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Geoelectric Tomography Carried Out on a Mass Movement Site of Kulcs Settlement (in Hungary)

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Abstract

Intensification of the surface mass movement processes on the right bank of the Danube river on the territory of village Kulcs caused serious damages during the past decade. Several significant rehabilitation projects have been performed in order to stabilize the area and protect the settlement. Following the last greater movement, the area of Hullám and Deák Ferenc Streets was declared to Life Hazard Zone. Experimental geophysical measurements along profiles were carried out on areas classified as Life Hazard Zone, in order to explore the possible geological causes of the mass movements. It was investigated if those – probably 2D or 3D – structures which may give explanation to the specific spatial distribution of the surface mass movements could be detected by geoelectrical methods. Multielectrodal direct current method was applied to image the subsurface electrical resistivity distribution. Any given formations identified on the obtained resistivity distributions can be corresponded to a rock type based on prior geological information. The applied geophysical methods contribute to our better understanding of the geological environment of the high bank, provide additional explanation to the causes of the mass movements, and may yield information concerning the place of potential future mass movements. Results may also help us plan further drillings on appropriate sites, and the necessary geotechnical procedures.

Keywords: Loess; Mass movement processes; Direct current measurements; Geophysical inversion; Electrical resistivity

Introduction

The Danubian bluffs (Figure 1) have long been in the focus of research in Hungary; however the mass movement processes only intensified in the recent years. Consequently, scientific attention shifted toward tracing the surface movements and the processes behind them.

The study area is located between Rácalmás and Adony on the eastern edge of Mezőföld ("Fieldland") (Figure 2). In that area the Danube's flood-free bank is 50-70 meters above medium level. Behind the loess-plateau there is a hilly terrain; foreground is a weathered loess-contained detrital slope. The study area represents a transition between the Transdanubian Hills and Danubian Plain based on topography.

The 20-25 km long flood-free bank between Kulcs and Dunaújváros is extended to approx. 200-300 m from the Danube watercourse. The 40-50 m thick loess cover is deposited on Pannonian clay. Old and newly formed mass movement deposits are observed between the high bank and the river. The major landslides frequently occur in the study area because Kulcs village is built on a riverbank where the Upper Pannonian and Quaternary layers are also present in the stratigraphic column [1].

The bluff comprises loess and loess-like sediments which are interrupted by thick paleosol horizons and sand layers. The Plio-Pleistocene terrestrial red clay underlies the Quaternary loess deposits. The clay is situated at the bottom of the bluff close to the water level of the Danube river. Underneath the red clay, the Pannonian (Miocene) marine clay can be found (Figure 3).

Tectonic movements (sinking of the Adony Basin) and the Danube's undercutting processes played a major role in the formation of the bluff. The accumulations of landslides, slumps, rotational and translational mass movements have built a debris slope at the foot of the bluff along the Danube. The state of activity of those landforms varies from relict to active. The reactivation of older slide planes can be observed in most cases of recent landslide events. The toe of the debris slope is eroded by the river.

A particular combination of geologic, hydrologic and geomorphologic factors is responsible for the landslides along the bluffs of the Danube river. The geological structures, lithology, neotectonic and geomorphological conditions play a significant role, but, in most cases, water can also be an important factor in landslides. A large amount of water that a landform is not used to receiving can trigger a landslide. Significant changes in precipitation, subsurface water flow, discharge of the Danube or human factors, like failures in water supply, lack of sewage network, or improper drainage runoff can all increase the probability of a landslide event.

Countless springs have their sources on the riverbank and on the slope of the bluff at different elevations. There are three main water horizons: the water of the uppermost horizon derives from the precipitation and human sources while the two other horizons have extended subsurface tributaries. The main zones of water flow are linked to tectonically determined, buried valleys. The groundwater flows out of the sandy layers, the water-permeable layers situated above the clay-bearing paleosol layers and the red clay. The debris slope at the feet of the bluff can effectively dam the groundwater flow and increase its pressure. The Danube river, if its water level is high enough, can hinder the groundwater flow out of the bluff, which results in increased amount of water at the bottom layers of the bluff. The enhanced water

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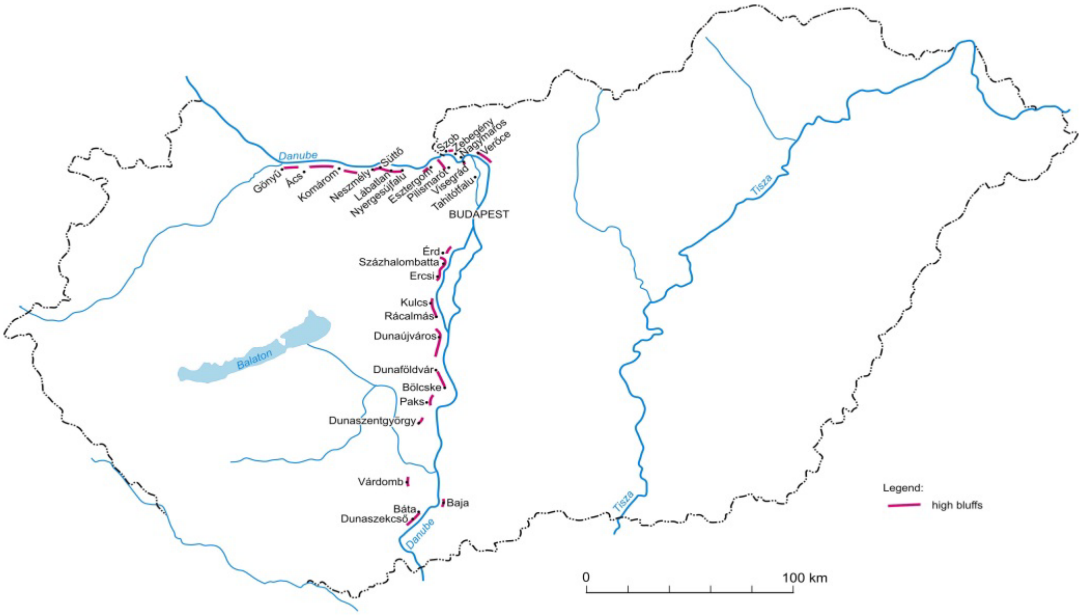

Figure 1: High bluffs along the Danube in Hungary.

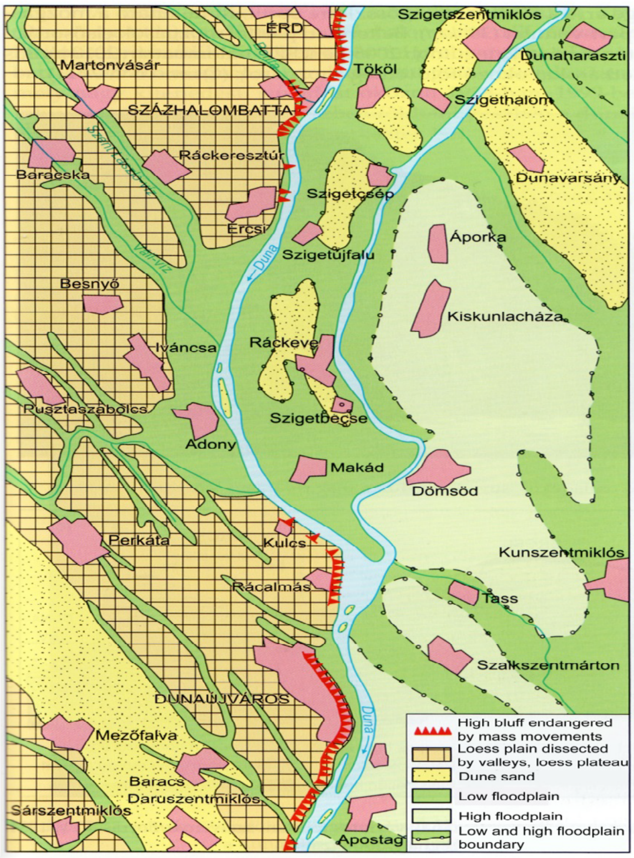

Figure 2: Geomorphological map of the study site (Edit: Balogh, J. – Schweitzer, F. 2010. In:[1]).

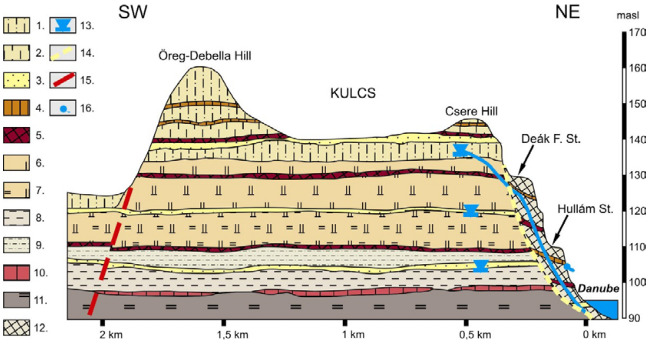

Figure 3: Geological profile of Kulcs between the landslide affected Csere Hill and Radicsa vineyards at Öreg-Debella Hill [2].

1.=Young loess, 2.= Young sandy loess, 3.=Sand, 4.=Fossil brown soil, 5.=Reddish brown fossil soil, 6.=Old loess, 7. = Old clayay loess with deposition horizons of marshes, 8.=Sandy aleurite, 9.= Clayey aleurite, 10. = Red clay, 11.=Upper Pannonic (Late Miocene) red clay, 12.=Reworked material of debris slopes, 13. = Ground water horizons, 14. =Slip face, arch collapse, 15.=Inferred fault, 16.=Spring

content makes the sediments heavier and makes the clay layers more plastic, which can lead to landslides. The slip planes of landslides are connected to the palesoils and clay-bearing layers. The most important in this regard is the red clay layer because of its position near the water level of the Danube river. It not only connected with the ground waters but communicates with the Danube's water as well, therefore the red clay layer is the primary slip plain of landslides at Kulcs.

In consequence of the last major mass movement (17 January 2011), several buildings were heavily damaged, roads, walls, fences have been damaged, the electrical wirings were busted in several places, and large cracks were formed on the surface (Figure 4).

Some previous studies on the surface movements at Kulcs were made using methods of other disciplines. Results from previous studies – geology (Geological and Geophysical Institute of Hungary), geochemistry-petrology (Eötvös Loránd University Department

Figure 4: Fractures caused by mass movements on Kulcs settlement.

of Geochemistry and Petrology), geography (Research Centre for Astronomy and Earth Sciences, Geographical Institute) – can be supplemented or confirmed by geophysical investigation. In this study, direct current (DC) geoelectrical method was used in order to obtain information on the subsurface resistivity distributions. The results of the geophysical survey can constrain the geological hypothesis on the structure of the studied area. In addition, geophysical surveys may facilitate the suitable planning of future research (e.g. drillings).

The results of our investigations clarify the movements-related questions risen in Kulcs area and may also provide research methodology for other areas in similar geological and geomorphological environment, i.e., that are potentially vulnerable to mass movements.

Geophysical Investigations

Due to the topography, the geological structure (the high horizontal and vertical segmentation of the rock physics parameters), the diverse positions and geometry of the formations, the research of the areas affected by mass movements belongs to the more difficult problems of geophysics. The research of the karstic areas represents a similar challenge for geophysics [2,3].

Applied geophysical methods offer many possibilities to study subsurface inhomogeneities, two-dimensional (2D) and three dimensional (3D) formations, but the effectiveness and resolution of the methods are very different. The more suitable geophysical methods and the measuring arrangement were selected based on sufficient a priori knowledge, depth of investigation, geometry, geomorphological mapping, geological and hydrogeological data, and rock physics parameters. Noise level was also taken into account. Application of high-resolution methods can be made only in detailed exploration phase, the preliminary research phase gives an overview about the nature and occurrence of the targeted formations.

Geophysical measurements provide information about various properties of rocks, such as density, flexibility, magnetism or electrical resistivity. The geoelectrical and electromagnetic methods are amongst the most diverse surface exploration geophysical methods. DC resistivity methods use artificial sources of current to produce an electrical potential field in the ground. DC or low-frequency alternating current considered DC are used.

DC geophysical measurements

DC methods are discussed in details in the literature [4]. In this study, only the most widely used measuring arrangements are summarized which were also used in Kulcs. The object of the geoelectrical measurement is the determination of the resistivity of the medium, for which artificially created electric field is used. The electric field depends on the electrical properties of rocks and their spatial distribution; therefore the measured data yield information concerning the resistivity distribution of the medium.

During the measurement, direct current is flowing into the ground trough current electrodes, denoted by A and B, and the potential difference between the measuring electrodes M and N is observed. In traditional electrode layout the ABMN electrodes are positioned in line along the measuring profile. In case of Schlumberger sounding the sequence of electrodes is AMNB and the measuring electrodes – M and N – are placed in the middle between A and B electrodes (Figure 5). The penetration depth is controlled by the distance of the current electrodes, as the distance between A-B electrodes is increased the currents flow more deeply and we get information of the resistivity of deeper medium. The Wenner electrode array consists of a line of four equally spaced electrodes, the sequence of electrodes is also AMNB. The dipole-dipole array consists of a pair of closely spaced current electrodes and a pair of closely spaced potential electrodes. In this case, the sequence of the electrodes is ABMN and the penetration depth is controlled by the distance of AB and MN electrode pairs. The pole-dipole layout is similar to the dipole-dipole layout, but one current electrode is positioned far away (theoretically in infinite) from the other electrodes in pol-dipole array.

The reliability of the obtained information on the resistivity distribution of the studied geological structure is different at each electrode configurations.

For example, the main difference between the Schlumberger and the dipole-dipole layouts is that the Schlumberger sounding gives good mapping for the vertical change of the resistivity, while the dipole-dipole array is more sensitive to the lateral change of resistivity.

The result of data processing is a model close to the real geological structure. The model is two-dimensional, which means that the structure does not change in perpendicular direction to the measuring profile. The geoelectrical model is calculated from the data measured along the profile by geophysical inversion. Detailed study of the inversion algorithms is beyond the scope of this paper, for more information see e.g., Tarantola [5]. In the inversion process, a model is determined by a given algorithm so that, based on mathematical criteria, the theoretical values resulting from the inversion model resemble the measured values.

The accuracy of the geophysical inversion is affected by several factors. The level of detail of the model is inherently limited by the number of measurement data, a reliable model cannot expected be described with more parameters than the number of measured data.

The inaccuracies of the measured data and subsurface 3D structures influence the reliability of the obtained model. The phenomenon of equivalence, i.e., almost the same theoretical data may belong to

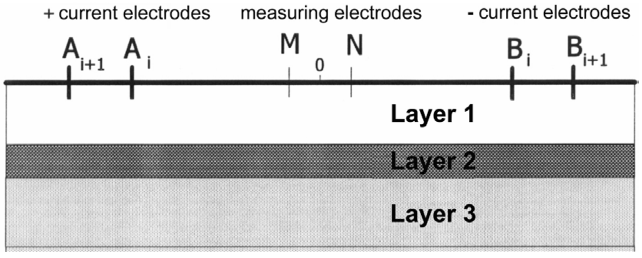

Figure 5: Direct current electrode array.

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different models, may occur even in case of large number of accurate data. Among potential different models the less likely may be excluded by prior geological knowledge.

Despite the minor difficulties that may arise, the geophysical measurements are worth to apply, because by they can provide a large number of data concerning the geological structure with relatively small investment in time and relatively low expenses. From these data the resistivity distribution of the medium beneath the surface can be estimated. The structures with dimension exceeding the electrode distance multiple times are recognizable more reliably than the smaller ones on the inversion model. Furthermore, the geoelectrical model may contribute to the planning of future, more specified geophysical and geological explorations (e.g. selection of a new drill site).

Geoelectrical measurements in Kulcs

In the settlement Kulcs four slip danger zone were distinguished. On the area denoted by 2 in Figure 6 [6], DC geophysical investigations were carried out in the Hullám Street and its vicinity. The measurements were made with the geoelectrical instrument SYSCAL PRO Switch. Measurements with multi-electrode arrays were performed along 5 different profiles. Applying different arrays – Schlumberger, Wenner, dipole-dipole, pole-dipole – on the study area, we have obtained 18 profiles (Figure 7). Based on the inversion models the Schlumberger soundings proved to be the most reliable.

First, it was examined if demonstrable structural change exists perpendicular to the Danube. Starting from the southeast end of the Hullám Street, we measured a relatively short cross section (52 m) with dense electrode separation. This section shows an approximately one-dimensional model. Results of the inversions on Figure 8 and 9 do not show complex structures or anomalies. However, the purpose of these measurements was in fact to test whether in the parallel direction to the profile any structural variation exists, or can be detected. Directly beneath the surface a 2 m thick layer with relatively high resistivity can be detected, under this layer considerable changes are not observed. This result was supported by the inversion results obtained from the Schlumberger and pole-dipole data (Figures 8 and 9).

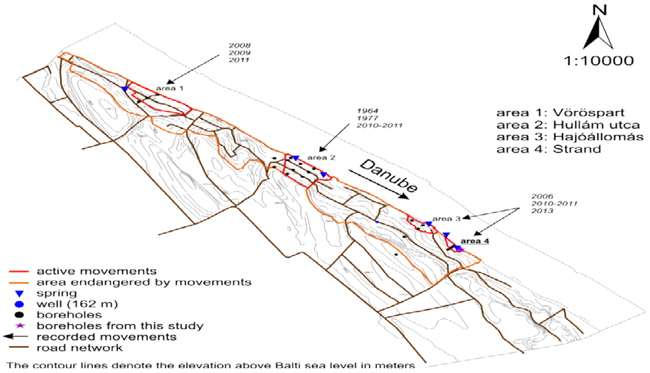

Figure 6: Surface mass movement areas in the region of Kulcs [6].

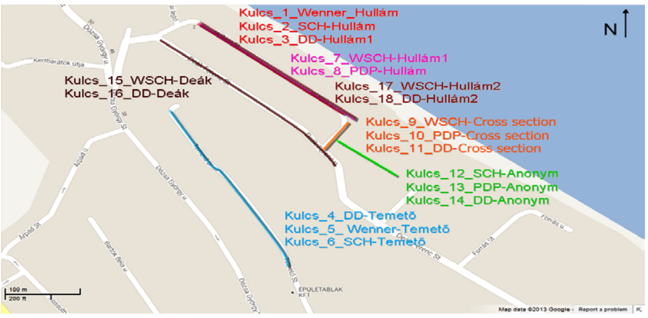

Figure 7: Geoelectrical profiles in the study *area* nr. 2 [7].

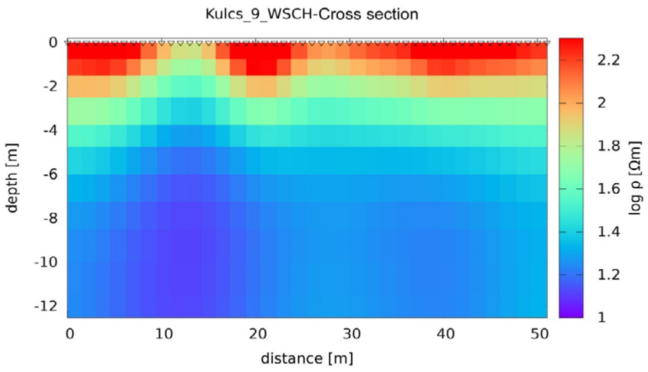

Figure 8: Result of geoelectrical inversion along the cross section (Wenner-Schlumberger array) [7].

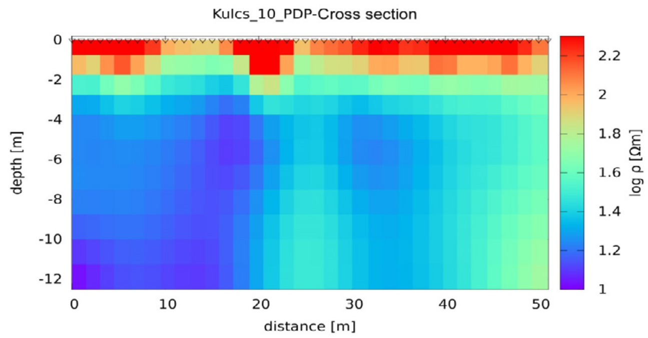

Figure 9: Result of geoelectrical inversion along the cross section (pole-dipole array) [7].

The next profile, parallel to the Danube river, was chosen on the area most affected by the last (2011) great mass movement. Circa 70 m away from the river in the Hullám Street, geoelectrical measurements were carried out (Figure 7) with 46 electrodes (5 m electrode distances) on a 230 m long profile. The inversion model obtained from the measured data shows a very interesting 2D structure. The inversion models in Figures 10 and 11 [7] were calculated from Schlumberger and dipole-dipole data. In the 10-20 m depth region, a horizontally and vertically well separated area appears with higher resistivity. The anomaly (2D structure) characterized by more than 200 ohm-m electrical resistivity is certainly not clay, but sand or gravel or possibly some sandy, gravelly or muddy formation.

Several drilling projects were implemented on the area previously. A continuous, large diameter hole was drilled down to 22 m in depth in the Hullám Street [8]. The results of the drilling show that loose sandy silt is present beneath the surface down to a depth of 11.8 m. Deeper, different clay layers are alternating. The drilling site is at 180 m on the geoelectrical profile. The apparent resistivity data of the sediments observed in the drill core is in agreement with the decreasing

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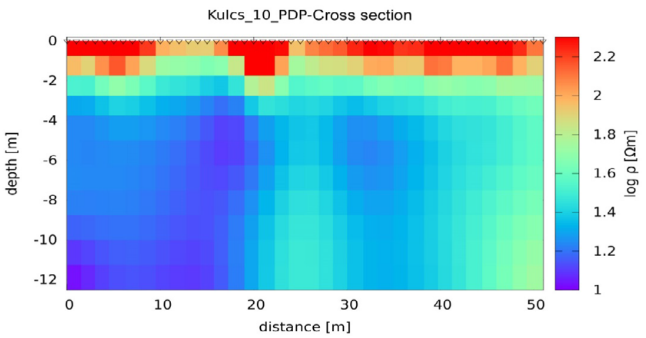

Figure 10: Result of geoelectrical inversion along the profile measured in Hullám street (Schlumberger array) [7].

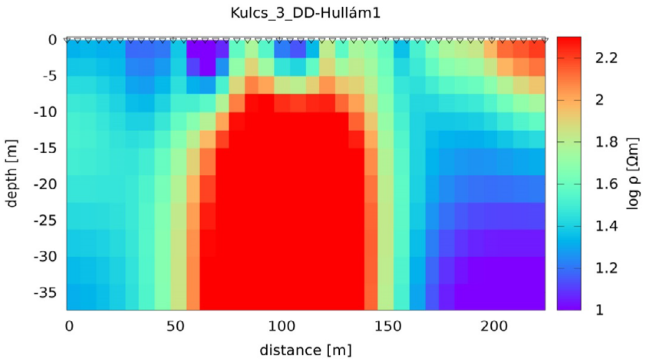

Figure 11: Result of geoelectrical inversion along the profile measured in Hullám street (dipole-dipole array) [7].

resistivities with increasing depth calculated for the inverted profiles (Figures 10 and 11).

Although, the results in the Hullám Street obtained from the Schlumberger and dipole-dipole arrays shows some minor differences, the common elements of the models are definitely remarkable. The observed small variations can be explained with the different sensibility of conductivity distribution imaging of the Schlumberger and dipole-dipole layouts. Features observed in both models calculated based on the results of the different layouts may be accepted with higher certainty.

In June 2013 before the flood (Figure 10) and after the flood peak (Figure 12) geoelectrical measurements were performed in the Hullám Street. The comparison of measurements performed in different times at different water levels on the same place shed light to some interesting features. The profile measured after the flood peak shows that the size of the well separated large formation with high resistivity which appears on the section measured before the flood is significantly reduced. The obvious discrepancy can be explained with the different level of water saturation of the sediments at the time of the two different measurements. Different physical parameters of the matrix (e.g. porosity, composition of the pore-filling fluid, shape, size and electrical conductivity of the constituent minerals) strongly influence the resistivity of the rock. From a geophysical point of view, high porosity translates to variable electrical conductivity because of the variations in the pore water content. This explains that the high resistivity formation (i.e. sediments with low pore water content) observed on the inversion profile of the geoelectrical measurements prior the flood (Figure 10) significantly decreases on the profile obtained after the flood (Figure 12), because the amount of the pore-filling water has increased.

Additional measurements were carried out parallel to the Danube. The profile nearest to the Hullám Street was measured is an unnamed street – referred here as Anonymous – on 103.5 m with 1.5 electrode separation. According to the local residents, a former building at the intersection of the Anonymous Street and the cross section was damaged substantially due to the surface movement in 2011 and it had to be demolished, but the house in its proximity remained intact. Besides the demolished house, the mass movements do not caused damages in the Anonymous Street, as verified during the field survey. According to the inverted profile (Figure 13), a relatively high resistivity layer with varying thickness can be identified near the surface, in 6-8 m in depth. Under this layer, significant changes of the conductivity distribution in the horizontal direction were not observed.

Experimental Results

The inversion model of the profile measured perpendicular to the Danube shows, that the geoelectrical structure is approximately one-dimensional in the entire length.

Similarly, the model obtained from the data measured in the Anonymous Street, the structure beneath the upper 6-8 m thick high-resistance layer becomes one-dimensional too.

The most interesting part of the measurements are the geoelectrical models based on observations performed along the Hullám Street

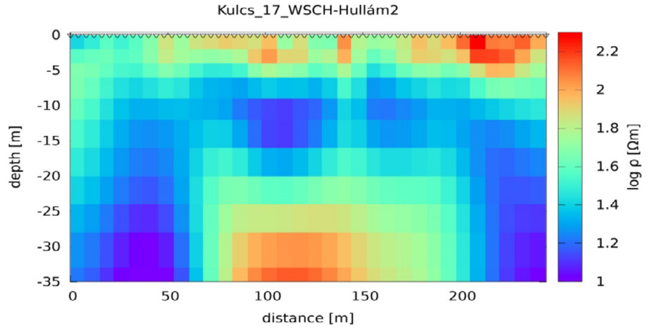

Figure 12: Result of geoelectrical inversion along the profile measured in Hullám street after the flood (Wenner-Schlumberger array) [7].

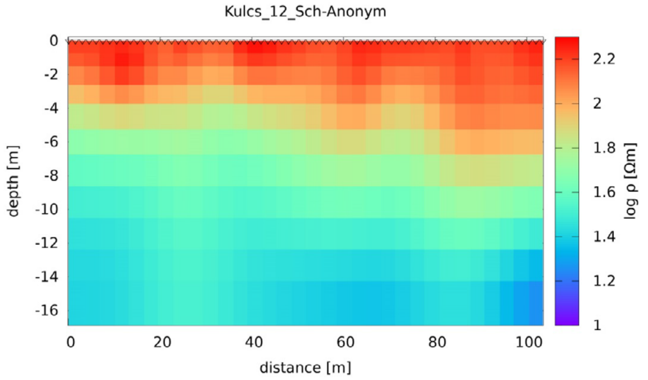

Figure 13: Result of geoelectrical inversion along the profile measured in Anonymous Street (Schlumberger array) [7].

with different electrode array. Up to a distance of 40-150 m from the north-west end of the profile in the inversion models calculated both from dipole-dipole or Schlumberger array data, a formation with high resistivity occurs at a depth of 10-15 m. The south-east rim of this high resistivity inhomogeneity is firmly separated from the environment and also the most devastating mass movements observed on the surface can be linked to this edge.

During the high water level of the Danube floods, these measurements were repeated in the Hullám Street. The purpose of the tests was to investigate the changes in resistivity in case of that rock with supposedly variable resistivity at higher water saturation. The hypothesis, i.e., the anomaly is caused by a sequence with high porosity, is supported by the measurements in this section (Figure 12). The resistivity of this sequence is influenced mainly by water content.

On the soundings carried out before the flood (Figure 10), the resistivity of the well separated formation was at least 200 ohm-m. This value decreased significantly, circa to 100 ohm-m on the sections calculated from measurements after the flood (Figure 12). In our experience, these resistivity values correspond to the resistivity values of water flooded sand, gravel or other sandy sediments.

This formation markedly appears in all profile, slight difference comes from the properties of the inversion (equivalence) and from the different mapping properties of the applied electrode arrays.

More precise constraints on the characteristics of the formation would be possible by drilling. Unfortunately, the drill hole in the Hullám Street, mentioned above, just avoids this formation.

In case of a future drilling project, we suggest to plan a drill hole transecting the 2D structure, based on the results of the geophysical measurements presented here.

Conclusions

Geophysical measurements have been carried out on a loess bluff subjected to landslides in order to constrain the geological causes of the mass movements. In additions, we examined whether the probably 2D and 3D structures, responsible for uneven spatial distribution of the mass movement occurrences, can be imaged by the geoelectrical method. The results confirm that the used method is capable of imaging the subsurface structures at the study area, the structural differences, if present, can be identified on the inversion profiles.

Higher resistivity formations on the inversion profiles correspond to sand, gravel or a mixture of both, while lower resistivity formations are related to clays or clay-bearing sediments, which usually provide the slip planes for the mass movement processes.

Data obtained along the profile which runs parallel and closest to the Danube river, prior and after the flood, shows the presence of pore water, which is one of the factors that can initiate mass movements processes, as detailed in the introduction chapter.

Results contribute to our knowledge of the complex geology of the bluff. Furthermore, they can also be helpful in choosing the locations of future drill sites, which could provide more information on the geology of the area, especially the Life Hazard Zone. This might even help us predict the locations of future mass movements.

Acknowledgement

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