be carried out in observatories built in the bedrock. Registrations made in sediment or in soil are disturbed by other effects of higher magnitude than the tidal waves and therefore the tidal phenomena cannot be observed. High buildings e. g. towers behaviours like a vertical pendulum and so they can gain the tidal effect acting on these buildings which transfer tidal waves to the ground in the vicinity of the object. That is the reason that in some special cases the tidal waves can be used for the investigation of the health of large structures and for the study of the interaction between objects and the surrounding ground. Below two examples are shown at the TV tower and at the church Kecske in Sopron.

3. Investigation of the Earth tidal effect at the TV tower in Sopron

To get insight into the mechanical coupling between a building and its close vicinity at the TV tower in Sopron two dual axis, borehole tiltmeters of type Applied Geomechanics Inc., model 722A with a resolution of 0.1 μrad were used. One of the tiltmeters was installed in an iron pipe placed on the concrete foundation 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 (Figure 2). By this experimental solution both the tower and the ground motions were measured by comparable instrumental set-ups. Both tiltmeters were installed so that their *Y* directions were parallel and corresponded to the North direction.

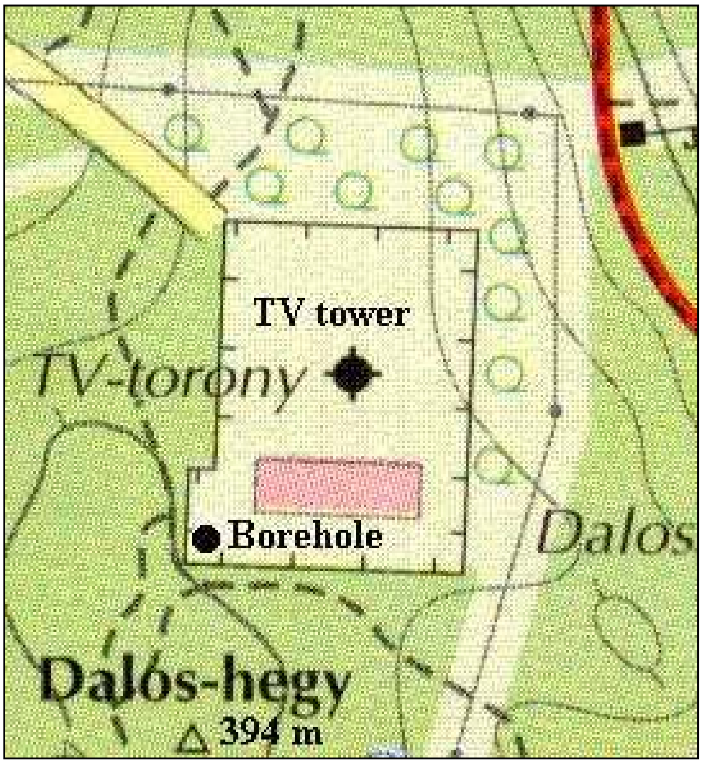

Figure 2: Site of the measurements

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.

To enhance the short periodic movements a polynomial of order 9 was fitted to the raw data and this polynomial was subtracted from the original data. To get the dominant frequencies of the variations, the residual signals were Fourier-transformed. The amplitude spectra are shown in Figure 4. Diurnal and semidiurnal periods appear both in the tower and the ground tilt signals. Diurnal signal K_1 has much higher amplitude than the usual K_1 tidal component because the thermal effect gains this tidal constituent. The obtained frequency of this component: 0.04175 1/hour = 1.002 1/day coincides with the theoretical one given in [5]: 1.002737909 1/day. The frequencies of 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 proves that the obtained dominant frequencies are of tidal origin.

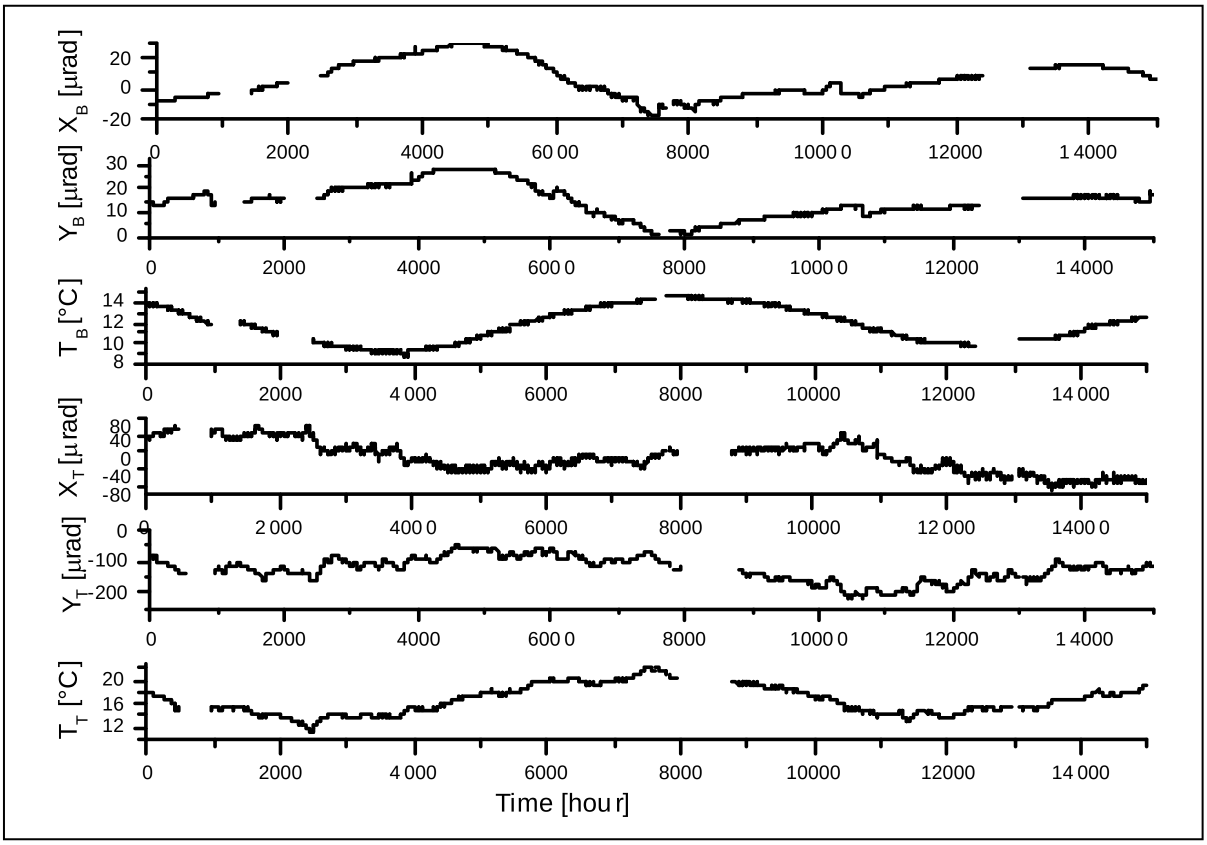

Figure 3: Raw data recorded at the TV tower from 11.04.1999 to 05.07.2001

Because the diurnal and semidiurnal waves are gained significantly by the daily temperature variations, the detected tilt components can have an occasional agreement with the tidal ones, therefore the temperature data were also Fourier-transformed to control the tidal frequencies in this data. There are no characteristic spikes in the amplitude spectrum of the temperature data because the temperature was measured in the borehole and in the basement of the tower and the temperature is stabile on both places.

The amplitude ratio of M_2 and S_2 measured in the borehole corresponds to the theoretical one. In the spectrum of the tower tilt the wave M_2 cannot be seen. The reason is that S_1 is very large because of the temperature effect and therefore only the solar waves can be seen in the spectrum. The amplitude of K_1 and S_2 is much higher at the tower than in the borehole. The reason is the temperature effect. The tower has also a deformation caused by the course of the Sun which causes a typical tilt with a daily period. The reason is 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. So the tilt of the tower has a magnitude four times higher in the X (east-west) direction than in the Y (north-south) one. The ratio of the amplitude of K_1 obtained at the tower and at the borehole is 30 in X direction and 15 in Y direction. It proves that the tilt of the tower is mainly of thermal origin. Maybe the change of the ratio of the amplitudes K_1 obtained for the tower and the borehole can be used for detection changes in the transfer function between object and ground.

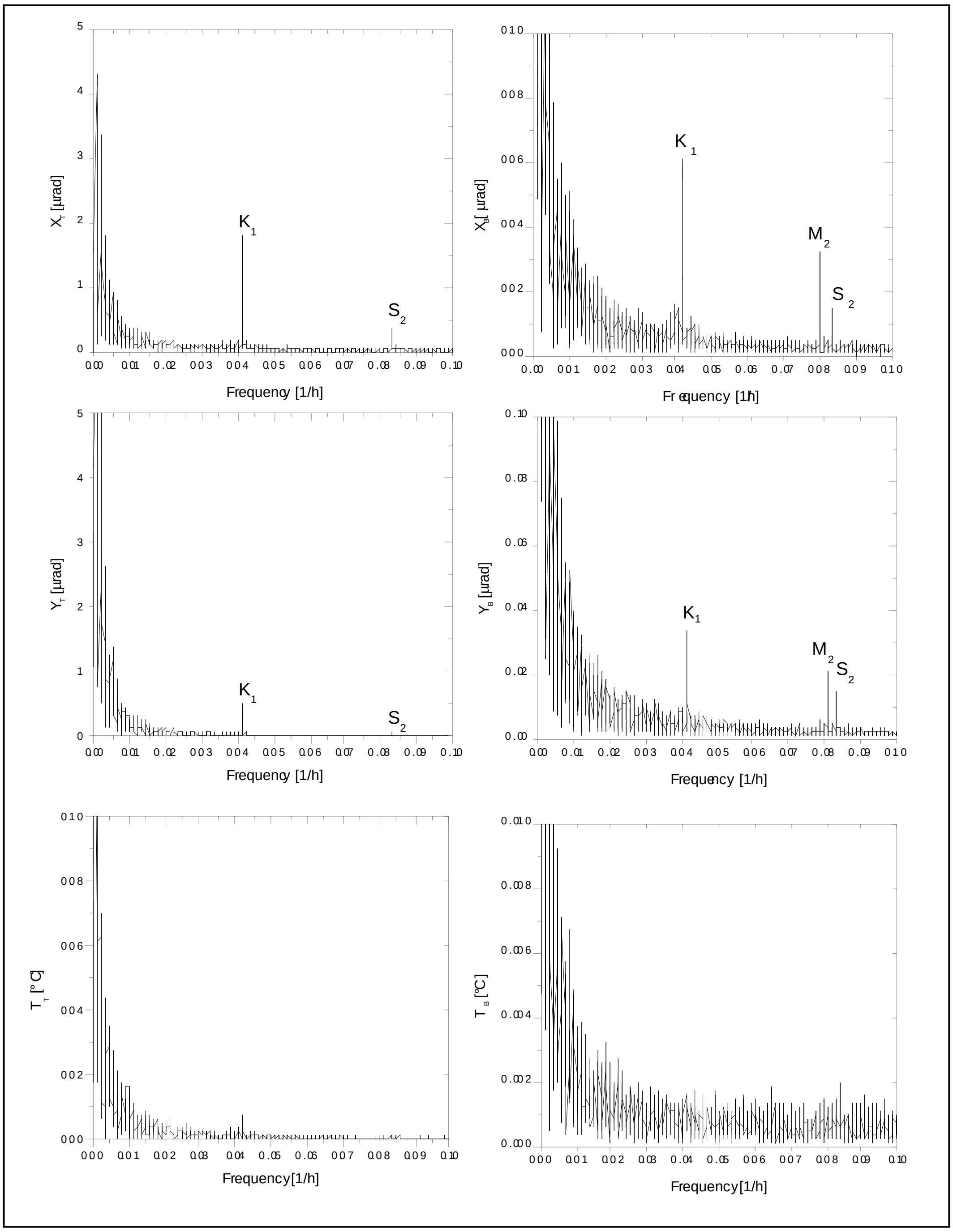

Figure 4: Amplitude spectra of the residual signals

4. Investigation of the Earth tidal effect at the Church Kecske in Sopron

Figure 5a shows the side and top view of the Church Kecske in Sopron. A tiltmeter type 722A was placed in the choir and fastened to the wall by means of two straps (Figure 5b). The place of the tiltmeter and the directions of the measured tilts are shown in Figure 5a. The X axis of the tiltmeter shows westwards and the Y one to the south. Data were recorded at a sampling rate of 1 hour/data from 22.05.2001 to 31.12.2002. The short periodic variations and the Fourier-spectra were calculated in the same manner as it was done at the TV tower.

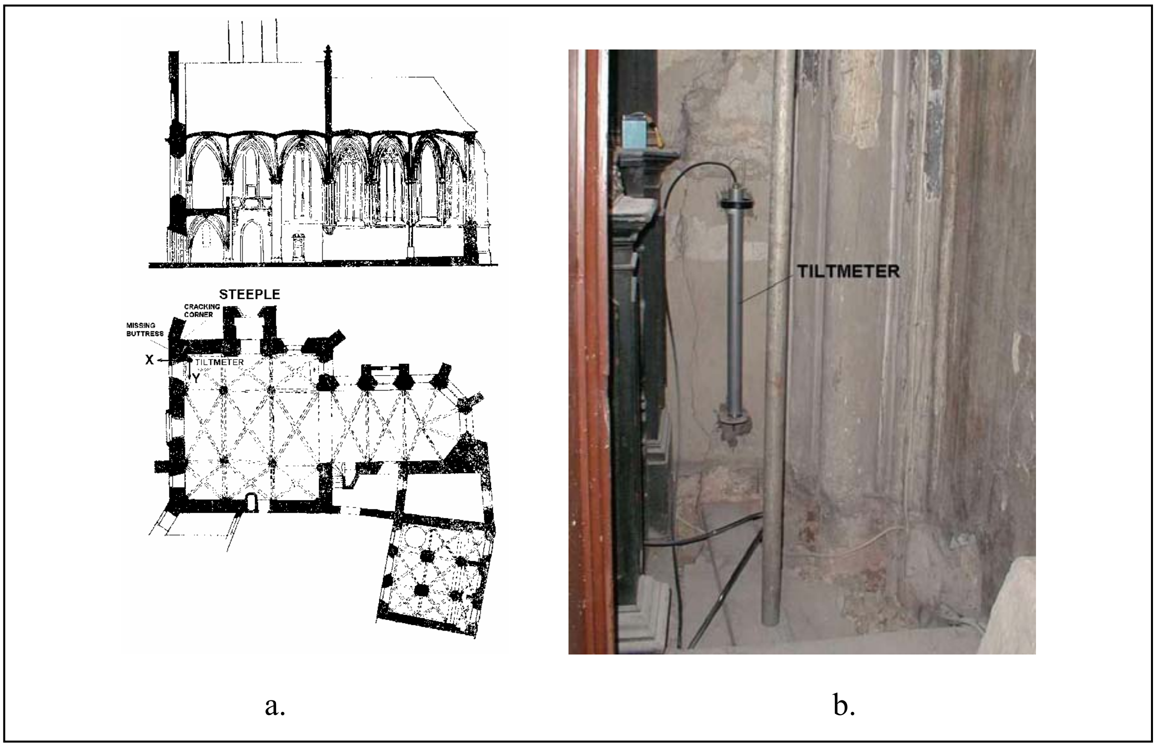

Figure 5: Installation of the tiltmeter in the Church Kecske

The amplitude spectra of the tilt data are shown in Figure 6. The frequency is given in cpd (cycles per day). In both tilt components diurnal, semidiurnal, third diurnal and constituents of higher frequencies are present. The highest amplitude is at the frequency of 1 cpd which is due to the temperature variations. At this frequency there are many spikes very close to each other, because besides of tilts caused by temperature other constituents are also present.

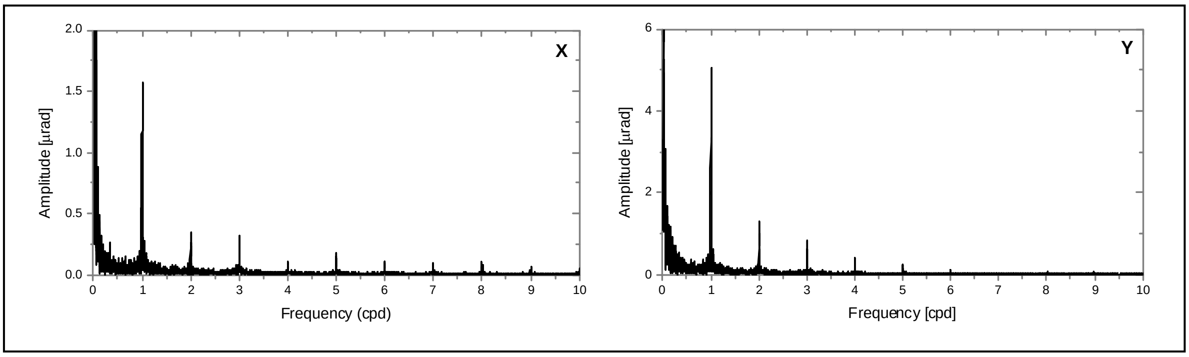

Figure 6: Amplitude spectra of the tilt signals measured at the Church Kecske

The measured data were also analyzed by the ETERNA 3.30 tidal analysis program developed by Wenzel [6]. The results are given in Table 2. The program ETERNA calculates the amplitudes for groups of waves having frequencies close to each other therefore the amplitudes obtained by tidal analysis are slightly different from the ones obtained by Fourier-transformation. The differences between the calculated and theoretical frequencies of the individual tidal components are very small and can be the result of the temperature effect. As a consequence of the temperature the amplitude ratios between the calculated tidal amplitudes are somewhat different from the theoretical ones [5]. The deviations are especially high at K_1 and P_1 because the frequency of these two components is very near to 1 cpd and therefore the influence of the temperature effect is very strong. Summarizing the results of the tidal evaluation we can say that tidal constituents in the tilt data are present.

Tidal waves	Theoretical frequency [cpd]	Calculated frequency [cpd]	Amplitude of the X tilt [μrad]	Amplitude of the Y tilt [μrad]
Q_1	0.893244836	0.89355	0.06414	0.18501
O_1	0.929532006	0.92871	0.08523	0.13500
P_1	0.997264448	0.99756	1.14715	2.60418
K_1	1.002738963	1.00195	1.56523	5.06725
J_1	1.039036005	1.03557	0.14551	0.37570
N_2	1.895984200	1.89697	0.02873	0.03168
M_2	1.932280717	1.93213	0.06227	0.06041
S_2	2.000000000	1.99951	0.34653	1.30189
K_2	2.005477926	2.00537	0.26298	0.38748

Table 2: Results of the tidal analysis of the data measured at the Church Kecske in Sopron

5. Conclusions

The tidal waves can unambiguous be detected at large objects and in special circumstances in their vicinities. The tidal components with daily period are strongly influenced by the daily variation of the temperature. According to our investigations the observation of long term variations of the tidal amplitudes can be used for detecting changes in the deformations and movements of large objects and in the transfer function between ground and object. The reason that tidal waves can be observed on large objects is maybe that these objects gain tidal waves like pendulums.

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