Proceedings of the 9ICEG
9th International Congress on Environmental Geotechnics
25-28 June, 2023 | Chania, Greece

https://doi.org/10.53243/ICEG2023-449

Forensic Geotechnical, Hydrological and Hydrogeological Analysis of Instability Phenomena Occurred at a Waste Management Centre

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ABSTRACT

One part of what is generally called Environmental Geotechnics is related to natural hazards, such as landslides. But often, landslides are not 100% natural and a significant contribution to their occurrence is brought by man-made activities. The paper presents a complex geotechnical, hydrological, and hydrogeological forensic analysis for instability phenomena that occurred on the slopes of a Waste Management Centre (WMC). The ground in the WMC area is composed of marl deposits (Pannonian age) with sometimes small millimetric and sub millimetric sand formations with a general slope. Above the marl deposits there are quaternary deposits composed of clay, silty and sandy clay formation of 1 – 15 m thickness and of sand and gravel in clayey matrix unevenly distributed on the area, followed by silty and sandy clays. The geological, morphological, and topographical model along with the climatic characteristics of the area imposed the hydrological and runoff settings. The landslides were triggered by the civil works on site, corroborated to the natural settings and they have developed in several stages, for which various consolidation works have been carried out. Insufficient initial investigation has been performed, not adapted to the site's geotechnical and hydrogeological specific. The forensic analysis was meant to explain the phenomena that occurred on site and their cause, including the decision if the landslides were of an unpredictable nature. The study presents the results of the thorough forensic investigations, the developed geological, hydrogeological, and topographical models, measurements in unsaturated conditions, explains the phenomena occurred on site and the errors in the design, leading to the final conclusions and lessons learned.

Keywords: geotechnical analysis, hydrogeological and hydrological modelling, landslide

1 INTRODUCTION

In the framework of a Waste Management Centre (WMC) comprising a municipal landfill, a sorting and a mechanical – biological treatment stations and administrative area, located in a hilly region, several slopes had to be created in order to accommodate the designed works. Soon after the works started, local instability phenomena occurred in the man-made slopes related to the sorting and treatment stations area, which have been locally remediated first by geometrical methods (initially berms have been introduced, then slopes inclination has been reduced). The cause has been identified at that time as being the "unpredictable" groundwater presence, as the geotechnical investigation and the subsequent geotechnical design didn't take into consideration the groundwater. Several such instability phenomena occurred during the time, with several remediation methods, from the simplest ones (geometrical) to more complex ones including retaining walls supported by micro-piles and ground anchors, drainage works, monitoring etc. At each stage another technical expert was called to investigate and report, several studies have been carried out, most of them not being able to emphasize the hydrological particularities of the site and the real cause of the phenomena.

The case ended up in court of law, which asked for a forensic judicial analysis and established several objectives of this analysis, including origin of water infiltrations in the area, analysis of the stability of the ground, and, especially, to establish if the phenomena were unpredictable. After studying all documents, studies, projects etc. it was clear that the existing investigations, especially regarding groundwater, were insufficient and also that the geotechnical design was poor. Therefore, in the framework of the forensic analysis, has been required to conduct a complex geotechnical, hydrological, and hydrogeological investigation and numerical modelling, including also unsaturated measurements. This has been completed with slope stability analyses. Even though the instability phenomena themselves were not complex and without very important consequence, except the cost of the many remedial works, the forensic analysis revealed a complex setting of the area, lack of proper investigation and geotechnical design, which also led eventually to consequences in terms of national technical regulations. The paper presents the results of geotechnical, hydrological, and hydrogeological analysis, and also the results of the slope stability analysis, along with the final conclusion of the case. Here below are presented some photos of the site.

Figure 1. *Local instability phenomena and (at right) initial remediation (berms)*

Figure 2. *Final works, including drainage, mechanical consolidation works, hydrological measures; at right signs of ongoing instability*

2 CASE STUDY

2.1 Geological, hydrogeological, and hydrological settings

The study area is situated in the SE area of the Transylvanian Depression (central part of Romania – Figure 3), towards its contact with the Apuseni Mountains. This behaves as a depression represented by deposits belonging to the Neozoic era (*Paleogene, Neogene, and Quaternary*) which rest on a foundation of crystalline schists. From a geologically point of view, on the Aiud-Teiuș-Sântimbru alignment, the formations belonging to the Upper Neogene (*Volhinian-Bessarabian* and *Pannonian*) and the Quaternary (*Pleistocene* and *Holocene*) are representative for this case study. Starting from the basal part of the *Neogene*, an intense subsequent magmatic activity occurred within the Metaliferi Mountains, which unfolded in three cycles. The first cycle is represented at the *Tortonian* level (lower Neogene) by successive deposits of rhyolites and andesites. The second cycle is represented by volcanic tuffs, quartz ferrous diorites, and dacites, and occurred in the *Volhinian-Bessarabian*. The last cycle of volcanic activity occurred in the Pannonian and is represented by pyroxene andesites and basalts.

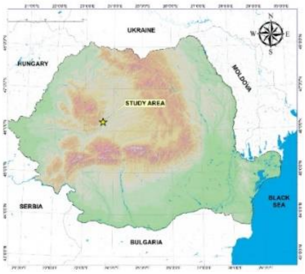


Figure 3. *Study area location*

The WMC site is located on the Western flank of a syncline whose axis is oriented on the alignment of the localities Aiud-Teiuș-Berghin. If the isobaths are taken as a reference at the base of the Tortonian, the inclination of the Western flank in the site area should be 6-8 degrees towards NE. The age of the investigated sedimentary deposits is post-Pannonian (Pleistocene) when the waters that occupied the Transylvanian Depression retreated with the onset of the glacial period. As a result of a warmer climate, the Mureș River begins to form its course and to deposit coarse materials that can be observed in the current terraces. The base rock is represented by Pannonian marls, with a general inclination from SW to NE (towards Dăneț stream), the inclination being approximately on the same direction as the natural terrain. These rocks have a greyish colour, are weakly stratified, with or without sub-millimeter sand films. Above these, there are Quaternary deposits which, from a genetic point of view, are represented by: deluvium, proluvium and alluvium deposits.

The studied area is in the hydrographic basin of the Mureș River. From a morphological point of view, the location belongs to the hydrographic basin of the Dăneț stream. The hydrographic basin of the Dăneț stream upstream of the WMC has an area of 4.61 km^2. The maximum altitude of the hydrographic basin is 430 meters above sea level, while the minimum is 270 meters. Therefore, the hydrographic basin has a relief energy of approximately 160 meters. The high relief energy highlights the young character of the hydrographic network. The maximum slope value within the basin is 19^0 and it is in the areas connecting the formed terraces and the interfluve zone.

A proper aquifer consisting of porous permeable non-cohesive material has not been identified in the study area. The only non-cohesive lithologic type identified is represented by the gravel with sand from the outside limit of the waste deposit, which has a lenticular shape, with a narrow width estimated at 150-170 m, surrounded by sand with gravel in a clayey mass and limited in roof and bedding by clayey rocks. This material could constitute a reservoir rock, but without a significant contribution to the groundwater dynamics reported for the entire studied perimeter.

2.2 In-situ investigation

In the area of the site a series of in-situ investigations were conducted (geological and hydrogeological drilling and piezometric wells installation, geological and morphological mapping, infiltration and hydraulic testing, topographical measurements, geophysical investigations, flow and river measurements). There were a total number of 4 terrain investigation campaigns.

Hydrological mapping was carried out during field campaigns through direct measurements of the hydrostatic levels and flow rates, the physical and chemical parameters of the water in boreholes or surface water. The geomorphological mapping was carried out throughout the studied area (the right bank of the Dăneț stream up to the watershed towards the Galda valley). Thus, the current dynamics of the relief and geomorphological processes such as (1) cracks and drying fissures (Figure 4), (2) detachment surfaces, (3) gully erosion and ravine processes were identified.

Figure 4. *Drying cracks (left in the plateau area upstream of the site)*

To quantify the hydraulic characteristics of the area, a series of tests and measurements were carried out in boreholes and in the field. Hydrogeological tests were conducted using the recovery method. Water from wells was pumped out, and subsequently the recovery of the piezometric level was measured using an automatic pressure transducer. The hydraulic tests consisted of evaluating infiltration coefficients in the unsaturated zone at various locations upstream of the WMC area. The tests were performed using the Single Ring Infiltrometer Method. During the field campaigns, a total of 13 tests were carried out.

Within the site, a total of 11 electrical resistivity tomography (ERT) investigation profiles were conducted. The total profile length was approximately 2500 m. During the data acquisition phase for electric resistivity, the SYSCAL Pro Resistivity and IP device, produced by IRIS INSTRUMENTS, was used. The primary data was filtered to eliminate systematic errors using the ProSYS2 program, and subsequently the filtered data was modelled in the RES2INV program and the ERT-Lab1 program (Figure 5).

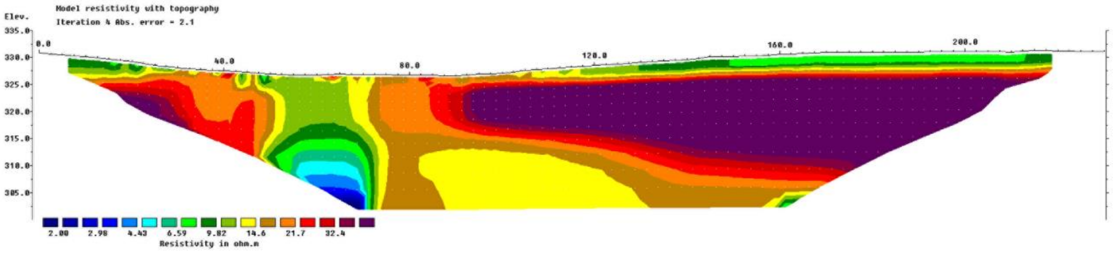


Figure 5. *Inverse Model Resistivity Section*

Along with the in-situ measurements a serios of geotechnical tests were carried out on 52 soil samples in the Technical University of Civil Engineering Geotechnical Laboratory.

2.3 Hydrogeological monitoring

5 hydrogeological wells were monitored during a period of 90 days (autumn – winter time). The groundwater level and temperature were monitored using automated pressure and temperature data loggers (Figure 6).

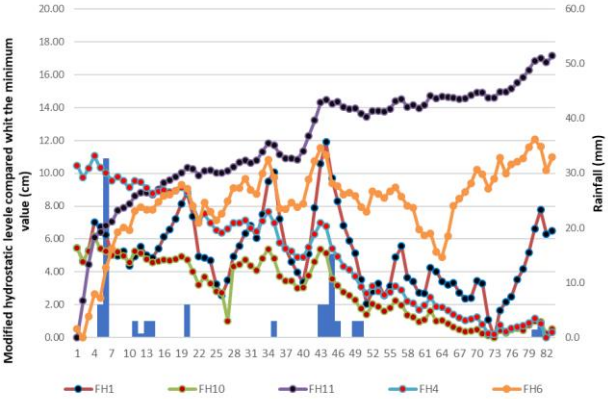


Figure 6. *Groundwater monitoring data*

3 METHODS AND APPROACH FOR HYDROGEOLOGICAL ANALYSIS

Along with the in-situ investigation, a series of models were developed to simulate the physical behaviour of water (surface and groundwater) within the study area. The first developed model was a morphological and topographical model (digital terrain model - DTM) based on direct differential GPS measurements and morphological mapping (visible landslides, cracks, etc.). The geological 3D model was developed using the DTM, the lithological information gathered from new drilled and older boreholes, and geophysical data gathered during the ERT tomography profiles investigation. Based on the DTM, the hydrological flow measurements, land cover classes and climatological data a runoff complex model was developed using the HEC-HMS software package. The final model combined findings from all previous models and developed the groundwater flow model using also the hydraulic in-situ data (pumping hydraulic tests, groundwater head measurements, infiltration hydraulic tests). The hydrogeological model was developed in 2 stages: (1) a first general model developed on a certain time stamp (the period of in-situ investigation) in steady conditions and (2) an unsteady hydrogeological model to simulate the groundwater flow under different scenarios.

3.1 Geological model

The geological model (Figure 7) has a rectangular shape, with the SW boundary set at a sufficient distance from the upstream limit of the WMC. Therefore, drainage works don't influence the boundary condition of hydraulic head imposed, as specified boundary condition within the hydrogeological model. The characteristics of the model are: (1) length L = 1352.245 m and width l = 646.961 m; (2) maximum ground elevation Z_{max} = 350 m. The minimum elevation of the model was set 5.70 m below the minimum elevation of the marl deposits determined by the study drillings, namely Z_{min} = 255 m.

Five layers were considered, from top to bottom: (1) L1-topsoil, (2) L2-silty clay, yellowish silty clay, yellowish-brown or greyish-brown, (3) L3-gravel with sand, with or without boulders in clay matrix, (4) L4-silty marl clay, yellowish-brown or greyish-brown silty clay marl and (5) L5-gray marl.

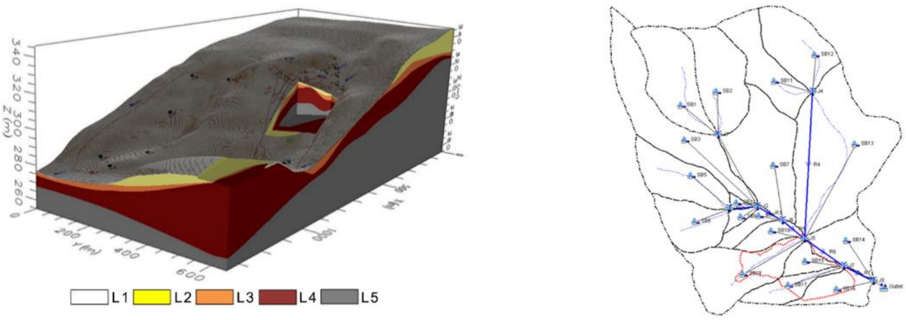


Figure 7. *Geological 3D Model (left) and hydrological model scheme (right – with red line is the delineation of the WMC).*

3.2 Hydrological model

To achieve a more relevant analysis of the hydrological regime of the analysed watershed, a hydrological modelling (rainfall-runoff) was carried out using the HEC-HMS software package. The hydrological model (Figure 7) was based on the hydrological schematization of the relevant sub-watersheds, and the quantification of climatic, morphometric, and hydrological parameters. Thus, the model considered: (a) The average slope of each sub-watershed; (b) Land use and soil type; (c) Surface runoff parameters (Soil Conservation Service method, Curve Number); (d) Base flow; (e) Precipitation. The watershed was divided into 18 sub-watersheds of different sizes based on surface runoff accumulation. Their delimitation was performed in a GIS environment. A total of 18 sub-watersheds were obtained, with areas ranging from 0.8 km² to 0.01 km².

3.3 Hydrogeological model

The purpose of the assessment of initial hydrogeological conditions is to specify the spatial distribution of hydraulic head within the flow domain at a given reference time, in the absence of any hydrodynamic disturbance. The results obtained from the steady-state flow simulation represent the initial hydrodynamic conditions for simulating the effect of perturbing agents, in this case the drainage system. The general characteristics of the steady state hydrogeological model are: (1) the surface of the hydrogeological model coincides with that of the geological model, (2) since the values of hydraulic conductivity characterize several lithological horizons that share the clay-loam character, the five horizons in the geological model (L1...L5) were reduced to a single horizon (L1); (3) the starting value for hydraulic conductivity is the one resulting from the average of the measurements in the hydrogeological wells $k_x=k_y=k_z=k=0.02245$ m/day; (4) the average total porosity of the deposits (according to the granulometric curves) is n=0.55; (5) the effective porosity was considered equal to the specific yield coefficient $n_e=S_y=0.0605$; (6) the cells on the left bank of the Dăneț stream were considered inactive, as they don't have a significant contribution to the dynamics of groundwater in the opposite slope; (7) due to the presence of contraction fissures on the ground surface, many with centimetre-sized openings and development in depth, the aquitard hydro-structure was considered with a free water level. The second hydrogeological model was developed using the findings from the previous steady-state model. The values resulting from the steady-state modelling are quantitative and represent the initial situation (prior to excavation and drainage works). To highlight the evolution of the system at certain time intervals, in relation to the initial situation, a simulation was carried out in unsteady state. The duration of the simulation was set at 720 days, considering this time interval to be sufficient for the system to tend towards equilibrium and would approximately correspond to the period between the completion of the drains and the final values entered in the model.

Figure 8 below presents the 3D representation of the groundwater level in the area, while Figure 9 shows the groundwater after drawdown.

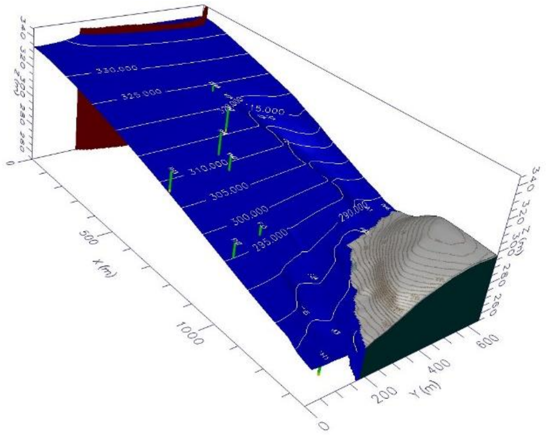
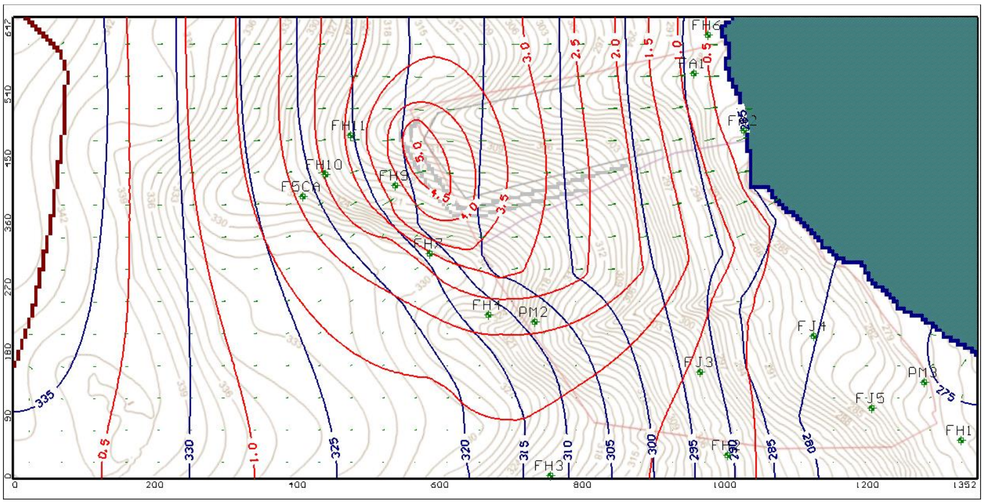


Figure 8. 3D representation of the groundwater table



Groundwater table

Drawdown;

Figure 9. Groundwater morphology influenced by the drain system

3.4 Results and discussions

The hydrological model confirmed the field measurements. The average annual flow rate of the receiving WMC basin ranges between 0.5-1 l/s. During dry periods, the flow rate drops below 0.5 l/s. At the basin level of the Dăneț stream, the same variability of flow rates is observed, ranging from values below 0.1 l/s during dry periods to 1.8 m^3/s during rainy periods.

At the surface, the clay material is affected by drying cracks oriented approximately parallel to the contour lines, with millimetric and centimetric openings. It has been observed that after periods of precipitation, these cracks close due to clay swelling as it becomes saturated.

Except for the upper horizon of yellow clays, groundwater was identified in all lithological types of clay or marl nature at the bottom, which is why they were included in a single hydro structure when defining the hydrogeological model.

The hydraulic conductivity values and active porosity do not indicate a classic aquifer hydro structure that stores and releases water easily, with obvious and observable dynamics in wells or other types of investigation works during their execution. The sand and gravel lens found upstream of the waste deposit have the role of accumulating water over time, but not of rapid release, being surrounded by rocks with low hydraulic conductivity. The hydro structure in the analysed area is an aquitard type, meaning a structure that stores water which is released rather slowly, over a long period of time. Sometimes, the release phenomenon may not be noticed in the form of groundwater appearing in short duration drilling works.

From the hydrogeological model in steady state, before the landfill was built (initial situation), it results that the recharge of the hydro structure in the area is mainly through groundwater flow from upstream to downstream (88.34 m^3/day). The vertical recharge from rainwater is low (3.99 m^3/day) due to the high slope of the ground. However, it is possible that in the case of high intensity rainfall events occurring after a long dry period, this recharge rate may increase through water infiltration into the contraction cracks until these are close.

The characteristics of the aquitard structure indicate a slow dynamic of the hydro structure and explain why the water hasn't been found in the previously executed geotechnical boreholes over a short period of time, leading to the wrong conclusion regarding the existence of groundwater. Most of the time, in such hydro-structures (especially in those with an active porosity lower by about one order of magnitude than that of the clayey rocks, as is the case here), it is difficult, if not impossible, to highlight the existence of groundwater in the absence of an adequate number of monitoring wells covering a representative area and in the absence of hydrogeological monitoring over a long period of time.

4 GEOTECHNICAL ANALYSIS

4.1 Analysis of causes of instability phenomena

From a technical point of view, the forensic analysis showed that the landslides occurred have been produced due to a cumulative effect of natural and anthropogenic aspects:

Site lithology: an upper layer (deluvium) composed of swelling clays, laying over the bedrock composed of marls; this lithology is leading to upper layer slipping over the one below, at their contact, when water infiltrates to the area, softening the interface in between.
Groundwater presence: this is influencing both by increasing the water pressure in the fissures and by reducing shear strength of the clays. The water infiltrated in the soil is drained very slowly due to low hydraulic conductivity and to slow-dynamics hydro-structure.
Excavations: the earthworks performed on site created a drainage path for the water accumulated in the ground, which outflowed and ran off and through the slope;
Swelling clays: these led to contraction fissures in the ground, through which rainwater could infiltrate;
Slope inclination: designed slopes were too steep with regard to above mentioned soil and water conditions.

In this case, numerous site investigations have been conducted, with different complexities, all lacking to identify some aspects: 6 geotechnical studies (3 before and 3 after the landslides occurred), 1 hydrogeological investigation (but for water supply purpose). The complex final geotechnical, geomorphological, geological, hydrological and hydrogeological study conducted for the forensic analysis is presented Chapter 3. But: (1) None of the 3 geotechnical studies conducted before the landslides emphasized the stability problems of the site. Another geotechnical study carried out for the nearby landfill mentioned groundwater infiltrations, presence of swelling clays and noticed gullies on the site in SW – NE direction, up to 2 m depth, but this was not taken into consideration. (2) No stability analyses have been conducted prior to instability phenomena. The slopes didn't take into consideration the specific behaviour of swelling clays which imposes very low inclination of the slopes. The national regulation in force with this respect recommends slope inclinations of 1: 3 – 1:4, while the slopes on site were inclined 1:1.5 for 26 m maximum height, with no berms; (3) The studies that mentioned water infiltrations in the ground underlined the importance of a proper hydrogeological study and monitoring, but these were not followed (only after the phenomena occurred).

An additional geotechnical study, conducted after the first local instabilities occurred, included stability analyses, but using a horizontal lithology and no groundwater. Given the clayey nature of the ground, the good practice and the national design guidance according to Eurocode 7 impose to consider a saturation hypothesis. Also, the swelling clays presence requires to check the stability with reduced shear strength parameters due to possible contact with water.

The national technical norm on geotechnical investigation in force at that date had some provisions with regard to hydrogeological data, being requested to provide groundwater level and type of aquifer, the possible excess pore water pressure and hydrogeological cross sections. But, it also refers to EN 1997-2, where detailed provisions are included in 2.1.4 and 3.6. that cover all possible general situations.

Once the instability phenomena occurred, several consolidation measures were taken, based on reports of several experts and all these seems to be a kind of “trial-and-error” approach. Among the consolidation measures were included: Stage 1: less steep slope (1:2.5) including also berms (2 berms on the slope of max. 26 m height), drainage works in one corner of the site where water sources were identified, collection of runoff water on each berm, surface protection against erosion; Stage 2: sub-horizontal drainages and drainage trenches; discontinue, reinforced concrete, retaining walls founded on micropiles and anchored, with a “saw teeth” disposal (one section of the wall on one of the berm, the following section on the other berm at higher or lower level); monitoring; Stage 3: new interventions on the retaining walls as new instability phenomena occurred, new drainage works.

The monitoring performed on site after the instability occurred and after drainage and consolidation measures have been taken was mainly focused on displacements, and groundwater has been monitored using piezo – inclinometers, which haven’t the proper accuracy for groundwater measurements, especially in such environment (aquitard). Also, the lack of proper hydrogeological modelling led to a “chaos” in the data interpretation, no trend being correctly identified. As well, water management was poor on the site, not predicting that water accumulated upstream in the clayey soil will arrive downstream on the slopes and without proper initial measures provided against water runoff on slopes.

4.2 Stability analyses

The geotechnical design didn’t address the stability of the initial natural slope, before the works. Reconstituting the initial slope geometry and using the geological model previously developed and the geotechnical parameters determined in laboratory, we have performed stability analyses for the slopes with a groundwater level as shown previously chapter 3. These included a hypothesis for the total saturation of the ground and another one for reduced shear strength parameters due to swelling clays (30% of the peak values, as recommended by national norms). Analyses have been conducted with only characteristic values of geotechnical parameters (for the natural slope without constructions) and a seismic situation has also been considered. Slip surfaces were considered either circular or at the contact between the clay and the marl. Some of the results are shown in Table 1, proving that the initial

Table 1. *Results of stability analyses for the natural slope*

Case no.	**Description**	**Overall safety coefficient using characteristic values**		**ODF (over-design factor = F_s/ $F_{s\ allow}$**	
		static	**seismic**	**Static $F_{s\ allow} = 1.5$**	**Seismic $F_{s\ allow} = 1.1$**
Natural slope					
1	Circular slip, GWL as measured	3.77	2.05	2.50	1.86
2	Circular slip, GWL at GL	2.07	1.66	1.38	1.51
3	Polygonal slip at contact with the marl, GWL as measured	4.38	2.25	2.92	2.04
4	Polygonal slip at contact with the marl, GWL at GL	3.49	1.79	2.33	1.63
5	Circular slip, no GWL, shear strength parameters reduced at 30%	1.28	0.70	0.96	0.63

natural slope was stable in almost all situations, except the one with reduced shear parameters. But, one can notice that in case of a natural slope this hypothesis is not so relevant, as its surface is not exposed as in the case of a cut slope, being protected by vegetation. So, a first conclusion was that initial stability of the natural slope was ensured, including for seismic or saturation conditions, and that causes are related to the works and the errors committed at the design stage.

The results of the stability analyses performed for the man-made slopes (initial inclination 1:1.5) are shown Table 2. The initial design is not ensuring stable slopes and an inclination of 1:4 would have been required or to provide mechanical consolidation and drainage measures. More stability analyses have been performed for the situation after geometrical remodelling of the slopes (part of the slope with inclination 1:2.5), some of the results being also shown in Table 2.

Based on these results was concluded that even though the groundwater was the primarily cause of the instability phenomena and the design should have consider it, this has been superposed over basic design errors, as slopes were designed too steep and didn't consider the presence of swelling clays and that water can infiltrate through the contraction fissures, reducing drastically the shear strength parameters.

Table 2. *Results of stability analyses for the man-made slopes*

Case no.	**Description**	**Overall safety coefficient using characteristic values**		**Analysis according to EN 1997 (over-design factor) Approach 3 (ODF = F_s/ $F_{s\ prescribed}$)**	
		static	**seismic**	**Static $F_{s\ prescribed} = 1.35$**	**Seismic $F_{s\ prescribed} = 1$**
Slopes 1:1.5 without berms (initial design – Figure 10)					
1	Circular slip, no GWL (as designed)	2.33	1.89	1.33	1.43
2	Circular slip, GWL at GL	1.86	1.48	1.07	1.13
3	Circular slip, no GWL, shear strength parameters reduced at 30%	0.69	0.56	0.40	0.43
Slopes 1:1.5, without berms – another profile not considered in the design					
4	Circular slip, GWL as measured	1.52	1.23	0.87	0.95
5	Circular slip, GWL at GL	1.17	0.95	0.68	0.75
6	Circular slip, no GWL, with reduced shear strength parameters at 30%	0.54	0.44	No further reduction of parameters	No further reduction of parameters
Remodelled slope – (Figure 11)					
7	Circular slip, GWL as measured	2.41	1.77	1.38	1.37
8	Circular slip, GWL at GL	2.10	1.54	1.21	1.20
9	Circular slip, no GWL, reduced shear strength parameters at 30%	0.97	0.70	0.55	0.54

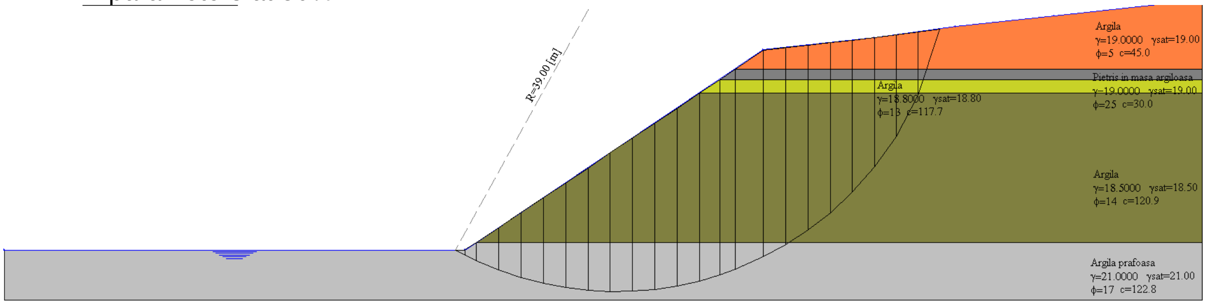


Figure 10. *Results of stability analyses for the initially designed cut slope 1:1.5, no berms, GWL at GL, static conditions, parameters as determined in the initial geotechnical report.*

Note: Clay (orange), Clayey gravel (grey), Clay (yellow), Clay (green), Silty clay (light grey)

The remodelling intervention of the slope (berms and partially less steep slopes) was not sufficient as the stability analyses show it and also what happened further on site. Therefore, were required more interventions, consisting of: 39 sub-horizontal drains for collecting groundwater infiltrations, 46 segments of reinforced concrete retaining walls each supported by 5 – 6 micro-piles and 3 – 4 pre-tensioned ground anchors, disposed in zigzag on the berms (at the lower and middle section of the slope). Despite these extensive consolidation measures the swelling characteristic of the soil has still not been considered and no detailed stability analyses performed. When analysing the consolidation measures through the stability analyses presented here-above it was concluded that in some sections the retaining walls were not properly disposed for intercepting the slip surfaces, leaving many areas of the upper part of the slope not covered. This has been confirmed by the monitoring of ground displacements showing that the movement is still active and that signs of continuing instability phenomena have been identified. The consolidation measures proved to be insufficient as the retaining walls were not continuous, they were not able to intercept in all sections the slipping surfaces and their effect was not checked using stability analyses, in fact their design being made as for a normal retaining structure, not for one supposed to stop a landslide. Drainage works have been poorly designed in absence of a proper hydrogeological investigation.

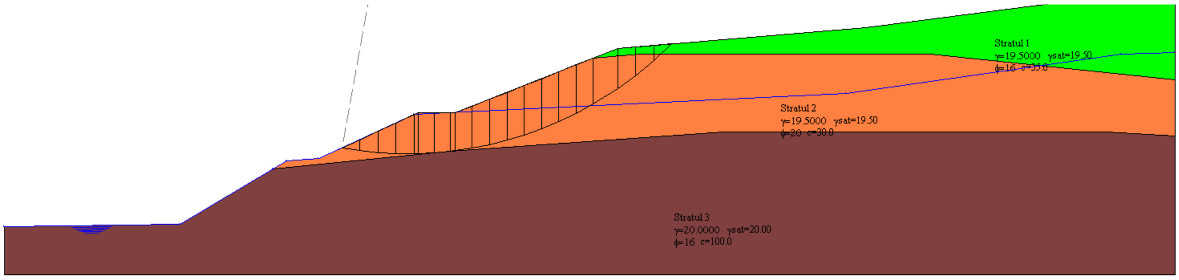


Figure 11. *Results of stability analyses for the remodelled cut slope, GWL as measured, static conditions, parameters as determined in the final geotechnical report.*

4.3. Unpredictability analysis

When it comes to forensic analysis and court in law files related to natural phenomena, often the experts are required to give answers about the unpredictable character of the analysed phenomena, as contracts are mentioning exclusion of such unpredictable phenomena and lawyers are speculating a lot about these. This was also the case in the presented situation. When resuming the causes, the general overview is as follows:

Lithology: upper clayey layer over a marl bedrock, prone to slippage of the upper part over the lower one when water penetrates.
Groundwater: excess of porewater pressure in the fissures, reduction of shear strength parameters of the clayey soil, slow drainage due to geotechnical and hydrogeological features of the site. Slow hydro-structure (aquitard).
Excavation works on a natural slope: leading to a drainage path for the water accumulated in the ground, which ran off through and on the cut slope.
Swelling clays presence: leading to drying fissures through which rainwater infiltrated easily.
Investigation: Unproper hydrogeological investigation, no long-term monitoring. The aquitard is difficult to be identified.
Design: too steep slopes for the site conditions, unproper stability analyses, non-respect of national legislation and of good practice, no measures regarding groundwater
Legislation: with regard to the hydrogeological investigation, the national legislation is not very clear, sometimes separating the geotechnical investigation from the hydrogeological one.

The conclusion was that such a combination of natural and man-made causes produced the landslides, but this could be avoided by proper investigation and design, therefore it cannot be considered as unpredictable.

5 CONCLUSIONS

Environmental geotechnics deals with natural and anthropogenic hazards, among which landslides. Many of the construction works can lead to slope instability phenomena due to both natural and man-made causes, if not properly investigated and designed from both geotechnical and hydrogeological point of view. The paper presents a complex forensic analysis of such instability phenomena, which, despite the first impression of simplicity (cut slopes in clay soil), showed a hydrogeological specificity not so easily to be correctly identified (aquitard with a slow dynamics), a geotechnical specificity (swelling clays), improper investigation and design, non-respect of good practice and legislation, but also a lack of clarity in the technical norms which has to be corrected (the most recent revision of the national technical norm for geotechnical investigation relied on these findings). For being able to answer to all objective formulated by the law court a complex investigation, analysis and numerical modelling had to be conducted from hydrogeological and geotechnical point of view, which are descried in the paper. This case study showed also the importance of a good cooperation between geotechnical engineers, geologists, hydrogeologists etc., the need for long term monitoring, rarely carried out due to time and financial constraints. An economical analysis would certainly show a large discrepancy between the price of a proper hydrogeological investigation and monitoring and the one for extensive consolidation measures that had to be taken. Not mentioning that the analysis showed that these are not sufficient for stopping the phenomenon, therefore more measures have to be foreseen.

The paper was published in the proceedings of the 9th International Congress on Environmental Geotechnics (9ICEG), Volume 4, and was edited by Tugce Baser, Arvin Farid, Xunchang Fei and Dimitrios Zekkos. The conference was held from June 25th to June 28th 2023 in Chania, Crete, Greece.