LANDSLIDES IN THE DANUBE – BLACK SEA CANAL AREA

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Abstract. This paper presents the results of the study carried out in two areas of the Danube – Black Sea canal, concerning the slope instability of the right bank. The information achieved during the site works, as the inclinometric, geoelectrical and topographical measurements offer a better knowledge and understanding of the factors responsible for the landslide. Groundwater flow has also been taken into account, as it has a major influence on the landslide phenomena. Two landslide areas along the canal have been delineated and characterized. Numerical modelling in both areas provided the main groundwater flow directions, towards the canal, favouring the occurrence of landslides.

Keywords: landslide, loess, infiltration, sliding plan, numerical modelling, groundwater flow direction

INTRODUCTION

The landslides are often triggered by many simultaneous causes. Along with shallow erosion or shear strength decrease caused by rainfall (Florea, 1979), causes triggered by anthropogenic activities such as additional weight above the slope, digging at middle or at the foot of the slope, can also be considered.

Landslides occurring in two areas along the Danube – Black Sea canal are due to lithology, water infiltrated from precipitation and irrigation system and inappropriate stabilization works. The designed works of consolidation consist of isolated reinforcements, reinforced concrete buildings, rearrangement (Rogers, 1992), drains at the base of the loess deposit and draining belt at the base of the red clays (Avădanei *et al.*, 2004). Investigations in both landslide areas have been carried out by means of geotechnical laboratory analyses, inclinometers, groundwater level measurements and vertical electric soundings. The results of these investigations indicated that the landslides are active.

GEOLOGICAL FRAMEWORK

The structure of the deposits crossed by the Danube – Black Sea canal is complicated, as they are affected by the regional NNE – SSW and ESE – WNW fault systems of the South Dobrogea area.

Description of the geological formations cropping out along the canal has been carried out on several sectors (Dinu *et al.*, 2007).

On the first sector, upstream of the Cernavodă lock, in the flood area, the Danube – Black Sea canal the following formations are present:

- the Berriasian – Valanginian – Hauterivian deposits, represented by the Cernavodă formation (Dragastan, 1985), consisting of bioclastic limestones, oolites, marly limestones, clays, microconglomerates with limestone elements and breccia levels, which are the oldest sediments cropping out in the South Dobrogea;
- the Middle – Upper Aptian deposits (Gherghina formation - Avram *et al.*, 1988) covering the previous assemblage

consist of a succession of red pebbles and conglomerates, sands, kaolinitic clays and thin layers of coal;

- the Upper Aptian – Albian deposits, representing the Cochirleni formation (Avram et., 1988) are composed of detrital sediments rich in authigenic glauconite;
- the Quaternary deposits consist of clay, silty clay and loess with sand and gravel lenses.

Between the Cernavodă lock and Basarabi, the Danube – Black Sea canal crops out the following deposits: previously mentioned Berriasian – Valanginian – Hauterivian deposits, Senonian deposits, represented by the Murfatlar formation (Avram *et al.*, 1988) and the Satu Nou formation (Dragastan *et al.*, 1998). All this assemblage consists of white chalk with a conglomerate and sandstone basal level and previously mentioned Quaternary deposits.

Between Basarabi and the Agigea lock, the canal crops out the altered and jointed Senonian chalks, which may be locally covered by Quaternary calcareous coarse gravels, clays, loess; the Sarmatian limestones are locally covered by Quaternary red clay or loess.

GEOLOGICAL AND HYDROGEOLOGICAL CONDITIONS IN THE AREAS AFFECTED BY LANDSLIDE

In the area of the Basarabi and Agigea plateau, the Danube – Black Sea canal waterway has been achieved through a cutting of about 20 km long and up to 70 m deep. The digging for the canal execution was intercepted under a package of 7 to 8 m thick loessoid soils covering deposits of red, brownish or green clay, chalk, limestone and sands. On a segment about 7 km long, between "Km 53" and "Km 60", under the package of loessoid soils, there is a layer of red clay, with variable thickness between 8 and 35 m. The excavations and the direct exposure to weather agents have caused contractions and micro-fissures, in contact with dry atmospheric air, and swells, in contact with water. This is manifested by a drastically decrease of the shear stress, with direct involvement on the slopes stability. The slopes were designed based on stability calculations with assumed risk (Avădanei *et al.*, 2004).

The stable slopes of the red clay layers, resulted from calculation, are too low. This would have led to an increased value of the canal width on sectors with high thicknesses of these types of soils. Thus, works of draining capture and controlled evacuation of the groundwater accumulated at the base of the loess package were foreseen in the design phase. Landslides started to occur in the red clay formation, on some sectors with inefficient protection by loess and soil and without collecting systems and drains.

In order to stabilize the slopes in the red clay affected by sliding, consolidation and water collection works have been carried out.

Landslides are detrusive and occurred mainly due to accumulation of water infiltrations, at the contact between loess deposits and underlying red clay.

Another reason that led to sliding was the inappropriate maintenance of the existing works.

By means of perimeter mapping, many areas were found affected by the moisture excess, inappropriate drainage works and counter slope allowing accumulation of water from precipitation.

Landslide from "Km 58"

The phenomenon of instability occurred in early 2001 and had degraded the finished slopes, the works of draining and surface water flow as well as the plantations of shrubs placed between elevations 60, in the plateau area, and 26.

The landslide in this sector is of progressive type and was mainly triggered due to the water infiltration, at the contact between loessoid deposits and the red clay from 11.00 m depth and also at the contact surface between the red clay and yellowish – brownish sandy clay (Fig 1).

For landslide monitoring, few field works were carried out, in order to establish the optimal methods for land stabilization. Hereby, geotechnical drillings have been equipped as piezometers and inclinometers. Topographical survey and geophysical measurements (vertical electrical soundings) have also been carried out. The sliding monitoring from the "Km 58" zone has been done through three inclinometers located in the sliding body (FG1, FG2 and FG3) and one piezometer F15 (Fig. 1).

The position of the sliding plan has a certain degree of approximation and it is located in the area of maximum concentration curves of the inclinometer chart (Fig. 2).

The designed works of consolidation consist of isolated reinforcements with simple concrete, with pile of resistance between them, reinforced concrete buildings executed behind some existing works of consolidation, drains at the base of the loess layer and draining belt at the base of the red clay.

Two aquifers have been delineated based on the lithological data: the upper aquifer, consisting of loess, extended on the southern half of the „Km 58" zone, and a lower aquifer, consisting of clay, sand and gravel alternations, extended on the whole study zone. A clay layer, extended as much as the upper aquifer, is located between the two aquifers.

The upper aquifer, covering about 22000 m^2, is developed between the elevations 62 m south and 46 m east. The groundwater heads are between 50 m north and 50.9 m south.

The lower aquifer, covering about 42460 m^2, is developed between the elevations 36 m and 22 m, with thickness between 6 m south and 14 m towards the canal. The groundwater heads are between 23.5 m (FG3) and 35.8 m south.

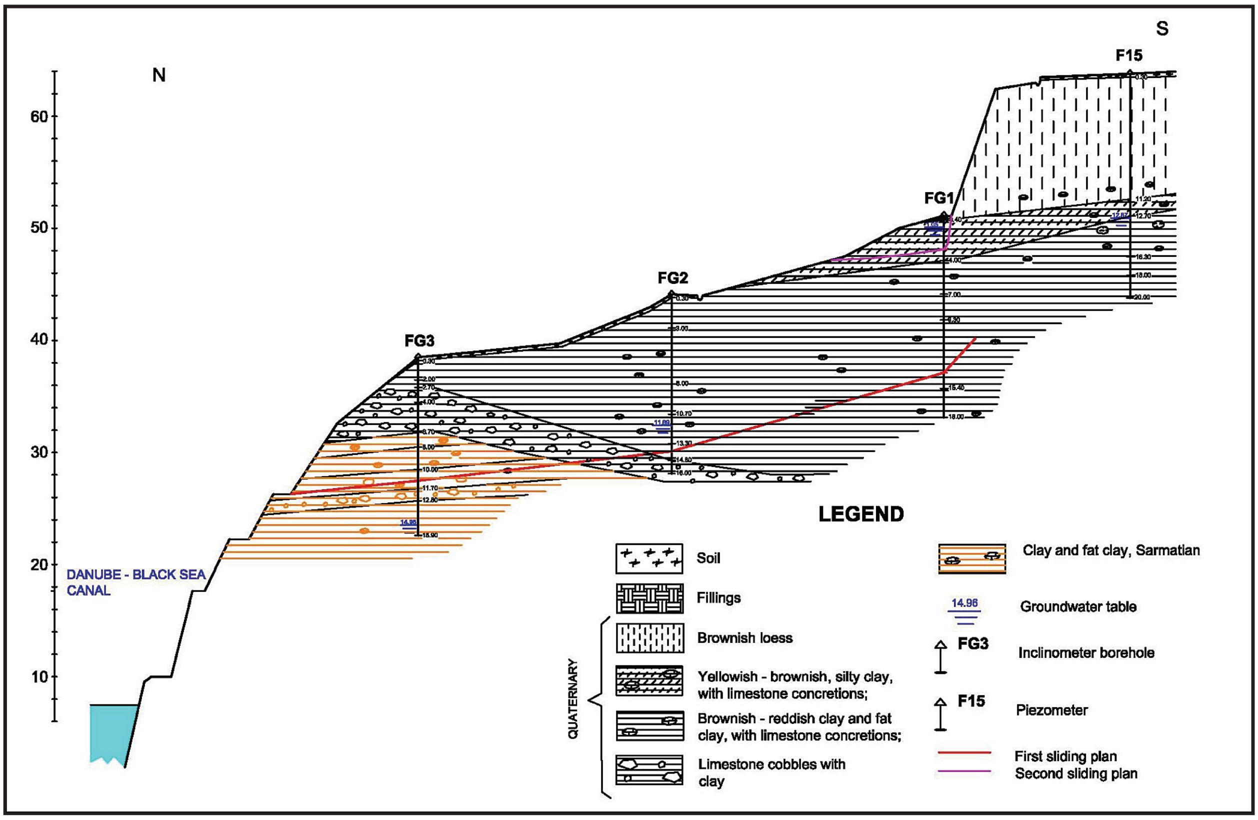

Fig. 1 Geological cross section on Km 58 landslide

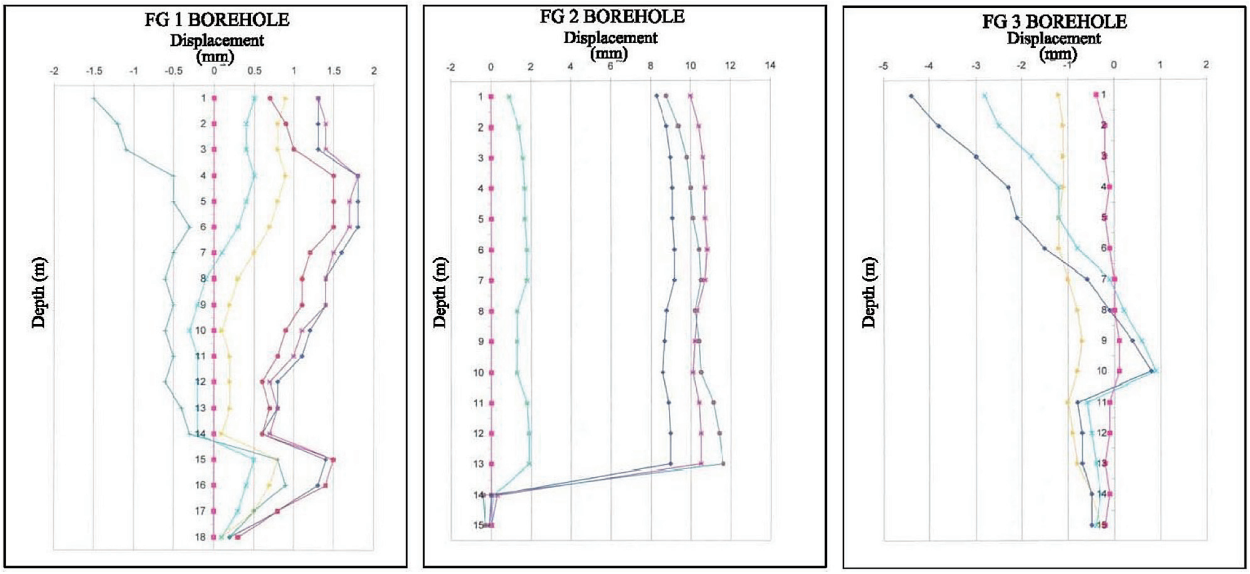

Fig. 2 Displacement charts of "Km 58" zone inclinometers

A line of drains in the upper aquifer provides a total discharge rate that has been determined as 37.32 m^3/day. These drains were made in order to decrease the water table.

Landslide from "Km 60"

Similarly to the landslide from "Km 58" zone, the slope stability loss was determined at the contact between the loessoid formation and the red clay.

In the present case, the landslide affected the slope from the right side silt, at the first step of detachment, along around 115 m, and at the basic level along around 160 m. The landslide extension, perpendicularly on the slope, within central axial zone, is around 75 m. The landslide extends from about 2 m from the exploitation road on the plateau to beyond the piles of rock fills placed at the lower part of the slope.

The land elevations are between 49 m at the exploitation road level and 25 m at the basic landslide level. The arranged slope has, at the top zone, an elevation around 1 m with respect to the exploitation road.

The landslide had, at the front level, a detachment step of around 7 m and the rock fall from the landslide base had around 2 m height and a furrow appearance. The slopes and terraces, as well as the drainage works placed at the slope level, were affected, the landslide being disposed after 5 steps.

The gravitational rearrangement of the landslide determined a lot of landline and perpendicular fissures, one crevasse with 2 m depth and 1 m opening, reverse slope at the detachment step level, appearance of streams at the top of the landslide, which drain the water both from the landslide and the level of the separation plan between the stable and unstable zones.

For "Km 60" landslide monitoring, as well as for the "Km 58" landslide, the geotechnical drillings have been made and equipped as piezometers and inclinometers. Also, topographical survey and vertical electrical soundings have been carried out. The sliding monitoring from the "Km 60" zone has been done through two inclinometers located in the sliding body (FG4 and FG5) and two piezometers F18 and F18B (Fig.3).

The position of the sliding plan has a certain degree of approximation and it is located in the area of maximum concentration curves of the inclinometer chart (Fig. 4).

Two aquifers have been delineated based on the lithological data, same as for the "Km 58" zone: the upper aquifer, consisting of loess, extended on the southern half of the "Km 60" zone, and a lower aquifer, consisting of clay, sand and gravel alternations, extended on the whole study zone. A clay layer is located between the two aquifers and it is extended as much as the upper aquifer.

The upper aquifer, covering about 1650 m^2, is developed between the elevations 44 m south and 49 m east. The groundwater heads are between 44.5 m north and 45.8 m south.

The lower aquifer, covering about 11700 m^2, is developed between the elevations 18 m and 49 m, with thickness between 3 m north, towards the canal, and 12 m south. The groundwater heads are between 29 m northeast, towards the canal, and 36 m south. Unlike the "Km 58" zone, here there are no drains anymore.

METHODOLOGY

Vertical electric sounding

Geophysical investigations by means of the vertical electric sounding method (Milsom, 2003), were applied in both areas affected by landslides. The principle of the method of vertical electric sounding (VES) is the determination of the apparent resistivity of a succession of layers using a quadripolar device, with two plugs for electric current emission AB and two plugs MN for measuring the induced difference of potential. Resistivity of the medium varies with depth. In multi-layered deposits, the depth of the penetration layer of the current increases with the length of the emission line and, thus, it may increase by the simultaneous and continuous moving away of the AB plugs. VES were performed using a TERRAMETER SAS 300C.

Inclinometry

The inclinometric system (Green and Mikkelsen, 1986) measures lateral movement below ground level. A permanent casing, usually made from a solid plastic or aluminium, is installed in a borehole. The casing has four longitudinal grooves on its inside wall, named A0, A180, B0 and B180. The A0 – A180 is the reference direction and it is perpendicular on B0 – B180 direction. The casing is always read twice per survey, bottom to top, first run facing the casing A0 and reversed to A180 direction for the second run. In rare cases the B axis is also read, requiring 4 passes of the probe to gather data for each survey. Generally, the results are presented as a Cumulative Displacement plot, showing the change in the position of casing since the initial set of readings. The results could be presented as well as Incremental Displacement, showing the displacement over each probe length since first survey or Absolute Position, showing the verticality of the installation.

The inclinometric surveys were performed by a Soil Instruments device.

RESULTS

Geoelectrical measurements

Nine vertical electrical sounding (VES) were carried out, on three profiles on the level curve, for each landslide. For interpretation, other three transversal sections have been built on the sliding axe by drillings FG1 and FG2 and the east and west side for "Km 58" landslide and drillings FG4 and FG 5 and the west side for "Km 60" landslide.

By correlating the borehole data (lithological limits, sliding planes and infiltration levels) with the geoelectrical information on Figs. 5 and 6, one can notice a succession of inflexions of resistivity isolines that delimit the layers, separating limestones and clay with limestone concretions.

The sliding plans for "Km 58" landslide are more developed because the clays are more extended, and also due to the water presence. On the cross-section from Fig. 4, there are two sliding plans with two infiltration levels:

- from the elevation 55.50 m to 50.50 m – as emphasized on the F15 and FG1 logs – on 45 m length from south to north, the plan correlated with a linear anomaly of minimum, at the same elevation (50.50 m) on the geoelectrical section;
- from the level 47.50 to 41.50 - according to FG1, the plan correlated with the isoline of 9.0 Ohmm on the geoelectrical section.

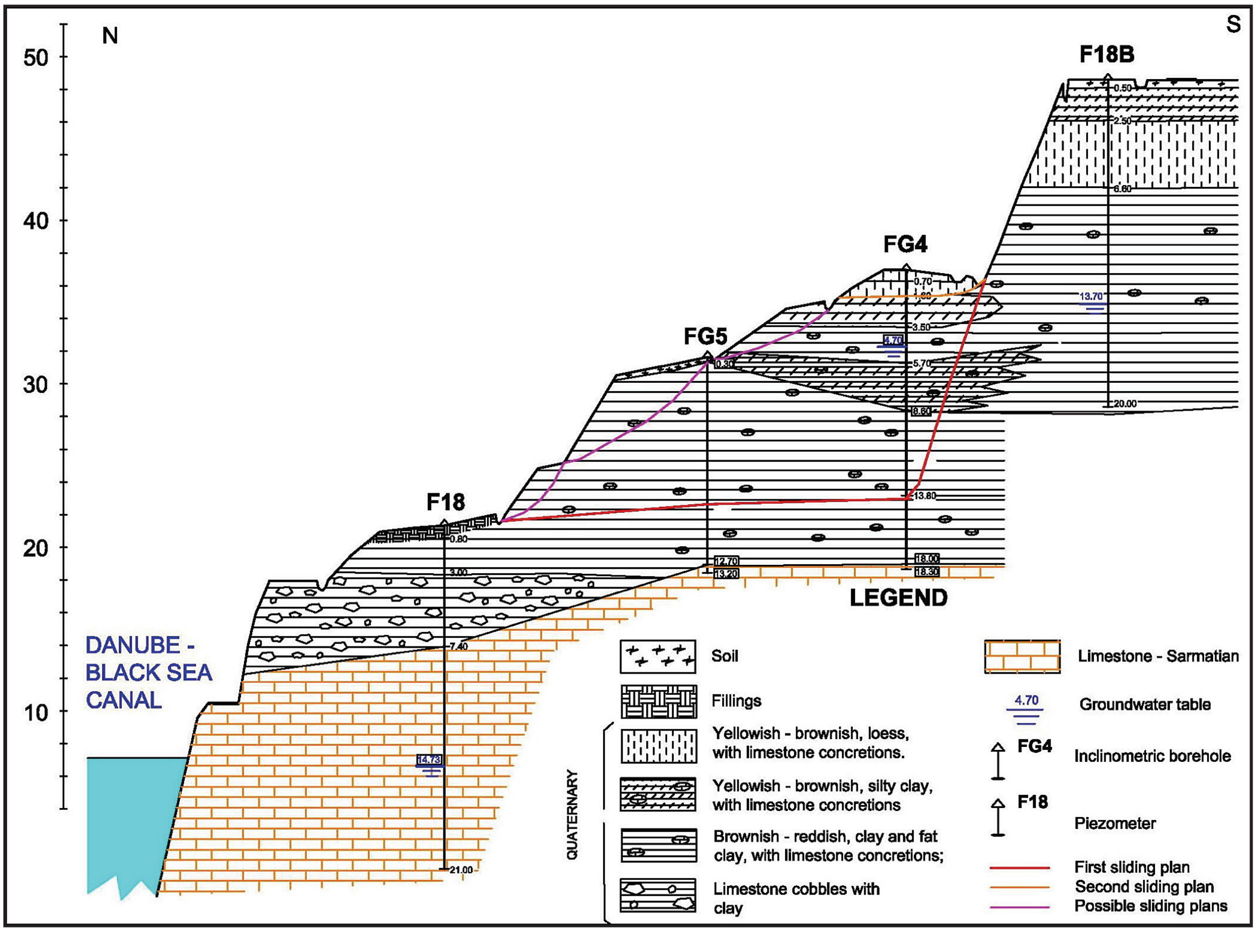

Fig. 3 Geological cross section on Km 60 landslide

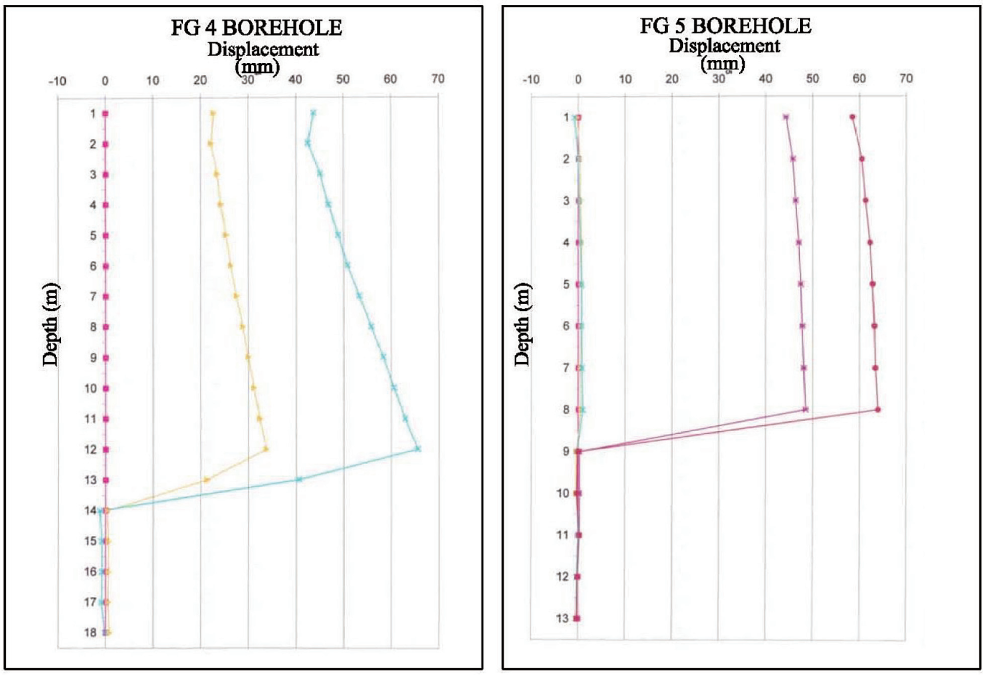

Fig. 4 Displacement charts of "Km 60" zone inclinometers

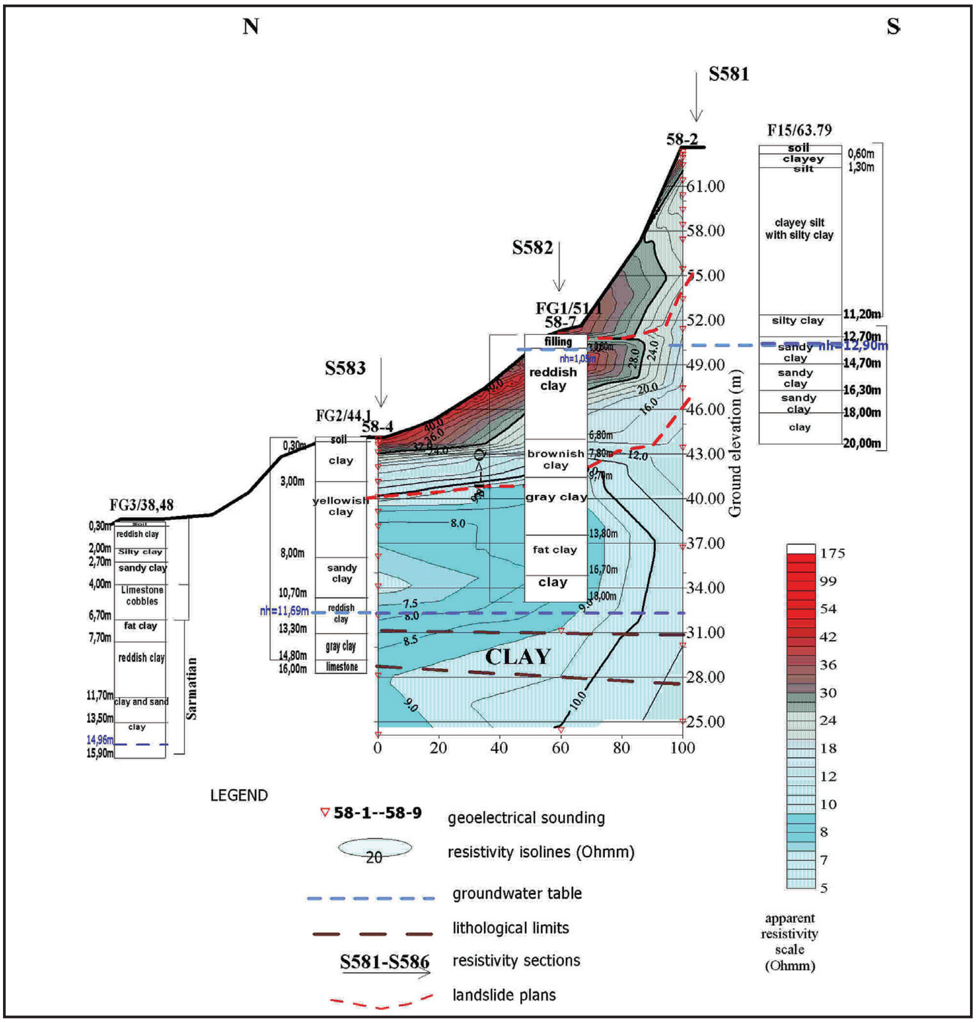

Fig. 5 Geoelectrical cross section on "Km 58" landslide

In conclusion, the sliding phenomenon is widely developed due to the presence of sandy and silty clay, with limestone concretions at different levels.

For the "Km 60" zone, the first sliding plan is less developed, having 40 m length from the upper side to the canal, where silty clay and loess appear on the first 6.00 m and clay with limestone concretions underneath. The water surface appears at the 34.93 m elevation (13.70 m depth).

By means of the geolectrical interpretation (Fig. 6) tree sliding plans were determined:

- superficial plan, active, from elevation 43.00 (contact surface between loess and clay) to 35.00 (water surface level);
- second sliding plan, less active, from elevation 33.50 to 29.00;
- old sliding plan at the contact surface between clay and fat clay, from elevation 31.00 to 26.00.

In conclusion, the "Km 60" zone landslide has a smaller scale than the "Km 58" zone landslide.

Inclinometric measurements

For the "Km 58" landslide, the inclinometric survey was performed in three boreholes equipped as inclinometers, with 18 m (FG1) and 15 m depth (FG2 and FG3). The measurements were done every month, for a 8 months period. The results (Fig. 2) show small movements along the slope direction: 1.5 mm at 15 m depth for FG1, 10.9 mm at 13 m depth for FG2 and 1 mm at 10 m depth for FG3.

For the "Km 60" landslide, the inclinometric survey was performed in two boreholes equipped as inclinometers with 18 m (FG4) and 13 m depth (FG5). The measurements were done every month, for a 3 months period in FG 4 and 6 months period in FG 5. FG 4 inclinometer was drilled later by reason of landslide mitigation works. The movement measured in FG5 inclinometer being ample, the device could be stock in the inclinometric case and, then, the survey was stopped. The results (Fig. 4) evidence ample movements along the slope direction: 65 mm at 12 m depth for FG4 and 63 mm at 8 m depth for FG5.

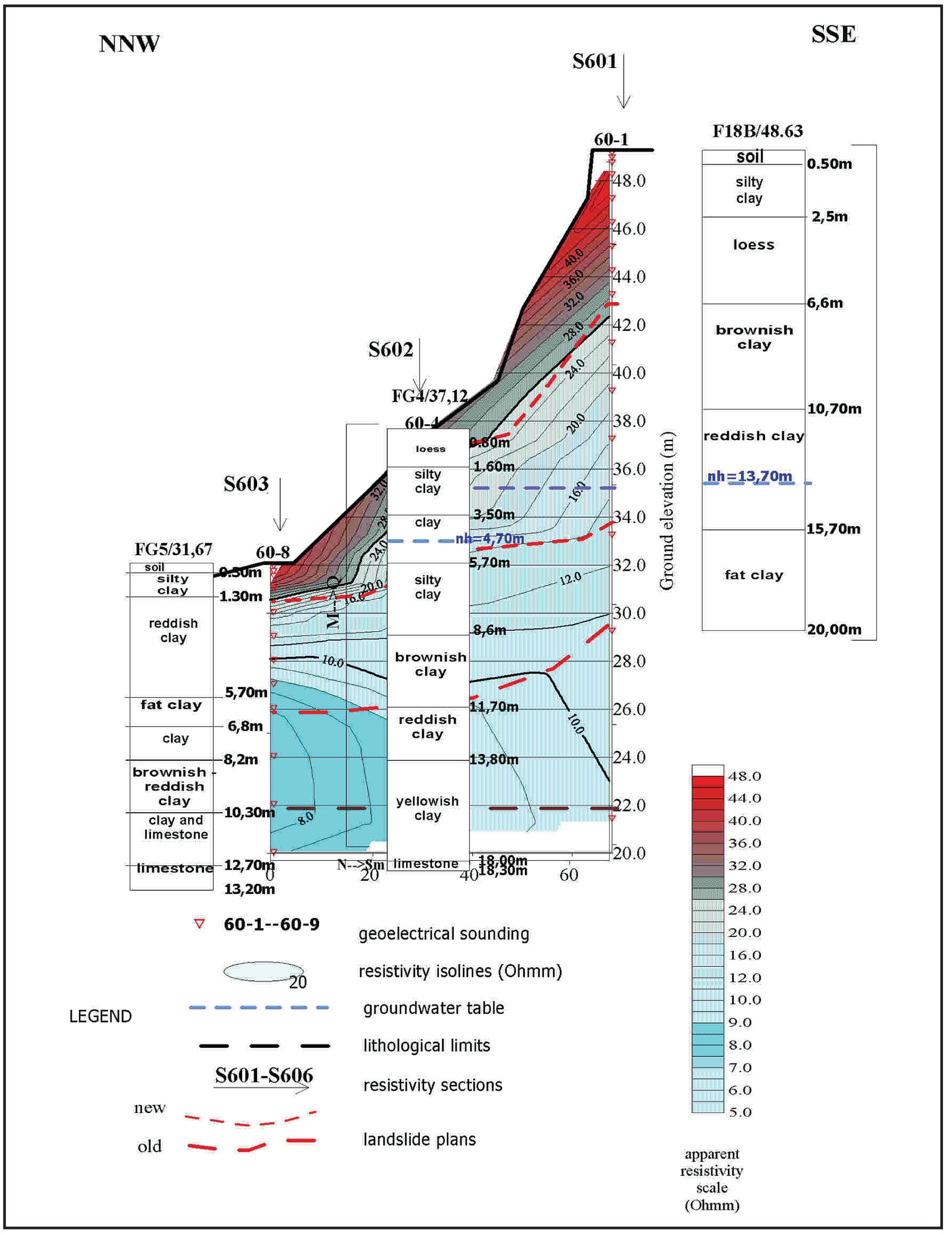

Fig. 6 Geoelectrical cross section on on "Km 60" landslide

Groundwater flow modelling in the "Km 58" and "Km 60" zones

Groundwater flow modelling was considered necessary in the "Km 58" and "Km 60" zones in order to estimate the influence of the hydrodynamic conditions on the occurrence of landslides. Visual Modflow (Guiguer and Franz, 1996) was used for both local models.

"KM 58"

The flow model in the "Km 58" zone was built based on the data provided by the borehole F15 and inclinometers FG1, FG2 and FG3, as well as data provided by the vertical electric soundings (VES) 58-1 to 58-9.

The modelled domain is bounded by the VES locations 58-1, 58-2, 58-3 south, 58-8 and 58-9 west, 58-3, 58-6 and 58-5 east and the inclinometer FG3 north. The zones without data were considered inactive.

The horizontal dimensions of the grid are 5 m x 5 m. The boundary conditions are constant-heads, prescribed based on the measured groundwater heads.

The system of drains is represented by a prescribed head condition. It wasn't possible to measure the head in any drain. The head in the system of drains and the hydraulic conductivity of the upper aquifer were adjusted until the calculated rate of the drain became as close as possible to the rate determined on the field. In this way, the drain elevation of 49.7 m was obtained, while the rate of the drain provided by the model became 36.79 m^3/day, value close to the one determined on the field. The hydraulic conductivity of the upper aquifer is 2 m/day on the widest part and 0.2 m/day on the clayey stripe located north of the system of drains. At the same time, the system of drains takes over the water from the upper aquifer, so that there is no flow anymore north of it.

The groundwater flow directions in the lower aquifer converge towards the canal, being mainly SW – NE, but also S – N, SE – NW (fig. 7). The hydraulic conductivities in the lower aquifer, resulted from the calibration of the model are between 0.2 m/day and 5 m/day on a strip located approximately between the borehole F15 and the inclinometer FG3 (fig. 8). This zone can be interpreted as being more fissured, thus allowing a preferential pathway for groundwater, also emphasized by longer velocity vectors (fig. 7).

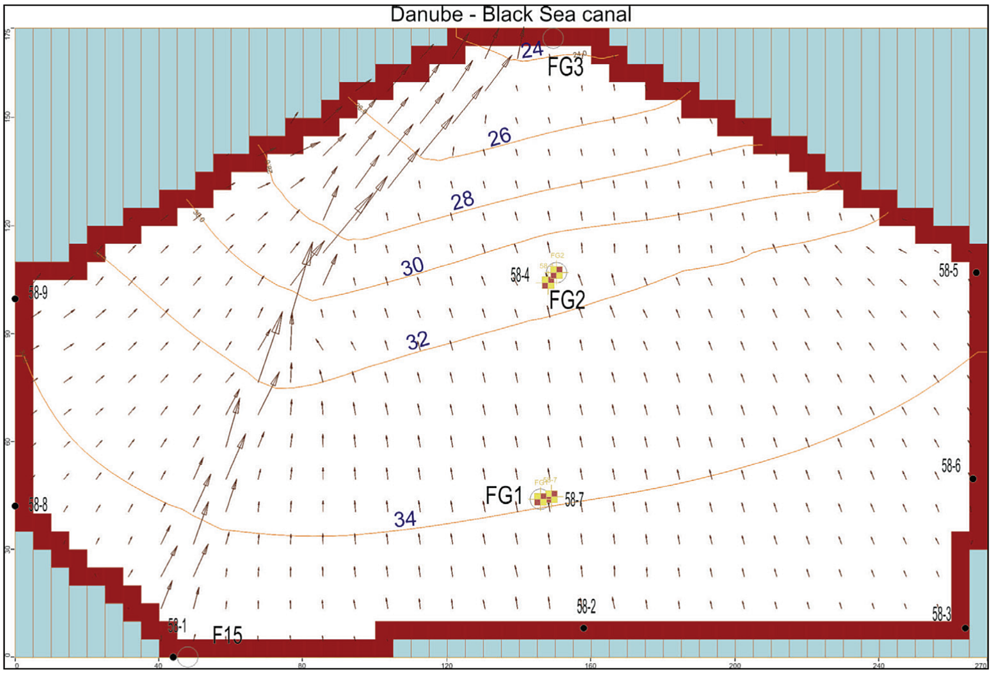

Fig. 7 Piezometric map and groundwater flow directions in the lower aquifer from the "Km 58" zone

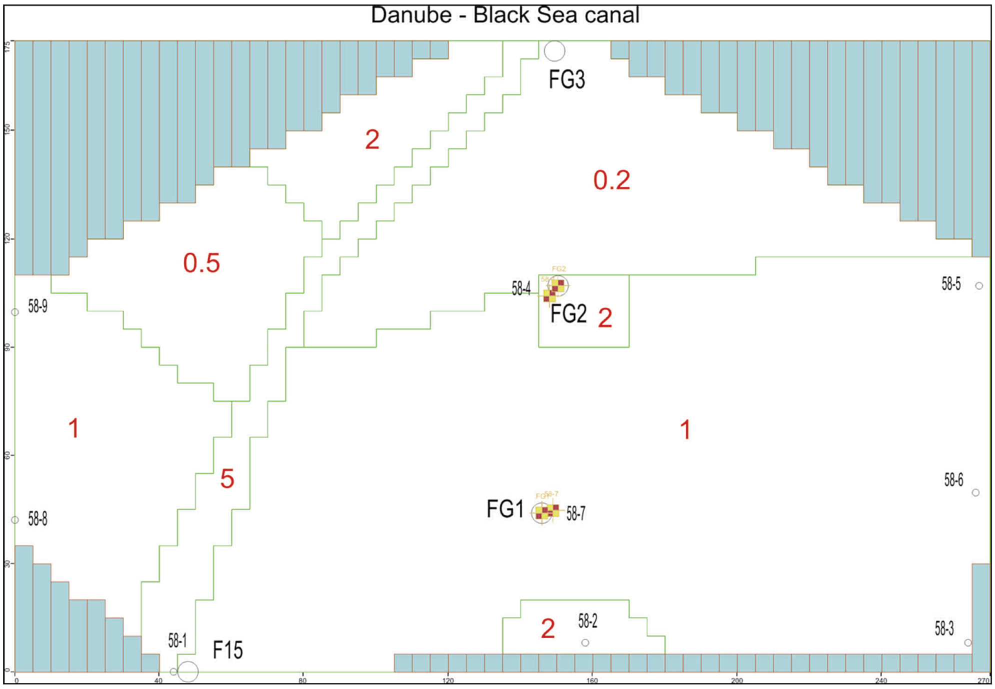

Fig. 8 Distribution of the hydraulic conductivities (m/day) of the lower aquifer from the "Km 58" zone, resulted from the calibration of the model

"KM 60"

The flow model in the "Km 60" zone was built based on the data provided by the inclinometers FG4 and FG5, as well as data provided by the vertical electric soundings (VES) 60-1 to 60-9.

The modelled domain is bounded by the VES locations 60-2, 60-5 and 60-9 west, 60-3, 60-6 and 60-7 east, 60-1 – 60-3 south and 60-7 – 60-9 north. The zones without data were considered inactive.

The horizontal dimensions of the grid are 2.5 m x 2.5 m. The boundary conditions are constant-heads, prescribed based on the measured groundwater heads.

The main groundwater flow direction in the upper aquifer is W – E and the hydraulic conductivity was considered 2 m/day.

The groundwater main flow direction in the lower aquifer is S – N, towards the canal (fig. 9).

The hydraulic conductivity in the lower aquifer is 2 m/day on the widest part of the represented domain and 1 m/day on the eastern half of the southern part.

Both for the "Km 58" and the "Km 60" zones the groundwater flow directions are towards the canal, as shown on figs. 7 and 9. Thus groundwater flow favours the occurrence of landslides. Moreover, in the "Km 58" zone, preferential pathways were formed in zones with higher conductivity.

These models prove that interpretation of landslide phenomena must be done also taking into account the influence of groundwater flow.

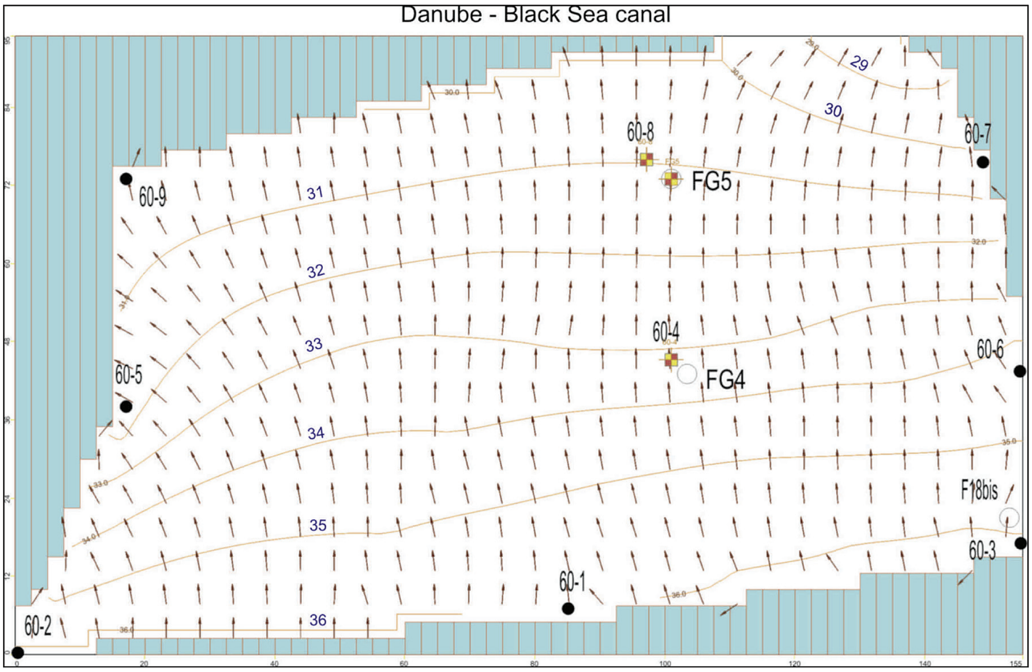

Fig. 9 Piezometric map and groundwater flow directions in the lower aquifer from the "Km 60" zone

CONCLUSIONS

The sliding phenomenon from the "Km 58" and the "Km 60" zones on the right bank of the Danube – Black Sea canal, was triggered mainly as a result of water accumulation at the contact between loess deposits and the underlying red clay. Groundwater sources are the infiltrations of the rainwater and from the old irrigation system. In both study zones, the groundwater flow directions are mainly S – N, towards the Danube – Black Sea canal, favouring the occurrence of landslides. Also, the defective maintenance of existing works conduct to the slopes instability.

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