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SLOPE STABILITY ANALYSIS OF ELEVATED SHORELINE AT BALATONFÖLDVÁR

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1. Abstract

The Balatonföldvár high coast cliffs, towering 25-45 meters above Lake Balaton in Hungary, present a complex geotechnical challenge that juxtaposes the area's natural beauty with the need for structural stability. Concerns regarding erosion and stability necessitate a thorough investigation to safeguard the integrity of local infrastructure and resident safety. This research encompasses a comprehensive review of literature, laboratory analysis, and advanced computational modeling to analyze the stability of these cliffs.

In-depth laboratory tests on soil samples from various depths of the cliffs have provided crucial data for constructing a detailed soil profile. The laboratory analysis revealed the loess layer has a cohesion of 56 kPa, internal friction angle of 46°, and oedometric modulus of 27 MPa. These parameters are instrumental in the stability assessment conducted via the Geo5 software. The study meticulously examines the cliff's safety factor to the Eurocode 7 requirements, providing an informed perspective on the cliff's structural soundness.

Limit equilibrium methods were employed to assess three cross-sectional models. Model one examined the literature cross-sectional geometries, and models two and three examined newly evaluated cross-sections with a variety of soil layer orders and properties. With each model yielding different safety factors. Model three exhibited the most precarious situation with a safety factor of 0.85, pointing to potential local failure near the cliff edge. Models one and two, while yielding higher safety factors of 0.97 and 1.17, respectively, still do not satisfy the Eurocode 7 recommended safety factor of 1.35.

The findings from the laboratory tests were critical in identifying the variations in safety factors among the models, highlighting the importance of soil mechanical properties in geotechnical stability assessments. The TDK project concludes by emphasizing the need for strategic structural interventions to reduce risk and preserve the safety of the community. This study aims to contribute to geotechnical engineering, providing a nuanced analysis of the Balatonföldvár cliff stability and setting a precedent for future research in similar geological settings.

2. Introduction

The Balatonföldvár high coast, an impressive geological feature reaching vertical cliff face heights of 25-45 meters above Lake Balaton in Hungary, stands as a subject of both aesthetic allure and rigorous geotechnical scrutiny. This commanding geological formation, characterized by its sheer cliffs, commands the attention of the scholarly community due to the complex geotechnical challenges it presents. A nuanced understanding of this landscape is essential to ensure the structural stability of nearby infrastructure and, crucially, the safety of the local populace.

Over the past decades, discernible trends of continuous erosion and localized failures have manifested along the Balatonföldvár high coast (near Lake Balaton). These erosional processes have eroded the cliffs and instilled profound concerns regarding the structural integrity of residential structures and transportation routes close to the elevated cliff's edge. It is necessary to note that vital transportation networks, including roadways and railways, are located beneath the high coast, intensifying the urgency of grappling with the stability issues engendering this geological feature.

The overarching aim of this research is to gain a clear understanding of the geotechnical elements that govern the high coast's stability. This involves a comprehensive state-of-the-art evaluation of existing literature, gathering historical data on laboratory tests of soil specimens collected from the site from different layers. These data sets made it possible to determine an accurate soil profile with appropriate physical parameters. Cross-sections were compiled from the area using archive drilling data and on-site observations. The slope stability was modeled with computer code Geo5. Input parameters were determined for each modeled layer and included dry and saturated unit weight, angle of internal friction, cohesion, Poisson ratio, and modulus of elasticity. The failure surfaces were obtained using the computer code, and the slope stability was calculated. The current factor of safety will be determined, and the possible failure surfaces identified.

The analytical exploration delves deeply into the fundamental geotechnical elements that govern the high coast's stability. This involves the evaluation of the current factor of safety that the cliff holds, in comparison to the required safety factor of 1.35 according to Eurocode 7. Noteworthy consideration extends to discerning the impacts of groundwater dynamics and precipitation patterns originating from the surrounding terrain, factors that substantively shape the high coast's equilibrium. The significance of this examination is underscored by its relevance to adjacent residential settlements, roads, and rail networks. Historical instances of catastrophic failures affecting analogous geological formations surrounding Lake Balaton, such as the Balatonakarattya 1908 high cliff failure, underscore the urgency of these investigations, emphasizing the imperative for proactive intervention.

This paper furthermore encompasses the retrieval and subsequent laboratory analysis of soil specimens extracted from the stratigraphic layers of the high coast. These empirically derived parameters, in turn, serve as the foundation for the construction of a finite element model meticulously designed to simulate the high cost's mechanical behavior. The computational model undergoes validation through final comparisons to safety factors obtained from the literature.

In circumstances where the analytical inquiry reveals critical vulnerabilities intrinsic to the stability of the Balatonföldvár High Coast, this academic endeavor advances toward the formulation of a comprehensive structural reinforcement strategy. This strategy, conceived to mitigate the geological and geotechnical risks posed by erosional processes, stands as a practical manifestation of the research findings.

In summation, this project aspires to furnish a significant contribution to the corpus of knowledge surrounding geotechnical engineering challenges associated with vertical cliffs. Concurrently, it offers invaluable insights into the protection of critical infrastructure and the well-being of communities residing near these geological formations.

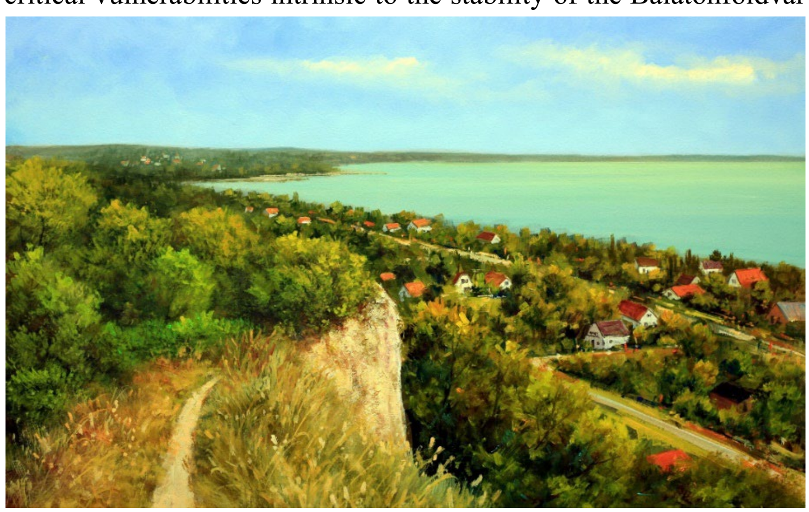


Figure.1 (Lantos György: Kenesei Löszfal)

3. Literature review

3.1. Frequent forms of surface movement in Hungary

It is well understood that surface movements stem from a myriad of varied factors. The complex interaction between chemical and biological processes, dynamic geological development, and fundamental structural and morphological aspects complicates the establishment of agreed general principles. Soil mechanical specialists are however generally in consensus over two major factors. These are the decrease in shear parameters and/or the increase in shear stresses that are present in the soil body. Furthermore, the following factors can lead to the loss of equilibrium (increase in water content/groundwater level (GWL), specific morphological and geological conditions, mineral composition and rock quality, and human interferences). [17]

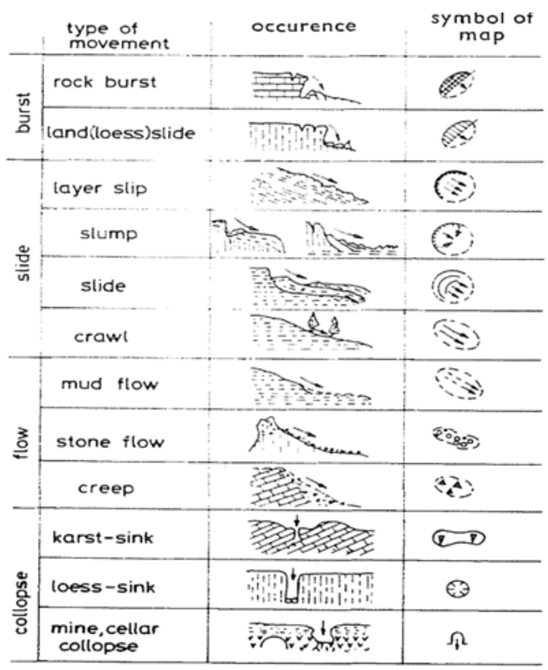


Figure.2 (Common Hungarian surface movements) [17]

3.2. Slope failure mechanisms

Real Sliding

Primarily sliding occurs when, on a slope, the upper layers move along a particular layer plane. thus on a plane pre-defined by nature, typically at the boundary of a sand and clay layer, or along thin water-conducting sand streaks within their clay layers. In these layers, the layer plane has often been saturated and slippery for a long time, but the movement usually only commences if we cut through the base of the slope or overload the upper layers. This form of ground movement is widely discussed in the literature; however, it scarcely occurs in Hungary. [25]

Movement on a slope can occur within homogeneous layers even without external intervention, especially if the layer material becomes saturated and loses its shear resistance. In this scenario, there isn't a predetermined slip plane for the movement. Instead, the slip plane forms where the greatest internal stresses from the layer's self-weight and the least resistances meet, corresponding to the level of saturation and current force conditions. [25]

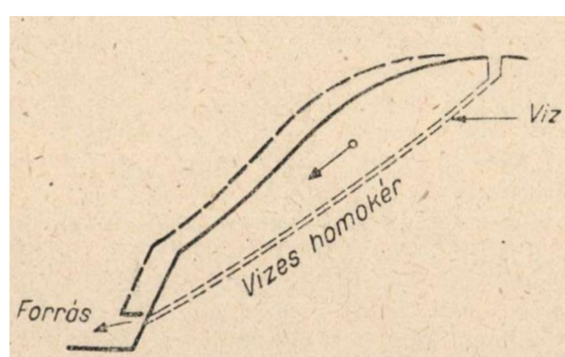


Figure.3 (Real sliding failure sliding plane) [25]

Failure due to mud/soil flow within the clay layer

Soil or mudflow can happen due to saturation under certain conditions. Typically, post a rainy summer, a prolonged winter creates a water-tight frost crust on the ground surface. Water from afar can accumulate behind this crust, saturating especially the clay layers interrupted by silt and sand streaks. The water usually becomes pressurized as it's blocked in its path, causing the entire layer to start flowing either during spring thaw or even earlier if the pressure is too high. [25]

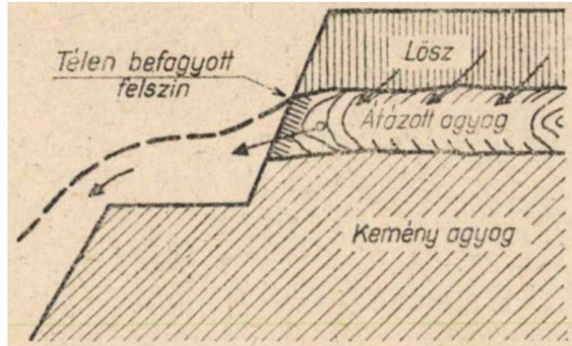


Figure.4 (Failure due to mud/soil flow within clay layer) [25]

Sliding due to overloading

There is another form of ground movement, often referred to as sliding, however, this form of sliding does not occur due to natural causes. This occurs due to the overloading of soils or the construction of overly steep slopes, leading to failure.

A unique variant of this movement tends to occur on the slopes of excavations in hard clay. This happens because the clay, relieved from geological pressure, swells, and densely cracks, and along these cracks, potentially many years after the excavation is completed, a low-resistance slip plane forms. [25]

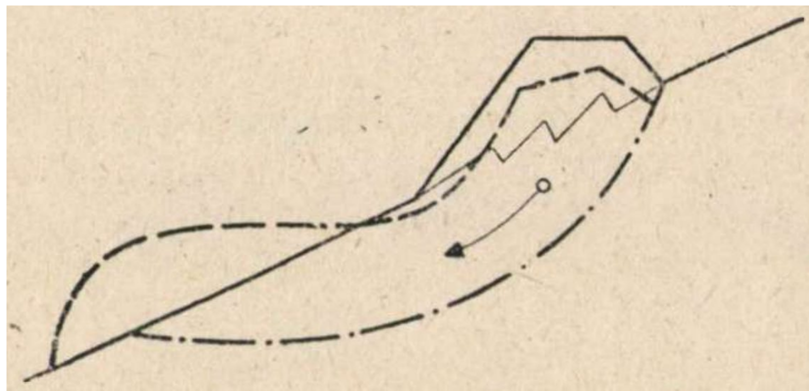


Figure.5 (Failure due to overloading) [25]

Failure of high cliffs

Behind the facade of high banks, which are exposed to wind, rain, and sun, vertical shrinkage stresses and subsequent cracks develop. Along these cracks, the connection between the bank and the detached soil slab ceases, allowing the cracked part to rely solely on its base for support. The deeper the crack reaches, the more load the base must bear. There will be a certain column height at which the base can no longer withstand the pressure, it collapses, and the slab sinks. Even with a small column height, this sinking can occur if the base of the slab becomes saturated for some reason and loses its strength. [25]

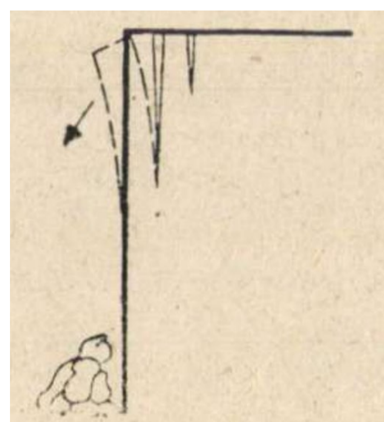


Figure.6 (Cliff failure) [25]

Force Balance

The movement of high banks over centuries is a recurring process, and when studying its laws, it's crucial to start from an initial state. Near both the Danube and Balaton, there are high vertical banks that steeply fall to the level of the preceding river or lake (Figure.7). Behind these high banks, soil, and groundwater accumulate in the catchment area, and they flow towards the low point (the lake or river). They emerge as springs at the base of the bank or connect directly to the recipient water level below the surface. However, these often 50-60 m high walls are battered by rain, baked by the sun, and affected by temperature changes, similar to the eternal decay of rocks, leading to cracking, sinking, and eventual collapse of detached parts that fall to the base of the wall. Over time, a massive debris slope accumulates (Figure. 8). [25]

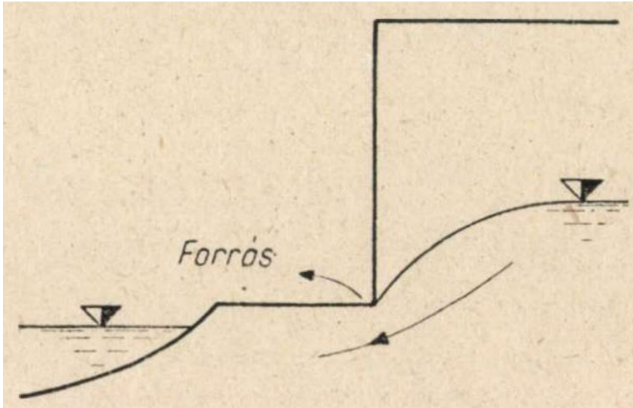


Figure.7 (Hydrogeological conditions under high cliffs) [25]

The material of the high banks along the Danube and Balaton, as well as the material of the debris, is almost entirely water-resistant. Therefore, on the sections where the water from the rear area emerged as springs at the base of the wall, the debris clogs the passages, altering the previously established hydrological conditions. The previously free-flowing water is halted, and backed up, its level rises, and its hydrostatic pressure increases until it finds an outlet at the point of least resistance either sideways, upwards, or downwards. Meanwhile, some of it penetrates the broken and loose debris slope, saturating it, and in many places, liquefying it, initiating a sinking process within the debris slope. [25]

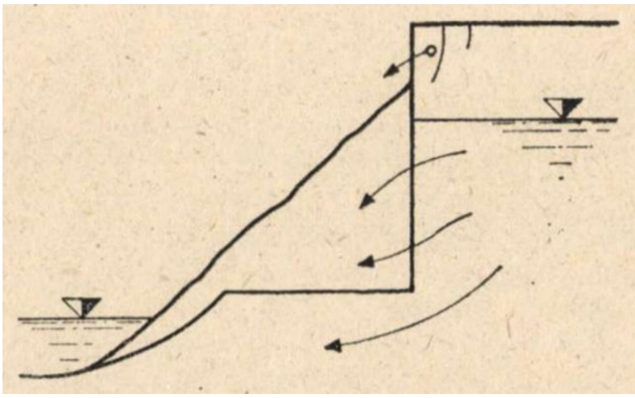


Figure.8 (Debris slope under high cliff) [25]

When the equilibrium in the debris slope is disrupted due to saturation, and sinking process begins. The debris moves until the masses, corresponding to the reduced frictional resistance, regain their equilibrium position along some lesser slope. Then the movement stops, and a natural slope forms beneath the high bank. However, as numerous examples show, the movement of high banks does not stop everywhere.

Every movement of a steep slope, excluding real slides and mudflows, can ultimately be explained by the laws of a two-armed scale. On one side of the scale is the higher, thus heavier mass, and on the other side is the lower, thus lighter mass (Figure. 9). The equilibrium between the two differently loaded scale arms is maintained along some curved slip plane by the soil's shear resistance. [25]

If this shear resistance is so high that the weight difference between the masses on the right and left cannot overcome it, the slope or bank remains standing. However, if for some reason, either the shear resistance decreases or the weight difference between the two arms of the scale increases, the scale tips, the higher part sinks, and the lower part rises until the external forces' weight difference is again smaller or at least equal to the shear resistance.

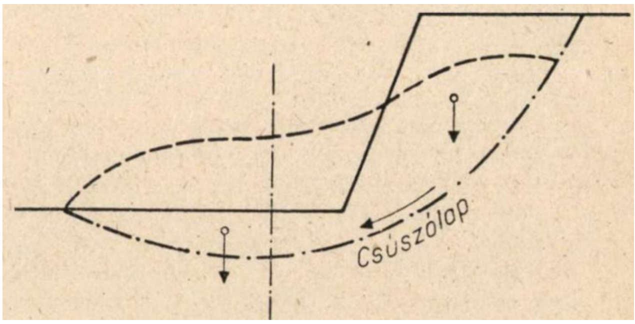


Figure.9 (Slope failure force balance) [25]

3.3. Morphological and structural factors

Hungary’s landscape isn’t especially varied, nor does it have complex tectonic features. Even so, destabilizing incoherent sedimentary rocks doesn’t require extreme conditions. In hilly areas with solid rock foundations, slopes tend to be much steeper. This often results in rock bursts and the movement of rubble. In these rock environments, noticeable tectonic slashes at the hillsides can lead to the collapse of steep walls. [17]

On the other hand, in areas with a foundation of loose sedimentary rocks, the landscape is somewhat less varied. However, the positioning of impermeable layers is crucial. Early in the century, it was observed in the Buda side of the capital, a place of frequent movement, that the Oligocene "kiscelli clay" stratum - which forms a sliding plane - has a gentle downhill slope. Analyzing over six hundred movements revealed that the sliding plane in most surface movement cases has a 10-15 degree downhill gradient. [17]

Thus, the growing disruption of slopes requires careful monitoring. Among preventative methods, supportive structures like walls, piles, and iron reinforcements are crucial. Resistance is often enhanced with soil nails, and other less common geometric methods, like reducing the slope gradient and establishing berms, are utilized less due to their cost. [17]

3.4. Human interference

Expanding human endeavors, like building projects and increasingly widespread raw materials extraction, substantially alter the balance of natural environments, resulting in multifaceted implications. Activities such as mining, comprehensive open digs, and establishing thoroughfares and rail lines all act to destabilize the inherent balance of natural slopes. In contrast, urban development, select public infrastructure projects, and the inundation of surface strata shift the condition of rock formations, subsequently becoming a pivotal determinant in the progression of surface disturbances. The destabilization of equilibrium could instigate issues even in contexts where the rock formations were originally considered stable and solid. [17]

In Hungary, the past several decades have seen a rising number of settlements grappling with significant challenges due to subsidence, which represents a unique form of surface movement. This phenomenon can be visualized as a surface indication of the fracturing of rock-cut cellar ceilings. [17]

Human activities, as highlighted, engender noteworthy challenges for environmental conservation. Surface mines and unsystematic waste heaps distort urban vistas and perpetually usher in the risk of mishaps. Their restoration has heretofore been fraught with complications: while some drainage mechanisms have been compromised due to damage, a considerable volume of waste matter has been amalgamated into backfill material. In the years that followed the backfilling process, groundwater levels ascended, facilitating the transport of contamination through the waste matter. [17]

3.5. Loess in Hungary

The formation, transportation, and deposition of loess soil in Hungary manifest through a series of interconnected geological, climatic, and pedogenic processes. Initially, the formation of loess material emerges from three pivotal events: the creation of particles, their subsequent distribution across the landscape driven by river action, and ultimately, aeolian (wind) transportation leading to their deposition. During cold periods, high-altitude weathering and glacial actions in the mountains generate a significant volume of plastic debris. This debris is then conveyed by summer meltwater floods of rivers to expansive areas where it settles as fine-grained sediments. Once unfrozen and exposed to deflation, these sediments get deposited as loess beds flanking both sides of the rivers. Pedogenic geochemical processes are instrumental in the genesis of the initial loess material. [16]

The transportation of loess material is significantly governed by wind dynamics. Both low and high-altitude winds, which intensify during glacial periods, transport fine silt and clay grain size fractions of the sediments, predominantly in suspension. However, a notable characteristic is that most silt grains tend to fall out of suspension rapidly, depositing near their pick-up zones, indicating a proximal source. Fine sand grains, on the other hand, are chiefly transported by strong near-surface winds, especially during glacial periods. They could be mobilized by traction, saltation, or suspension, with the mode of transportation being contingent on the balance between the settling velocity of the grains and the vertical velocity component of the wind. [16]

Delving into the sources of loess material, the Danube loess material emanates from three major sources: debris from Alpine glaciers conveyed primarily by the Danube River; North European glacial debris channeled through the Moravian depression by meltwater; and materials sourced from flysch and related rocks in the Carpathian Mountains. Various studies, leveraging heavy mineral analyses and other techniques, pinpoint several potential sources of loess in the Carpathian Basin, encompassing local Neogene and Quaternary sediments (flysch and molasse), and other non-sedimentary rocks. [16]

The distribution and deposition of loess material exhibit a spatial alignment with paleo wind directions, predominantly northwest-southeast during cold periods of the Pleistocene in Hungary. The Danube and its tributaries on Transdanubia transport garnet-rich sediments derived from various geological formations such as the Alps, Western

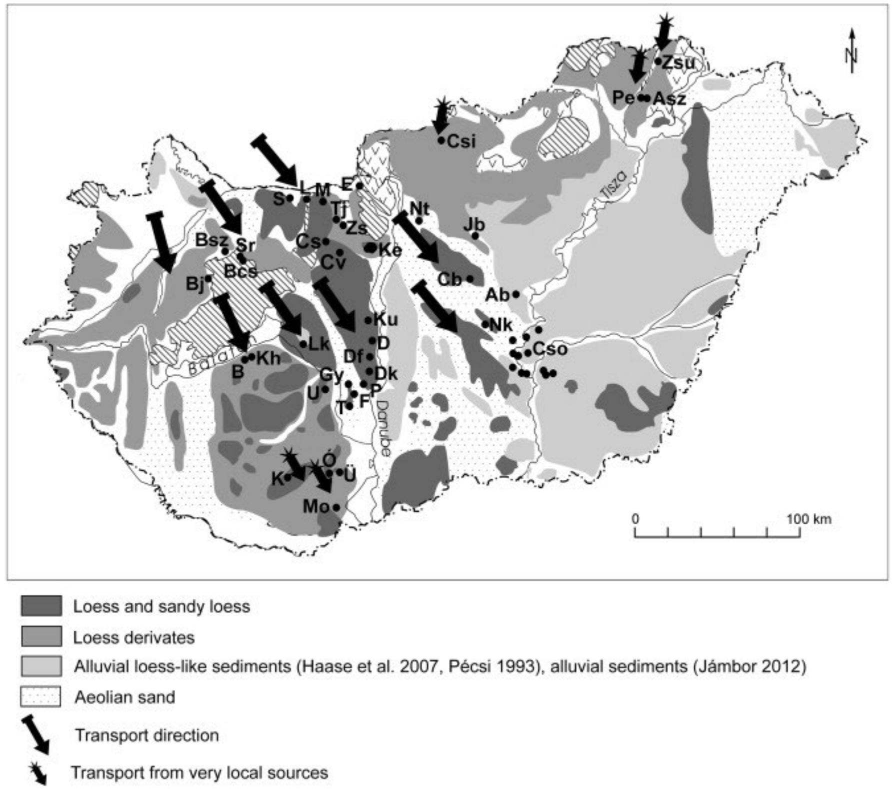


Figure.10 (Deposition of Loess in Hungary) [16]

Carpathians, Bohemian Massif, and the Transdanubia Central Range. The fine sand in most of the loess sediments of Hungary could have originated from aeolian reworking of the floodplain sediments of the Danube River and other rivers of Transdanubia, as well as from local older (Cenozoic) sands. [16]

Examining the geochemical parameters and mineral composition, geochemical parameters in southwestern Hungary indicate a reworking of dust particles from older sedimentary rocks. In contrast, in the northeast Hungarian Plain, a strong resemblance in heavy mineral composition among loess, dune, and fluvial sediments suggests a reworking from floodplain sediments of proximal rivers. The loess and paleosols within the same section typically share similar detrital heavy mineral composition, reflecting uniform sources and the alteration of loess to soil during warmer and more humid phases of the Pleistocene. [16]

Weathering and soil formation processes also play a pivotal role. Weathering during soil formation processes leads to a relative decrease in the abundance of unstable or moderately stable heavy minerals while amplifying the frequency of very stable and stable minerals. This weathering also engenders changes in the geochemical composition and an increased clay fraction in paleosols relative to loess. [16]

Lastly, a distinction between loess sediments derived from local versus distant sources can be highlighted. Some loess sediments possess material from very local sources, while others exhibit evidence of material from distant sources. For instance, pyroxene-rich loess samples in certain areas are analogous to fluvial sands of nearby rivers, signaling a local source. Conversely, small (2-8 μm) dust particles exhibit a provenance from very distant sources such as Africa, hinting at a more complex, potentially continent-wide transportation process. [16]

3.6. Areas in Hungary at risk of surface movement

Upon comparison of the below (Figure. 11) to the previous (Figure. 10) which shows the deposition of loess in Hungary. It can be seen that the areas with significant surface movement are strongly related to the areas where there are loess depositions. The Hungarian loess depositions are prone to hazardous movement throughout the country.

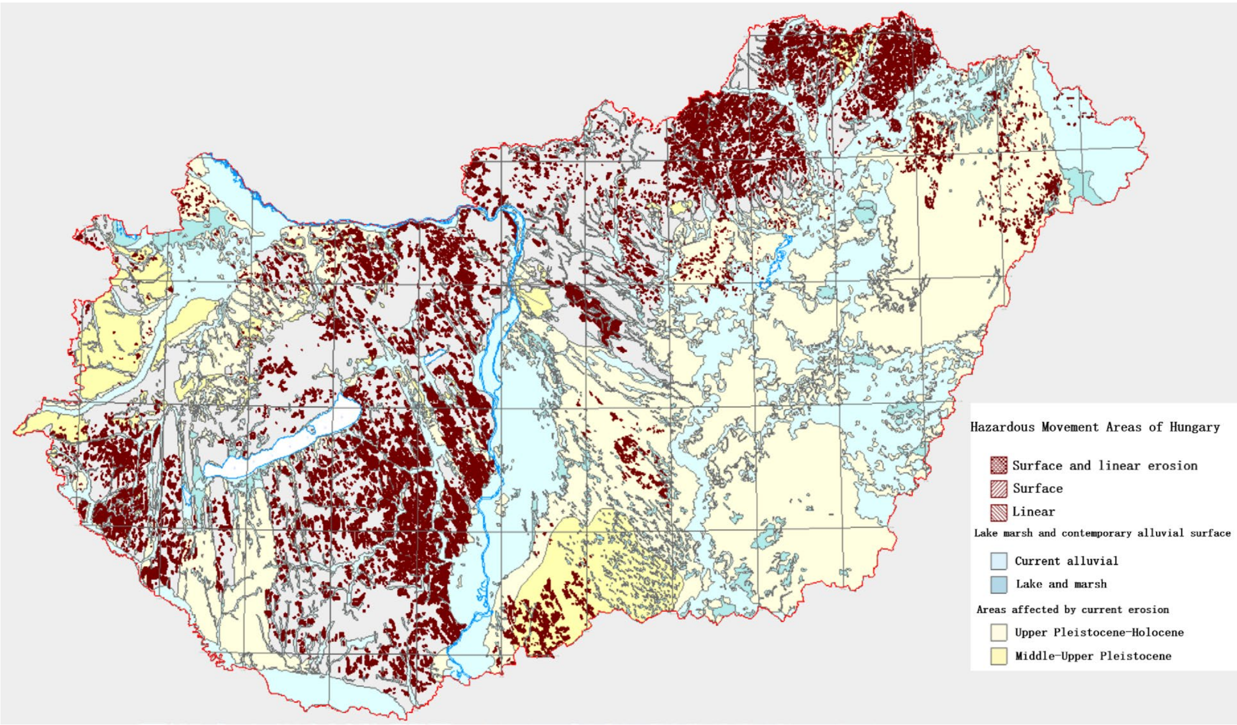


Figure.11 (Hazardous movement areas of Hungary) [3]

Similarly, in (Figure. 12) the areas where loess can be specially located around Lake Balaton, correlate with hazardous surface movements. Recent instances of significant surface movement in Balatonföldvár have been denoted in (Figure. 12) by red circles. 1B, is the movement of a high cliff in a mediumly urbanized zone, the potential reasons for this movement could be a combination of human activities. 2B, is the collapse of the high cliff, reoccurring in periodic intervals. 3B, is a collapse not related to the high cliff.

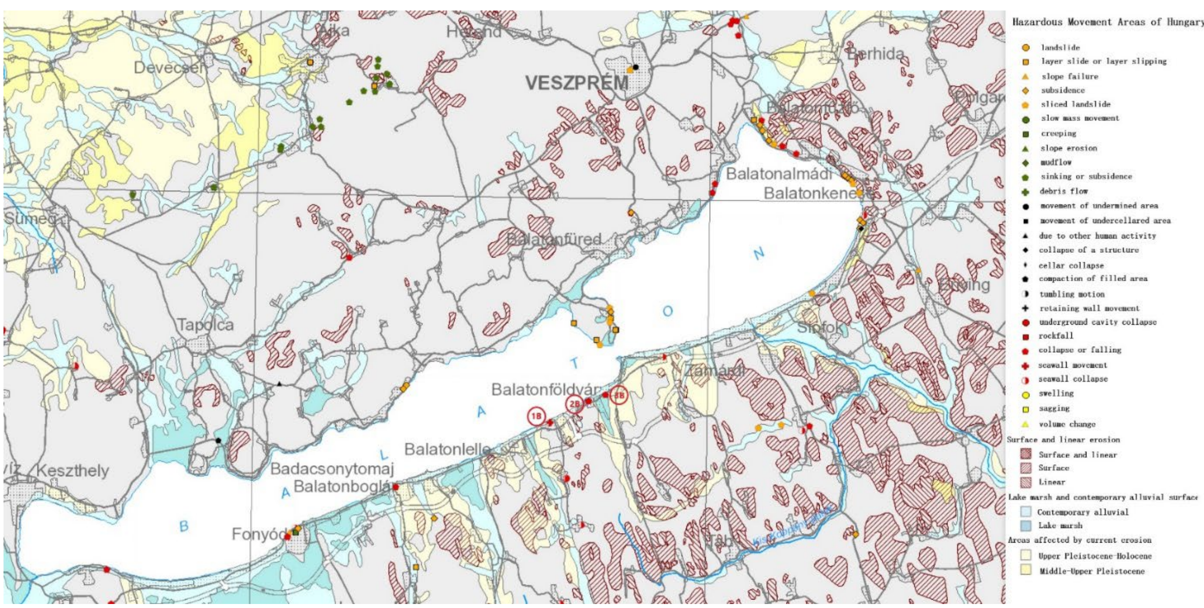


Figure.12 (Hazardous movement areas/events Lake Balaton) [3]

3.7. Hungarian high cliffs

In diverse locations across Hungary, hazardous loess cliffs are prominently observed, such as on the banks of the Danube, extensive stretches of Lake Balaton, and the southern periphery of Lake Fertő. Of these, the Hernád's elevated banks are the most dynamically active. The major area where the high cliffs can be found is marked in blue in Figure. 13.

Figure.13 (High cliff locations in Hungary)[1]

It is notable that many Hungarian communities currently facing challenges with these loess formations were founded during times when the inherent risks of such cliffs were not widely acknowledged. The issue of human responsibility emerges when there's conscious decision-making involved in building upon or near these cliffs, knowing the intrinsic dangers. An illustrative case in point, is the 1999 landslide event in Hollóháza, where, despite prior knowledge of a slope's susceptibility to landslides, construction was pursued.

The location of these steep cliffs has become a concern as urbanization has moved closer to their vicinity. Today, houses, railroads, public works, and road networks can be found all within tens of meters of the sheer faces of these cliffs. In many cases, the monitoring and erosion maintenance of the cliffs has gone forgotten. This can lead to accidents and property damage such as what many homes faced in the Tolna and Verőcén districts of Hungary (Figure 14 and 15).

Figure.14 (Loess wall failure in Tolna Hungary. Photo by: Lendvai Péter)[2]

Figure.15 (Loess wall failure in Verőcén, Hungary. Photo by:Mihádák Zoltán)[2]

3.8. Balaton high cliffs

The eastern and southern shores of Lake Balaton boast dramatic high cliffs that frame its picturesque landscape, with Balatonfüzfő, Balatonberény, Balatonföldvár, and the Tihany Peninsula standing as prominent examples. The Tihany Peninsula, in particular, exhibits similar towering cliffs. These cliffs have stood for millennia. Noteworthy are the surface shifts during the railway construction in Lake Balaton's eastern basin from 1875 to 1946, causing eight significant landslides

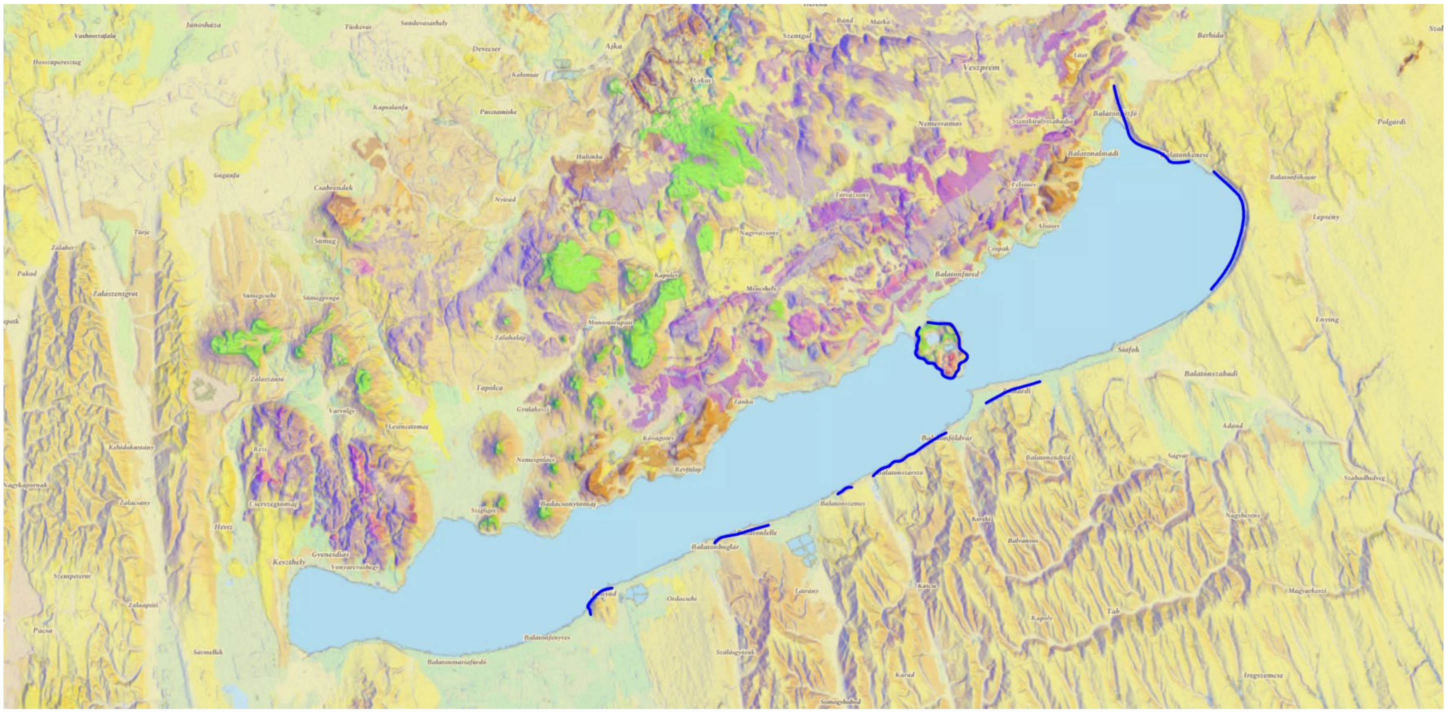


Figure.16 (Balaton High Cliffs)[3]

from Balatonfüzfő to Balatonakarattya. The Balatonakarattya high cliff failure in 1908 was the most tragic as the landslide caused the derailment of a commuter train. Moreover, the intervention in the eastern basin of Lake Balaton during the railway construction essentially disturbed the natural balance of high cliffs, significantly affecting their geological conditions.[4]

Over the past few decades, dedicated exploration efforts and protective measures have effectively mitigated the once-significant risks posed by large slumping failures in the Lake Balaton vicinity. The last major slumping event, which occurred in 1946 on Balatonkenese Sándor Hill, marked the end of large-scale collapses. However, subsequent years saw a gradual increase in minor surface movements within smaller territories. This uptick in surface movements is primarily attributed to recent construction activities that have altered the natural terrain by depositing spoil material near high cliffs. Moreover, human actions such as blocking natural drainage channels and clearing forests have exacerbated the situation. These factors, particularly after heavy rainfall or thawing periods, have contributed to localized slumping events. [4]

While Balatonfüzfő and Balatonföldvár consist primarily of thick layers of Upper Pannonian sands and loess sands (Figures 17 and 19), Balatonfüzfő is characterized by the presence of finer-grained sands and sandy clay. In Balatonfüzfő, these layers contain denser sand layers and sandy clay layers, which extend toward Lake Balaton. Layer thickness varies considerably at depths of 28-30 meters, often forming distinct boundaries. Marshy layers are also present, as are the layers of yellowish sands and loamy sands. [4]

The first layer consists mainly of thick layers of sand and clay in Balatonfüzfő (Figure 9), while it consists of thin layers of sand and clay in Fonyód (Figure 18). Here, the natural groundwater level is particularly elevated from 150 to 165 meters above sea level at a depth of 105 mBf. at Balatonfüzfő and a level of 103 meters above sea level in Fonyód. Above the water-bearing layers, there are loose Pannonian, and Upper Pannonian layers of sand, the basic formation consists of loess-like sandy clay and clay layers. Among these layers, several brownish layers are interspersed, including some gray sandy layers. Some silt layers are also present. These differences are significant in understanding the hydraulic differences, which play a crucial role in the water conditions. While the Balatonföldvár area mainly consists of thick layers of sand and loess sand (Figure 17), fine-grained deposits dominate in Balatonfüzfő (Figure 4). These include sandy clay, loess sands, and sands. [4]

The most important aspect of these layers is that they are all under pressure and contain confined groundwater. In this context, the topmost layer is the most relevant. Horváth Zsolt [4], examined these types of groundwater, and not that what the gray sand layer at a depth of 54-55 meters was penetrated, the groundwater level rose to a height of 45.40 meters. This indicates that the groundwater pressure was approximately 0.1 MPa at the time of measurement in 1952.

These water-bearing layers receive constant replenishment from the surrounding areas. Once these waters infiltrate the slope, combined with heavy precipitation, they saturate the slope, significantly reducing its stability. Therefore, when dealing with protection against slump failures, solutions involving the surface and sub-surface water protection of the slope should be considered. [4]

Human interventions have significantly shaped the geological and hydrogeological conditions of these high cliffs. Notably, the regulation of Lake Balaton's water level stands out as a critical intervention. The current regulated water level, approximately 105 meters above sea level, is considerably lower than historical levels. Higher water levels, coupled with prevailing northeast winds, previously caused substantial erosion along the southern and western shores of Lake Balaton, resulting in the gradual retreat of high cliffs. However, the regulation of Lake Balaton's water level has effectively eliminated the risk of erosion in these areas. [4]

One of the most notable examples of human intervention is the relocation of the railway line near Sándor Hill in Balatonfüzfő, which removed the dynamic impact of the railway on the high cliffs. Additionally, surface and subsurface water management systems, including ditches and infiltration measures, have been implemented on Sándor Hill's high cliffs to reduce the risk of erosion and instability. [4]

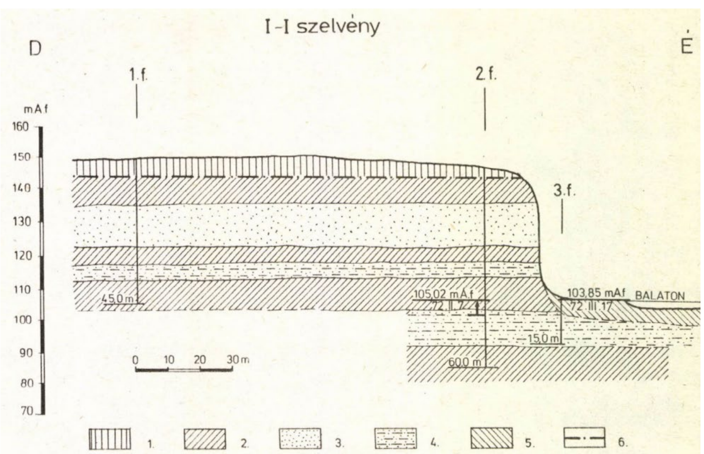


Figure.17 (Balatonföldvár High Cliff Section) [4]

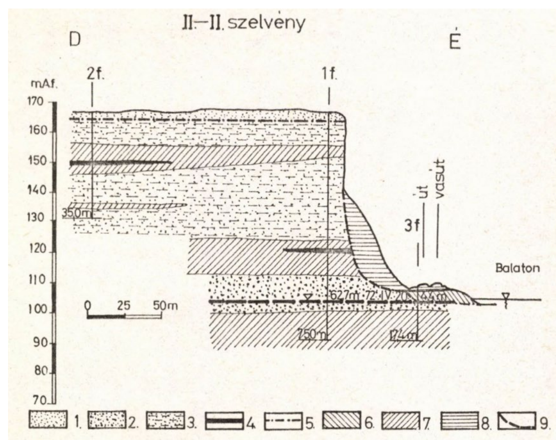


Figure.18 (Fonyód High Cliff Section) [4]

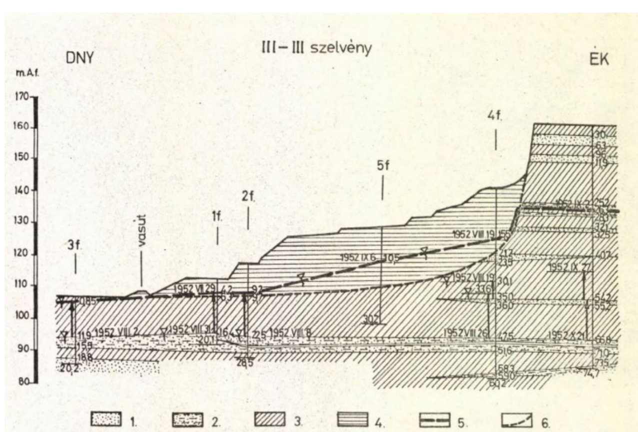


Figure. 19 (Balatonfüzfő High Cliff Section) [4]

3.9. Balatonfüzfő high cliff stability

The following case analysis is based on the case study presented by Domjan Jenő-Papfalvy Ferenc in the Hidrológiai Közlöny 33. évf. 1953. 9—10. Sz titled 'A balatonfűzfői magaspart talajmechanikai vizsgálata' [6]. The Hydrological Society of Hungary before this investigation had already addressed the issue of the high bank of Balatonfűzfő and the railway line in prior excerpts, however, due to conflicting expert results a further detailed investigation was needed to conclude the decision for the Hungarian State Railways (MÁV). The following section will discuss the state-of-the-art analysis of prior studies conducted by Domjan Jenő-Papfalvy Ferenc.

Lajos Lóczy Sr. in his fundamental work titled "The Scientific Study Results of Lake Balaton" addressed the landslides of the northeastern shores of Lake Balaton and incorporated them into his theory about the formation of the lake. Based on his research, he assumed that in the early Pleistocene era, due to tectonic subsidence, four separate endorheic basins were formed, separated by ridges connecting the northern and southern shores. These basins could have persisted due to wind deflation coming from the Balaton Uplands.

The basins were gradually enlarged by wave erosion until the ridges separating the individual basins disappeared, and the four bodies of water merged into a unified Lake Balaton. The waves eroded the shores and steepened the attacked sides, causing them to continuously collapse and recede. As a result of this wave erosion, a wide, flat ledge formed in the Pannonian clay layers up to the steep cliffs all around Lake Balaton.

To support the described processes, Lajos Lóczy Sr. collected data regarding the movements of the northeastern shore. Through this prior research, he was able to warn of the high shore collapse in Akarattya on April 19, 1908. Based on his research, in 1914, at the request of the Hungarian State Railways, it was recommended to relocate the railway closer to Lake Balaton.

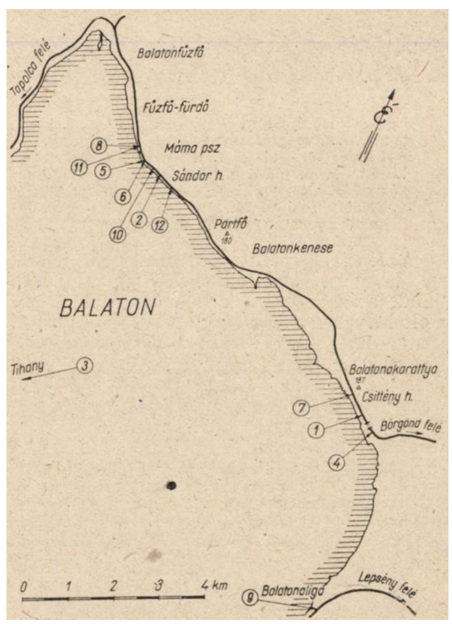


Figure.20 (Lake Balaton eastern shore, locations of high shore movement) [6]

Between 1936-37, Lajos Raab dealt with soil movements on the Börgönd-Tapolca railway route. He summarized his findings in the journal "Railway Maintenance" in its November-December 1937 issue. His findings concluded that the precipitation accumulating in valleys parallel to the high shore, which cannot be drained elsewhere, seeps towards the lake beneath the plateau, bursting as springs at the foot of the high shore. Landslides from the high shore occasionally block these springs, forcing the water to find another drainage route. This process saturates the underlying layers prone to sliding, making them direct causes of landslides. However, some of this water doesn't emerge as springs at the edge of the high shore but gravitates towards Lake Balaton through cracks from earlier soil movements. These waters are deemed less significant. [6]

Figure.21 (Balaton Akarattya high cliff failure) [6]

Another cause of the landslides was the abnormal amount of precipitation in 1936-37, which couldn't drain on the unstructured slope but seeped into the internal soil layers, saturating them even more. Lastly, he mentions the dynamic impact of hundreds of cubic meters of earth breaking away from the high shore as a fourth cause for instability-related issues of the high cliffs. [6]

To ensure the railway's security, it was suggested to relocate the track at least 60 meters towards Lake Balaton. Another effective but expensive solution would be to dry out the 250-meter-wide area between the upper edge of the shore and the railway using drains, tunnels, and shafts. Due to high costs, initial ideas weren't feasible, leading only to partial drainage and terrain organization. Even though these partial solutions were able to support summer traffic that year, new ground movements appeared by the end of 1937. Thus, the work did not meet the expected outcomes. [6]

Dr. Jáky József, between 1938 and 1942, addressed the issue and shared expert opinions three times. On July 15, 1938, he discussed the soil movements between certain sections of the MÁV railway and the Lake Balaton ring road. He referenced Raab Lajos's article and the work done in 1936-37. [6]

Dr. Jáky detailed that the most dangerous waters are those not surfacing as springs because they moisten clay soils throughout their length. However, he considered the dynamic effects of collapsing soil masses not essential. Based on his research, Dr. Jáky proposed the establishment of a middle drainage system that would dry out the entire waterlogged soil mass. This would ensure complete stability at a relatively low cost. [6]

Due to recurring ground movements and costly maintenance, MÁV developed a proposal to relocate the track towards Lake Balaton. Dr. Jáky, on December 20, 1942, provided his expert opinion on MÁV's proposal. He considered the nearly 3 km-long track relocation and its extent (average 120 m) excessive. He believed a shift of only 20-30 meters would suffice against landslides. [6]

Dr. Vendl Aladár, in his geological expert opinion dated around December 18, 1942, also commented on the Hungarian State Railways (MÁV) track relocation plan. According to him, based on the rock formation, landslides are possible along the entire length of the high shore. He furthermore exclaimed that the landslides in the past, as well as during the Pleistocene period, were larger than current movements. He identifies the precipitations falling behind and, in the absence of any other runoff, moving towards Lake Balaton under the high shore as the cause of the landslides. Comparing the morphology of the high shore's landslides to examples from the Transylvanian Plateau, as well as Italy, Southern France, and Central Siberia, he states that under given conditions, landslides of similar height shores are not longer than 100-150 meters from the rupture, thus the planned line relocation would provide full security. However, he finds it necessary to capture the waters seeping on the plateau-like area on the side of the high shore with open trenches and, in general, to drain the surface waters. He also finds it appropriate to leave the rock masses at the base of the high shore in their place. [6]

Dr. Lóczy Lajos similarly submitted a preliminary geological expert opinion about the MÁV plan in the following year. In his preliminary opinion, he described the general geological conditions and already drew attention to the fact that the sliding planes of the landslides often extend deep below the water level of Lake Balaton, causing significant bed elevations. Based on the soil exploration data conducted, he considered that deep ancient landslides had disturbed and shattered the Pannonian sediments below the lake's sedimentation. Dr. Lóczy Lajos carried out soil exploration along the planned line on the shore of Lake Balaton and in the lake itself and detailed these results in his supplementary opinion. [6]

To determine this reliably, he would have found it necessary to drill a 90-meter-deep hole from the high shore, which would provide the normal profile of the layering. Since, in his opinion, landslides and slides have been continuously taking place on the segment since ancient times, he considered that the planned extent of the line relocation was insufficient, deeming it desirable to drain the high shores. With this solution, he hoped that the spread of the "márnái" slide to the north, if not permanently prevented, could be delayed by at least a few decades. On other sections, he recommended moving the line further out from the high cliff zone further inland on the plateau side. [6]

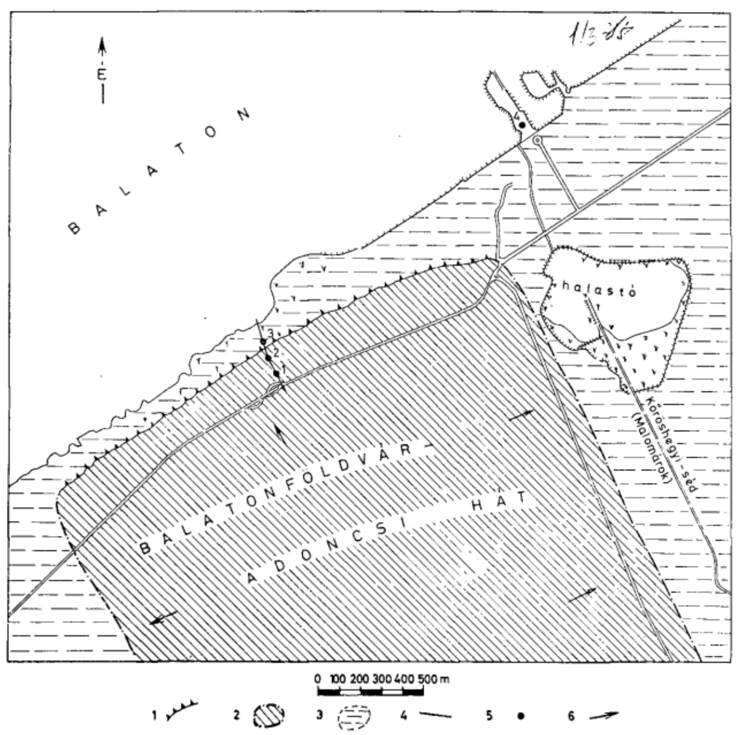
The northeastern shores of Lake Balaton, with their history of landslides, present a complex geological challenge that has garnered the attention of numerous experts over the years. Lajos Lóczy Sr., for instance, traced the origin of the lake and its susceptibility to the tectonic shifts of the early Pleistocene era as well as internal springs that perpetually moisten the intermediate clay layers, making the high cliffs prone to failure. Subsequent research by individuals like Lajos Raab and Dr. Jáky József highlighted the significant role of water accumulation in the internal soil layers, leading to verifying Lajos Lóczy Sr.'s conclusions. Furthermore, Vendl Aladár and Dr. Lóczy Lajos also emphasized the role of historical landslide events, the depth of sliding planes, and the underlying sediments in influencing the region's stability. Various solutions, from the establishment of middle drainage systems to significant railway relocations, have been proposed and implemented. Still, achieving a long-term resolution remains elusive, indicating that the interplay between the region's geological makeup and hydrological conditions requires a multifaceted approach to mitigation. [6]

3.10. Balatonföldvár and Fonyód high cliff stability

The following case study to be examined has been published by Horváth Zsolt and Dr. Scheuer Gyula in the Földtani Közlöny, Bull, of the Hungarian Geol. Soc. (1915) 105. 335—343, under the title ‘A balatonföldvári és a fonyódi magaspartok állékonyságának mérnökgeológiai vizsgálata’[5]. The case study was conducted based on preliminary on-site observations, in which the high shores of South Balaton, especially the cliffs of Balatonföldvár and Fonyód, were considered to be the most susceptible to landslides. Their company (Land Surveying and Soil Testing Company) was commissioned on behalf of the Somogy County Council to conduct an engineering geological examination of these areas deemed at risk of movement, to determine their stability, and to devise potential protective measures.

The high banks of Balatonföldvár and Fonyód, situated on the northern edge of the Outer Somogy landscape, rise between 30 to 60 meters above the level of Lake Balaton. These cliffs present a nearly vertical upper section which transitions into a steep slope comprised of fallen rocks, covered in lush vegetation. Historically, the formation of these high banks can be attributed to the abrasive action of Lake Balaton. However, with the construction of railways, highways, and shore protection structures, the lake's ability to shape and erode the banks has significantly decreased, leading to major alterations in the shoreline's evolution.[5]

Geographically, the high bank of Balatonföldvár belongs to the Balatonföldvár-Adonycsi ridge and forms its northern boundary. The peak of this area reaches an elevation of 145-150 meters above sea level, standing 40-45 meters above the lake's surface (Figure. 5). While the ridge's surface sharply descends towards the Köröshegyi valley, it gradually decreases in height towards the Szabadi valley. [5]

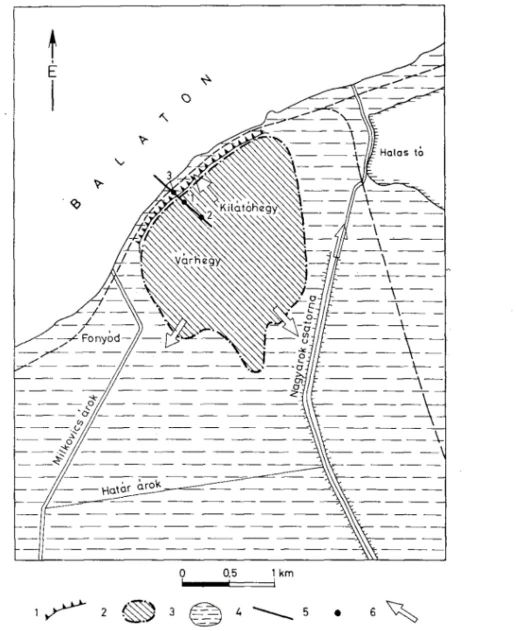


A balatonföldvári magaspart helyszínrajza. J e l m a g y a r á z a t: 1. A magaspart pereme, 2. Kiemelt terü-let, 3. Mélyfekvésű területek, 4. Szelvényvonal, 5. Fúrási pontok, 6. Vízáramlási irányok

Figure.22 (Balatonföldvár-Adonycsi ridge)[5]

On the other hand, the Fonyód high bank stands out from the low-lying, swampy area of Nagyberek, resembling an island hill facing the lake (Figure. 6). This hill has two prominent peaks: the taller Vár-hill and the Kilátó-hill, both covered in trees and patches of forest. Its highest section is about 60-65 meters above the lake's surface. The upper cliff is vertical, followed by a steep tree-covered slope extending to the M-7 highway. Detailed examinations of both high banks show no signs of slips or any indications suggesting movement of the cliffs, though minor landslides and erosion can be observed in certain areas. Moreover, where surface waters are channeled to the edge of the cliff, noticeable erosion can be seen. [5]

The geological structures of the high banks consist of Upper Pannonian, Upper Pliocene, and Quaternary formations. In Balatonföldvár, loess or its variations are deposited on top of the Upper Pannonian sediments. Contrarily, the Fonyód island hill showcases a different development. Here, the Upper Pannonian formations lay the foundation, which was later pierced by basalt tuff related to the volcanic activities in the Balaton upland region. The Pannonian layers have minor Pleistocene granular deposits accumulated on them, with loess being less dominant than in Balatonföldvár. [5]



A fonyódi magaspart helyszínrajza. Jelmagyarázat: 1. A magaspart pereme, 2. Szigethegy, 3. Mélyfekvésű területek, 4. Szelvényvonal, 5. Fúrási pontok, 6. Vízáramlás iránya

Figure.23 (Fonyód High Bank) [5]

The foreground of the high banks is primarily made up of debris falling from the high banks and lake sediments, typically sandy and muddy in composition. These towering shores, rising to 60 meters above Lake Balaton, are predominantly constructed of Upper Pannonian formations. Thus, the physical properties and sedimentary conditions of these layers are crucial for understanding the stability of the cliffs. The cross-sections can be examined in (Figures 2 and 3). [5]

The engineering geology and hydrogeology of the Balatonföldvár and Fonyódi cliffs were explored using boreholes oriented perpendicular to Lake Balaton. At Balatonföldvár, north of the urban zone, two boreholes were placed on the cliff. Logistical challenges led to the drilling of another borehole about 65 meters northeast of the section line at the cliff's base. An additional borehole was drilled near the pier for a more detailed geological assessment. All discussed borehole locations can be seen in (Figures. 22 and 23).

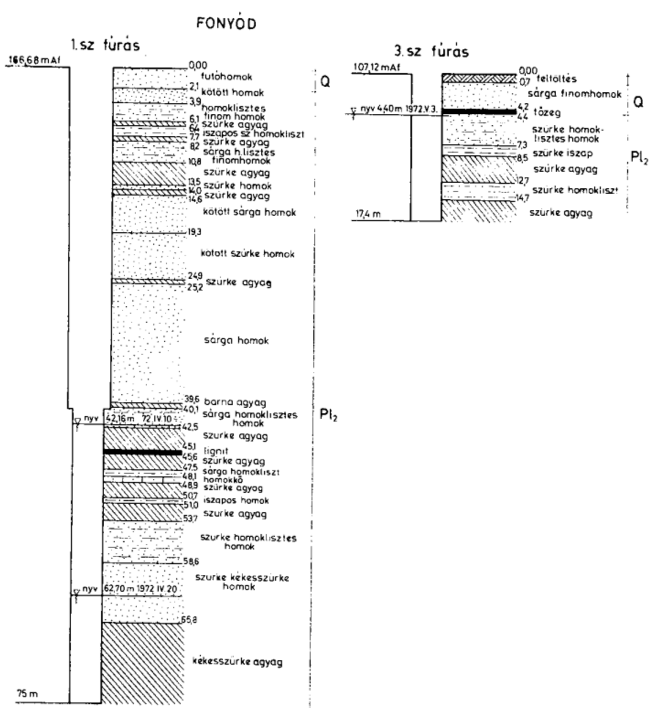


Figure.24 (Fonyód borehole section) [5]

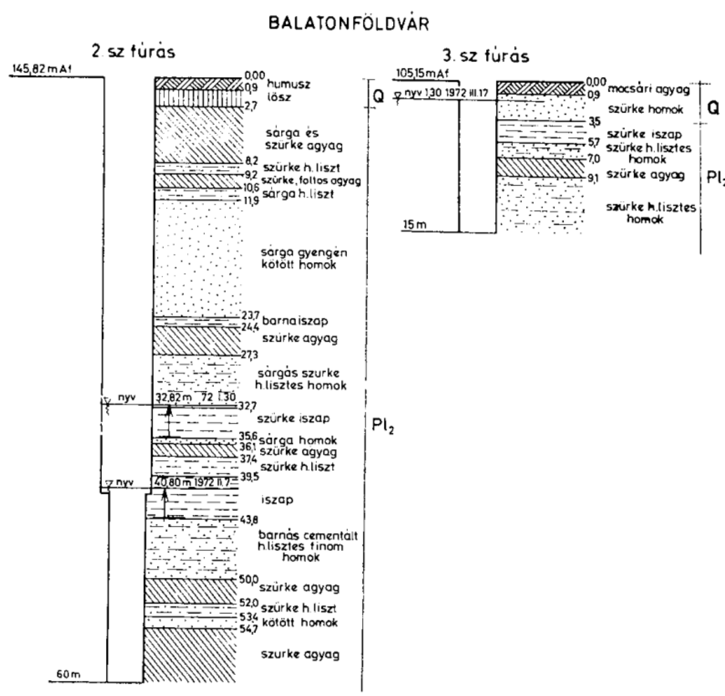


Figure.25 (Balatonföldvár borehole section) [5]

The cliff's geological structure in Balatonföldvár comprises layers from both the Pleistocene and Upper Pannonian periods. The Pleistocene strata are characterized by a relatively thin 3–7-meter layer of loess that sits atop Pannonian sand and clay formations (as shown in Figure 5). The visible sections of the Pannonian layers predominantly consist of sands or cement-bound sands, interspersed with variable-thickness clay layers. Notably, a clay layer more than 10 meters thick exists in the lower portion of the cliff, succeeded by a sand layer. [5]

Sediments up to 5.5 meters deep, attributed to Lake Balaton's deposition, are present at the cliff's base. Below these, layers of Pannonian-era sand or silty sand extend to the explored depth.

The fourth borehole was positioned at the Balatonföldvár pier and reached a depth of 15 meters. This borehole, situated on the Köröshegy valley's center, unveiled gravel strata made up of limestone, basalt, and red sandstone. This discovery supports the theory that before the Balaton basin's subsidence, watercourses from the Bakony and Balaton highlands deposited sediments in valleys reminiscent of the Köröshegy valley. [5]

Hydrogeologically, the significant aquifer in the cliff section is identified in the silty sand layer's lowest point. A well-sourced from this layer was dug below József A. Street No. 13, with its base set at 103.29 meters above sea level. The static water level in this well registered at 105.29 meters above sea level on February 20, 1972. After penetrating this silty sand layer in the second borehole, the static water level was noted at 105.02 meters above sea level on February 7, 1972. The boreholes three and four revealed a groundwater level in the Lake Balaton sediments matching Lake Balaton's level. [5]

For the Fonyód investigations, two boreholes were drilled on the cliff. However, logistical issues near the main road meant that the third borehole could be placed only about 50 meters northeast of the planned section line at the cliff's base.

The core samples show layers of Pleistocene-Holocene sands, measuring between 1-8 meters, topped with upper sections of gravel bands, sitting on Pannonian formations. The Upper Pannonian sequence showcases clay, clay-laden sand, and larger layers of sand, spanning 5-12 meters (see Figure 26).

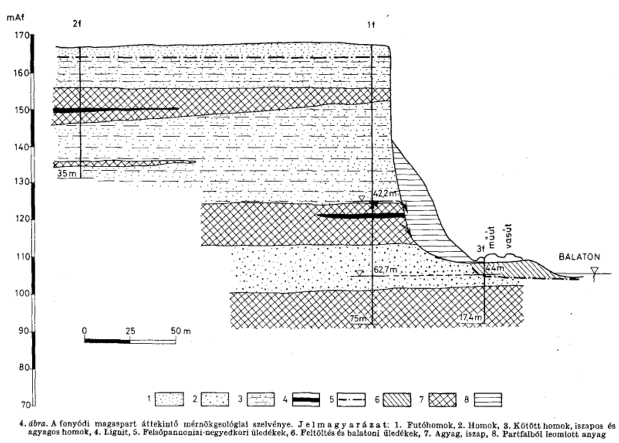


Figure 26 (Fonyód High Bank Section) [5]

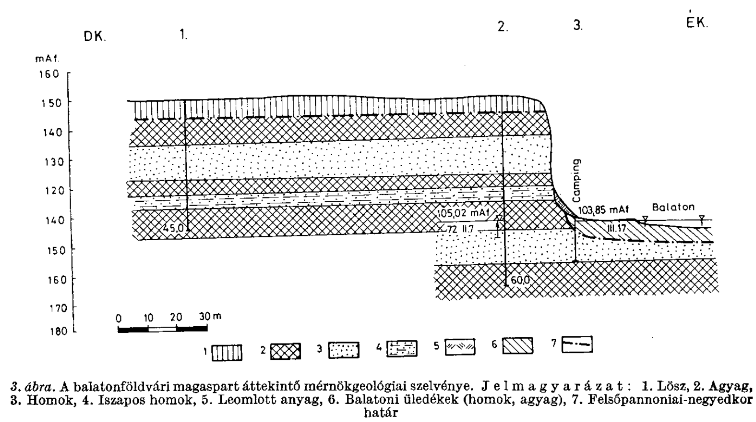


Figure 27(Balatonföldvár High Cliff Section) [5]

Lake Balaton's relocated sediments cover up to 4.2 meters at the cliff's base. Below this layer, identical formations of sandy clay, sand-rich clay, and clay-rich sand are found, resembling those of the cliff.

From a hydrogeological viewpoint, the cliff's entirety was almost completely dry. Only at an elevation of 123.3 meters above sea level (recorded on April 9, 1972) was groundwater found, and it didn't saturate the sand layer's full depth. This water occasionally seeps at the cliff's base.

Another aquifer was identified below the cliff's base at 102.8 meters above sea level (recorded on April 20, 1972). Like the former, this water manifests as free-flowing groundwater behind the coastal cliff and subsequently as soil water in Balaton's sediments. Hence, there's a direct relationship between the groundwater and Lake Balaton's prevailing water level, with the lake serving as the groundwater's primary source of replenishment.

Before intensive human intervention and the reorganization of the Balaton shores, the high shores were continuously eroded by the lake. As a result of this erosive activity, when the abrasion disrupted the equilibrium of the cliff's stability, landslides occurred. The constant influence of the Balaton played a crucial role in the periodic development of these landslides.

Human intervention altered these processes. With the construction of railways and roads at Balatonföldvár and Fonyód, the destructive actions of the Balaton on the cliffs ceased. Consequently, one of the causative factors of movement was eliminated.

The study indicates that the driving factors of movement, including morphological, geological, and hydrogeological conditions, show favorable developments concerning the cliffs' stability. Morphologically, there are differences among other high shores of Balaton considered to be at risk of movement. The high shore of Balatonföldvár has a narrowing plateau behind it, while Fonyód's high shore is associated with a relatively prominent isolated hill [5]. Such morphological forms significantly affect hydrological conditions and water replenishment. Due to their morphological features, these two studied high shore sections indicate a favorable structure concerning cliff stability.

Upon comparing the geological characteristics of various high shore sections, key differences were observed. Boreholes in Balatonakarattya and Balatonkenese show a sequence dominated by sand layers and thin sand beds that incline towards Balaton. Boreholes at Balatonföldvár and Fonyód reveal different Upper Pannonian layer developments, with several substantial sand and clay layers. Importantly, these layers gently incline in a NE direction. Notably, the debris resulting from erosion and landslides is either absent or only present in a limited form. These layers are depicted in the borehole sections found in (Figures. 24 and 25). [5]

From a hydrogeological perspective, the studied sections are deemed favorable. This is the result of the combined effect of multiple factors. Firstly, during drilling, groundwater was only found at the base of the shore wall and within confined aquifers. Near Balatonföldvár, this aquifer water is under slight pressure, while in Fonyód, the water flowing in the sand layers is not under pressure due to limited recharge and only partially fills the water-conducting sand layer. [5]

The water-bearing layers uncovered in the cliff-side drillings continue beyond the shore wall and are directly or indirectly connected to the groundwater and Lake Balaton. Consequently, conditions are ensured for the natural emergence of waters coming from the hinterland areas. The investigations show that the amount of water coming from the areas behind the shore wall is minimal, and there are no conditions or features that would unfavorably influence the current hydrological equilibrium. The minimal water quantities reaching the shore wall can be explained by the morphological and geological conditions of the feeding area. [5]

The Fonyód hill, which stands out like an island mountain, has a small catchment area, and near the surface, there are clayey layers that prevent the infiltration of precipitation waters. Also, according to surface conditions, the infiltrated water drains in every direction, towards the low-lying areas of Nagyberki. Approximately similar conditions can be found near Balatonföldvár where the examined cliff-side and elevated area segments are bounded by stream valleys, hence the movement of limited infiltrating precipitation water mainly heads towards these stream valleys. As a result, water quantities reaching the shore wall are very limited, and conditions for their drainage are met. [5]

Correspondingly, we can conclude that, due to the hydrogeological conditions, the water entering the Upper Pannonian formations is scarce, so there is no significant seepage pressure on the shore wall or significant hydraulic pressure on a potential slip surface. [5]

Rock-physical examinations indicate that the Upper Pannonian sedimentary sequence uncovered in the drillings consists of bound materials — silt, clay, and grainy sand, sand silt. Predominantly, granular formations are represented. [5]

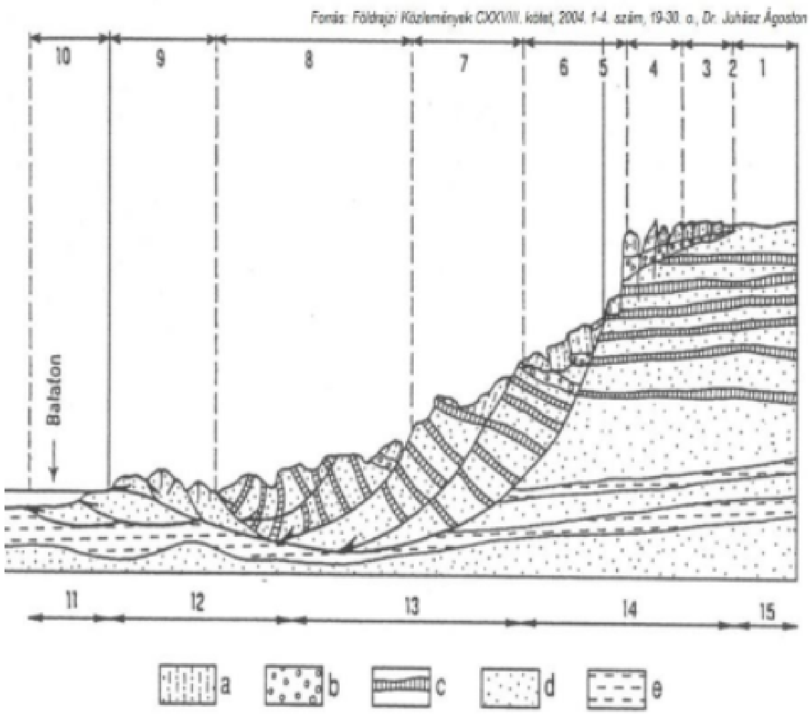
The strength parameters needed for stability examinations were appropriately determined. Based on the conducted stability calculations**,** the safety factor is n = 1.45 for Balatonföldvár and n = 1.24 for the Fonyód cliff at a distance of 20 meters from the cliff edge. This would mean that in the current standards, the Balatonföldvár high cliffs would satisfy design codes while the Fonyód cliff would need appropriate measures to e taken to achieve suitable safety factors. [5]

In conclusion, it was found that the high shores demonstrate favorable natural conditions for stability, especially concerning hydrogeological and geological relations. To maintain this stability, the current state should be preserved. Necessary protective measures, like building restrictions, surface water management, and sewage drainage, need to be implemented. Otherwise, anthropogenic influences might adversely impact the current stability.

3.11. Balaton high cliff hydrogeological parameters

The following review is based on the publication by Kápolnainé Nagy-Göde Fruzsina and Dr. Török Ákos [7]. The cliffs' current shapes have been shaped by ongoing changes on the land's surface. In Lake Balaton's eastern region, the primary type of movement is a specific kind of rotational sliding called slumping failure. This causes notable changes in the natural tilt of geological layers (see Figure 28) and produces mixed debris slopes. On these slopes, it becomes challenging to correlate geological and soil patterns. The sliding layers of these movements are influenced by how wet the area is and the existing forces at play. Lóczy noted that these sliding areas sometimes stretch below Lake Balaton's bottom level, which in the past resulted in parts of the lakebed rising and forming islands, however, these have since disappeared. [7]

In the area before the cliffs, the groundwater level is easily visible and changes based on Lake Balaton's water level. Behind this area, we find layers of water that are under pressure and flow towards the lake, sometimes appearing as springs. In between layers of clay, there are layers of sand that help water move easily. Groundwater in these sandy layers is connected to the water layers above it, and they share similar pressure levels. Jáky pointed out that waters that don't come out as springs are the most concerning. This is because they not only move in the direction of the slope but also wet the entire length of clay soils as they have no opportunity to dry out, due to the constant replenishment from the springs. Therefore, within the mixed material of the debris slopes, due to the mixed-up layers of soil, it's likely that there are pockets of sand and similar materials where water can be trapped under pressure.[7]



1. Potencial sliding hazard zone
2. Influence line of cracks
3. Cracked zones
4. Land slide prone earth trianglates
5. Sliding/falling failure front zone
6. Debris zone
7. Sliding/falling danger zone
8. Temporarily stabilized zone
9. Sliding/falling failure zone material build up
10. Past failure remnants stabilized zone

Dynamic state:

11. Stable base zone
12. Compression stress zone
13. Transitional dynamic stress zone
14. Shear and tension stress zone
15. Stable zone

a. Loess
b. Gravel
c. Clay - Pannonian settlements
d. Pannonian sand
e. Pannonian clay

Figure.28 (Geomorphological model of slumps)[7]

Moreover, water saturation was found to be an even more statistically significant factor that relates to the number of movements. The way the land gets wet, and shifts depends on the water conditions beneath the surface. The water flowing inside mountains often disrupts the equilibrium and can cause collapses. The paper published by Toborffy, G. 1921 found a close link between periods of heavy rainfall and times when landslides occurred. Factors causing these landslides include heavy rainfall, the pattern of rain over time, the water that seeps into the ground, the paths this water follows underground, and how underground water storage areas get refilled. The graph (Figure. 29) depicts the yearly rainfall for the 20th century along with the times of landslides. It can be seen from the chart that commonly landslides seem to occur after large rainfalls. [7]

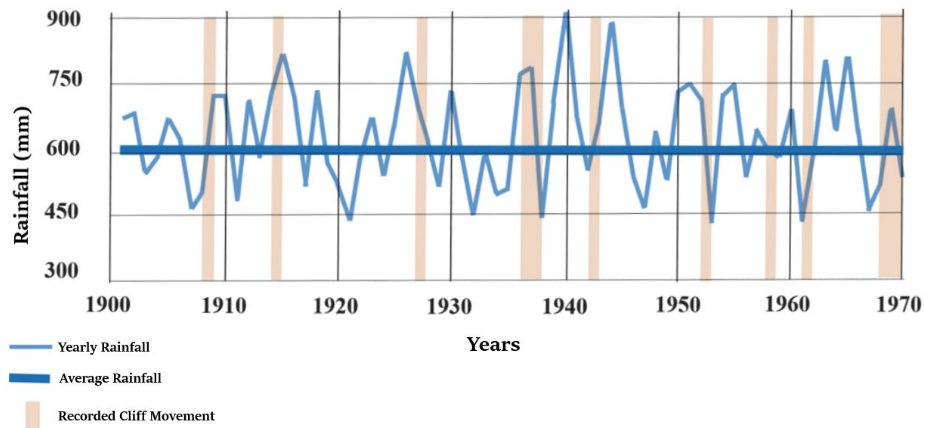


Figure.29 (Rainfall and instances of cliff movement)[7]

Within the prior sections, the key factor of groundwater originating from springs has been highlighted by Dr. Jáky József, Lajos Raab, Dr. Vendl Aladár, and Dr. Lóczy Lajos throughout multiple examinations of the high cliffs on the eastern shores of lake Balaton. The consensus can be drawn that internal springs within the cliff are feeding water and moistening the internal thin clay layers of the cliff. This intern can cause failure by hydrogeological mechanisms, primarily causing the shear strength of the layer to be drastically reduced and a slip surface to be formed. The next section will primarily focus on the examination of clay-rich layers in the formation of slope instabilities.

“High-plasticity clays, such as the members of the smectite group, considerably decrease the shear strength, thus causing landslides at very low gradients” [8]. In such cases, small clay layers which are often overlooked can have a very significant impact on the stability of the entire slope, as effectively a slip surface by the clay layer. Effectively as the clays take on water, the surface of the clay becomes more slippery as a larger percentage of the clay is water, and the coefficient of friction for water is nearly negligible. The clay surfaces on one another begin to slip as the coefficient of friction between the two bodies is much smaller. This phenomenon coupled with destabilizing normal forces against a slightly inclined layer surface has the potential to destabilize the slope. Furthermore, the expansive properties of the clay could have the potential to disturb the initial equilibrium pre-swelling, adding to this phenomenon.

An evident, statistically substantial correlation exists between precipitation distribution and the frequency of surface movement [17]. When clay sediment becomes thoroughly saturated due to precipitation, its consistency alters and its shear strength reduces. Extensive testing indicates that maximal saturation is commonly observed at layer boundaries, which, due to their lubricative effect, become sliding surfaces. Comprehensive saturation is further evidenced by the frequent occurrence of landslides, often evolving into mudflows. Movements predominantly occur on undulating slopes where groundwater levels may not be consistent. However, widespread underground seepage is observed, and during rainy periods, an elevation in the piezometric level triggers movement. Water intermittently emerges through minor seepages or springs, and the absence of systematic, adequate drainage could also instigate movements. Observations indicate that the insufficient maintenance of drainage systems, particularly in reclaimed former mine pits, can induce saturation and deterioration. Addressing this issue is pivotal, with preventive strategies often centering on reducing pore water pressure and rock water content, and lowering the groundwater level, subsequently enhancing shear strength and reducing shear stress. [17]

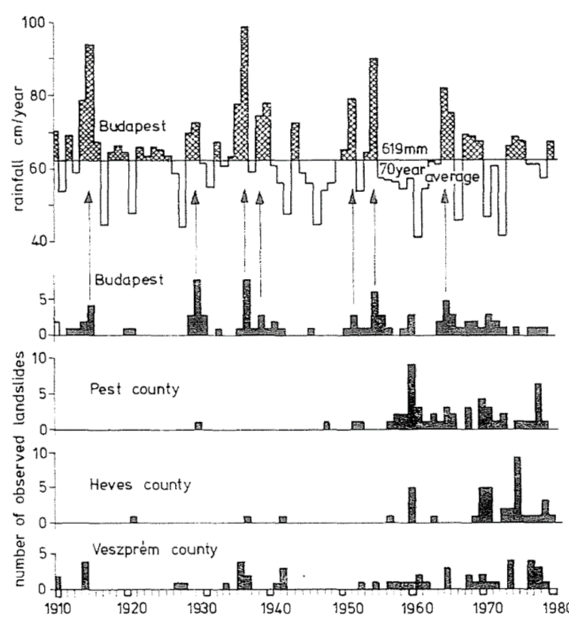


Figure.30 (Relation of surface movement and rainfall) [17]

3.12. Soil parameters in previous studies

A significant corpus of research has been conducted on the stability analysis and geological setting of the Balaton high cliffs. In the previous sections, a detailed examination of current research has been presented, through the likes of expert reports and case studies on these Balaton high cliffs. Particularly in section 2. B (Balaton High Cliffs) the comparison and overall differences and similarities of the cliffs were highlighted. The overarching similarity between the cliffs is the similar layer orders and types of soils that can be found. The major differences are the thickness of the layers and the ground/surface water conditions that are present.

As core samples were not available for laboratory testing during this report. Deterministic soil parameters from prior research will be utilized. The soil layers will be matched with corresponding layers/soil parameters from similar high cliffs in Balatonakarattya. The research that will be utilized is from Fruzsina Nagy-Göde, Ákos Török, Eszter Horváth-Kálmán [14].

The following soil physical parameters (Figure. 25) were 'determined based on explorations, macroscopic layer descriptions, and laboratory investigations. The layer order that was applied can be seen in the cross-section of the analyzed slope.

	Sa/1	Cl/1	Cl/2	Si/1	Sa/2	Sa-Si-Cl	Cl/3
γ_{unsat} [kN/m²]	17	19	20	18	17	20	21
γ_{sat} [kN/m²]	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/m²]	5 - 8	50	60	25	1	30	80
φ [°]	24	22	26	18	20	25	34

Figure.31 (Soil Physical Parameters One) [14]

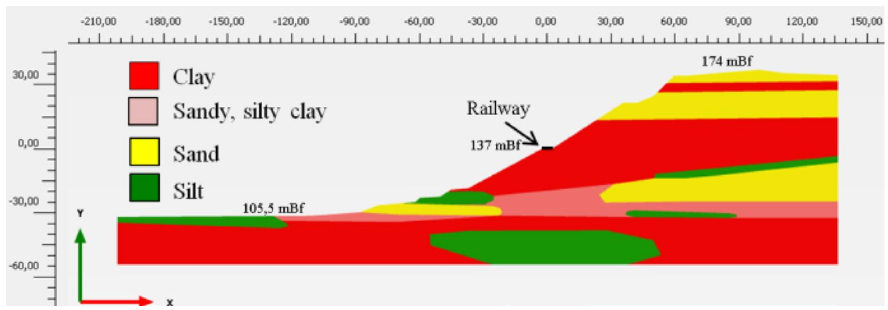


Figure.32 (Applied Model Cross section A) [14]

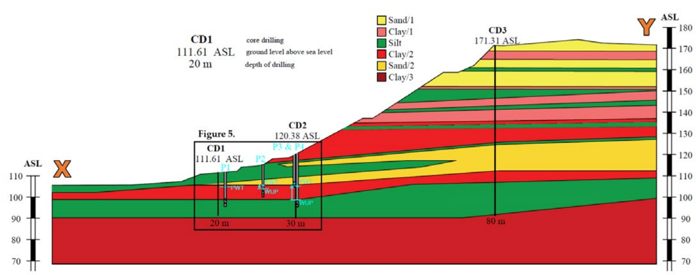


Figure.33 (Applied Model Cross Section B) [15]

	γ_{unsat} [kN/m³]	γ_{sat} [kN/m³]	E [Mpa]	ν [-]	c [kPa]	φ [°]
Sand/1	18	19	15	0,35	12	26
Clay/1	19	20	10	0,3	60	16
Silt	19	20	18	0,4	35	20
Clay/2	20	21	11	0,4	80	18
Sand/2	18	19	15	0,35	20	22
Clay/3	21	22	16	0,4	100	20

Figure.34 (Soil Physical Parameters Two) [15]

3.13. Parameters of loess soils

Typical loess is characterized by a high carbonate content; however, these carbonates are prone to being dissolved due to frequent water inflow through surface layers. This is the type of loess that can be found around Lake Balaton and also comprises the upper portion of the Balatonföldvár high cliffs. [13]

- $CaCO_3 = 14 - 27\%$ *Carbonate content in the soil*
- $Dm = 0.046 - 0.050$ mm *Mean particle diameter.*
- $e = 0.65 - 1.1$ *Void ratio, indicating the voids to solids ratio.*
- $n = 39 - 52\%$ *Porosity, the percentage of void space in the soil.*
- $W_L = 31 - 42\%$ *Water content at the plastic limit.*
- $W_P = 20 - 25\%$ *Plasticity water content, water content where the soil changes from a semi-solid to a plastic state.*
- $I_p = 4 - 22\%$ *Plasticity index, indicating the range of water content over which soil behaves plastically.*

Parameters of Deep loess layers

The deeper layers of loess display a greyish color and generally exhibit fine stratification, mixed with silt and clay from floodplains. A low plasticity index characterizes them, with organic matter frequently present, and a variable carbonate content. [13]

- $CaCO_3 = 12 - 38\%$ *Carbonate content in the soil*
- $Dm = 0.025 - 0.052$ mm *Mean particle diameter.*
- $e = 0.59 - 0.73$ *Void ratio, indicating the voids to solids ratio.*
- $n = 37 - 42\%$ *Porosity, the percentage of void space in the soil.*
- $W_L = 22 - 42\%$ *Water content at the plastic limit.*
- $W_P = 15 - 23\%$ *Plasticity water content, water content where the soil changes from a semi-solid to a plastic state.*
- $I_p = 7 - 23\%$ *Plasticity index, indicating the range of water content over which soil behaves plastically.*

Parameters of Loess from Detrital Sediments

Detrital sediments are materials derived from the mechanical breakdown of pre-existing rocks through processes like weathering and erosion. They consist of particles like sand, silt, and clay, and are transported by natural agents such as water, wind, or ice to a new location where they accumulate and may eventually form sedimentary rocks like sandstone or shale.

Loess of detrital origins has rounded sand particles, the yellowish color of loess in these levels turns greyish. This type of loess most commonly occurs in undulating landscapes and planes. [13]

- $CaCO_3 = 10 - 15\%$ *Carbonate content in the soil*
- $Dm = 0.058 - 0.066$ mm *Mean particle diameter.*
- $e = 0.52 - 0.59$ *Void ratio, indicating the voids to solids ratio.*
- $n = 34 - 37\%$ *Porosity, the percentage of void space in the soil.*
- $W_L = 17 - 22\%$ *Water content at the plastic limit.*
- $W_P = 11 - 17\%$ *Plasticity water content, water content where the soil changes from a semi-solid to a plastic state.*
- $I_p = 5 - 10\%$ *Plasticity index, indicating the range of water content over which soil behaves plastically.*

Parameters of Clayey Loess / Loess Loam

In hill landscapes and near mountains with higher precipitation and abundant vegetation, the initial loess structure transforms into clayey loess due to intense weathering and advanced soil formation. The resulting loess loam has a higher mineral content, a darker color, and is more compact. It's hard when dry and becomes plastic when moistened. [13]

- $CaCO_3 = 2 - 10\%$ *Carbonate content in the soil*
- $Dm = 0.02 - 0.055$ mm *Mean particle diameter.*
- $e = 0.50 - 1.22$ *Void ratio, indicating the voids to solids ratio.*
- $n = 33 - 55\%$ *Porosity, the percentage of void space in the soil.*
- $W_L = 33 - 50\%$ *Water content at the plastic limit.*
- $W_P = 18 - 25\%$ *Plasticity water content, water content where the soil changes from a semi-solid to a plastic state.*
- $I_p = 17 - 30\%$ *Plasticity index, indicating the range of water content over which soil behaves plastically.*

Data Representation

Observing the data above (Figures. 35 – 37) approximations for the Balatonföldvár loess can be made. Considering that the loess in Balatonföldvár is of the Typical loess category the compression modulus (E) for the depth ranges of zero to six meters can be considered from 0 – 6 MPa. [13]

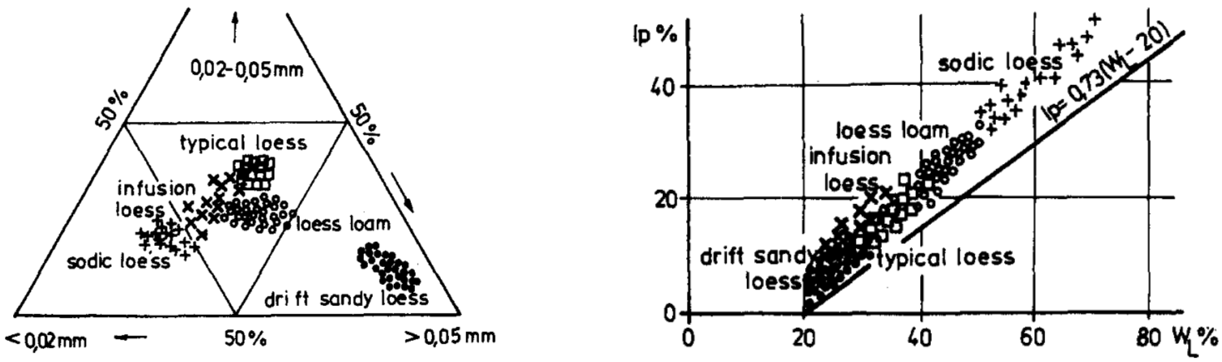


Figure. 35 (Plasticity and grain size of loess types) [13]

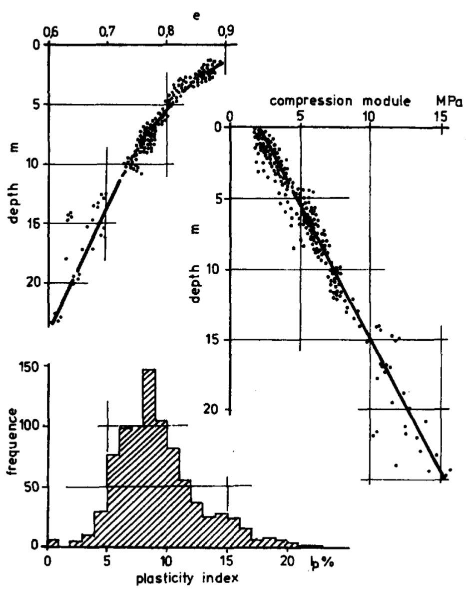


Figure. 36 (Loess thickness and parameters) [13]

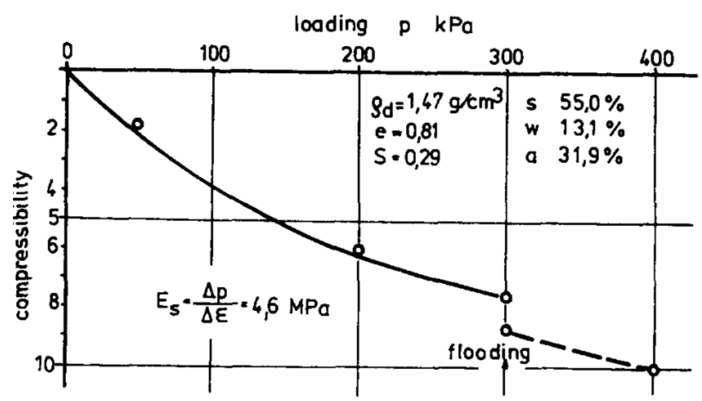


Figure.37 (Compressibility and Elastic Modulus of Loess) [13]

4. Methods

4.1. Geo5 software

The analysis of slope stability forms a critical part of geotechnical engineering, ensuring the safety and sustainability of structures and terrains. In this section, we utilize the GEO5 Slope Stability software, a comprehensive tool designed for conducting slope stability analysis. The software finds applications in analyzing a variety of scenarios including embankments, earth cuts, anchored retaining structures, and Mechanically Stabilized Earth (MSE) walls. The distinctive feature of GEO5 is its ability to analyze slip surfaces, which can be modeled as either circular or polygonal, employing well-established methods like Bishop, Fellenius/Petterson, Janbu, Morgenstern-Price, or Spencer for circular surfaces.

The GEO5 Slope Stability software is equipped with features that allow verification analysis following the EN 1997-1 standard or a classical approach encompassing limit states and factors of safety considerations. It also facilitates a simplified input of layer geometry, making it user-friendly while ensuring precision in analysis. Moreover, the software provides options to tailor the analysis with partial factors based on National Annexes EN 1997, thus offering flexibility in accommodating varying design approaches and situations.

4.2. Limit equilibrium methods

Limit Equilibrium Methods (LEMs) are employed in geotechnical engineering to assess slope stability by approximating a Factor of Safety (FoS) against sliding along a presumed failure surface. Initially, a potential failure surface is assumed, typically being circular or planar. The soil mass above this surface is divided into vertical slices, and for each slice, forces including the weight, shear strength along the base, and any additional forces like pore water pressure or surcharge loads are computed. The driving forces trying to cause sliding are compared to the resisting forces preventing sliding, with the primary resisting force being the shear strength of the soil along the failure surface. The FoS is then calculated as the ratio of the sum of resisting forces to the sum of driving forces; a FoS greater than 1 indicates stability, while a FoS less than 1 indicates instability. Various LEMs employ different equilibrium conditions to compute the FoS, and often, an iterative process is utilized to evaluate different potential failure surfaces to identify the one yielding the lowest FoS, hence representing the most critical failure scenario.

Factor of safety

The factor of safety is described as the multiplier needed to reduce the shear strength to bring a material mass to a state of limited equilibrium along a designated slip surface. The shear force for saturated soil can be articulated based on the failure criterion for any given slice. In the case of unsaturated soil, the impact of matric suction should be incorporated in the equation representing the mobilized shear force, as per Fredlund et al., 1978.

$$S_m = \frac{\beta}{F_s}\left\{c' + (\sigma_n - u_w)\tan\phi'\right\}$$

where:

S_m = shear force mobilized,

c' = effective cohesion of the material,

ϕ' = effective angle of internal friction,

u_w = pore-water pressure at base of a slice,

β = length along the base of a slice, and

σ_n = normal stress acting on the base of a slice.

Figure.38(Saturated) [21]

$$S_m = \frac{\beta}{F_s}\left\{c' + (\sigma_n - u_a)\tan\phi' + (u_a - u_w)\tan\phi^b\right\}$$

where:

u_a = pore-air pressure at the base of a slice,

$u_a - u_w$ = matric suction, and

ϕ^b = the angle defining the rate of increase of strength due to an increase in suction.

Figure.39(Unsaturated) [21]

Fellenius / Peterson

The Fellenius or Ordinary method divides a sliding mass into slices to analyze slope stability, simplifying the calculation of a linear factor of safety. This method is easy to implement manually.

It assumes that interslice shear and normal forces are zero. Two static equilibrium equations are used to solve for the factor of safety. However, there's a theoretical limitation: it assumes inter-slice forces cancel each other out, and are parallel to the base of each slice to be excluded from the statics equation.

But, moving to the next slice changes the direction for summing forces at the base, requiring interslice forces to have a slightly different direction to join two slices. This is a fundamental error from a statics perspective.

Therefore, the Ordinary method isn't considered acceptable due to this statics flaw, violating Newtonian static equilibrium. It's included in software mainly to bridge the transition from earlier to subsequent methods, and its use in geotechnical engineering isn't recommended. *[21]*

Bishop

In 1956, Bishop introduced a limit equilibrium method of slices, working under the premise that interslice shear forces could be disregarded while keeping the interslice normal forces. Essentially, the resulting interslice forces operate horizontally, but the total horizontal force equilibrium is not achieved. [21]

The equation illustrating moment equilibrium about the rotation center for the overall slope is fundamental for deriving the factor of safety, Fs.

$$\Sigma M_0 = 0$$

The equation showcasing vertical force equilibrium for each slice is utilized to determine the normal force, N, at the base of each slice.

$$\Sigma F_v = 0$$

The factor of safety equation regarding the moment equilibrium around the rotation center (or center of moments) is identical to that used in the Fellnius /Peterson method The force equilibrium equation is outlined in the vertical direction for each slice.

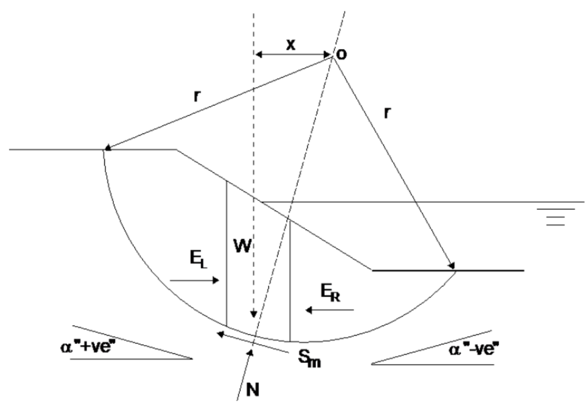
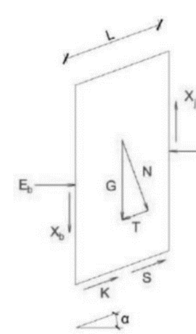


Figure.40 (Forces associated with Bishop method of slices) [21]

Spencer

The Spencer Method suggests that the relationship between two types of forces in the sliding mass stays the same throughout. It separately balances both the side-to-side force and the twisting force, leading to two measures of safety, one for each type of balance - we'll call them Ff for force balance, and Fm for moment balance. This way of relating the two forces, labeled as X for shear force and E for normal force, is a specific example of a more general approach called the General Limit Equilibrium (GLE) method. In the GLE method, a formula suggested by Morgenstern-Price in 1965 connects these forces. The Spencer method is a case where a particular value, lambda (λ), is 1.0, and a function, f(x), stays constant and equals (tan θ) according to the GLE method. [21]



[22]

$$X = E \tan \theta$$

X	= interslice shear force,
E	= interslice normal force, and
θ	= angle of the resultant interslice force from the horizontal.

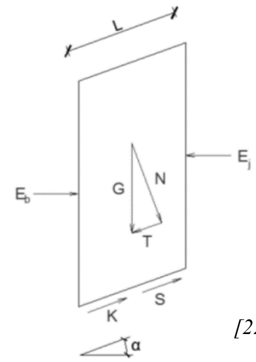
(Interslice forces) [21]

$$X = E\lambda\, f(x)$$

(Spencer) [21]

Janbu simplified method

The equations used in Janbu's Simplified Method for checking balance are similar to those used in Janbu's Generalized method. In the Simplified version, it's assumed that the combined forces between slices are aligned horizontally. This means that the shear forces between slices are left out when figuring out the safety factor. This means that the horizontal force equilibrium is satisfied, but not the overall moment equilibrium. An iterative or repeatable process is necessary to solve for the safety factor, much like what's done in Bishop's Simplified method. *[21]*



[22]

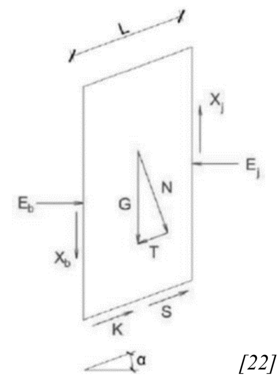
$$F_s = \frac{\sum \left[c'\beta + \left(\frac{W + [D\sin\omega]}{\cos\alpha} - u\beta \right) \tan\phi' \right] / m_\alpha}{\sum \{W + [D\sin\omega]\} \tan\alpha + \sum kW - [D\cos\omega] \pm A}$$

(Janbu's factor of safety calculation) [21]

Morgenstern-price

The Morgenstern-Price method, devised in the 1960s, utilizes the limit equilibrium theory to analyze slope stability in cohesive and non-cohesive soils. It segments the slope into vertical slices, each assumed to be in equilibrium. Calculating the forces on each slice compares resisting forces to driving forces to evaluate slope stability. The factor of safety (FS), the ratio of these forces, determines stability; a slope is stable if FS is above 1, and unstable if below 1. This method assumes a circular slip surface, accounts for pore water pressure in the soil, and suits a variety of slope geometries and soil conditions. However, its assumption of a circular slip surface may not always be accurate, especially in slopes with complex geology or unusual soil properties. [21]

The original Morgenstern-Price method from 1965 employed an integration-type solution utilizing a modified Newton-Raphson solver. In contrast, the software implements a summation approach akin to those used for other methods of slices. However many software, apply a Rapid solver to compute the factor of safety in alignment with the M-P method. This Rapid Solver procedure operates as follows for Plaxis software as an example (Figure. 40). [21]



[22]

1. Set an initial value for λ = 2/3 'cord slope' where the 'cord slope' is defined as shown in Figure 8,
2. Obtain the initial factor of safety using the Ordinary method and increase the computed value by 17%. The estimated value for F_s, is used as the initial F_s, for solving the *M-P* method,
3. Compute a set of $(F_s)_m$ and $(F_s)_f$ (i.e., moment and force equilibrium factors of safety)$_f$ using the initial, λ,
4. Compare the two factors of safety and select a second λ value,

$$if\ (F_s)_m > (F_s)_f,\ then\ \lambda = \lambda + 0.1$$
$$if\ (F_s)_m < (F_s)_f,\ then\ \lambda = \lambda - 0.1$$

5. Compute a new set of factors of safety (i.e., (Fs)m and (Fs)f using the newly estimated lambda value, λ, and compare the difference in the two factors of safety to the tolerance. If the tolerance criterion is satisfied then the computations can be stopped,
6. If the tolerance criterion is not satisfied, repeat Step 3 using a new λ value estimated from the two previous sets of factor of safety and λ calculations.

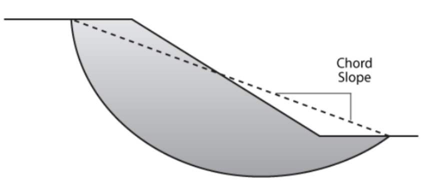


Figure.41 (Morgenstern-Price rapid solver in Plaxis) [21]

4.3. Mohr-Coulomb soil model

The Mohr-Coulomb model is recognized for its elastoplastic behavior, offering reliable insights for general nonlinear ground analysis (Figure 42.), hence its widespread use in simulating various terrains. This model assumes a linearly elastic and perfectly plastic material behavior. According to the model, the flow condition, which only encompasses stresses and material characteristics, dictates that only elastic deformations arise until the fracture line is reached. However, this assumption is often disproven in practice, especially during the soil settlement process. For instance, along the K0-line following unloading, there's an ongoing compression, indicating plastic deformation, which doesn't completely cease, contradicting the model's assumption of solely elastic deformations up to the fracture line. [23]

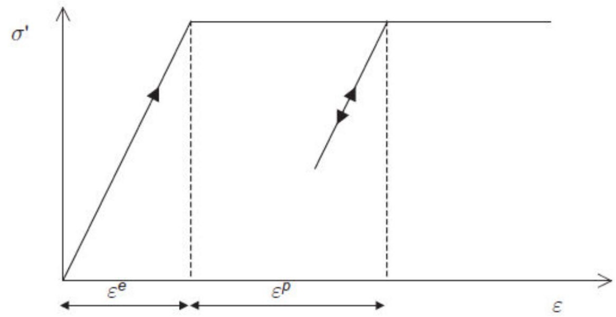


Figure.42 (Elastoplastic material model) [23]

The Mohr-Coulomb model's failure criterion is based on a linear equation, representing a straight line in the shear stress-normal stress space. This criterion is pivotal as it demarcates the conditions under which a soil mass will succumb to failure. An integral aspect of this model is the incorporation of dilatancy, representing the volume change linked with shear deformation, which is especially pertinent when dealing with dense sands or over consolidated clays. [23]

Despite certain limitations, including its assumption that the intermediate principal stress doesn't influence yield and the constant strength parameter (angle of friction) regardless of changes in the confining or hydrostatic pressure, the Mohr-Coulomb model remains a frequently used tool due to its simplicity and reasonable accuracy within a common confining pressure range. It finds its application in a plethora of geotechnical scenarios, although its linear failure envelope often falls short in accurately capturing the behavior of soils under a wide range of stress conditions, especially when compared to more advanced models like the Hardening Soil Model or the Cam-Clay model. [23]

Soil shear strength, significantly impacted by its cohesion and friction angle, varies based on soil type. These parameters are usually determined through laboratory tests or field observations, aiding in the meticulous analysis of soil behavior under various loading conditions. Unlike other construction materials, soils exhibit minimal resistance to tension, typically experiencing shear failure when subjected to external forces or self-weight. [23]

According to Coulomb, soil shear strength is the sum of cohesion and the product of normal stress and the tangent of the interior friction angle. Cohesion represents the shear strength at a zero interior friction angle, similar to the undrained shear strength of cohesive soils. Specifying cohesion also sets the tensile strength, but since tensile resistance is generally overlooked for geo-materials, a tension cutoff is applied to avoid unrealistic resistance behavior to tension. [23]

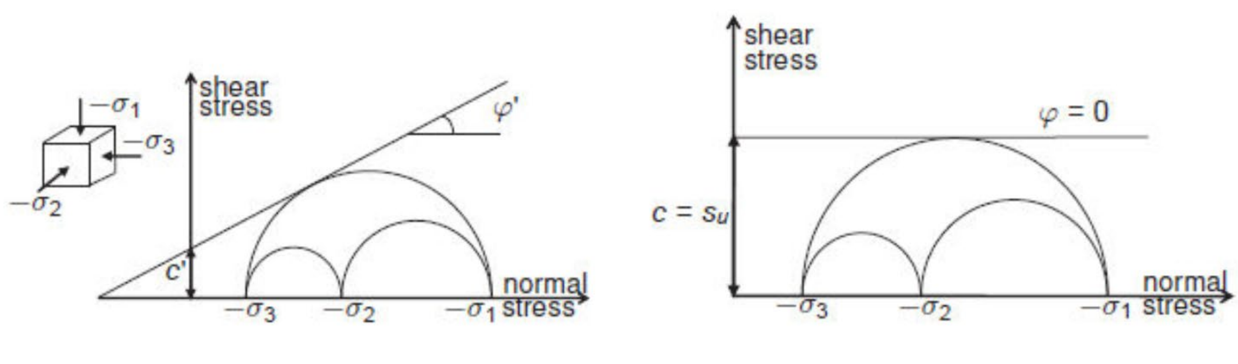


Figure.43 (Drained and Un-drained Mohr-Coulomb failure envelope curves) [23]

The Mohr-Coulomb model is also widely implemented in numerical simulations using common geotechnical engineering software. Its parameters can be easily derived from standard soil tests, making it a practical choice for many engineering applications. Moreover, the flexibility to adjust parameters like cohesion based on depth and confining pressure allows for a more nuanced simulation of ground behavior, even within a layer of identical material. For instance, defining a deep soil layer with a 'strength parameter' might limit the detailed simulation of ground behavior. Adjusting cohesion based on height or subdividing the ground layer for modeling are alternative approaches to tackle this limitation.

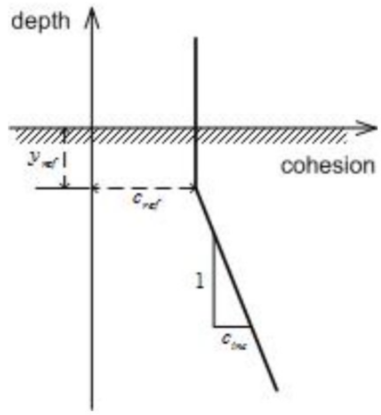


Figure.44 (Cohesion increment) [23]

4.4. Laboratory testing

Sampling

The sample location is indicated on the Site Plan with the MK2 marker. The location was at the top of the debris slope just at the start of the vertical cliff face (a sample was taken from the cliff face). The piece was chosen to collect a relatively large intact piece for sampling.

Figure.45 (Collected sample)

Examinations conducted

All examinations conducted were carried out by the MSZ EN ISO 17892- 10:2019 standards.

Water content

Test Information

Water is naturally present in most soils, and its amount, known as moisture content, has a significant impact on soil behavior. Moisture content is measured as the proportion of water to the dry solid particles by mass. It serves as a guide for classifying natural soils and as a control criterion in recompacted soils. Additionally, moisture content is an essential parameter for various field and laboratory tests. The standard method for determining moisture content is through the oven-drying method, where soil samples are heated at temperatures below 110 °C until no more water can be removed (placed in oven for 24 hours). This method ensures consistent and reliable measurements, providing valuable information for geotechnical analyses.

Test Preparation

- Prepare the weighing container by ensuring it is clean and dry. Weigh it accurately to the nearest 0.01 g (m1). Take a soil sample of at least 30 g, crumble it, and place it loosely in the container. and weigh the container and contents to the nearest 0.01g (m2).
- Place the container with its contents in the oven and dry them at a temperature between 105 °C and 110 °C. The drying time will depend on the soil type and sample size. The sample is considered dry when there is no significant difference in successive weighing of the cooled sample.
- Weight the container and the soil sample together after they have both cooled to room temperature.
- To determine the moisture content, measure the weight of the dry soil. Then, subtract the weight of the dry soil from the weight of the wet soil to obtain the moisture content. Finally, divide this difference by the weight of the dry soil.

Shear-box test

Test Information

Soil shear strength is pivotal in determining the stability and load-bearing capacity of the soil, which directly impacts foundational integrity and overall slope stability. To measure this property, the soil specimen is positioned within an apparatus called a shear box. This equipment comprises two metallic plates, two porous stones, two screws, a gripper disk, and a loading cap where the normal stress is applied. The design of the shear box is such that it limits the specimen's horizontal strain while facilitating shearing at the intersection of the two metallic plates. This shearing is facilitated by lateral loading of the lower shear box. The test is compiled for the intact specimen with vertical loads of 50, 100, and 150kPa. Further, to examine the properties of when the loess has been disturbed. Three more samples were constructed from loess-powered, compacted by hand. These specimens were also loaded by 50,100, and 150 kPa.

Test Preparation

The samples were created by carving out an approximate shape that would fit into the square testing apparatus. The sample was left a little larger and then the square sampler, which was then pressed on top of the soil to obtain as intact of a sample as possible. Start by determining the dimensions of the shear box, noting its height and diameter.

Figure.46 (Shear-box test)

The samples were created by carving out an approximate shape that would fit into the square testing apparatus. The sample was left a little larger and then the square sampler, which was then pressed on top of the soil to obtain as intact of a sample as possible. Start by determining the dimensions of the shear box, noting its height and diameter.

- Secure the base of the shear box using the provided screws.
- Set up the shear box by positioning both the gripper disk and porous stone inside.
- Take an initial weight of the entire soil amount.
- Transfer the soil specimen into the shear box (using a plunger to press the undisturbed sample into the apparatus).
- Place porous stone, and finally, cap it with the loading cover.
- Insert the assembled shear box into the shearing apparatus.
- Adjust both the horizontal and vertical dial gauges to zero.
- Equalize the shear force to a null setting.
- Apply a vertical force onto the sample.
- Record any vertical shifts in the soil due to its consolidation.
- On the shearing apparatus, select the desired shear rate.
- Initiate the shearing process.
- Continue shearing until 7mm of total deformation has been reached.

Oedometer test

Test information

At its core, the oedometer test is an experiment designed to simulate the natural conditions that soil experiences deep below the ground. A confined soil sample, restricted from lateral movement, undergoes vertical compressions induced by a series of controlled weights. This restriction is intentional, emulating the true conditions of a deep-set soil layer, where lateral expansions are inherently restricted due to the overlying soil mass.

The test starts with the initial phase of loading, where the soil undergoes sequential compressions with stresses of 50 kPa, 100 kPa, 200 kPa, and 300 kPa. Each of these stress increments is reflective of potential stress histories that a soil deposit might have undergone, either due to natural sedimentation or human-induced construction activities. With each load, the vertical settlement is meticulously measured over time, culminating in a time-settlement graph. From this, crucial data points such as the time required for both 50% and 90% consolidation can be extracted.

Following this initial loading, the soil sample is saturated, typically facilitated by the introduction of water from its base. The intent behind this step is to ensure that subsequent loadings are in the realm of consolidated drained conditions, which is vital for accurate data interpretation.

Post-saturation, the sample undergoes consolidation under the highest previously applied load, in this case, 300 kPa. This step is foundational in accounting for any recompression that might have arisen due to the saturation process. The subsequent stage involves subjecting the soil to a more substantial load of 500 kPa. This additional load is not just a random escalation; it is chosen to explore the soil's reaction to stresses beyond its historical experiences, a realm termed "over-consolidation."

Test Preparation

The samples were created by carving out an approximate shape that would fit into the circular testing apparatus. The sample was left a little larger and then the sampler, which was then pressed on top of the soil to obtain as intact of a sample as possible. The top and bottom were then scrapped off to be flush with the sides.

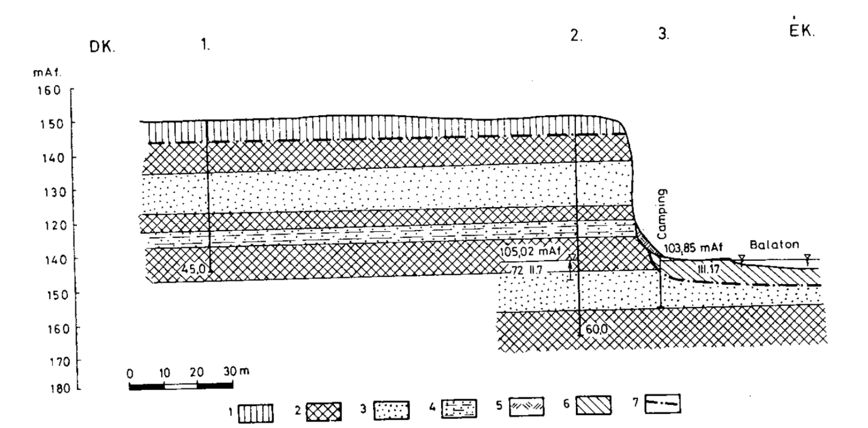
Figure.47 (Oedometer test)

- Confining Ring: Begin by carving the confining ring circumferentially around the soil sample. This ring ensures that there is minimal lateral displacement during the test, allowing for the primary focus to be on vertical compressibility.
- Placement of Porous Stones: Place a porous stone at the base of the confining ring. These stones are highly permeable and serve to enable the drainage of water from the soil specimen.
- Addition of Filter Papers: Position filter papers between the soil sample and the porous stone. This step is crucial to prevent the soil from clogging the pores of the stone.
- Soil Sample Installation: Introduce the soil specimen into the confining ring. Ensure it sits snugly between the filter papers and the porous stones.
- Loading Cap Installation: Position a loading cap on the top of the soil specimen. This cap serves to transfer the vertical loads uniformly to the soil during the test.
- Initial Load Application: Commence the testing procedure by applying an initial load of 50kPa. This step simulates the natural stress conditions the soil might experience.
- Subsequent Loadings: Sequentially increase the vertical loads. Apply loads of 100kPa, 200kPa, and 300kPa respectively, ensuring that each load is maintained until primary consolidation is achieved at each stage.
- Sample Saturation: After the application of the 300kPa load and ensuring complete consolidation, saturate the soil sample. This process is crucial to simulate conditions where the soil might be exposed to water ingress, such as groundwater or rainfall.
- Final Load Application: After achieving complete saturation, apply a final loading of 500kPa. This step examines the soil's behavior under a higher stress condition post-saturation

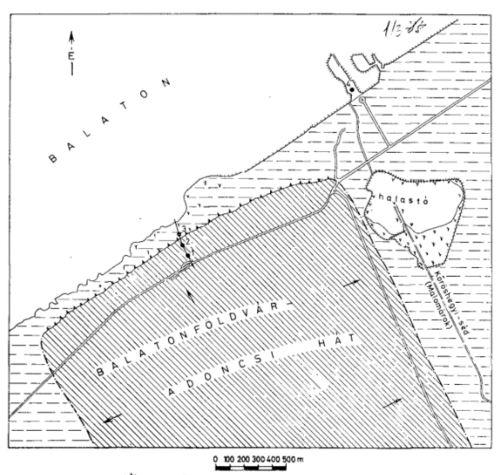
5. Modeling

5.1. MODEL ONE: Analysis of slope section and layer order obtained from literature

The next section will be dedicated to examining the cross section with soil strata thickness and order obtained from literature "*A balatonföldvári és a fonyódi magaspartok állékonyságának mérnökgeológiai vizsgálata*" writen by Horváth Zsolt and Dr. Scheuer Gyula. The findings from their publication have been discussed in sections (2. b and 2. c). The cliff cross-section and soil layers can be visualized in the following figure.



3. *ábra*. A balatonföldvári magaspart áttekintő mérnökgeológiai szelvénye. J e l m a g y a r á z a t : 1. Lösz, 2. Agyag, 3. Homok, 4. Iszapos homok, 5. Leomlott anyag, 6. Balatoni üledékek (homok, agyag), 7. Felsőpannoniai-negyedkor határ



A balatonföldvári magaspart helyszínrajza. J e l m a g y a r á z a t: 1. A magaspart pereme, 2. Kiemelt terület, 3. Mélyfekvésű területek, 4. Szelvényvonal, 5. Fúrási pontok, 6. Vízáramlási irányok

Figure.48 (Balatonföldvár High Cliff Section) [5]

The soil characteristics supplied are listed purely as a basic description which can be found under the figure above. The uppermost layer comprised of loess will be implemented by data obtained from laboratory tests conducted during this TDK project (section 7. Laboratory testing). The remaining soil parameters have been obtained from the article "*Rainfall-Induced* *or Lake-Water-Level-Controlled Landslide? An Example from the Steep Slopes of Lake Balaton, Hungary*" written by Fruzsina Kápolnainé Nagy-Göde and Ákos Török. The soil parameters have been collected in the following table.

	Loess	Clay/1	Silt	Clay/2	Sand/2	Clay/3	Debris
Unsaturated unit weight (kN/m^3)	18	19	19	20	18	21	20
Saturated unit weight (kN/m^3)	19	20	20	21	19	22	21
Oedometric modulus (E) Mpa	27	10	18	11	15	16	16
Cohesion (c) kPa	56	60	35	80	20	100	30
Internal friction angle (deg)	46	16	20	18	22	10	25

5.2. MODEL TWO: Analysis of slope section created by laser measurement and literature soil layer

During this section, the evaluation, inspection, and modeling of a new cross-section taken from the Balatonföldvár loess cliff will be discussed. The aim of analyzing a new section was established by the need to inspect the cliff amid a highly urbanized zone. In this zone, the high cliff is encapsulated above and below with neighborhood roads as well as railway lines.

The nearest structure is just three meters from the vertical edge, with the average distance of buildings along the cliff's edge being 15.2 meters. The buildings' mean distance from the base of the debris slope at the bottom of the cliff is 10.4 meters. The cliffs witness regular pedestrian traffic along the top and a staircase that intersects the cliff. Additionally, roads with vehicular traffic are situated within a 30-meter distance both at the top and bottom of the cliffs.

The site inspection was conducted with a Lazer handheld distance measuring device (as seen in Figure. 49). Eight points were placed (seen on the site map) designated along the cliff encompassing the whole height range. These points were logged with their coordinate into Google Maps, allowing for a clear visualization of where the points lie horizontally from one another. The known base level of the road was established first, and then the distance between the points was measured vertically and horizontally from one another. This process was repeated from the bottom of the cliff to the top and then once more from the top of the cliff to the bottom, the values matched. Furthermore, the elevation data of the base and top of the cliff was referenced to geodetic measurements.

The next phase was outlining the Google maps upon which the points were marked. These points and objects, such as the base and top of the cliff line, buildings, roads, railways, staircases, and key trees were marked. In the next phase, contour lines were drawn for the known points. Such as the base and top of the cliff and the ten marker positions that were taken. The elevation between these points was split up and contour lines were assigned. Based on notes, photos, and experiences from the site visit, the elevation lines were adjusted.

Figure.49 (Laser measure) [29]

Finally, a cross-section was taken from the zone where the cliff face was the steepest. The contour line intersections with the section line were projected at 90 degrees to give a section view of the cliff.

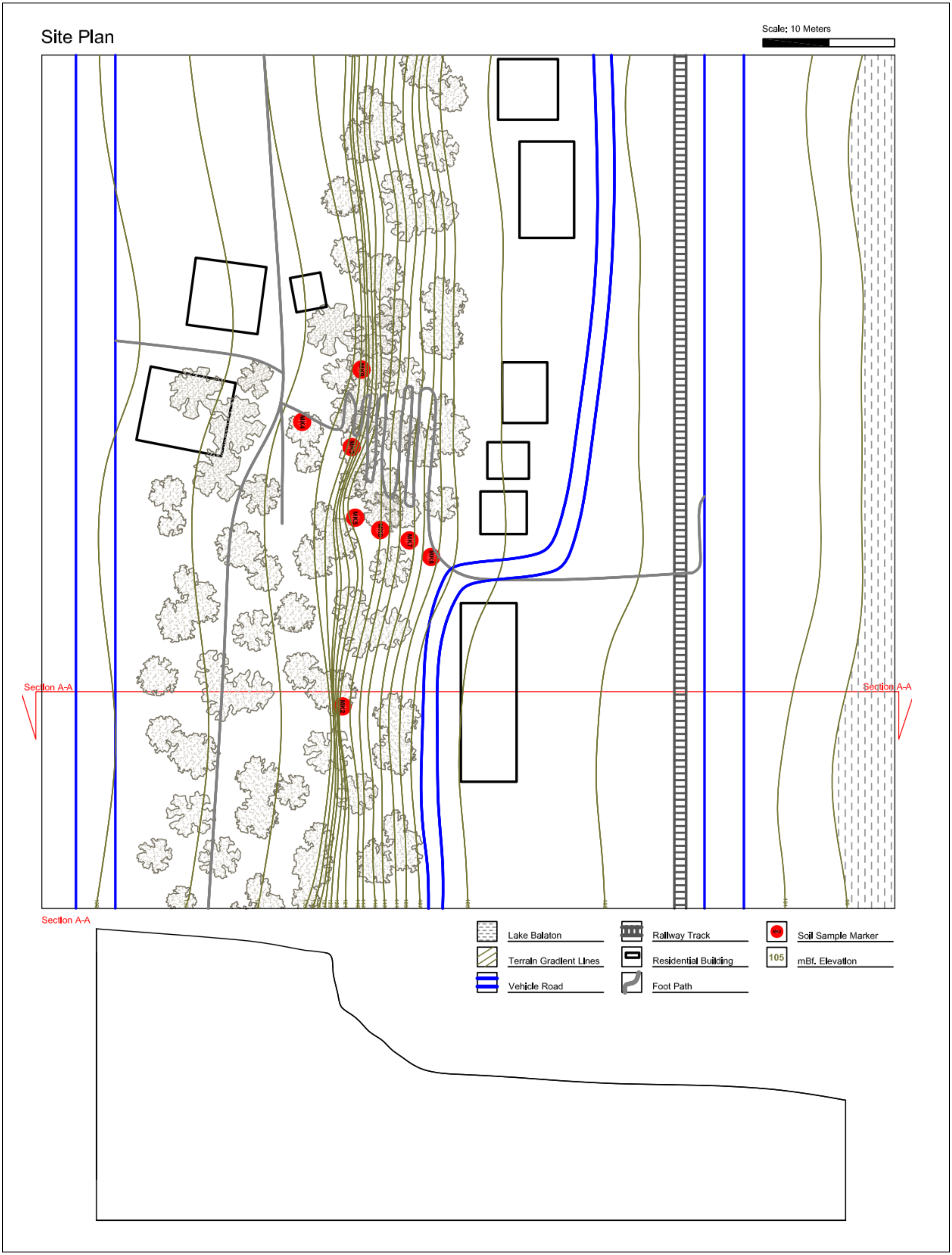
The uppermost layer comprised of loess will be implemented by data obtained from laboratory tests conducted during this TDK project (section 7. Laboratory testing). The remaining soil parameters have been obtained from the article "*Rainfall-Induced or Lake-Water-Level-Controlled Landslide? An Example from the Steep Slopes of Lake Balaton, Hungary*" written by Fruzsina Kápolnainé Nagy-Göde and Ákos Török. The soil parameters have been collected in the following table.

	Loess	Clay/1	Silt	Clay/2	Sand/2	Clay/3	Debris
Unsaturated unit weight (kN/m^3)	18	19	19	20	18	21	20
Saturated unit weight (kN/m^3)	19	20	20	21	19	22	21
Oedometric modulus (E) Mpa	27	10	18	11	15	16	16
Cohesion (c) kPa	56	60	35	80	20	100	30
Internal friction angle (deg)	46	16	20	18	22	10	25

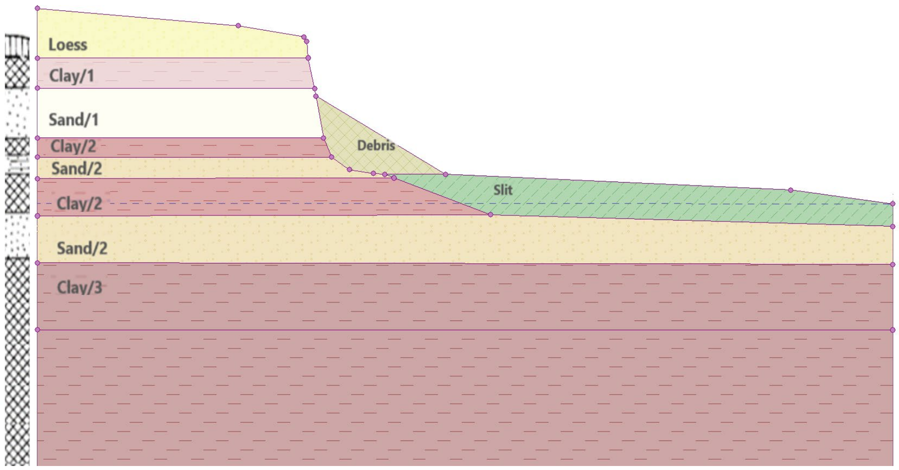
The soil layer order implemented in the model is taken from the expert opinions outlined in "*A balatonföldvári és a fonyódi magaspartok állékonyságának mérnökgeológiai vizsgálata*" writen by Horváth Zsolt and Dr. Scheuer Gyula. The findings from their publication have been discussed in sections (2. b and 2. c). The cliff cross-section and soil layers can be visualized in the following figure.

To summarize the parameters of the Geo5 model; the layer orders and soil properties are taken from expert reports. The soil parameters of the loess layer have been determined from laboratory testing conducted during this TDK project. The geometry of the section is obtained from measurements and site inspection conducted during the TDK project.

The site plan and cross-section constructed from the site plan can be found on the following page.


Site Plan
Scale: 10 Meters
Section A-A
Section A-A
Section A-A
Lake Balaton
Terrain Gradient Lines
Vehicle Road
Railway Track
Residential Building
Foot Path
Soil Sample Marker
105
mBf. Elevation

The following is the cross-sectional view constructed from the geometry of the slope from the above site plan constructed by laser measurement. The layer order applied is from the literature.



5.3. MODEL THREE: Analysis of slope section created by laser measurement and layer order constructed from borehole data

In the following section, we will examine the geometry of the soil section developed in model 2, created by laser measurement. However, in this section, the soil layer implemented in the model is created from the compilation of three boreholes from within the vicinity of the specific cross-section analyzed. The location of these boreholes can be seen on the following map.

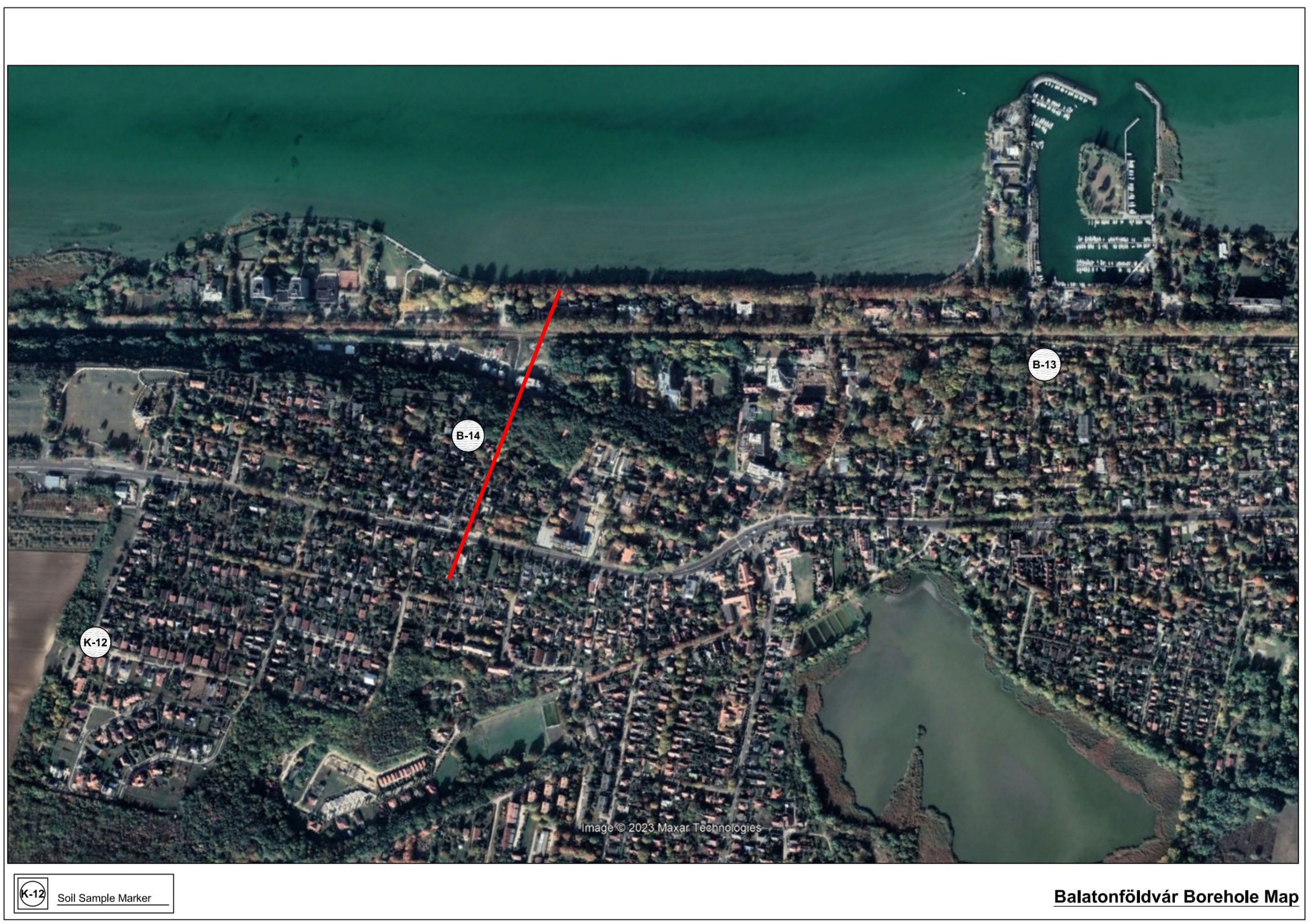


Figure.49 (Balatonföldvár borehole map (B14, B13, K12))

The borehole sections marked on the map above have been obtained from the Hungarian Mining and Geological Service. The cross sections have been simplified to visualize the predominant layers, suitable for modeling of the high cliffs, these sections can be seen in the following diagram.

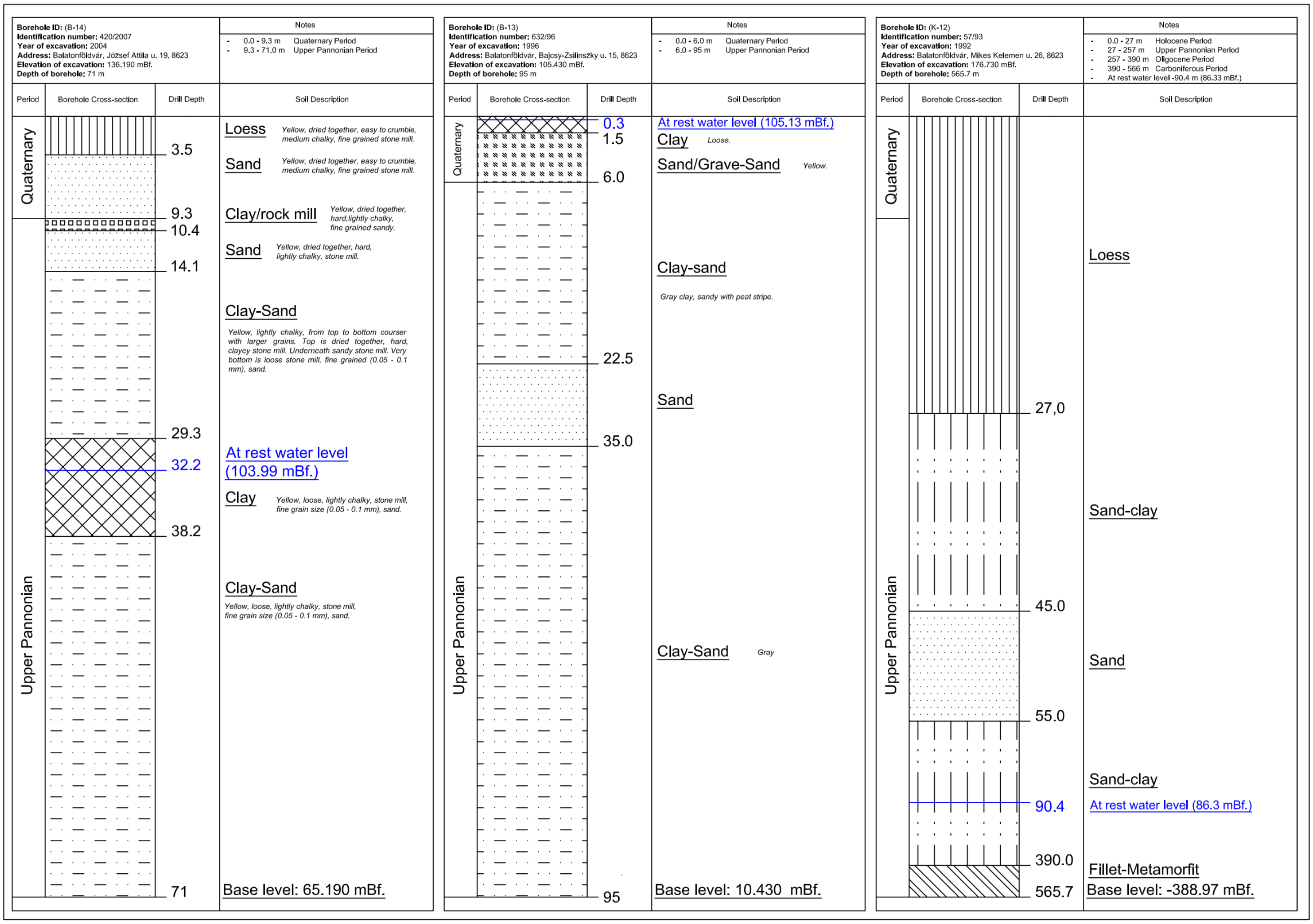


Figure.50 (Borehole cross sections (B14, B13, K12))

The following cross-section is obtained from the geometry of the slope which has been measured by laser measurement. The layer order applied is constructed from the above three boreholes.

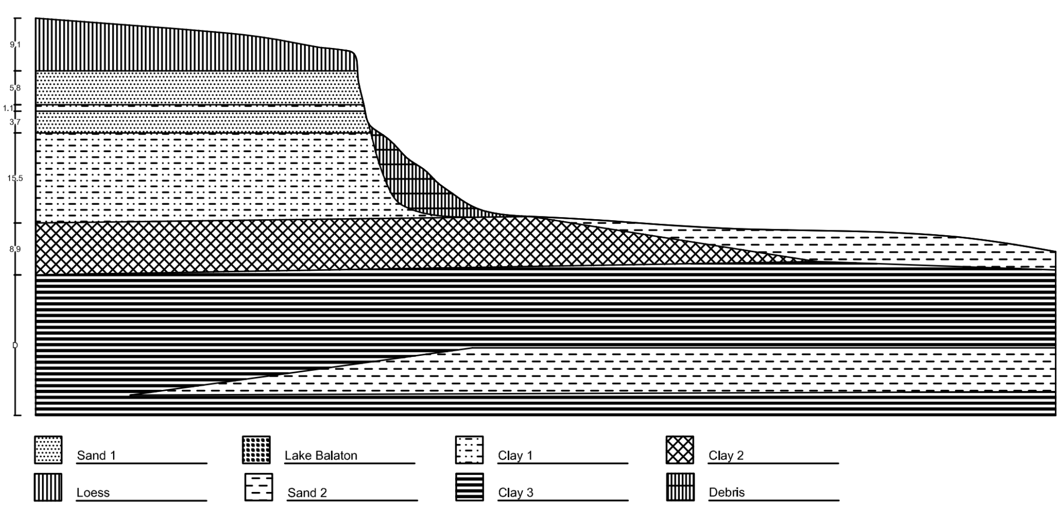


Figure.51 (Cross section created from borehole cross sections (B14, B13, K12))

The soil parameters of the layers visualized in the boreholes have been determined as follows. The uppermost layer comprised of loess will be implemented by data obtained from laboratory tests conducted during this TDK project (section Laboratory testing). The remaining soil parameters have been obtained from the article "*Rainfall-Induced or Lake-Water-Level-Controlled Landslide? An Example from the Steep Slopes of Lake Balaton, Hungary*" written by Fruzsina Kápolnainé Nagy-Göde and Ákos Török. The soil parameters have been collected in the following table.

	Loess	Clay/1	Silt	Clay/2	Sand/2	Clay/3	Debris
Unsaturated unit weight (kN/m^3)	18	19	19	20	18	21	20
Saturated unit weight (kN/m^3)	19	20	20	21	19	22	21
Oedometric modulus (E) Mpa	27	10	18	11	15	16	16
Cohesion (c) kPa	56	60	35	80	20	100	30
Internal friction angle (deg)	46	16	20	18	22	10	25

6. Site survey

6.1. Site overview

Figure.52 (Site location)

The site is located in Balatonföldvár, a town on the Southern shore of Lake Balaton. The site can be split into three zones. The top of the cliff, the bottom of the cliff, and the area between these two points. The cliffs at the studied cross section, seen in (Figure. 62) are 35 meters tall.

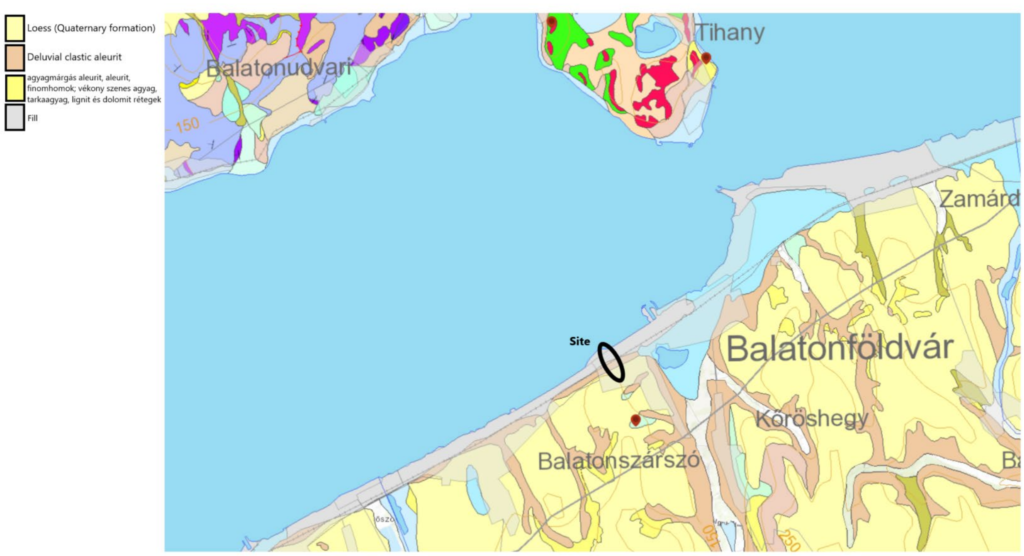


Figure.53 (Geological base sections of Hungary) [3]

6.2. Groundwater conditions

Through the evaluation of multiple borehole reports and expert reviews. The groundwater level fluctuates only slightly and maintains the water level of Lake Balaton. According to the expert reports, discussed in section 2.C. the cliffs are considered completely dry, and no springs have been noticed from the explorations.

6.3. Climate

Temperature

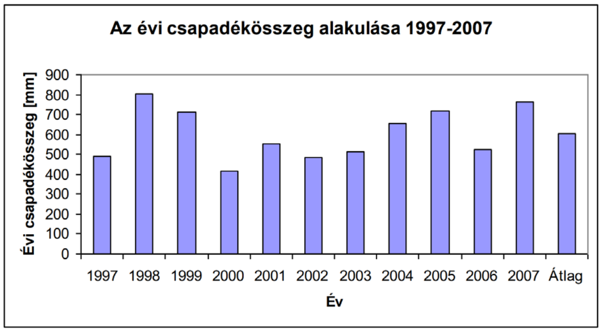
Balatonföldvár has a humid continental climate characterized by hot summers and cold winters. The climate is strongly influenced by its proximity to the lake and the surrounding hills and the region's prevailing winds and weather patterns. During the summer months, typically from June to August, the temperature in town can reach above 30°C (86°F). The warm weather is often accompanied by high humidity levels, making the area feel even hotter. The summer months are also the wettest time of the year, with frequent thunderstorms and rainfall. In the winter months, typically from December to February, the temperature can drop to as low as -5°C (23°F). The cold weather is often accompanied by snowfall, with an average of 40-50 snowy days per year. Winter is also the driest time of the year, with very little rainfall. The spring and autumn months are mild, with temperatures ranging from 10°C to 20°C (50°F to 68°F). Mild temperatures, moderate humidity, and moderate rainfall characterize these seasons. [26]

Hónap	I.	II.	III.	IV.	V.	VI.	VII.	VIII.	IX.	X.	XI.	XII.	Átl.
Léghőmérséklet (C°)	-0,4	1,8	5,8	11,1	16,6	19,7	21,1	20,5	15,4	10,9	5,4	0,5	10,7

Figure.54(Balatonföldvár average monthly temperature from 1997-2007) [26]

Rainfall

Lake Balaton plays a significant role in shaping the microclimate of Földvár and the surrounding area. The lake has a moderating effect on the climate, which means that it helps regulate the region's temperature and humidity levels. During the summer, Lake Balaton’s water absorbs significant heat, which helps cool the surrounding area. This creates a cooler and more comfortable microclimate than other areas of Hungary during the hot summer months. Additionally, the lake's proximity to the town can create a cooling breeze that makes the area feel even more pleasant. In the winter months, the lake also moderates the climate, but in the opposite direction. The water in the lake retains heat, which helps to keep the surrounding area relatively warmer than other areas of Hungary. This can lead to milder winters in Balatonföldvár compared to other regions with similar latitudes. 11 The lake also affects the humidity levels in the region. During the summer, the lake provides a source of moisture, which can increase the humidity levels in the surrounding area. [26]



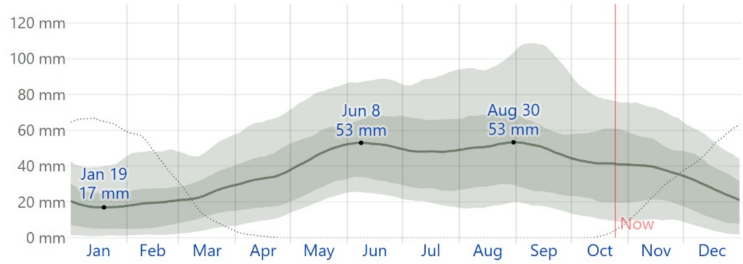


Figure.55(Balatonföldvár average monthly rainfall between 1997-2007) [26,27]

6.4. Field observations

Figure. 57, visualizes the closest structure on the edge of the 35-meter cliff in Balatonföldvár. The back edge of the building is only three meters from the shear cliff face. Local failures of the cliff could lead to a destabilizing effect, coupled with the overpressure of the structure leading to a catastrophic failure. The water runoff from the roof in case of heavy rain must be deposited into the central sewer system. Intense wetting of the loess near the edge of the structure (close to the cliff face) can be a compromising factor, as the loess loses cohesion drastically when wetted.

Figure.56(Structure nearest to cliff edge, Balatonföldvár)

Over the last 20 years, local deformations at the crest of the high cliffs have led to the detachment of protective railings from the edge. The yellow line (uppermost) marks the initial position of the oldest railing, which is no longer visible. The white line represents a railing that's likely to fall off the cliff face in the coming years, with parts already losing support due to localized cliff failure. The most recent railing (marked in red) is placed two meters behind the edge railing (white), acting as a visual indicator of the ongoing and progressive erosion of the cliff.

Figure.57(Protection rail cliff face)

The presence of pistol-butted trees is a discernible manifestation of slope creep phenomena. Slope creep, a type of gravitational soil movement, occurs at a glacial pace due to the shearing stress exceeding the soil's shear strength. As the geotechnical processes gradually displace the soil downslope, arboreal entities exhibit adaptive growth patterns to maintain orthotropic tendencies, leading to the characteristic bent or pistol-butted morphology at their bases. This morphological adaptation serves as an empirical indicator for geotechnicians in evaluating slope stability and the extent of creep deformation in geomorphological and geotechnical investigations. [28]

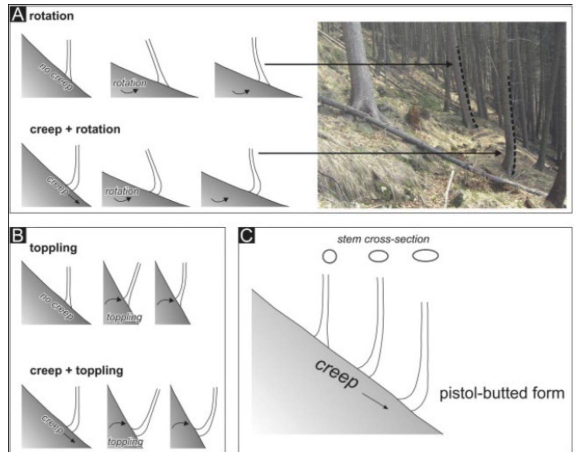


Figure.58(Tree deformation as an indication to slope movement) [28]

Figure.59 (Tree deformation seen on the debris slope)

The debris slope at the foot of the high cliffs is covered with threes. Most of the trees take on the pistole-butted form; a visual indication of the sliding and rotation effect of the slope. Attributed, to the imbalance of the stabilizing and destabilizing forces, as discussed in section (6. B.v Force balance).

Figure.60(Loess cliff face close)

In the above three images (Figure. 61) the weathered surface of the cliff can be seen. There are larger pieces of delamination that can be found. Furthermore, veins of eroded/washed-away material can be seen covering large flat parts of the cliff face. Large cracks between the delaminated bodies of loess can be noticed. This is most likely due to freeze-thaw cycles and the expansive and contractive nature of the soil due to the clay content. The material was crumbly and easy to scrape off within the first 1.5 cm. However, behind the weathered surface, the loess is very dense, hard, and uniform.

Figure.61 (Loess cliff face)

In the above image, we can see the vertical loess cliff face. The part starting from the base of the support fence can be considered as the debris slope. The cliff in parts has been reinforced by geo-mats, however, these are sparse and in bad condition. Channels of water runoff can be seen. In many locations, there are roots and vegetation present, which can increase the local stability of the wall. Visually the soil mass seems to be very uniform, it was difficult to identify any layering. This can be due to the high degree of weather that the loess face has experienced.

7. Results

7.1. Laboratory results

Water content

Three samples of soil were tested. The average of the moisture content can be seen above (0.79 %). The soils are very dry, and almost no moisture is present. This level of dryness could be a result of the sample being on the outermost of the cliff. The moisture content can reflect that the sample was harvested after weeks of prolonged summer dryness. The potential this could artificially increase the strength parameter of the loess. The values obtained are only specifically valid for the outermost part of the loess wall.

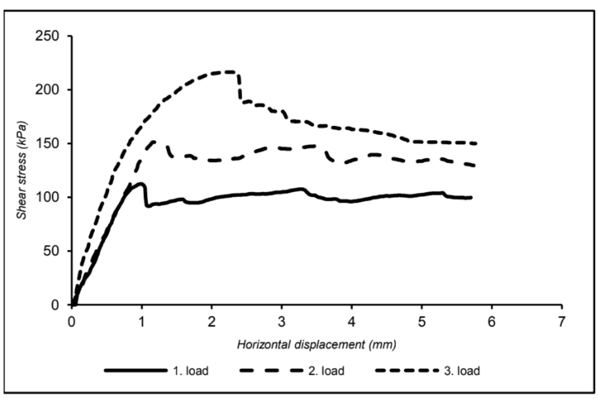
container No	Empty wieght(g)	container+moist soil (g)	container+dry soil (g)	Water content %	Average water conent %
35	54.77	161.32	160.5	0.77556039	0.798564583
72	53.88	159.18	158.48	0.669216061	
67	54.1	159.2	158.21	0.950917299	

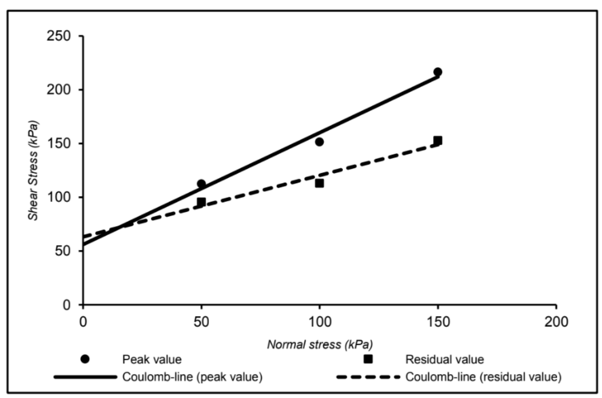
Unsaturated Unit weight (kN/m^3)	18.34
Saturated Unit weight (kN/m^3)	19.21

Shear-box test

Undisturbed sample

For the three loads, as they increase from 50 kPa (1. load) to 100 kPa (2. load) to 150 kPa (3. load), the peak shear stress also increases. This is expected; as the confining pressure or normal stress increases, the shear stress required to cause sliding also increases. The sharpest increase and highest peak is observed for the third load (thickest dashed line), followed by the second load (medium dashed line), and then the first load (solid line). This suggests that the soil consolidates or compacts more under higher loads, increasing its resistance to shearing. Peak Angle of Internal Friction is 46°: This value is relatively high, suggesting the sample has good resistance against shearing. This value is significantly higher than expected from literature values of similar soils in Balatonakarattya. Residual Angle of Internal Friction angle of 30°: A drop from the peak value, but still significant. This indicates that even after some particle realignment, the soil maintains a reasonable resistance to shear. The increase in residual cohesion could mean testing inaccuracies**.**

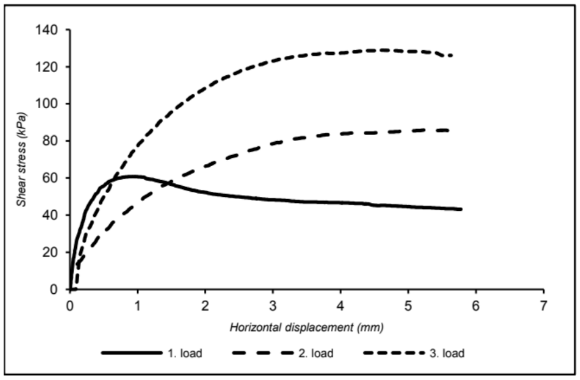


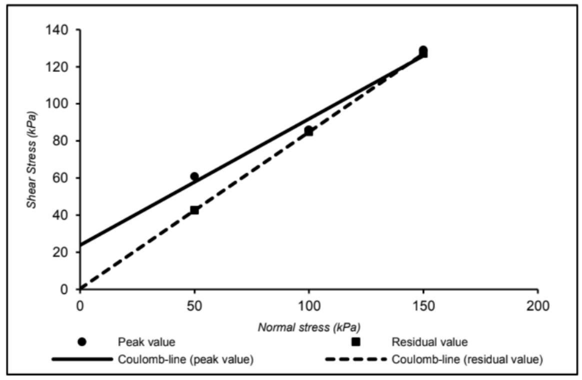


SHEAR STRENGTH PARAMETERS			
	PEAK VALUE	f' 46,0 °	c' 56,0 kPa
	RESIDUAL (END) VALUE	f'_r 30,0 °	c_r' 63,1 kPa

Artificially compacted sample

The Peak Angle of Internal Friction is 34°: A relatively moderate value indicating decent resistance against shearing. The residual Angle of Internal Friction is 40°: An increase from the peak value, which is uncommon. This suggests that post-sliding or at larger deformations, the soil might be realigned in a manner that offers more frictional resistance. Residual Cohesion is 0.4 kPa: A drastic reduction from the peak value. This shows that after significant shearing, the soil loses almost all its cohesive strength. Otherwise, it can also be a sign of inadequate compaction and testing errors. Overall, for the artificially compacted sample, we can see a drastic reduction in shear strength parameters compared to the natural state.



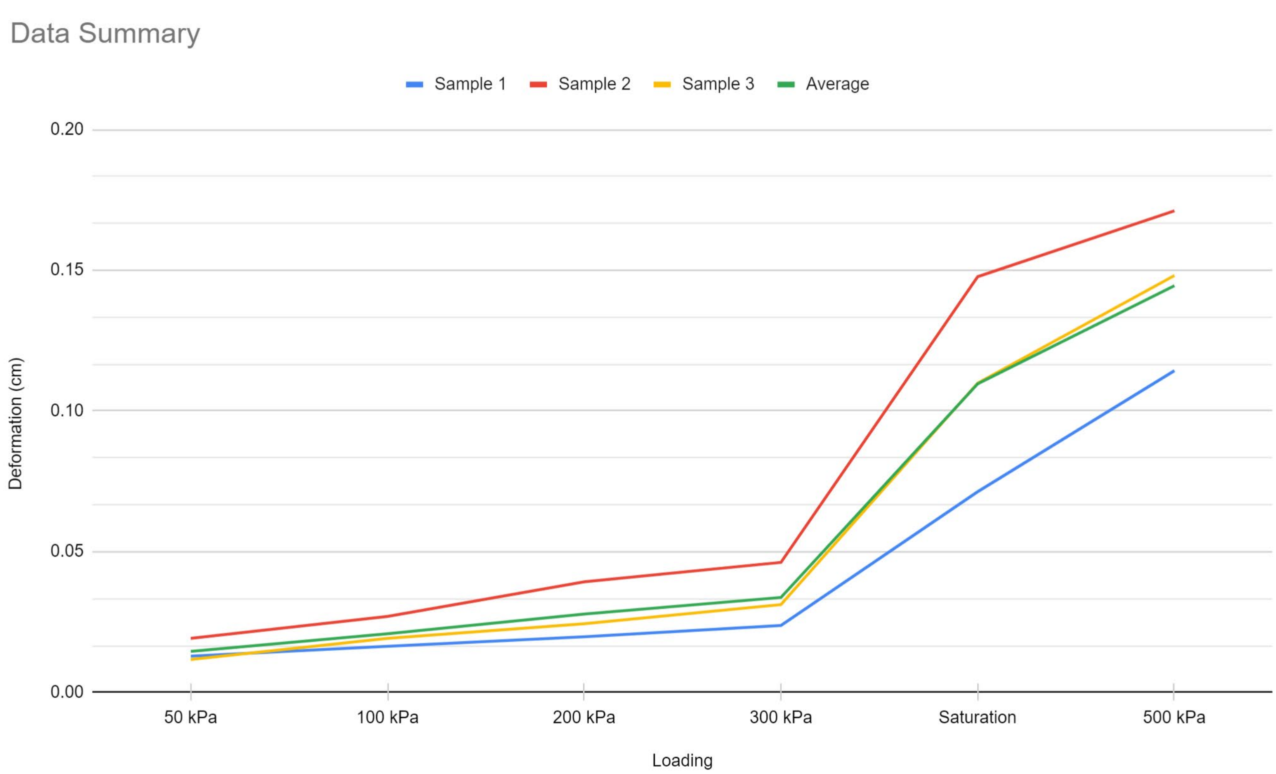


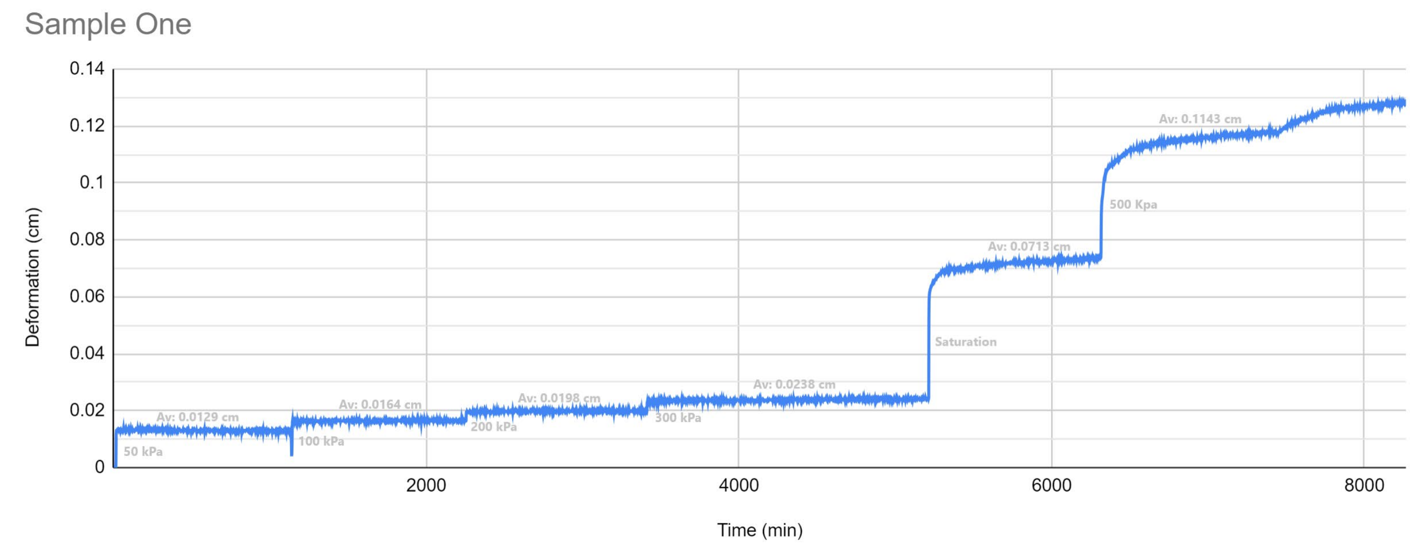
SHEAR STRENGTH PARAMETERS	**PEAK VALUE**	**f' 34,0 °**	**c' 23,8 kPa**
	RESIDUAL (END) VALUE	**f'_r 40,0 °**	**c_r' 0,4 kPa**

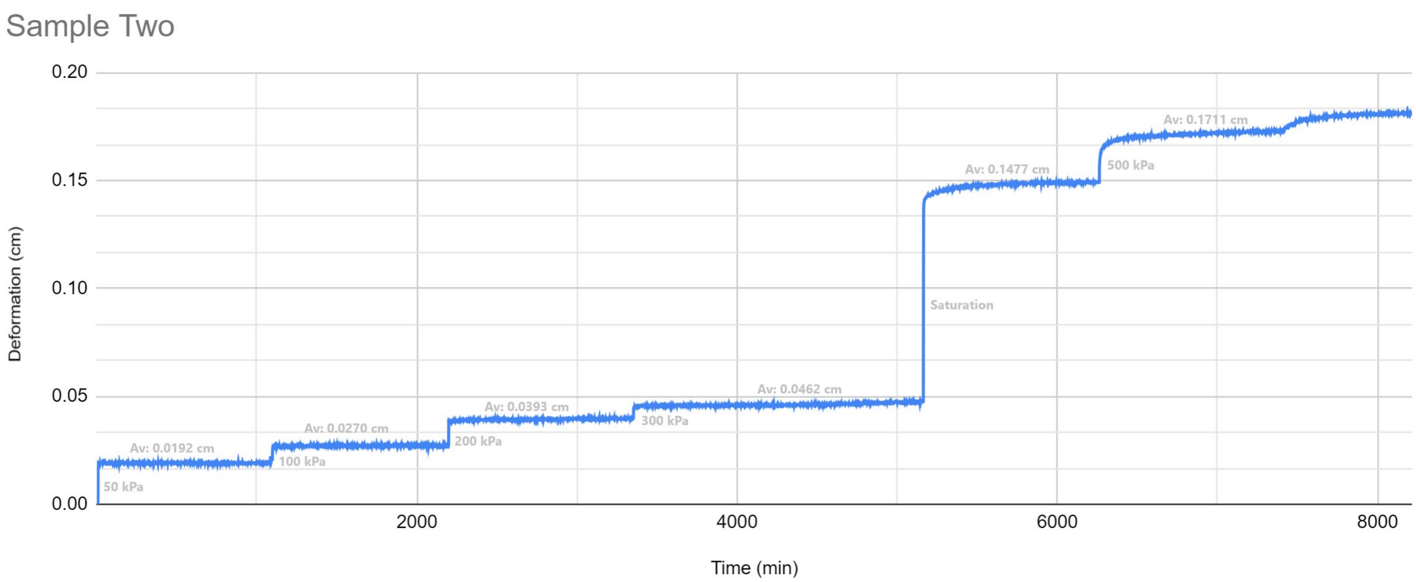
Oedometer test

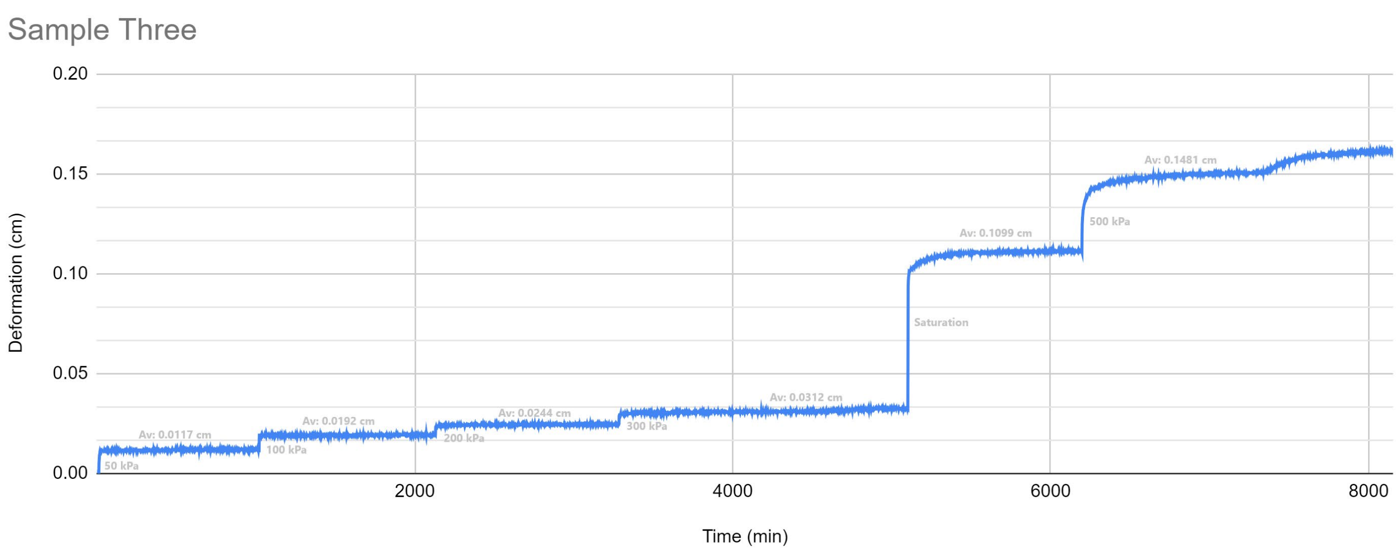
Loess soils, though demonstrating substantial initial strength, exhibit a metastable nature. When subjected to moisture, the intergranular bonds are compromised, especially in loesses with a lower clay content. This degradation process is notably accelerated in these cases, whereas in loess with heightened clay content, the destabilization phase is protracted.

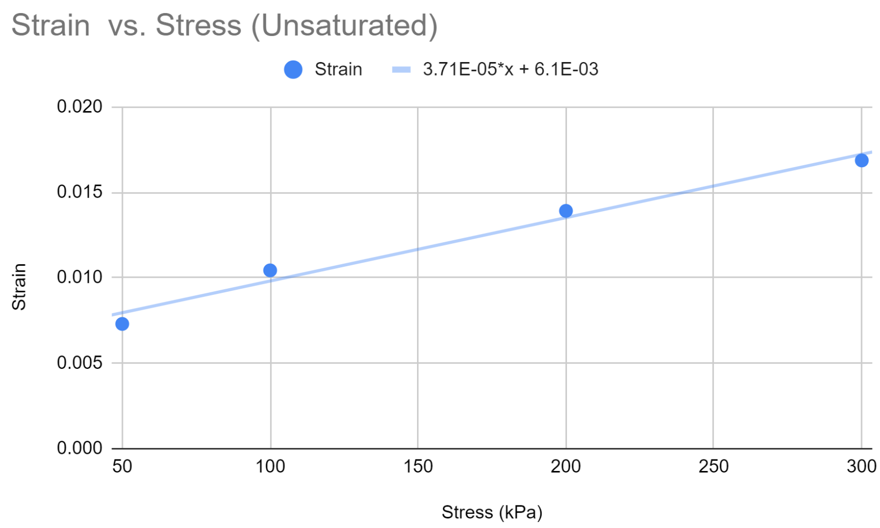
This susceptibility to rapid moisture-induced weakening might shed light on the localized failures, particularly near the cliff edge. The phenomenon can be attributed to rainwater permeating the loess on the edge, leading to a sudden loss in strength and subsequent failures. Such incidents are observed only at the cliff ridge in Balatonföldvár due to the absence of internal springs or groundwater sources within the loess strata. Moreover, the region's hydrological patterns generally divert rainwater runoff away from the cliffs, safeguarding the majority of the terrain.




Sample One
Deformation (cm)
Time (min)
0
0.02
0.04
0.06
0.08
0.1
0.12
0.14
2000
4000
6000
8000
50 kPa
Av: 0.0129 cm
100 kPa
Av: 0.0164 cm
200 kPa
Av: 0.0198 cm
300 kPa
Av: 0.0238 cm
Saturation
Av: 0.0713 cm
500 Kpa
Av: 0.1143 cm


Sample Two
Deformation (cm)
Time (min)
0.00
0.05
0.10
0.15
0.20
2000
4000
6000
8000
50 kPa
Av: 0.0192 cm
100 kPa
Av: 0.0270 cm
200 kPa
Av: 0.0393 cm
300 kPa
Av: 0.0462 cm
Saturation
Av: 0.1477 cm
500 kPa
Av: 0.1711 cm


Sample Three
Deformation (cm)
Time (min)
0.00
0.05
0.10
0.15
0.20
2000
4000
6000
8000
50 kPa
Av: 0.0117 cm
100 kPa
Av: 0.0192 cm
200 kPa
Av: 0.0244 cm
300 kPa
Av: 0.0312 cm
Saturation
Av: 0.1099 cm
500 kPa
Av: 0.1481 cm



Stress	Sample 1 (mm)	Sample 2 (mm)	Sample 3 (mm)	Average deformation (cm	Strain
50 kPa	0.0129	0.0192	0.0117	0.0146	0.0073
100 kPa	0.0164	0.027	0.0192	0.02086666667	0.01043333333
200 kPa	0.0198	0.0393	0.0244	0.02783333333	0.01391666667
300 kPa	0.0238	0.0462	0.0312	0.03373333333	0.01686666667
Saturation	0.0713	0.1477	0.1099	0.1096333333	0.05481666667
500 kPa	0.1143	0.1711	0.1481	0.1445	0.07225

Slope of trendline: $m := 0.0000371\ kPa^{-1}$

Eodometric modulus: $E := \frac{1}{m} = 26.954\ MPa$

Test result data summarization

The Balatonföldvár loess shows considerable strength properties as compared to the uppermost sandy layer found in Balatonakarattya. The table with the Balatonakarattya soil data can be seen below. Specifically, the cohesion 56 kPa, the internal friction angle 46 (degrees), and the oedometric modulus 27 MPa are significantly higher. These results can explain the different physical appearance of the cliffs. Balatonföldvár the high cliffs have a shear face with an almost vertical edge. The transition from the vertical face to the top of the cliff is almost a 90-degree angle. The cliffs found in Balatonakarattya on the other hand have a much shallower slope and are not nearly as vertical.

Oedometric modulus (E) MPa	27
Internal friction angle (deg)	46
Cohesion (c) kPa	56
Unsaturated unit weight of soil (kN/m^3)	18
Saturated unit weight of soil (kN/m^3)	19

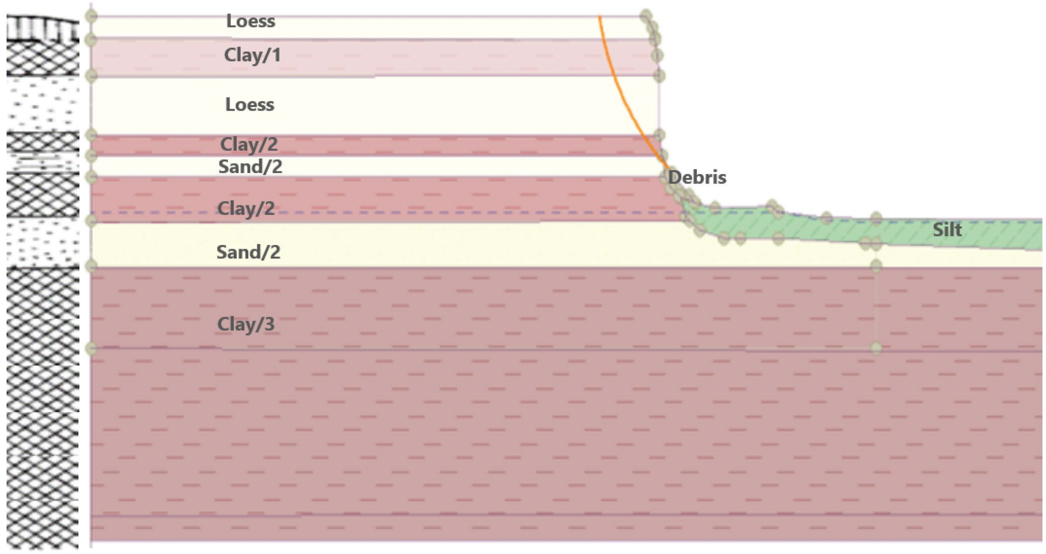
Laboratory test results from sample MK2 Balatonföldvár loess

	γ_{unsat} [kN/m^3]	γ_{sat} [kN/m^3]	E [Mpa]	ν [-]	c [kPa]	φ [°]
Sand/1	18	19	15	0,35	12	26

Literature soil results for the upmost sand layer in Balatonakarattya

7.2. Modelling using literature data (Model 1)

The geometry of model one and layer orders are formed from the literature cross section found in “*A balatonföldvári és a fonyódi magaspartok állékonyságának mérnökgeológiai vizsgálata*” writen by Horváth Zsolt and Dr. Scheuer Gyula. The soil parameters are taken from the laboratory testing results of the loess and the values for the deeper layers are taken from literature.



Method	Factor of safety
Bishop	0.89
Fellnius/Petterson	1.01
Spencer	1.01
Janbu	0.98
Morgenstern-Price	0.98

The image showing the modeled slope is shown above, along with the model we can see the literature layer order that was used for modeling. The slip surface that was identified by the limit equilibrium methods implemented can be seen.

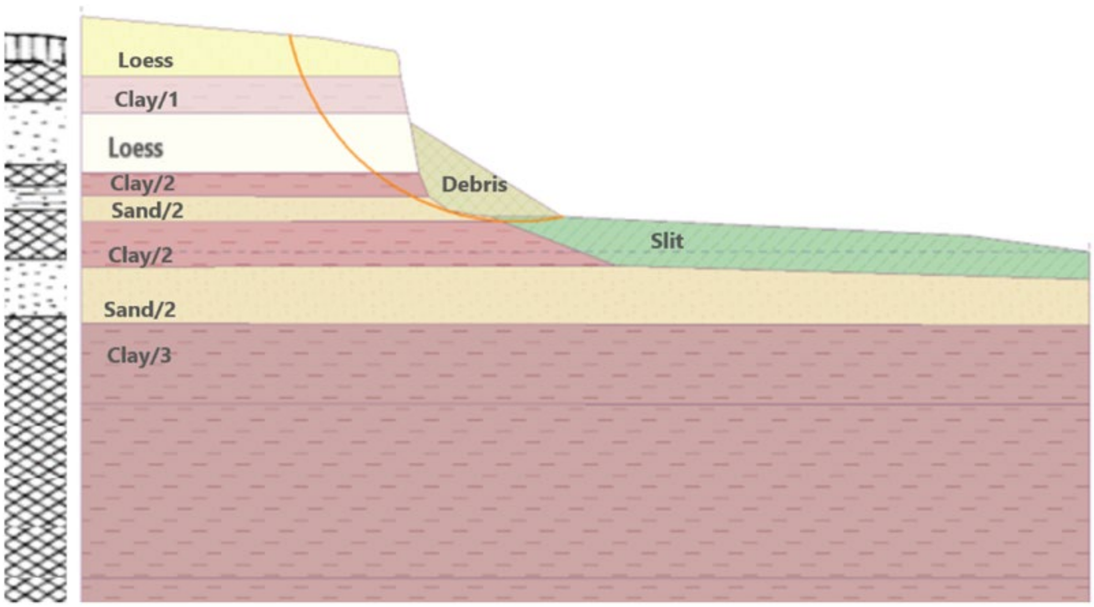
In this case, the model does not reach the required safety factor of 1.35 according to MSZ EN 1997 (Eurocode 7). However, with a safety factor of 1, the slope can stand. Furthermore, only the Bishop method found a safety factor value significantly less than one. This can be attributed to the Bishop method neglecting interslice shear forces; being a key element of stability at the edge of the cliff, this can create failure.

The model illustrated that the edge of the cliff is on the verge of failure while global stability is maintained, accurately representing the frequent small-scale failures that occur on the cliff edge in this zone.

7.3. Modelling using laboratory test data and geometry from references (Model 2)

Model two has geometry obtained by the laser measurement of the site.

The soil layer applied is obatianed from "*A Balatonföldvári és a Fonyódi magaspartok állékonyságának mérnökgeológiai vizsgálata*" writen by Horváth Zsolt and Dr. Scheuer Gyula. The soil parameters are taken from the laboratory testing results of the loess and the values for the deeper layers are taken from literature.



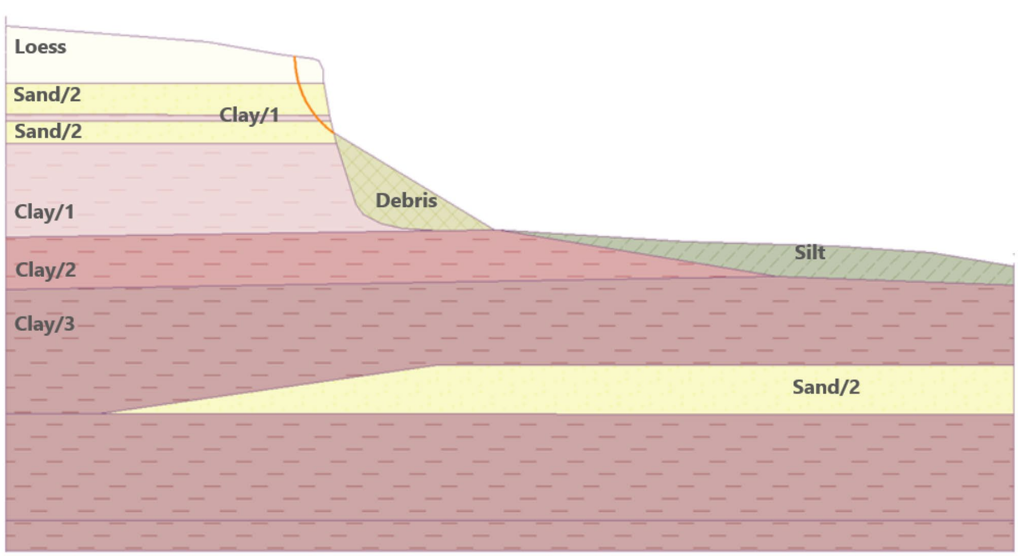
Method	Factor of safety
Bishop	1.2
Fellnius/Petterson	1.14
Spencer	1.22
Janbu	1.24
Morgenstern-Price	1.24

The critical condition no longer appeared as a local failure at the edge of the cliff but as a global failure within the sand layer. Applying the optimization check for all within an all-encompassing slip surface, the factor of safety failed the required safety factor of 1.35 according to MSZ EN 1997 (Eurocode 7).

7.4. Modelling using laboratory test data and slope geometry of own measurement (Model 3)

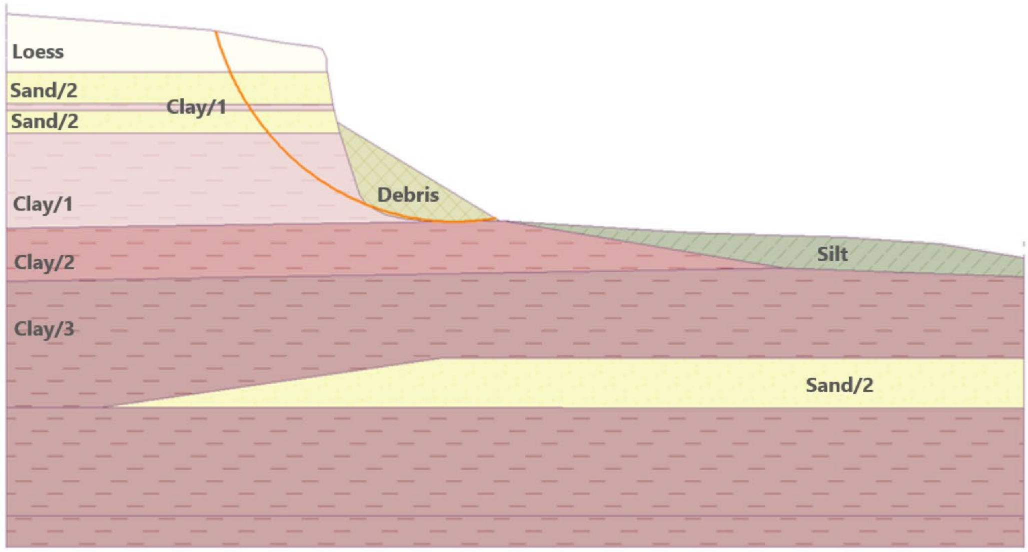
The geometry of model three was created by laser measurement of the site (same as model two), however, the layer order obtained in this model is created by the analysis of three boreholes that are in the vicinity of the site.

In the following models, we can see the failure surface occurred for both local and global failure scenarios. Furthermore, we



Method	Factor of safety
Bishop	0.85

In the model seen above, the local failure of the cliff through the weakest sand layer (Sand/2) is determined by the Bishop method. Perhaps the reason for this is that interslice shear forces are neglected. Shear forces at the edge of the cliff have a significant role in stability control, this could be the reason why the weaker Sand/2 layer is effectively sliding down the more solid Debris layer. It is furthermore important to note that with a safety factor of 0.85, the cliff should effectively fail, however does not match reality. In the following section, the analysis methods perhaps more closely reflect reality.



Method	Factor of safety
Fellnius/Petterson	1.18
Spencer	1.24
Janbu	1.26
Morgenstern-Price	1.26

The following analysis method has yielded a global failure of the cliff through the base. This is more realistic as interslice shear forces are considered in this method. Meaning that the shear forces are effectively able to hold the composure of the vertical cliff edge. This also matches the real-world situation as the cliff is standing, matching the obtained safety factors. Furthermore, the safety factors are less than the required safety factor of 1.35 according to MSZ EN 1997 (Eurocode 7). However, with these safety factors, the stability of the cliff is still ensured.

8. Discussion

Limit equilibrium analysis was performed on three separate models. Model one layer order and geometry were obtained from literature, model two was a new section created by laser measurement and applying soil layer order obtained from literature, model three had the same geometry as in model two, however, the layer order was determined from boreholes in the vicinity. The soil parameters applied in the sections were based on the determined values from laboratory experiments and literature values.

The analysis indicated that the lowest safety factor of 0.85 was obtained from model three, suggesting local failure at the cliff edge (above the debris slope), as determined by the Bishop method. Other limit equilibrium methods indicated a global failure at the base of the cliff, but with significantly higher safety factors between 1.24 and 1.26. The average safety factor for model three was 1.18.

For model two, the safety factors ranged from 1.14 to 1.24. The larger loess layer within the cliff that intersects the top of the debris slope is significantly stronger than the Sand/2 layer found in model three. For this reason, local failure was not achieved, as compared to model three. Model two has an average safety factor of 1.17.

For model one, the average safety factor was lower, mainly because the vertical extent of the cliff is greater due to a smaller debris mound at its base. The safety factor ranged from 0.89 to 1.01, averaging 0.97. This theoretically implies that the cliff should collapse, a finding that aligns with observed local failures at the cliff edge.

The average safety factor across all models was 1.133, the safety factor does not meet the required 1.35 according to MSZ EN 1997 (Eurocode 7).

9. Conclusions

Throughout the TDK project, the Balaton high cliffs, and more specifically, the Balatonföldvár loess cliffs, have been thoroughly examined using a multifaceted approach. Initially, the formation and geological composition of the cliff were studied, followed by an analysis of the specific intrinsic properties of the Balatonföldvár loess cliffs. The investigation then proceeded to explore the soil characteristics inherent to the cliffs.

To provide a comprehensive review, the numerical methods used for stability verification were also detailed. The soil properties of most layers were derived from previous studies on the Balatonakarattya high cliffs. However, the uppermost loess layer in Balatonföldvár showed substantial differences from the properties reported in the literature. For this reason, new samples from the Balatonföldvár cliffs were collected, and laboratory tests were conducted to ascertain their exact properties.

The findings of the laboratory analysis show that the Balatonföldvár loess has considerably higher strength properties as compared to other high cliffs found in Balatonakarattya. the cohesion of 56 kPa, internal friction angle 46 (degrees), and the oedometric modulus 27 MPa. These results can explain the different physical appearance of the cliffs. Balatonföldvár the high cliffs have a shear face with an almost vertical edge. The transition from the vertical face to the top of the cliff is almost a 90-degree angle. The cliffs found in Balatonakarattya on the other hand have a much shallower slope and are not nearly as vertical.

Expert reports on the Balatonföldvár loess cliffs were thoroughly reviewed. The cross-sections analyzed were taken from the town's outskirts, where the cliffs pose no threat to urban development. Consequently, a new location and cross-section were selected at the steepest part of the cliffs, situated amidst a densely populated neighborhood.

The vertical and horizontal alignment of eight points on the cliff face was determined using a handheld laser distance meter. With the positions of these points and the known locations of the cliff's edge and base, a detailed site plan with contour lines was generated, allowing the geometry of the loess cliff section to be defined.

Limit equilibrium analysis was performed on three separate models using the Geo5 software. Model one layer order and geometry were obtained from literature, model two was a new section created by laser measurement and applying soil layer order obtained from literature, model three had the same geometry as in model two, however, the layer order was determined from boreholes in the vicinity. The soil parameters applied in the sections were based on the determined values from laboratory experiments and literature values.

The average safety factor across all models was 1.133, compared to the value of 1.45 found in the literature before the advent of computer modeling. These results lead to the conclusion that the modeling successfully assessed the slope conditions and confirmed the inadequacy of the slope stability, as the safety factor did not meet the required 1.35 according to MSZ EN 1997 (Eurocode 7).

Based on these conclusions, several recommendations are made. More borehole drilling should be performed near the analyzed cross-section. The soil obtained should undergo laboratory tests, and with these parameters, the cross-sectional geometries should be reanalyzed to provide a more accurate depiction of reality. Additionally, given the reduction in strength properties of the Balatonföldvár loess when wet, it is advised to study the surface water conditions and their interaction with the cliff's position, as wetting the loess could significantly lower the obtained safety factors.

Finally, considering the heavy urbanization around the Balatonföldvár high cliffs, plans should be made to reinforce and stabilize the cliffs to achieve the safety factor of 1.35 required by Eurocode 7.

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