Gy. Mentes*

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

DOI 10.1515/jag-2016-0020
Received June 15, 2016; accepted March 17, 2017

Abstract: In Hungary, the high loess bank of the River Danube in Dunaszekcső has been moving with varying rate since 2007. On the high bank a geodetic monitoring network was established in September 2007. At the same time two borehole tiltmeters and later two ground water level sensors were also installed. The high-sensitive tiltmeters made it possible to study the relationships between the small tilts of the high bank and the ground water levels and 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 investigations also showed 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. The characteristic tilt processes, 3–4 weeks before large movements, and the slope stability changes inferred from the relationships between tilts and water level variations can be useful 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 [1]. For study of the kinematic and dynamic properties of landslide processes, geodetic observations, usually the traditional GPS, EDM measurements and precise levelling 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 [2]. The new geodetic measurement techniques, monitoring by automatic tacheometer [3], low cost GNSS network [4], time domain reflectometry (TDR) and reflectorless video tacheometry (VTPS) techniques [5], ground-based microwave interferometry [6] have sufficient temporal resolution to monitor daily variation of movements but their resolution is not sufficient for observing very small displacements in the range from 0.1 μm to 0.1 mm. Persistent scatterer SAR interferometry (PSInSAR) allows observation of the temporal and spatial evolution of slow (several mm per year) landslides [7]. Its temporal resolution depends on the period between two acquisition times [8], which is in a period of 12 days. For development of early warning systems in landslide monitoring different measuring methods were integrated to a complex network with a knowledge base. In these systems deformations, movements, meteorological, geophysical, hydrological parameters are continuously measured, analysed and interpreted on the basis of existing geodata [5, 9, 10, 11, 12].

At present inclinometric measurements are generally used for tilt monitoring, e.g. [13, 14]. 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 0.1 μm/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 [15, 16]. Such kind of tiltmeters were used for landslide monitoring by e.g. García et al. [17]. Highly sensitive, continuously recording borehole tiltmeters 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

***Corresponding author: Gy. Mentes,** Geodetic and Geophysical Institute, Research Centre for Astronomy and Earth Sciences, Hungarian Academy of Sciences, Csatkai E. u. 6-8, H-9400, Sopron, Hungary, e-mail: mentes@ggki.hu

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. The previous publications [18, 19, 20] only described the movement processes of the high bank measured by GPS, precise levelling and borehole tiltmeters but the reasons for the movements were not effectively investigated. The purpose of this paper is to show the applicability of highly sensitive, continuously recording tiltmeters for understanding the effect of different agents on evolution of landslides. Since the effect of the precipitation, temperature and the vegetation is investigated in [21] and the study of the effect of recent tectonics needs long-term records (10–20 years), 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 only investigated. The results of the measurements are interpreted on the basis of the geological structure of the high bank. It is shown that the stability variations of the high bank can be inferred from the connection between water levels and tilt values which can be used as input parameters for an early warning system.

2 Test site

In Hungary the high (30–60 m) loess banks along the right side of the River Danube are prone to landslides. The high loess bank in Dunaszekcső has been moving with varying rate since 2007. One of the dangerous landslides occurred here 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 oblique aerial photo of the high bank.

The height of the loess bank at the study area is 142 m a.s.l. The basement formations at Dunaszekcső are Triassic-Jurassic limestones located at 200–250 m below the surface. The basement rocks are overlaid with clayey and sandy sediments formed in the Upper Miocene and Pliocene. Above these layers, the uppermost 70 m sediment sequence consists of sandy and clayey loess layers with brown to red fossil soils accumulated during the Pleistocene (see also Fig. 6). The detailed description of the geologic structure of the high bank and its surroundings is in [22].

After the large landslide in 2008 the movements of high bank continued with varying rate and new cracks appeared (see Fig. 2).

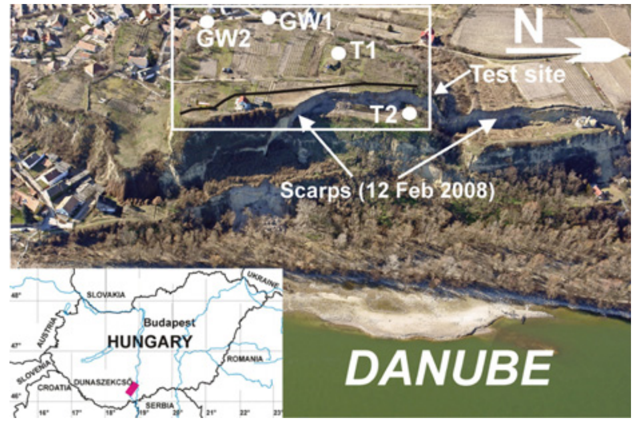

Figure 1: Location of the test site in Hungary (left lower corner) and the oblique aerial photo of the high loess bank (source: László Körmendy 17.02.2008) with the location of the instruments. T1 and T2 denote the borehole tiltmeters on the stable and on the moving part of the high bank, respectively. GW1 and GW2 show the locations of the ground water table sensors. Black line denotes the new crack arisen in 2010.

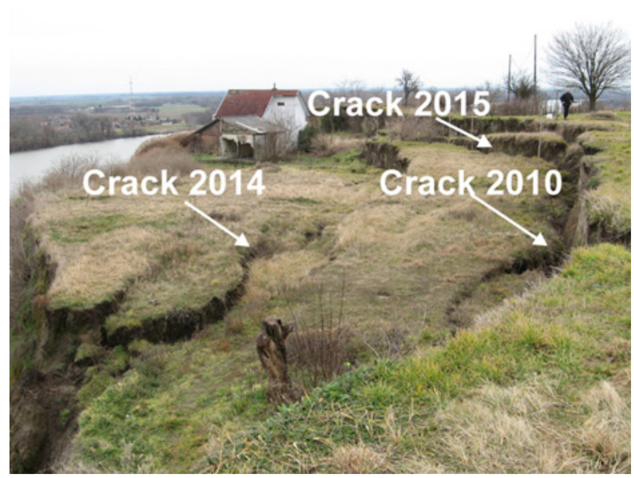

Figure 2: New cracks on the test site with the date of their appearance.

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. 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 [23]. 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. in detail [24]. 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).

To get a quantitative insight into the effect of the ground and river water level variations on the high bank tilts, the data series were subjected to Multivariable Regression (MVR) analysis. Data processing was carried out by the ORIGIN 9.1 program [25].

4 Results and discussion

Figure 3 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 T1N 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 westward tilt of the stable part can be explained by the slow sinking and eastward tilt of the unstable part which pushes the wet, loose loess into the River Danube and under the stable part of the high bank (see Fig. 6). The river washes away the loess from under the unstable part causing its eastward tilt. During the continuous subsiding of the high bank the ground water from the hinterland of the high bank and the water of the river washes the loess from the south part of the high bank much more intensive than from the north part causing the southward tilt both the stable and unstable part of the high bank. 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. 3 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 slid down together with the unstable part and recorded the slide within its measuring range as it can be seen in Fig. 3. 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.

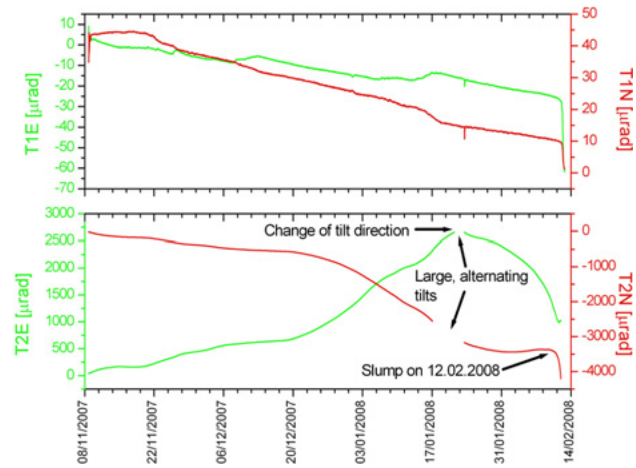

Figure 3: Tilts of the stable (T1E, T1N) and unstable (T2E, T2N) part of the high bank between 8 November 2007 and 12 February 2008. T1E and T2E are the east and T1N and T2N are the north components of the tilts. Curves going in the positive direction mean eastward and northward tilt, while going in the negative direction mean westward and southward tilts.

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 4 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. This small tilting in alternating directions is in connection with the slow after-subsidance of the slid unstable part. The mass of the sliding loess pushes the loose loess under the ground water level both under the stable part and into the river as it is described above. When the ground water flowing into the River Danube and the river washes away this loose loess

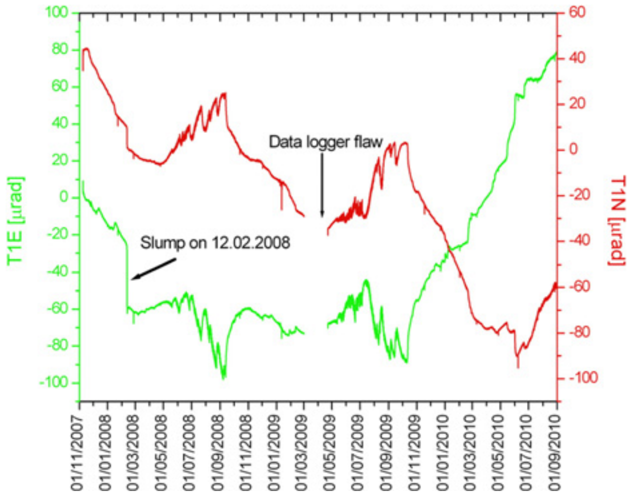

Figure 4: Tilts of stable part of the high bank (T1E, T1N) between 8 Nov 2007 and 31 Aug 2010. T1E and T1N are the east and north components of the tilts, respectively. Curves going in the positive direction mean eastward and northward tilt, while going in the negative direction mean westward and southward tilts.

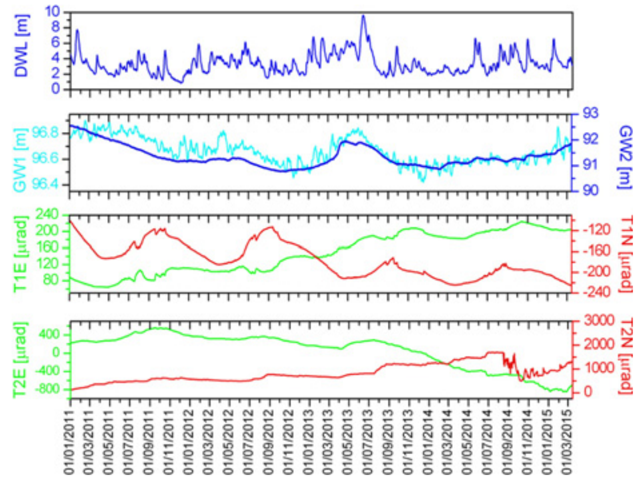

Figure 5: Tilts of stable (T1E, T1N) and unstable part (T2E, T2N) of the high bank between 1 January 2011 and 15 March 2015. T1E, T2E and T1N, T2N are the east and north components of the tilts, respectively. Curves going in the positive direction mean eastward and northward tilt, while going in the 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.

from under the stable and unstable part of the high bank the sinking of the unstable part is going on with accelerating motion (see Fig. 6). From this process it can be inferred that the stability of the high bank depends on the interaction between the hydrostatic pressure of the ground water and that of the water of the river.

Figure 5 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 south and in the east directions from the beginning of 2013, but the resulting tilt in both directions is less than 120 µrad, not considerable.

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 Figs. 2 and 6). 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.

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. Since the tilts and movements of the high bank were small in the years 2011–2013 (see Figs. 2 and 5) and the large movements in 2014 and 2015 can not be closely linked to characteristic weather periods, the calculations were only 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 slump 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 arisen cracks (see Fig. 2). Figure 6 shows the geological settings of the high bank, the approximate dates of the arising of the cracks and the presumed ground water flow and material transport during the landslide process as it is written above.

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 coef-

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
	2015	2	−37	−1	0.862
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
	2015	28	−44	−2	0.775
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
	2015	−334	−2430	40	0.800
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
	2015	25	1246	−208	0.272

ficients 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. 6). 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 on the tilt of the stable part. The River Danube is washing away the north part of the unstable section of the high bank more intensive than the south part and this undermining causes the long-term 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. 6). The ground water washes the loess continuously into the river causing the alternating east-west tilt of the high bank (Figs. 4 and 5).

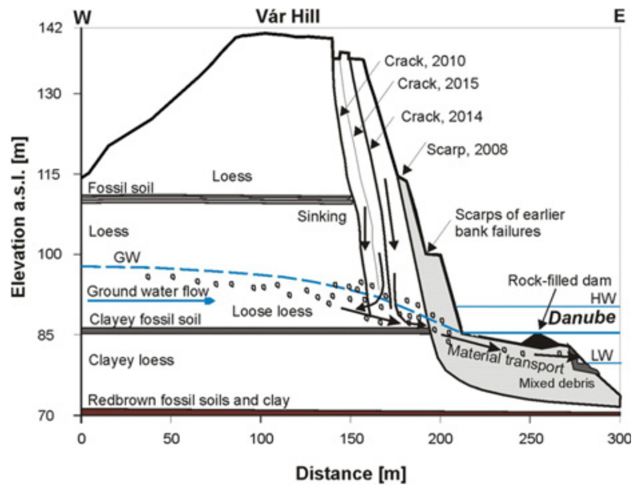

Figure 6: Landslide process of the high loess bank of the River Danube at Dunaszekcső. (after Moyzes and Scheuer [26], Pécsi et al. [27], Kraft [28], Újvári et al. [22]).

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 methods. 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:

- large 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.

The stability of the high bank can be continuously follow up using moving window multivariable regression analysis when the demonstrated measurements and methods are implemented into an on-line early warning system.

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.

Acknowledgment: Special thanks to Tibor Molnár for his careful maintenance of the instruments to Ágnes Gimesiné Németh, Ferenc Schlaffer for their help in the field works: drilling boreholes, battery changes and reading the data out.

Funding: This work was funded by Országos Tudományos Kutatási Alapprogramok (OTKA) under project K 81295.

References

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

[2] Gili, J. A., Corominas, J., Rius, J. (2000). Using Global Positioning System techniques in landslide monitoring. Engineering Geology, 55, 167–192.

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

[4] Glabsch, J., Heunecke, O., Schuhbäck, S. (2009). Monitoring the Hornbergl landslide using a recently developed low cost GNSS sensor network. Journal of Applied Geodesy, 3, 179–192. doi:10.1515/JAG.2009.019.

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

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

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

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

[9] Woschitz, H. and Brunner, F. K. (2008). Monitoring a deep-seated mass movement using a large strain rosette. Measuring the Changes 13th FIG Symposium on Deformation Measurements and Analysis, 4th IAG Symposium on Geodesy for Geotechnical and Structural Engineering, LNEC, Lisbon, 2008 May 12–15.

[10] Thuro, K., Wunderlich, Th., Heunecke, O., Singer, J., Wasmeier, P., Schuhbäck, St., Festl, J., Reith, Ch., Glabsch, J. (2014). Low Cost 3D Early Warning System for Alpine Instable Slopes: The Aggenalm Landslide Monitoring System. Wenzel, F. and Zschau, J. (eds.), Early Warning for Geological Disasters, 289. Advanced Technologies in Earth Sciences, doi:10.1007/978-3-642-12233-0_15, Springer-Verlag, Berlin, Heidelberg.

[11] Brückl, E., Brunner, F. K., Lang, E., Mertl, S., Müller, M., Stary, I. U. (2013). The Gradenbach Observatory—monitoring deep-seated gravitational slope deformation by geodetic, hydrological, and seismological methods. Landslides, 10, 815–829. doi:10.1007/s10346-013-0417-1.

[12] Lienhart, W. (2015). Case studies of high-sensitivity monitoring of natural and engineered slopes. Journal of Rock Mechanics and Geotechnical Engineering, 7, 379–384.

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

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

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

[16] Kümpel, H. J., Lehmann, K., Fabian, M., Mentes, G. (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, 699–713.

[17] García, A., Hördt, A., Fabian, M. (2010). Landslide monitoring with high resolution tilt measurements at the Dollendorfer Hardt landslide, Germany. Geomorphology, 120, 16–25.

[18] Mentes, Gy., Bányai, L. (2014). Observation of Landslide Movements by Geodetic and Borehole Tilt Measurements. Kopáčik, A., Kyrinovič, P., and Štroner, M. (eds.), Proceedings of the 6th International Conference on Engineering Surveying INGEO, 53–58.

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

[20] Mentes, G., Bányai, L., Újvári, G., Bódis, B. V. (2015). Rutschungsprozesse des Hochufers der Donau bei Dunaszekcső. Allgemeine Vermessungs-Nachrichten, 122 (5), 200–206.

[21] Mentes, G., Bódis B.V. (2012). Relationships between short periodic slope tilt variations and vital processes of the vegetation. Journal of Applied Geodesy, 6 (2), 83–88.

[22] Újvári, G., Mentes, G., Bányai, L., Kraft, J., Gyimóthy, A., Kovács, J. (2009). Evolution of a bank failure along the River Danube at Dunaszekcső, Hungary. Geomorphology, 109, 197–209.

[23] Applied Geomechanics Inc. (1991). User's Manual No. B-91-1004: Model 722 Borehole Tiltmeter. Santa Cruz, California, USA.

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

[25] ORIGIN 9.1 (2014) http://www.originlab.com. Accessed 11 August 2014.
[26] Moyzes, A., Scheuer, Gy. (1978). A dunaszekcsői magaspart mérnökgeológiai vizsgálata. (Engineering geological investigation of the high bank at Dunaszekcső). Földtani Közlöny 108, 213–226 (in Hungarian with German abstract).
[27] Pécsi, M., Schweitzer, F., Scheuer, Gy. (1979). Engineering geological and geomorphological investigations of landslides in the loess bluffs along the Danube in the Great Hungarian Plain. Acta Geologica Hungarica, 22, 327–343.
[28] 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, 8, 133–153 (in Hungarian).