Observation of Landslide Movements by Geodetic and Borehole Tilt Measurements

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Abstract

The high loess banks of the River Danube are prone to landslides. In 2007, a large slump of the high bank began to develop at Dunaszekcső. In August 2007 two borehole tiltmeters were installed for continuous monitoring of the high bank tilts and a geodetic network was established for GPS measurements, precise levelling and total station measurements. Geodetic measurement campaigns have been carried out 3-6 (generally 4) times a year depending on the intensity of the movements. A new adjustment method was developed to process measurement data obtained from the integrated geodetic observations. Groundwater table variations and the water level of the River Danube were also measured to investigate the relationships between the tilts of the high loess bank and the water levels. Numerical relations between tilts and water level variations were determined. The paper describes the measurement methods and results.

Key words: landslide, borehole tiltmeter, GPS measurement, precise levelling

1 INTRODUCTION

The high loess walls on the right bank of the Danube have been affected by landslides since centuries (Lóczy et al., 1989). The marks of these historical landslides can be seen along the Danube at Dunaszekcső and in its vicinity, (Újvári et al., 2009). A crack, about 220 m long, appeared nearly parallel to the river-bank in 2007, indicating the commencement of a new sliding process. This year a geodetic network was established and tiltmeters were installed to observe the deformations of the affected high bank. On 12 February, 2008, a large landslide occurred at Dunaszekcső and during the subsequent years the movements spread towards the south. The monitoring network was extended to observe the movements of the new unstable parts of the high bank. In this paper, we describe the measuring technology and the dynamic evolution of the high bank sliding using 6 years records of tilt and geodetic deformation monitoring (2007-2013) complemented with observation of ground-water level and water level of the River Danube.

2 GEODETIC MEASUREMENTS

Four concrete pillars were built on the test site in 2007 and the fifth was added in 2009, as reference benchmarks. Two of the benchmarks (100 and 200) were established far from the moving blocks, while the other three (300, 400 and 500) benchmarks were placed close to them. Twenty-one additional small concrete benchmarks were built on both the stable and the moving parts of the monitored area near the cracks. Figure 1a shows the Digital Terrain Model (DTM) of the test site. Black circles and red points denote the locations of the reference benchmarks (100-500) and the small benchmarks, respectively. The construction of the reference and small benchmarks are described by Újvári et al. (2009). In 2008, after considerable mass movements on 12 February, 2008, some benchmark points were lost and the measurements of several points became impossible due to the restricted visibility of GPS satellites. For this reason, new points were fitted into the network enlarging the study area to the south. Meanwhile a new rupture line appeared behind the scarp and extended onward to the southern part of the high bank. The new small benchmarks are denoted by white circles in Fig. 1a. Figure 1b displays benchmark numbering on the investigated part of the high bank together with crack lines.

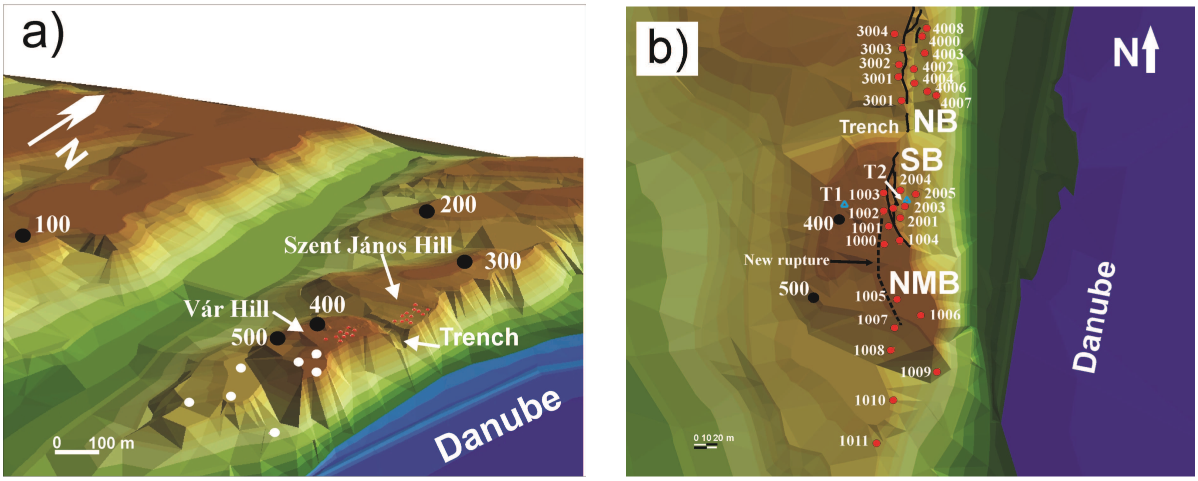

Figure 1 DTM of the Dunaszekcső test site. a) Reference benchmarks (black circle), small benchmarks (red points) established in 2007; small benchmarks (white circle) established in 2009. b) Numbering of the benchmarks; cracks appeared in 2007 (continuous black line); new rupture line appeared in 2010 (dashed black line); T1 and T2 denote the location of the borehole tiltmeters.

The horizontal and vertical displacements were measured first by two Leica 1200 GPS receiver pairs and later by five GPS receiver running parallel. The position of benchmark points on the sliding blocks of the high bank were also measured by total station Leica TC2002 and all of these data were processed together in a network adjustment procedure. Precise levelling was carried out in the same network. The GPS height determination of the small benchmarks was controlled by a precision levelling instrument Leica DNA 03 and levelling data were used to improve the heights measured by GPS.

During the first measuring campaign the initial coordinates of benchmark 300 were determined from the active GNSS network of Hungary. The baselines between the reference stations were determined on the basis of several hours of measurement time, while the smaller benchmarks were separately measured from two near reference stations (300, 400 or 500) for 15-30 minutes (Fig. 1a). The estimated baselines were adjusted rigorously by the GPS-NET program, which was developed for the identification of systematic errors (Bányai, 1991), the estimation of main phase centre offsets (Bányai, 2005) and the free adjustment of a local 3D deformation network.

The integrated adjustment of geodetic observations was carried out in the WGS-84 coordinate system (used by GNSS techniques) by means of a new adjustment procedure (Bányai, 2013). All the data were re-adjusted so that the coordinate changes of the pillars were minimized by least-squares method with respect to the coordinates measured in the first epoch. The accuracy of the adjusted coordinate components is 2-3 mm and the pillars fulfil the stability requirements. Results of the adjustment are the Cartesian coordinate time series of the monitoring points, furthermore the local topocentric coordinate changes (North, East and Up) are given relative to the first measurement epoch.

The movements of the closely related point groups – the north (NB), south (SB) and the newly moving block (NMB) – were investigated by similarity transformation (Fig. 3.). Initially a centre of gravity of the selected point groups (NB, SB, NMB) were determined in WGS84 coordinate system in the reference epoch, then the point coordinates (N, E and U) were transformed into the ellipsoidal topocentric coordinate system defined in the centre of gravity. All point coordinates measured in the first (reference) and subsequent campaigns were transformed into the initial topocentric system. Henceforth, in the first step, the mean coordinates of the points were determined for the investigated epoch, which gave the mean translations ($t_{N,}$ t_E and t_U) in the topocentric system. In the second step, the mean coordinates were subtracted from the coordinates and the average scale deviation was calculated using topocentric distances. After the correction of the scale deviation, the rotations about the axes were estimated by least-squares method and successive approximation. Figure 2a shows the positive rotation in the left-handed topocentric coordinate system. Figure 2b shows the normal vector of a rotated plane in the same coordinate system. The following equations can be written, which describe the connection between the two systems:

$$N_t = \beta , \quad (1)$$

$$E_t = -\alpha , \quad (2)$$

$$a = \tan\left(N_t\right), \quad (3)$$

$$b = \tan\left(E_t\right), \quad (4)$$

$$T = \tan^{-1}\left(\sqrt{a^2 + b^2}\right), \quad (5)$$

$$A = \tan^{-1}\left(\frac{b}{a}\right), \quad (6)$$

where N_t and E_t are the tilt values – they can also be measured directly by tiltmeters – towards the north and south, respectively; T is the maximal tilt and A is its azimuth.

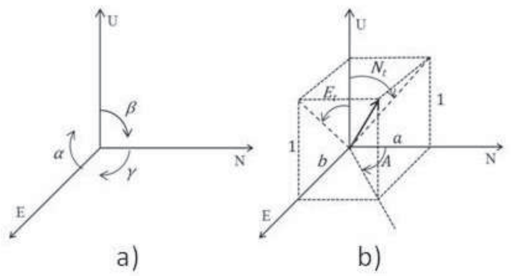

Figure 2 Coordinate system. a) Positive rotations of the left-handed coordinate system. N, E and U denote the north, east and up axes, respectively. b) The normal vector of a rotated plane in the same coordinate system.

Figure 3 represents some results of the geodetic measurements. In Fig. 3a the horizontal movements of the high bank can be seen between 17.06.2009 and 24.12.2012. The time series of the movements (N, E and U) of points 1000 and 1002 are shown in Fig. 3b. It is apparent, that the movement of the points increased in 2010. Point 1000 shows an intensive movement towards east and a significant subsidence. Figure 3c shows the tilts of NB, SB and NMB calculated from geodetic measurements. Tilt values determined from tilt measurements are also given for the epochs of the GPS campaigns, since tiltmeter T2 is placed on the area of the south block (Fig.1b). The tilt values measured by tiltmeters are much smaller than the block tilts determined from similarity transformation. The reason for this difference is probably that the block was broken up into fragments. Average displacements (t_N, t_E and t_U) and maximal tilts and their azimuths (T and A) of the NB and SB during the intensive rupture are listed in Table 1.

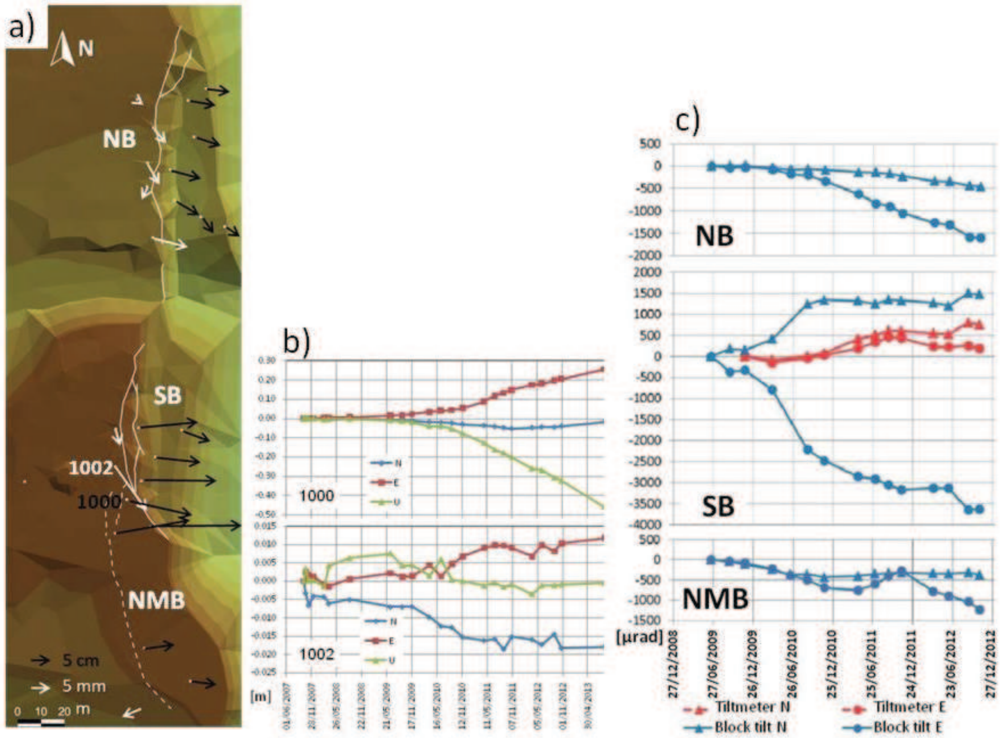

Figure 3 Results of geodetic measurements. a) Horizontal coordinate changes between 17.06.2009 and 24.12.2012 (the scale of the black and white arrows are different). b) Coordinate time series of points 1000 and 1002. c) Measured (red curves) and estimated tilts of the north (NB), south (SB) and new moving (NMB) blocks (see also part a).

3 TILT MEASUREMENTS

In 2007, two dual-axis borehole tiltmeters (Model 722A, Applied Geomechanics Inc., USA), were installed in boreholes with a depth of 3 m. The instruments have a dual-axis tilt sensor and a built-in temperature sensor for the measurement of the instrumental and ground temperature. The resolution of the tilt and temperature sensor is 0.1 µrad and 0.1 C°, respectively. The tiltmeters were installed so that their positive x tilt axes point to the east and their positive y axes to the north. One was placed on the stable part of the southern high bank (T1) and another on the southern sliding block (T2, see Fig. 1b). The installation of the tiltmeters is described by Mentes et al. (2013) in detail. The tilt data were recorded hourly. After the mass movements on 12 February, 2008, the tiltmeter on the southern sliding block went out from its measuring range and it had to be re-installed in an adjacent borehole. Tilt measurements by tiltmeter T2 were started in November, 2009 and continued till May, 2010, since the tilts were higher than the measuring range of the instrument. The tilt measurements were started again in August, 2010, when the tilts became small enough to be measured by the instrument.

Figure 4 shows the tilt record before the first slump on 12, February 2008. Tiltmeter T1 on the stabile part of the southern block recorded a continuous tilt to south and west directions while tiltmeter T2 on the unstable part (denoted by UB in Fig. 5.) recorded a continuous eastward tilt till 22, January 2008 and after that phase the direction of the tilt had changed till the slump. The tilt values were so high between the tilt direction change and the slump, that the tiltmeter went out of the measuring range. This phenomena was the precursor of the large slump. Figure 5 shows the high bank after the slump on 12 Feb 2008 and the locations of the groundwater sensors.

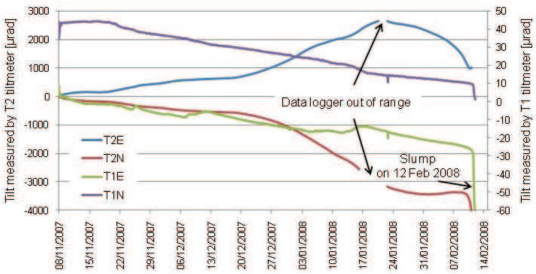

Figure 4 Tilt of the stable (T1) and unstable (T2) parts of the high bank before the landslide on 12 Feb 2008. T1N and T2N are the north, while T1E and T2E are the east components of the instruments. Tilt curves going to positive direction mean tilts toward to east and north

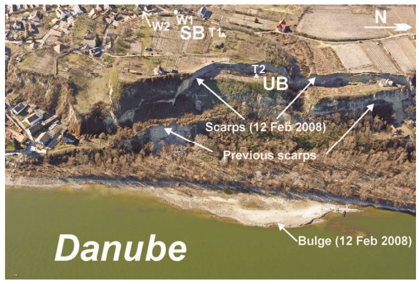

Figure 5 The oblique aerial photo of the high bank after the landslide on 12 Feb. 2008. UB and SB are the unstable and stable part of the southern block. T1, T2 and W1, W2 denote the location of the borehole tiltmeters and the ground water level gauges, respectively

The water level variations of the River Danube, the ground-water table variations and the tilt records are drawn in Fig. 6. A multivariable regression analyses was carried out between these quantities. The results are listed in Table 2. The ground level change in the W1 observing well causes the largest tilt: an increasing of the water level of one metre causes a tilt of 1028 µrad in east direction.

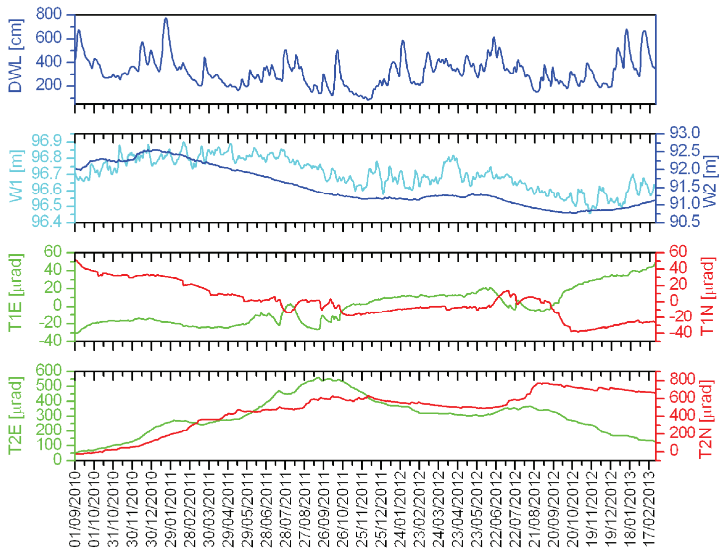

Figure 6 Water level variations of the River Danube (DWL), ground-water level (W1 and W2) relative to the Baltic Sea level and tilt recordings for the period of 1 Sept. 2010 to 27 Feb. 2013. Tilt curves going in positive direction mean tilts toward to east and north.

Table 1 Average translations (t_N, t_E and t_U) and maximal tilts and their azimuths (T and A) of the north and south blocks during the intensive rupture

	t_N [m]	t_E [m]	t_U [m]	T [°]	A [°]
NB	-0.47	2.48	-9.03	8	-101
SB	1.21	3.55	-6.96	19	84

Table 2 Linear regression coefficients between hydrological data and tilts [µrad/m]

Tiltmeter	Regression coefficients		
	W1	W2	Danube
T1 east	-36	-24	4
T1 north	-26	36	1
T2 east	1028	-208	-28
T2 north	576	-434	-20

4 CONCLUSIONS

Results show that the combined geodetic and tilt measurements are suitable for studying the dynamic and kinematic processes of landslides. The investigation of the relationship between tilt and water level (river and ground-water) variations revealed unambiguously that the ground-water variations have the largest effect on the stability of the high bank. The increased tilt values and the abrupt change of tilt directions can signal a landslide to be going to happen in the near future.

ACKNOWLEDGMENTS

This work was funded by the Hungarian National Research Fund (OTKA) under project No. K 78332 and K 81295.

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