DETECTION OF LANDSLIDE-PRONE AREAS ON THE BASIS OF GEOLOGICAL, GEOMORPHOLOGICAL INVESTIGATIONS, A CASE STUDY[1]

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Abstract: Relationships between regional tectonics, subsurface structures and mass movements were investigated on the high loess bank of the river Danube at Dunaföldvár based on remote sensing data and tilt measurements. The geological and morpho-tectonic situations of the study area were examined by evaluation of LANDSAT ETM, ENVISAT, ERS and SRTM data. Our tilt measurement results indicate that the movements are the consequence of erosion and undercutting caused by the Danube which led to slow loss of the base support of the high loess bank. The Danube's course at Dunaföldvár was pre-determined by tectonic events in addition to subsequent undercutting which suggested that the detected surface movements are indirectly related to the regional tectonics.

1. INTRODUCTION

Landslides arise due to different physical, geological, hydrological and meteorological processes. Development of mass movements can be influenced by tectonic movements which is able to modify the gravity field, the structural discontinuities, and the slope geometry by up-lifting, folding and erosion. Relationship between landslides and tectonics was mostly investigated on the basis of geomorphology until now (Sorriso-Valvo, 1991), because the rate of tectonic movements is generally very low, and therefore long-term and high accuracy deformation measurements are necessary to detect them or their indirect effects.

In Hungary a test site was established for the investigation of the connection between the different agencies of landslide development. The purpose of this paper is to study the relationship between tectonics, subsurface structures and landslides using remote sensing data and continuous tilt measurements.

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2. STUDY AREA AND THE TEST SITE

The western bank of the river Danube is one of the largest landslide endangered areas in Hungary. The steep, 20-40 m high banks are built-up of loose sediments exposed to river erosion. Both old and new settlements are built on the high loess bank and in their surroundings. Dunaföldvár is situated at the eastern margin of the loess-covered Mezőföld geographical unit on the bank of the river Danube where the loess highland falls nearly vertically to the flood plain of the river (Fig. 1). A part of the town is built on Felső-Öreg-hegy (Upper Old Hill) and Alsó-Öreg-hegy (Lower Old Hill) of the high loess bank. These two units are separated by a 150-200 m wide erosion-derasion valley in NE-SW direction, and they are bordered by the NNW-SSE directed, 1-1.5 km wide Bölcskei valley on west. The northern part of the high bank is Felső-Öreg-hegy (Upper Old Hill) measuring 120-130 m above sea level and its border-line on the Danube is very steep and about 20-30 m high. A major part of the town is built on this area. We selected this part of the high loess bank for our investigations, since in 1994 a large landslide caused damages here. Thus, this 400 m long section of the loess bank is prone to mass movements.

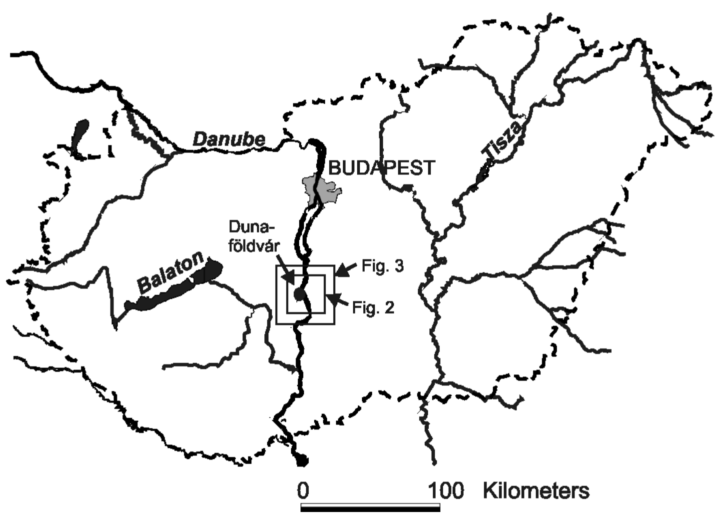

Figure 1 - Location of Dunaföldvár in Hungary

3. GEOLOGICAL SETTINGS

Based on drilling data, the Early Pliocene (ca. 4-5 Ma) formations in the study area are composed of sand and in many cases of clayey, muddy strata which are interstratified with sand layers or grey alluvial silts (Pécsi et al., 1979). These deposits are overlain by some ochre red, Mediterranean type silty soil, meadow soil and fluvial sand-mud intercalations originating from the Pliocene and Lower Pleistocene (between ca. 4 and 0.9 Ma) (Pécsi and Pevzner, 1974, Pécsi et al., 1979). This sequence is called the Dunaföldvár Formation (Pécsi, 1993). This formation consists of sand, silt, silty sand, alluvial meadow clay soil and red clay layers at the Felső-Öreg-hegy according to the data of the drilling project in 1994 (Pyrus, 1994).

Pleistocene loess accumulated in the Pannonian Basin from about 0.9 Ma during many cycles, while loess highlands developed at some areas that are built from loess and loess-like deposits with great thickness (40-80 m). The loess-paleosol sequence of Felső-Öreg-hegy differs from those of Alsó-Öreg-hegy according to the data of the drilling project in 1994. The main differences are that the entire Old Loess Series (~350–900 ka; Pécsi, 1995) is missing and the lower part of the Young Loess Series (~16–350 ka) is only partially formed at the Felső-Öreg-hegy. The thickness of loess-paleosol sequence at Felső-Öreg-hegy is about 20 m and it is about 44 m at Alsó-Öreg-hegy.

4. METHODS AND APPROACHES

Geological and morpho-tectonic situations of the study area were examined by evaluation of LANDSAT ETM, ENVISAT, ERS and SRTM data. On the basis of C-band SRTM data, recorded during the 11 day Shuttle Radar Topographic Mission in February 2000, morphometric maps (e.g.: hillshade, slope, aspect) were derived. For image processing the ENVI software and ArcGIS 9.1 by ESRI including ArcHydro tools were used.

Different colours of the lineaments were used to delineate linear image features visible on LANDSAT and SRTM morphometric maps. Black lines indicate linear image elements as a neutral term. The origin of these linear features can have different reasons. Red lines are those lineaments on LANDSAT imageries which are assumed to be related to fault zones – due to anomalies in the drainage pattern and morphology – green lines are linear geomorphologic anomalies mapped on SRTM data based morphometric maps. It means that the information of different data sets is summarized in the presented lineament map. The lineament map was compared with geologic maps and topographic data in order to verify the mapped lineaments. Most of the mapped lineaments are visible due to morphologic features such as the drainage pattern.

For tilt measurements two dual-axis borehole tiltmeters (Model 722A with a resolution of 0.1 μrad) made by Applied Geomechanics Inc. (AGI), Santa Cruz, California were used. Both tiltmeters were installed in shallow boreholes at a depth of 3 m. One tiltmeter (I) was installed on the top of the high bank at about 8 m far from its edge. The other instrument (V) was placed at the foot of the high bank about 50 m far from the river. The height difference between the tiltmeters was about 30 m. The positive y axes of the tiltmeters are perpendicular to the river Danube, while the positive x axes are directed to south and are parallel with the Danube. The temperature was also measured by means of the built-in thermometers of the tiltmeters. The data were collected with a sampling rate of 1 sample/hour from 06 June 2002 till 31 December 2007. From the hourly recorded data daily averages were calculated by moving average method.

5. RESULTS

5.1. Remote Sensing Data

Morphometric maps (e.g. hillshade; Fig. 2) show that the valleys, hills and streams, i.e. the main structural directions, are approximately NE-SW and NNW-SSE, west of the Danube. ENE-WSW and ESE-WNW directions could be also detected west and south of the test site on the basis of the drainage pattern and lineament map (Fig. 3).

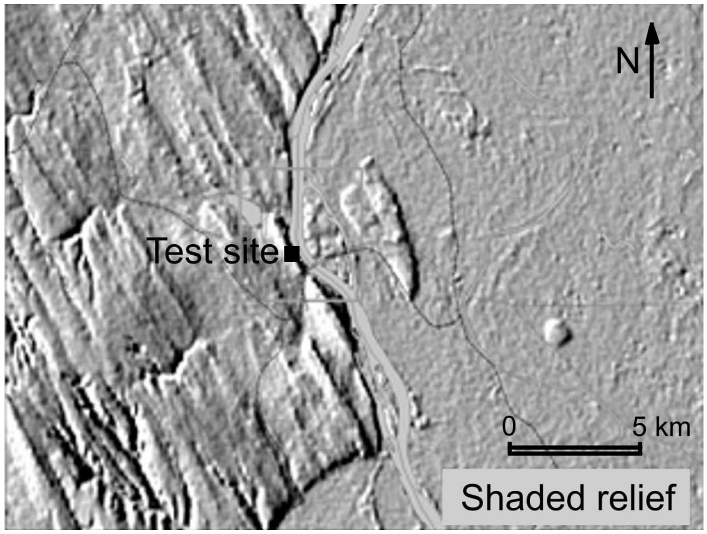

Figure 2 - Shaded relief map of the study area

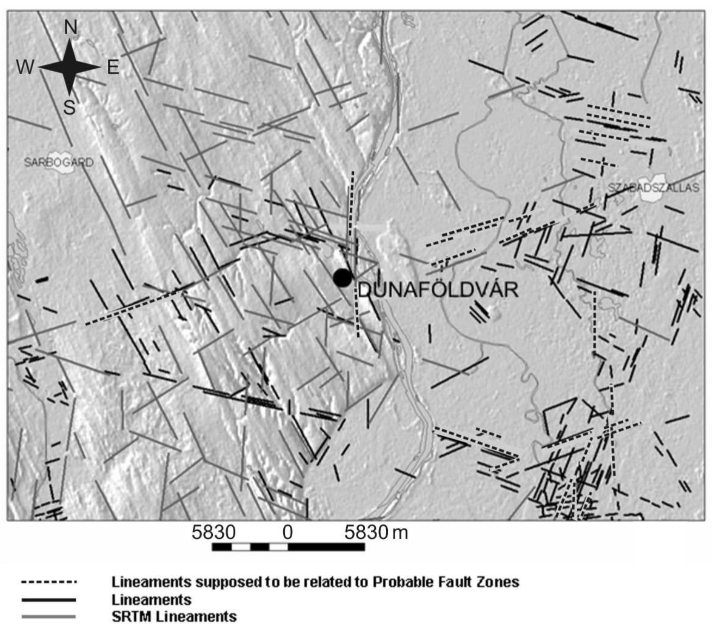

Figure 3 - Lineament map of the region

Statistical analysis of valley orientations and joint lines of strike in loess deposits on Mezőföld geographical unit indicated main NW-SE and secondary ENE-WSW structural directions (Horváth et al., 1990). The former is called Móri-valley direction which is sharply visible in satellite imageries as well as in the field and agrees with the radial valley network in Transdanubia (Síkhegyi, 2002) (Fig. 4), while the latter is the basement direction, as it comes up in Bouguer anomaly maps (Szabó and Sárhidai, 1985; Papp et al., 2004).

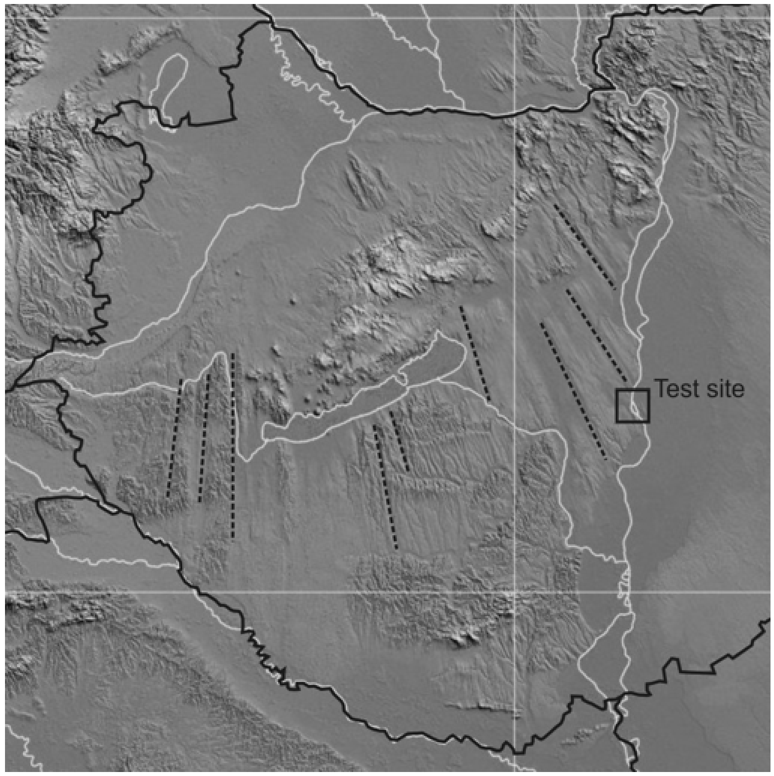

Figure 4 - Radial valley network

These directions are decisive west of the Danube, while a visible NNE-SSW direction is characteristic on the Great Hungarian Plain east of the river. There is a subsided area NW of the test site with several possible faults and the tectonically determined, NNW-SSE directed, and 1-1.5 km wide Bölcskei valley. A NW-SE orientated section of the Danube at Dunaföldvár follows a pre-existing structural line which is parallel with the Bölcskei valley. These orientations fit in the radial pattern of hydrograpy and valley network in Transdanubia (Síkhegyi, 2002). A NE-SW extension on the territory was identified on the basis of the morphological features of the Solt Plain, opposite side of the Danube at our test site (Fig. 5).

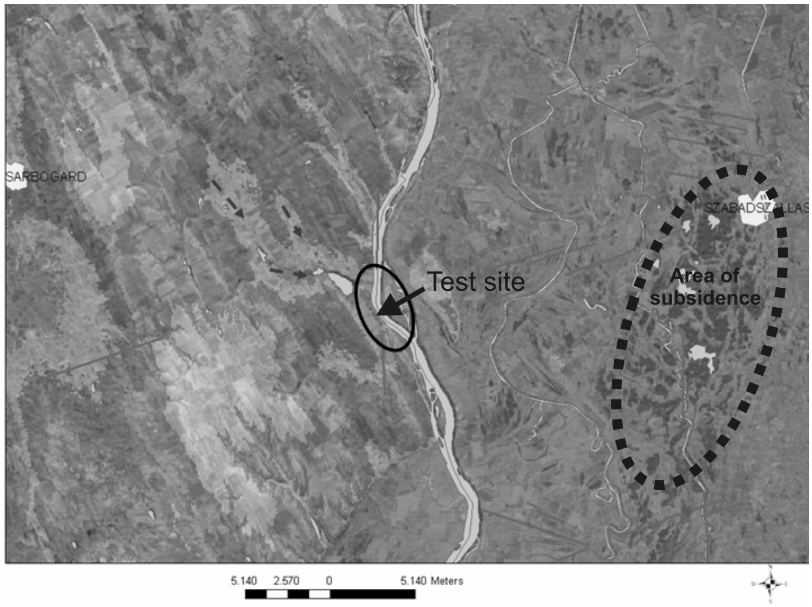

Figure 5 - Flow directions and possible subsidence

5.2. Tilt data

The linear trend of the recorded tilt data can be estimated by fitting a regression line to the tilt curves. The steepness of this line gives the rate of tilt. This tilt rates are: on the top of the high bank 47.3 µrad/year in SSW direction; at the foot of the high bank 3 µrad/year in SSE direction. In Fig. 6 the arrows show the directions of the measured tilts.

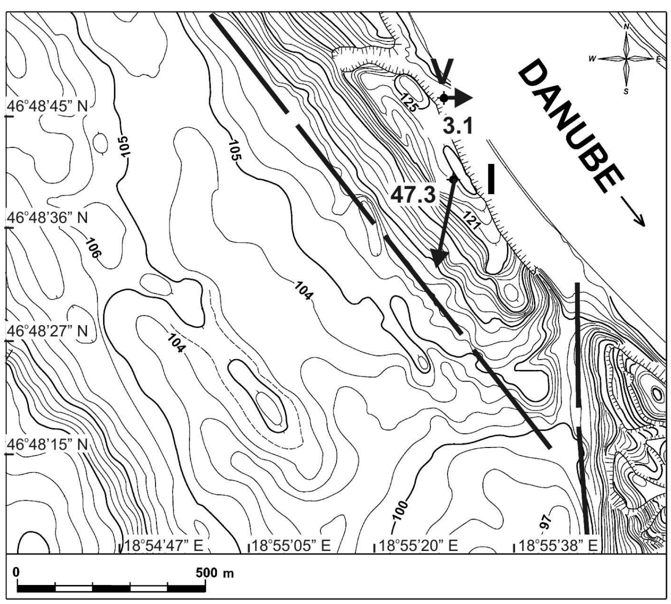

Figure 6 - Detected tilt directions and magnitudes

The correlation coefficients between the tilt and the time obtained on the top of the high loess bank (tilt components: IX and IY) are higher than 0.7. This means that the connection between the tilt and the time can be assumed linear but the tilt data are strongly disturbed by local and seasonal effects. The relatively short, four-year monitoring did not provide enough data to evaluate the effect of local conditions and seasonal variation of temperature, precipitation, water content of the loess and water level variations of the Danube. Our tilt measurements were statistically significant and good for data processing at the top of the high bank location, while at the foot of the high bank (tilt components: VX and VY) the error was too high and the correlation coefficient was low, thus the results are not reliable. These findings were obtained in consequence of the high disturbing effects relative to the low tilt rates. In spite of the low correlation coefficient we can assume that the VX tilt data have a very low trend and we can accept the obtained tilt rate (3 µrad/year) at this measurement site.

6. DISCUSSION

There is an obvious NW dipping in the gravity field (Szabó and Sárhidai, 1985; Papp et al., 2004), which is presumably related to the deepening of the pre-Tertiary basement in NW direction. The cause of the subsidence is the formation of a sub-basin (Kilényi et al., 1991) which represents a significant mass deficiency in the close vicinity (NW) of the test site. The orientation of this sub-basin is about ENE-WSW based on the Bouguer map of Hungary (Szabó and Sárhidai, 1985; Kiss, 2006). The lineaments, which were assigned by Horváth et al. (1990) on the basis of Bouguer anomalies, showed similar directions (from ENE-WSW to NE-SW), but the first order NW-SE directions, based on geomorphologic and remote sensing data, appeared only weakly and in mosaic-like fashion on wider areas. The ENE-WSW direction is the main strike of the basement determining a part of the morpho-tectonic situation.

The data of tilt measurements indicate continuous tilt in SSW direction on the top (I) and in SSE direction at the foot (V) of the high bank. The tilt rate is much higher (47.3 µrad/year) on the top than at the foot (3 µrad/ year) of the Felső-Öreg-hegy. The most plausible explanation for the obtained tilt on the top of the high bank is that the mass of Felső-Öreg-hegy is sliding slowly but steadily towards the Danube while it is also rotating counter-clockwise. These movements and conditions would theoretically predict a SW-SSW tilting which is coincides with the results of our tilt measurements (Fig. 6). The detected tilts and movements are presumably the indirect effects of tectonic movements. To support this idea we counted on the following possible explanations.

A radial pattern of valley network in Transdanubia determines the orientation of many sections of the Danube from Budapest to the south (Síkhegyi, 2002). The NW-SE orientated sections of the Danube follow pre-existing structural lines. At Dunaföldvár (Felső-Öreg-hegy), where the Danube flows also along an existing tectonically determined fault line, a receding river bank has been evolving due to persistent erosion and undercutting by the river. Felső-Öreg-hegy gradually losts its base support and it is slowly sliding into the Danube to ENE-NE direction with counter-clockwise rotation, causing a permanent SSW tilting with a high rate at the top of the high bank and with a low rate at the foot location. Our findings indicate that the „atectonic" movements are tectonically initiated and determined. Continuation of the GPS measurements could test this hypothesis. The last four-year GPS measurements showed about 2 mm displacements in the NE direction at some of the GPS locations but these displacements were not statistically significant (Bányai, 2004).

7. CONCLUSIONS

Our results confirmed that precise remote sensing data are essential for a detailed geomorphologic, geologic and hydrologic study of areas exposed to landslides. Both existing and recent tectonic processes and dynamics of river morphology evolution impacted the mass erosion along the high bank of the Danube. This connection between the landslides and tectonics was proved to be indirect on the basis of our short-term observations. Disclosure of the direct connections between recent tectonic processes and landslides is difficult and requires long-term monitoring and data collection on active landslides.

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