The stability analysis of a steep slope at a lake; Hungary

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ABSTRACT: Steep and high slopes are common in Hungary, especially along the Danube and at the shore of Lake Balaton, characterized by dynamic, ever-changing morphology and sliding activities. Due to the urbanisation, the area of these slopes is built-in with roads, railway lines and houses. The paper studies the stability and safety problems of a steep slope located at the lakeside of Lake Balaton, Hungary. Field observations, borehole data were used to outline the geology. Physical parameters of Quaternary soils and Late Miocene sediments were obtained from laboratory tests. The slope stability was assessed using Geo5 and Plaxis. Local failures and global stability were calculated. A rotational slip surface was identified by the software, and inclinometer readings also confirmed the slow displacements.

Keywords: coastal slope stability, Plaxis, Geo5, inclinometer, railway line

1. Introduction

Slope stability problems threaten many areas around the world. The number of landslides and mass movements is increasing in both mountainous [1,2] and coastal [3,4] areas. With the continuous growth of the infrastructural needs of society, more and more roads and railways are built in areas that are prone to landslides.

Coastal slopes often are subject to active erosion processes such that their morphology, and thus their stability, is changing rapidly; there may be several erosion processes. [5-8]

In Hungary, the construction of the railway line along Lake Balaton began in the second half of the 19th century, and since then, science has been dealing with mass movements there [9], which have already caused roadblocks and railway accidents in many cases. Interventions with human constructions have created harmful and dangerous movements on some parts of the shoreline. The paper deals with one of these shoreline sections, the slope of Balatonakarattya, where the railway passes through the middle of the slope, and there is a resort area at the bottom of the slope and also on the plateau of the slope. This area is recorded as an area with multiple landslides and has a high slope stability hazard.

The stability of the slopes can be examined by many numerical methods. [10, 11] Two common methods are Limit Equilibrium (LE) [12,13] and Finite Element Methods (FEM), for the application of which many geotechnical programs are available. The stability analysis of the examined section was modelled in Geo5 (LE), and Plaxis (FEM) software[14], and the results were compared [15], as was done for slopes located in India [16].

We can use slope inclinometers to understand the cause, behaviour, and remediation of landslides [17]. The slip surface obtained in our modelling was compared with the displacement curves measured in the inclinometer tube installed in the studied section.

2. Study area

2.1. Geography

The study area is located in Hungary, next to the largest lake in Central Europe, lake Balaton. The studied coastal slope is located in the eastern basin of the lake. The featured and modelled section – which has about 90 m level distance and near 350 m width – is located on the border of Balatonakarattya and Balatonkenese settlements. (Fig.1.)

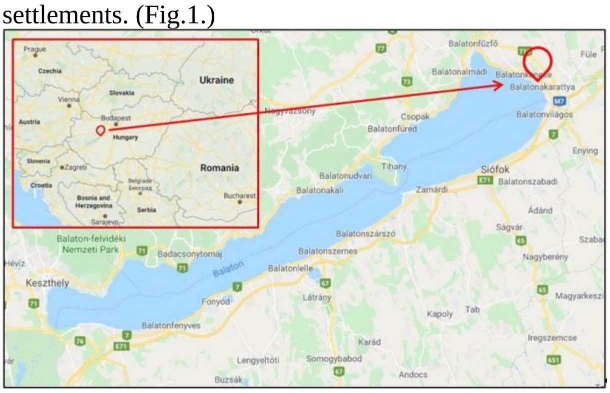


Figure 1. The location of the examined area

2.2. Geology

Upper Neogene and Quaternary layers form the major part of the area. The Neogene is represented by the upper

Pannonian clayey, silty, sandy, organic content accumulated layers, while in the Quaternary, loess and sediment of Balaton formed.

The detail of the geological map of Hungary [18] of the eastern part of the lake displays loose and partly cemented sediments (Fig. 2). It is clear how different layers make up different parts of the coastline. The layers of the studied area are highlighted.

The excavations revealed 1-2 m thick Holocene layers underlain by the deposits of 'Tihany Formation', which consists of different grain size but predominantly fine sand and silt. These are sediments of the preexisting deltas arriving at Lake Pannon [19]. The cold winds of the ice age formed a thin loess cover, which has been already eroded in many places, and elsewhere it is only present in a maximum thickness of a few meters. Loess is missing from the study area. On the lakeshore, lacustrine and bog deposits are found, while on the rest of the coast, eluvial deposits and debris are common besides late Miocene layers.

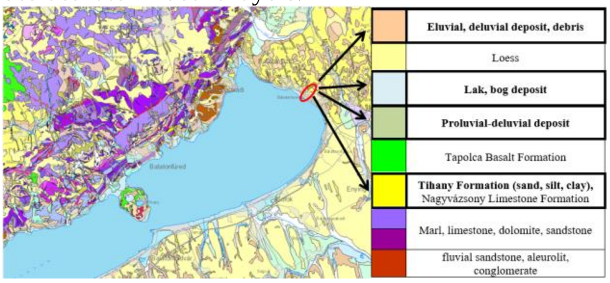


Figure 2. Geological map of the examined area [18]

2.3. Morphology and hydrogeology

Balaton has eroded the slope in the past period due to wave action, and sediments were deposited at the lakeside zones. Fig. 3 shows the changes in the water level of Lake Balaton from the 9th to the 20th century.

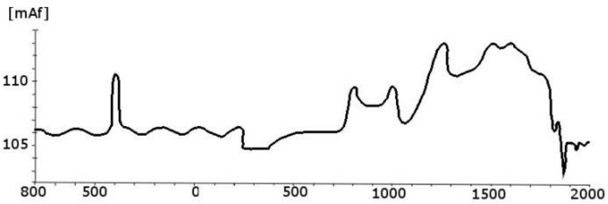
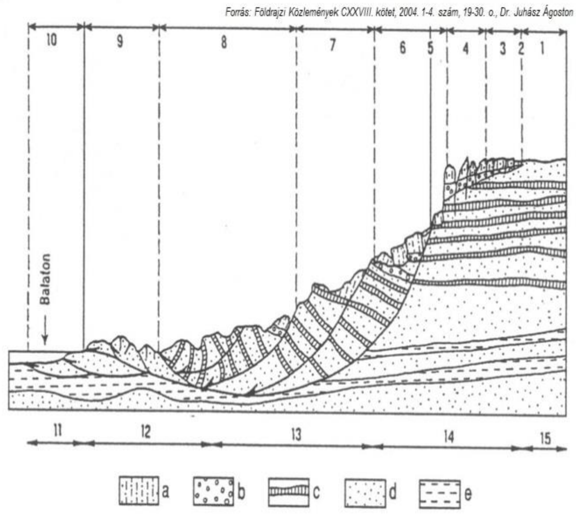


Figure 3. Changes in water water level of Balaton from the 9th to the 20th century [20]

The geomorphological setting and geological successions result from a very intense evolution period, especially during the Holocene. Slope movements have long been observed and described. Before the 19th century, there were two major islands before Balatonakarattya, which slope surfaces may have formed extended deep below the lake bed, thus causing bed rise. Significant surface movements also occurred in the early 20th century [9] (Fig 4.).

Figure 4. Landslides in the surroundings of the study area [9]

At that time (1914), a railroad train also fell victim to the movements. Morphological and geological investigations were carried out [21], then a general geomorphological model was made for the movements of slopes near Balaton [9] (Fig 5).



Key:
1 - areas of landslide hazard; 2 - boundary line of fissures;
3 - cleavage zone; 4 - humps with collapse hazard; 5 - failure front of the slide; 6 - accumulation zone of the deformed matter; 7 - zone with landslide hazard; 8 - zone of slopes with temporary rest; 9 – compression zone of landslides;
10 - stabilized remains of former slumps.
Dynamic state: 11 - stable zone at the base; 12 - zone of pressure tension; 13 - transitional zone of dynamically changing tensions; 14 - zone of shear and pull tensions; 15 - stable surfaces;
a = loess, sandy loess; b - gravel; c - Pannonian series with variegated clay; d - Pannonian sand; e - Pannonian clay

Figure 5. general geomorphological model of the movements of slopes near Balaton [9]

The current morphology of the area reflects past mass movements, and it gained its present form in the early 20th century by filling the areas near the lakeshore. With the landscaping of the lakeshore, sedimentation ceased in the area. Surface movements have continued in recent years; for example, in 2010, several roads and railway lines were closed. In the area of Balatonakarattya the railway track slipped along 70 meters wide zone in 2010. Next year the shoreline slipped along 100 metres. Finally, in 2017, 200-300 m^3 soil moved downslope.

The area lies on the border of two hydrogeological regions. The hydrogeology is unique since the hinterland feeds groundwater; additionally, there is a complex interaction of lower groundwater horizons with lake water. The lake level has been fluctuating, in ten meters of amplitude according to the records of the past 500 years. The groundwater table has an indirect link with precipitation. These conditions lead to the presence of confined aquifers that reduce slope stability.

Based on long-term time series, there is a close correlation between extreme rainfall and the time of slides and collapses [9].

2.4. Field observations

Several signs of slope movements are visible in the area. Two examples are displayed in Fig. 6, which shows curved trees and fallen, curved barriers suggesting a slow creeping movement of the shore.

Figure 6. Field observations

The retaining wall at the bottom of the slope is cracked, and little debris is in motion. Little springs appear on the slope, which represents the outflows of subsurface waters. Finally, at the edge of the top of the slope, local slumps can be seen. These signs all indicate a complex process of motion.

3. Stability calculation

3.1. Methodology

We calculated the stability of the slope using two different methods and softwares: Finite Elemet Method with Plaxis and Limit Equilibrium Method with Geo5. [22]

Both geotechnical software tests stability by reducing shear strength parameters. The theoretical basis of Plaxis calculation is the finite element method and ϕ-c reduction. [23, 24] The strength parameters, tan φ and cohesion c, of the soil are successively reduced until the slope collapses. The total multiplier ΣMsf is defined as the ratio of the strength parameters entered as input values over the reduced ones. The safety factor should be minimum 1,35 according to Eurocode7.

Fig. 7 shows the finite element mesh generated in Plaxis.

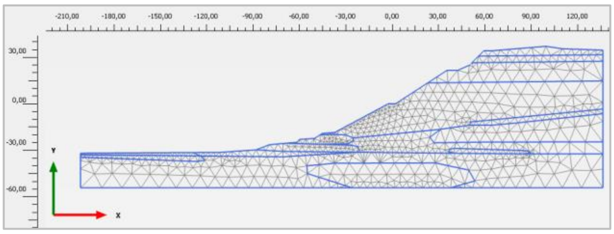


Figure 7. Finite element mesh

In limit equilibrium methods, the equilibrium of a soil mass tending to slide down under gravity's influence is calculated. [25] All these methods are based on the comparison of forces, moments, or stresses resisting the mass's movement with those that cause unstable motion (disturbing forces). Geo5 computes slope stability with circular failure surfaces (for example, Bishop, Janbu or Spencer method) or polygonal slip surfaces (the Sarma method). Geo5 software reduces design shear strength parameters, and it checks the utilization using classical methods, which should be below 100%.

3.2. Input parameters

3.2.1. Modell geometry

A geodetic survey of the terrain was available. To define soil stratification, an 80 meters deep drilling and a 60 meters deep geophysical survey measurement from the top of the slope, 30, 20 and 15 meters deep explorations and one CPT probe at the bottom of the slope macroscopic layer descriptions was used. Fig. 8 shows the layers of the drawn section, which was also used as model geometry.

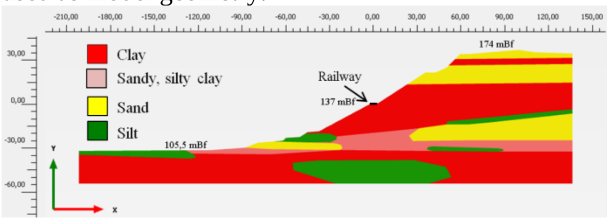


Figure 8. Examined section, modell geometry

Excavations were made on top and bottom of the high shore, so the geometry of the layers between them was created based on knowledge of geological development.

The foot of slope begins with lake sediments, then the debris slope is buit with the mixed layers of early movements. In the predominantly clayey environment of the slope, the lake's varying water levels for centuries may have formed lenses of silt and sand. The water level was modeled between 103.5 and 105 mBf.

3.2.2. Soil parameters

Soil physics parameters (Table 1) were determined on the basis of explorations, macroscopic layer descriptions, laboratory investigations.

Table 1. Soil physics parameters

	Sa/1	Cl/1	Cl/2	Si/1	Sa/2	Sa-Si-Cl	Cl/3
γ_{unsat} [kN/m^2]	17	19	20	18	17	20	21
γ_{sat} [kN/m^2]	18	20	21	19	18	21	22
E [MPa]	6	10	11	8	10	10	16
ν	0,35	0,3	0,3	0,4	0,35	0,4	0,3
c [kN/m^2]	5 - 8	50	60	25	1	30	80
φ [°]	24	22	26	18	20	25	34

4. Results

4.1. Local failure

Due to its calculation method, the Plaxis program always shows the failure method that is most likely to occur sooner. Therefore, the calculation results are greatly influenced by the parameters of the sand layers at the top of the slope. The instantaneous cohesion of these layers depends on the saturation of the layer and the vegetation of the surface. Fig. 9 shows our first results, according to which when the cohesion of the mentioned sand layers is 5 kPa a local erosion is visible. (Fig. 9) In this case, the safety factor is 1.18, thus falling below the Eurocode 7 standard of 1.35.

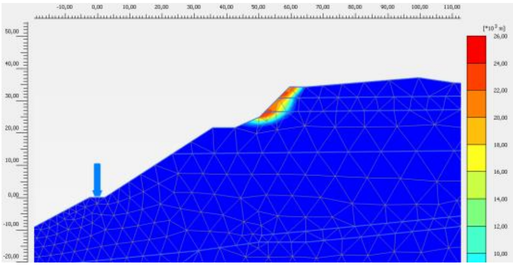


Figure 9. Total displacements in Plaxis – local failure

Taking into account the same soil physics parameters, with the minimum 10% saturation Geo5 software already shown utilization rate above 100%. (Fig. 10)

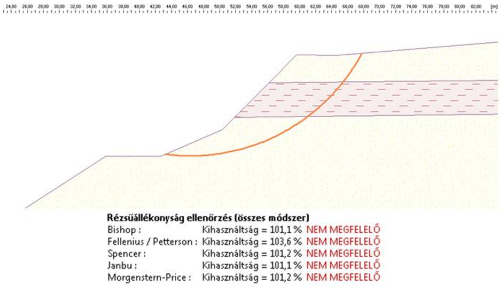


Figure 10. Local slope stability test is Geo5

It can thus be seen that local erosion is most likely to occur. Although these can happen at any time, and there have been several examples before, the signs of local movements can be seen in Fig. 11.

Figure 11. Signs of local movements at the top of the slope

A little wetness increases the cohesion of the sand, but the saturation of the layers and the rainy weather further increase the utilization and reduce the slope stabilty.

However, the main purpose of the research was to inspect global stability.

4.2. Global failure

In order to investigate the potential for global failure, which is less likely, but with much greater risks, the risk of local failure must be reduced, which can be achieved by increasing the cohesion of the upper sand layer in small steps. The iteration process provides an answer to the question of whether local failures can be followed by global ones.

When the cohesion of the upper sand layers reaches 8 kPa, a global slip surface is also drawn. This is shown in Fig. 12.

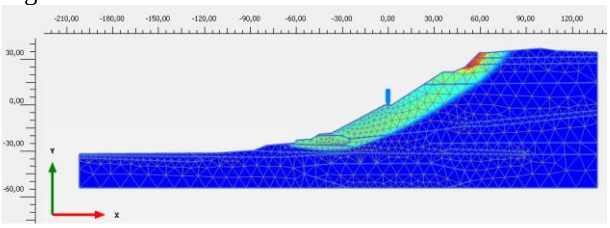


Figure 12. . Total displacements in Plaxis – local and global failure

The factor of safety that can be assigned to this state is 1.29, so it does not reach the level given by Eurocode 7 standard, 1.35. Geo5's classic methods show adequate utilization close to 100%, except for one method (Fig. 13). This exception is according to Fellenius and Petterson; the slope is not stable in this case, and the utilization is 104%.

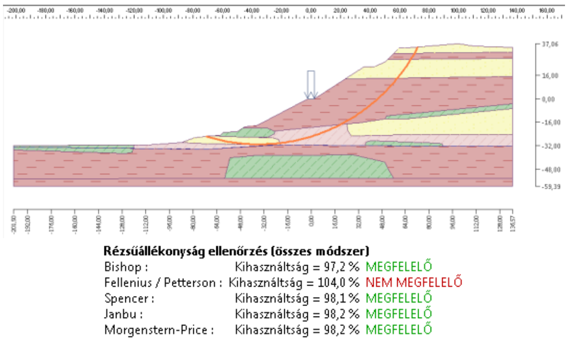


Figure 13. Global slope stability test in Geo5 software

Fig. 14. shows the calculated local and global slip surfaces and the position of an inclinometer measuring well. The displacement curves calculated from the inclination values measured in the 30 meters deep well every half meter for the period 2017-2020 mark these displacements.

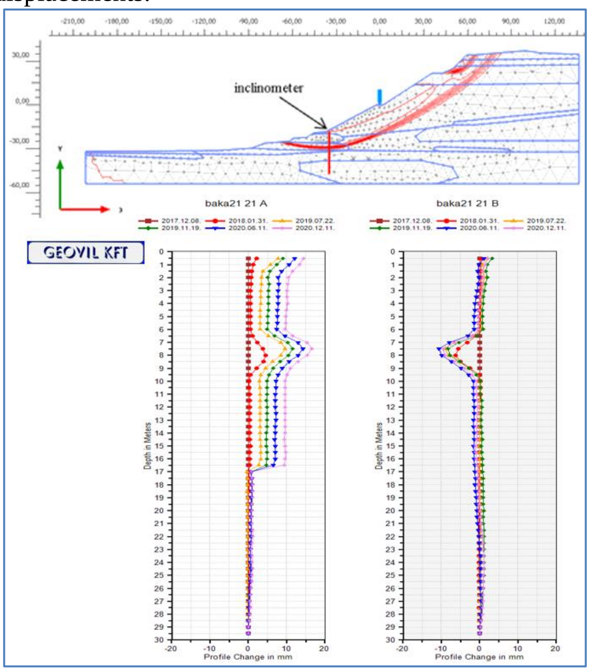


Figure 14. Inclinometer measurement (Geovil Ltd.)

The positive (right) displacements in the A axis (left side) means sloping displacements. The B axis closes 90 degrees clockwise with the A axis.

The inclinometer curves show a displacement roughly in the zone where the sliding surface identified from our calculations is also visible. At a depth of 7-8 meters, the boreholes did identify a weak layer, but the displacements of a few mm measured in it have not increased for quite two years now. However, at a depth of 17 m, deeper than the identified slides, there is a slow increase in displacement. It seems a very slow (~16mm/3 years) natural movement. Our recent studies have also shown large curved deep-seated sliding surfaces. [26] Movements appear delayed on the surface, and measurements are frequent enough to identify any accelerating motion in time. However, the curves are also influenced by a number of technical factors.

5. Conclusions

The comparative analysis of the stability of the slope of Balatonakarattya with Plaxis and Geo5 software and our on-site observations both suggest that both local and global failures can occur.

According to Plaxis software, the stability of the high bank does not comply with the Eurocode 7 standard, while according to almost all methods of Geo5, only a local slump can be dangerous. Rainy weather increases the risk of movements; failure might occur when subsurface waters reduce the cohesion of sedimentary layers.

According to the results, continuous monitoring of the slope movements is required, and the evaluation of the inclinometer readings helps in understanding possible slope failure modes and prevent damage events.

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