Observing slope stability changes on the basis of tilt and hydrologic measurements

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Abstract. In Hungary, the high loess bank of the River Danube in Dunaszekcső has been moving with varying rate since 2007. Here a large landslide took place in 2008. After this large slump the small movements continued and a new landslide has been developing since 2010. On the high bank a geodetic monitoring network was established in September 2007. At the same time two borehole tiltmeters were also installed on the area to be investigated. Two ground water level sensors were also installed in two wells in the background of the high bank. Additionally data of water level of the River Danube was available from the webpage of the Directorate of Water Management.

The high-sensitive tiltmeters made it possible to study the relationships between the small tilts of the high bank and water levels. In this paper the test area with the instruments and the results of the measurements are described. The investigations show that the movements are in very strong connection with the variation of the ground water level and less depend on the variation of the water level of the River Danube. Results of the multiple regression analysis between tilt components and water levels showed that the temporal variation of the regression coefficients is in close connection with the stability of the high bank. The characteristic tilt processes, 3-4 weeks before large movements, and the slope weaken inferred from the regression coefficients can be used for early warning of landslides.

Keywords. Borehole tiltmeter, ground water, river water level, landslide, slope stability

1 Introduction

Since landslides cause significant damage to human lives and properties in every year, new and effective methodologies are needed to be developed for a better understanding of landslide processes to enable rational decisions for landslide risk management (e.g. Sterlacchini et al., 2007). For study of the kinematic and dynamic properties of landslide processes, geodetic observations, usually the traditional GPS, EDM measurements and precise leveling are repeated at different time epochs. The intermittent, yearly once or twice repeated geodetic measurements are not suitable for detection of short periodic and small movements (Gili et al., 2000). The new geodetic measurement techniques, monitoring by automatic taheometer (Schmalz et al., 2010), low cost GNNS network (Glabsch et al., 2009), TDR and VTPS techniques (Thuro et al., 2010), ground-based microwave interferometry (Rödelsperger et al., 2010) have sufficient temporal resolution to monitor daily variation of movements but their resolution is not sufficiant for observing very small displacements in the range from 0.1 μm to 0.1 mm. Persistent scatterers SAR interferometry (PSInSAR) allows observation of the temporal and spatial evolution of slow (several mm per year) landslides (Nikolaeva et al., 2014). Its temporal resolution depends on the period between two acquisition times (Hanssen, 2001), which is in a period of 12 days.

At present inclinometric measurements are generally used for tilt monitoring (e.g. Simeoni and Mongiovi, 2007; Maio et al., 2010). These instruments measure the ground tilt (deformation of a borehole with a depth of 10-100 m). The inclinometer is moved in a borehole and the tilt of the borehole is measured at different depths with a resolution of about 0.1 mm/m (100 microradian). The measurements are repeated in time intervals of some weeks or months depending on the rate of the deformation. These instruments are applied to detect and determine the depth of the shear zones and the rate of the movements but they are also not suitable for monitoring of short periodic small movements. In contrast with the inclinometers the highly sensitive (0.1 μrad corresponding to 0.001 mm/m) continuously recording borehole tiltmeters are well suited for observation of short periodic and very small ground tilts due to ground water level and pore pressure variations, as it was proved by pump tests (Fabian and Kümpel, 2003; Kümpel et al., 2001). Such kind of tiltmeters was used for landslide monitoring by e.g. García et al. (2010). Highly sensitive, continuously recording borehole tiltmeters

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and extensometers provide more information about the landslide movements than the intermittent measurement techniques. They make possible to seek for quantitative connections between streambank movements and hydrological, meteorological processes (stream stage, ground water table variations and precipitation events), which are in connection with the slow seepage material transport from the basal to the river and the river erosion of the basal material. The direct effect of hydrological processes onto movements and deformations of landslide prone areas were barely investigated till now. To show the applicability of highly sensitive, continuously recording tiltmeters for understanding the effect of different agents on evolution of landslides, in this paper the possible quantitative relationships between tilts of the high loess bank of the River Danube and the variation of the water level of the river and the ground water table, are investigated by borehole tiltmeters on the high loess bank of the River Danube at Dunaszekcső. The earlier results of the tilt measurements were published by Mentes and Bányai (2014), Mentes (2015) and Mentes et al. (2015). In this paper the newest results are demonstrated.

2 Test site

The high (30-60 m) loess walls along the right side of the River Danube are prone to landslides. One of the dangerous landslides occurred in Dunaszekcső on 12 February 2008. Dunaszekcső is situated about 20 km towards north from the southern board of Hungary. Figure 1 shows the location (left lower corner) and the Digital Terrain Model of the test site. The geologic structure of the high bank at Dunaszekcső and in its surroundings is described by Újvári et al. (2009) in detail.

3 Methods

The tilt of the loess wall was measured by the highly stable and sensitive Model 722A borehole tiltmeters produced by Applied Geomechanics Inc (1991). This instrument has a dual-axis tilt sensor and a built-in temperature sensor which is used for the measurement of the borehole temperature. The resolution of the tilt and temperature sensors is 0.1 µrad and 0.1 °C, respectively (Applied Geomechanics Inc., 1991). Two borehole tiltmeters were installed on the high bank in 2007. One tiltmeter (T1) was installed on the stable and the other instrument (T2) on the unstable part of the high wall as it is shown in Fig. 1. The instruments are placed in boreholes with a depth of 2.5 m and they are oriented so that their +x axes point to the east and their +y axes to the north. The installation of the tiltmeters is described by Mentes et al. (2012) in detail. Tilt measurements are carried out since October 2007. Two ground water table gauges were installed at locations GW1 (in October 2009) and GW2 (in March 2010). GW1 is located ca. 100 m west of the sliding block, while GW2 is situated approximately 200 m south of GW1 at a slightly lower height (see Fig. 1). Tilt, borehole, air temperature and ground water level data were recorded hourly while water level data of the River Danube was available daily. The tilt and ground water data were downloaded from the data loggers when the batteries were changed every 40-50 days. Daily water level data of the River Danube is measured relative to the zero point of the water gauge, which has a height of 79.92 m above the Baltic Sea. This data has been downloaded from the publicly available website of the Directorate of Water Management (www.vizugy.hu, last accessed: 10 May 2015).

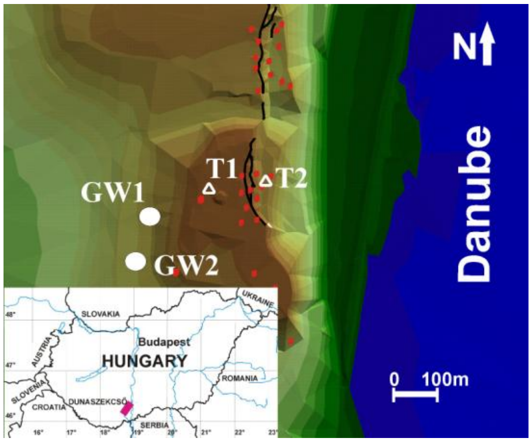

Fig. 1 Location of the test site in Hungary (left lower corner) and the Digital Terrain Model (DTM) of high loess bank with the location of the instruments. T1 and T2 denote the borehole tiltmeters on the stable and on the moving part of the high bank, respectively. GW1 and GW2 show the locations of the ground water table sensors. Black lines denote the cracks between the stable and moving parts. Red circles are geodetic control points.

To get a quantitative insight into the effect of the ground and river water level variations on the high bank tilts, the tilt data series were subjected to Multivariable Regression (MVR) analysis. Data processing was carried out by the ORIGIN 9.1 (2014) program.

4 Results

Figure 2 shows the tilts of the stable (T1) and unstable (T2) part of the high bank between 8 November 2007 and 12 February 2008. In this period the stable part of the high bank is tilting slowly to the west and to the south (T1E and T2N are going in negative direction). The unstable part of the high bank is tilting intensively to the east and to the south (T2E is going in positive and T2N to negative direction). The tilt of the unstable part accelerated from 20 December 2007 and the unstable part began to subside slowly with large alternating tilts (this part is deleted from Fig. 2. since the tilts were higher than the measuring range of the tiltmeter.). After these large tilts the direction of the tilt changed to an intensive tilt to the west till the large slump on 12 February 2008. The tiltmeter T2 slide down together with the unstable part and recorded the slide within its measuring range as it can be seen in Fig. 2. The large tilt values and the tilt direction change are in connection with the decreased and lost stability of the high bank and could be served as a precursor of the landslide.

After the large mass movement on 12 February 2008, the tiltmeter T2 on the sliding block went beyond its measurement range and must have been re-installed in a new borehole. Tilt measurements by this tiltmeter were started in November, 2009 and continued till May, 2010, since the tilts were higher than the measuring range of the instrument. The recorded data were unusable to study the tilt processes of the slumped part of the high bank. The second re-installation of the instrument was in August, 2010. Figure 3 shows the tilts of the stable high bank from 8 Nov 2007 till 31 Aug 2010 when the T2 tiltmeter was re-installed. It can be seen that the tilts were rather small but the stable part of the high bank was intensively seesawing looking for its new equilibrium state.

Figure 4 shows the high bank tilts, the ground water table and the water level variations of the River Danube between 1 January 2011 and 15 March 2015. The stable part of the high bank oscillated with an amplitude of 20-60 µrad in the north direction (T1N component). The east component (T1E) shows oscillating tilts of negligible amplitudes. The rate of the tilts increased both in the north and in the east directions from the beginning of 2013, but the resulting tilt in both directions is less than 120 µrad, not considerable.

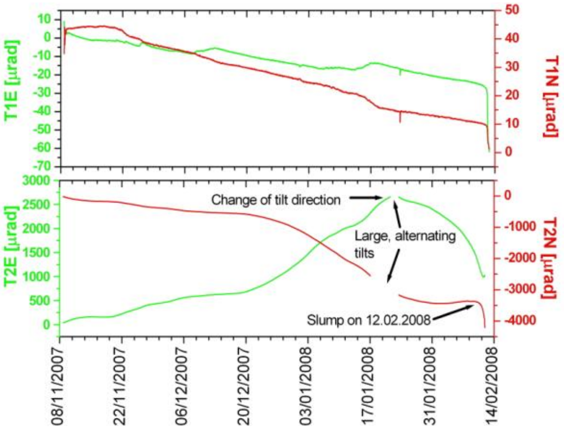

Fig. 2 Tilts of the stable (T1E, T1N) and unstable (T2E, T2N) part of the high bank between 8 November 2007 and 12 February 2008. T1E and T2E are the east and T1N and T2N are the north components of the tilts. Curves going in the positive direction mean eastward and northward tilt, while going in the negative direction mean westward and southward tilts.

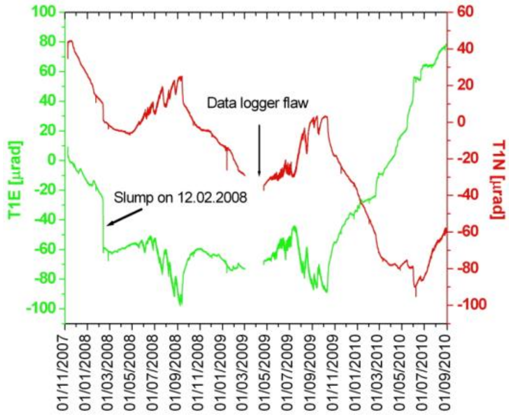

Fig. 3 Tilts of stable part of the high bank (T1E, T1N) between 8 Nov 2007 and 31 Aug 2010. T1E and T1N are the east and north components of the tilts, respectively. Curves going in the positive direction mean eastward and northward tilt, while going in the negative direction mean westward and southward tilts.

During this period the tilt of the unstable part was much higher than that of the stable part. The resulting tilt in both directions is in the order of

1000 µrad. The movement of the unstable part is characterized by high tilt rates in the west and in the north. The rate of the tilts increased both in the north and in the west directions from the beginning of 2013, similarly to the tilt rate of the stable part. The increased tilt rates are probably in connection with the arising of cracks (see Fig. 5). The subsidences with the magnitude of 0.5 - 2 m between the cracks were arising and developed during the high alternating tilts of the unstable part between August 2014 and March 2015.

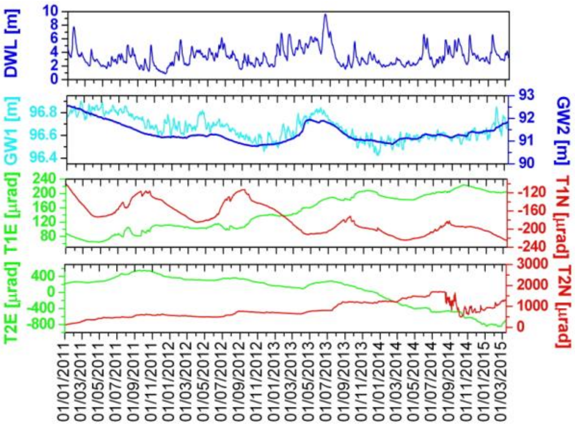

Fig. 4 Tilts of stable (T1E, T1N) and unstable part (T2E, T2N) of the high bank between 1 January 2011 and 15 March 2015. T1E, T2E and T1N, T2N are the east and north components of the tilts, respectively. Curves going in the positive direction mean eastward and northward tilt, while going in the negative direction mean westward and southward tilts. GW1 and GW2 denote the ground water tables and DWL denotes the water level of the River Danube.

The results of the MVR analysis are summarised in Table 1. The tilt components were separately involved together with the ground water tables (GW1 and GW2) and the water level of the River Danube into the MVR analysis. The table shows the regression coefficients (caused tilt per water level change of one metre) between each tilt components and the water levels. The calculations were carried out separately for each year to investigate the changes of the regression coefficients due to stability changes of the high bank. The first new crack after the large sump in 2008 appeared in the autumn of 2010. The high regression coefficients between the tilts of the unstable part and the water levels are very diverse showing the increased instability of the high bank. In 2013 and 2014 the regression coefficients are higher than earlier since some new cracks were arising in 2013 and 2014 and considerable parts of the high bank were subsided (0.5 – 2 m) between the existing and newly arised cracks. Figure 5 shows the geological settings of the high bank, the aproximate dates of the arising of the cracks and the presumed ground water flow and material transport during the landslide process.

Table 1. Regression coefficients between tilt data and the water level of the River Danube (DWL), the ground water levels (GW1 and GW2). T1E, T1N and T2E, T2N denote the east and north tilt components measured on the top (stable part) and on the unstable (sliding) part of the high bank, respectively. Plus sign denote tilts in the east and north, negative sign in the west and south directions. R^2 is the R-square of the adjustment.

Tilt	Year	GW1 µrad m^{-1}	GW2 µrad m^{-1}	DWL µrad m^{-1}	R^2
T1E	2011	-13	-35	4	0.800
	2012	-41	-44	3	0.658
	2013	-207	33	-2	0.484
	2014	-23	63	2	0.533
T1N	2011	-193	3	7	0.388
	2012	28	-98	-1	0.793
	2013	67	-56	1	0.619
	2014	0	28	2	0.335
T2E	2011	-400	-178	18	0.862
	2012	167	95	-8	0.373
	2013	369	-83	11	0.733
	2014	-156	-1095	15	0.859
T2N	2011	185	-287	-16	0.965
	2012	33	-512	-6	0.933
	2013	-1380	-71	-30	0.690
	2014	776	-1198	-22	0.531

It can be seen that the effect of the ground water on the high bank tilts is from one to two orders of magnitude higher than that of the water level changes of the River Danube. The changing signs of the regression coefficients can be explain with the different stability state of the high bank and with the interaction between the ground water level and the water level of the river. This latter is especially obvious in the case of the east tilt component of the unstable part of the high bank (T2E) where regression coefficients between T2E and GW2 have opposite signs. It means that the increasing water level of the River Danube hinders – by its hydrostatic pressure – the ground water flow into the river (see Fig. 5). The effect of the water level variation of the river on the tilt of the unstable part of the high bank is about one order of magnitude higher than of the tilt of the stable part. The River Danube is washing away the north part of the high bank more intensive than the south part and this undermining causes the northward tilt of the unstable part. The sinking masses of the highbank push the material simultaneously under the stable high bank and into the River Danube (Fig. 5). The ground water washes the loess continuously into the river causing the alternating east-west tilt of the high bank (Figs. 3 and 4).

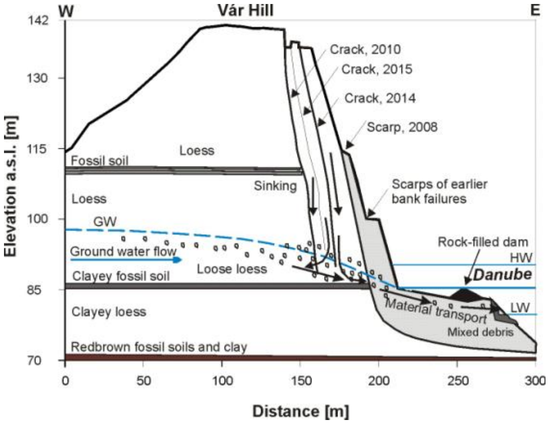

Fig. 5 Landslide process of the high loess bank of the River Danube at Dunaszekcső. (after Moyzes and Scheuer, 1978; Pécsi et al., 1979; Kraft, 2005; Újvári et al., 2009))

5 Conclusions

Our study showed that the results of the continuous borehole tilt measurements together with the ground water and river water level data can be used for study of sliding processes of high river banks and contribute to a better understanding of these processes than e.g. the intermittent geodetic measurements. The presented measurements can be used as continuous data source for an early warning system particularly when, the instruments are the parts of an on-line measuring system. However, a lot of research is still necessary to obtain an operating early warning system, the following results of this study can be assumed as a possible precursor of an impending landslide:

- high tilt values with alternating direction precede large movements. The duration between the beginning of the large tilts and large movements can be very different, from some weeks to some months. Other parameters must also be taken into consideration for a more accurate forecast of taking place of a large movement.
- increased tilt rates in a direction and an abrupt change of the direction.
- increasing regression coefficients between the tilts and the hydrologic parameters indicate that the stability of the high bank is growing weaker.

An exact date of the landslide cannot be stated on the basis of the above mentioned warning signals but they are very important for taking protective measures to mitigate possible damages.

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References

Applied Geomechanics Inc. (1991). User's Manual No. B-91-1004: Model722 Borehole Tiltmeter. Santa Cruz, California, USA.

Fabian, M., and H.J. Kümpel (2003). Poroelasticity: observations of anomalous near surface tilt induced by ground water pumping. Journal of Hydrology 281 (3), pp. 187-205.

García, A., Hördt, A., and Fabian (2010). Landslide monitoring with high resolution tilt measurements at the Dollendorfer Hardt landslide, Germany. Geomorphology 120, pp. 16-25.

Gili, J.A., Corominas, J., and J. Rius (2000). Using Global Positioning System techniques in landslide monitoring. Engineering Geology, 55, pp. 167-192.

Glabsch, J., Heunecke, O., and S. Schuhbäck (2009). Monitoring the Hornbergl landslide using a recently developed low cost GNNSsensor network. Journal of Applied Geodesy. 3, pp. 179-192. doi:10.1515/JAG.2009.019.

Hanssen, R.F. (2001). Radar Interferometry: Data Interpretation and Error Analysis. Kluwer Academic Publishers, Dordrecht, pp. 328.

Kraft, J. (2005). A dunaszekcsői Töröklyuk kialakulása és fennmaradása (Evolution and survival of the Töröklyuk cave at Dunaszekcső). Mecsek Egyesület Évkönyve a 2004-es egyesületi évről. Új Évfolyam, vol. 8, pp. 133–153 (in Hungarian).

Kümpel, H.J., Lehmann, K., Fabian, M., and G. Mentes (2001). Point stability at shallow depths: experience from tilt measurements in the Lower Rhine Embayment, Germany, and implications for high resolution GPS and gravity recordings. Geophysical Journal International 146, pp. 699-713.

Maio, C.D., Vassallo, R., Vallario, M., Pascale, S., and F. Sdao (2010). Structure and kinematics of a landslide in a complex clayey formation of the Italian Southern Apennines. Engineering Geology 116, pp. 311-322.

Mentes, Gy. (2015). Investigation of dynamic and kinematic landslide processes by borehole tiltmeters and extensometers. Procedia Earth and Planetary Science 15, pp. 421-427. doi:10.1016/j.proeps.2015.08.025.

Mentes, Gy. and L. Bányai (2014). Observation of Landslide Movements by Geodetic and Borehole Tilt Measurements. In: Kopáčik, A., Kyrinovič, P., and M. Štroner (Eds). Proceedings of the 6th International Conference on Engineering Surveying INGEO, pp. 53-58.

Mentes, Gy., Bányai, L., Gábor Újvári, G., and B.V. Bódis (2015). Rutschungsprozesse des Hochufers der Donau bei Dunaszekcső. Allgemeine Vermessungs-Nachrichten, 122 (5), pp. 200-206.

Mentes, Gy., Bányai, L., Újvári, G., Papp, G., Gribovszki, K., and B.V. Bódis (2012). Recurring mass movements on the Danube's bank at Dunaszekcső (Hungary) observed by geodetic methods. Journal of Applied Geodesy, 6 (3-4), pp. 203-208.

Moyzes, A., and Gy. Scheuer (1978). A dunaszekcsői magaspart mérnökgeológiai vizsgálata. (Engineering geological investigation of the high bank at Dunaszekcső). Földtani Közlöny 108, pp. 213-226 (in Hungarian with German abstract).

Nikolaeva, E., Walter, T.R., Shirzaei, M., and J. Zschau (2014). Landslide observation and volume estimation in central Georgia based on L-band InSAR. Nat. Hazards Earth Syst. Sci., 14, pp. 675-688, doi:10.5194/nhess-14-675-2014.

ORIGIN 9.1 (2014) http://www.originlab.com. Accessed 11 August 2014.

Pécsi, M., Schweitzer, F., and Gy. Scheuer (1979). Engineering geological and geomorphological investigations of landslides in the loess bluffs along the Danube in the Great Hungarian Plain. Acta Geologica Hungarica 22, pp. 327-343.

Rödelsperger, S., Läufer, G., Gerstenecker, C., and M. Becker (2010). Monitoring of displacements with ground-based microwave interferometry. Journal of Applied Geodesy. 4, pp. 41-54. doi:10.1515/JAG.2010.005.

Schmalz, T., Buhl, V., and A. Eichhorn (2010). An adaptive Kalman filtering approach for the calibration of finite difference models of mass movements. Journal of Applied Geodesy. 4, pp. 127-135. doi:10.1515/JAG.2010.013.

Simeoni, L., and L. Mongiovi (2007). Inclinometer Monitoring of the Castelrotto Landslide in Italy. Journal of Geotechnical and Geoenvironmental Engineering, 133 (6), pp. 653-666, doi:10.1061/(ASCE)1090-0241(2007)133:6(653).

Sterlacchini, S., Frigerio, S., Giacomelli, P., and M. Brambilla (2007). Landslide risk analysis: a multi-disciplinary methodological approach. Nat. Hazards Earth Syst. Sci., 7, pp. 657-675. www.nat-hazards-earth-syst-sci.net/7/657/2007/.

Thuro, K., Singer, J., Festl, J., Wunderlich, T., Wasmeier, P., Reith, C., Heunecke, O., Glabsch, J., and S. Schuhbäck (2010). New landslide monitoring techniques – developments and experiences of the alpEWAS project. Journal of Applied Geodesy. 4, pp. 69-90. doi:10.1515/JAG.2010.008.

Újvári, G., Mentes, Gy., Bányai, L., Kraft, J., Gyimóthy, A., and J. Kovács (2009). Evolution of a bank failure along the River Danube at Dunaszekcső, Hungary. Geomorphology, 109, pp. 197-209.