

LARGE-SCALE STABILIZATION OF DELUVIAL CLAY SLOPES THROUGH INTEGRATED DRAINAGE AND GEOMETRIC OPTIMIZATION: A CASE STUDY

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Received: 02.12.2025 / Accepted: 15.01.2026 / Revised: 17.02.2026 / Available online: 31.05.2026

DOI: 10.2478/jaes-2026-0010

KEY WORDS: slope stability, drainage, degree of saturation, piles.

ABSTRACT:

The paper deals with solving the instability phenomenon of a diluvial clay slope. The flysch deposits that predominate in the Curvature Subcarpathians are frequently affected by slope instability phenomena. The large volume of sediments entrained in movement requires that the stabilization method result as a consequence on the one hand of the scale effect, which implies a reduction of the mechanical parameters, and on the other hand due to cost constraints. Due to the fact that they generally have a creep character and do not have a visible catastrophic effect, they are analyzed as being of low risk, but their stabilization represents a major challenge from a technical point of view. The study case presents a stabilization method with minimal costs that has proven its effectiveness by acting on the entire unstable mass through superficial drainage and modifying the geometry of the slope by creating terraces and in the last instance a punctual intervention through support structures. After six years the aspect of the slope is still stable, uniform, clean, without irregularities.

1. INTRODUCTION

The flysch deposits that predominate in the Curvature Subcarpathian are very often unstable phenomena (Micu 2017; Mihai et al. 2010). This phenomenon hinders the harmonious development of the territory, access to natural resources and creates risks for human life and built heritage, which is contrary to sustainable development ("Special Issue on Slope Stability Problems in Stiff Clays and Flysch Formations" 2023).

Sustainable development is a conceptual framework that integrates the dimensions of economic growth, social inclusion and environmental protection, with the aim of building a sustainable future for and for the planetary ecosystem. In 2015, the United Nations established the 17 Sustainable Development Goals (SDGs), representing a coherent set of strategic targets that require urgent action, with the deadline for achieving stability for the year 2030. In this context, SDG Goal 15, entitled "Life on Land", aims to conserve, promote and restore terrestrial ecosystems, while preventing and combating desertification and land degradation (Hong-in, Takahashi, and Likitlersuang 2024). Studies have shown that landslides and rockfalls are characterized by distributions dependent on surface area and volume, with their frequency described by a power-law function, as it can be seen in Figure 1 (Tebbens 2020; Brardinoni and Church 2004; Brunetti, Guzzetti, and Rossi 2009; Catani et al. 2005; Chien-Yuan et al. 2007; Guthrie and Evans 2004a, 2004b; Guzzetti et al. 2002, 2005; Iwahashi, Watanabe, and Furuya

2003; BD and DL 1999; Martin et al. 2002; Massey et al. 2018; Zhang et al. 2016).

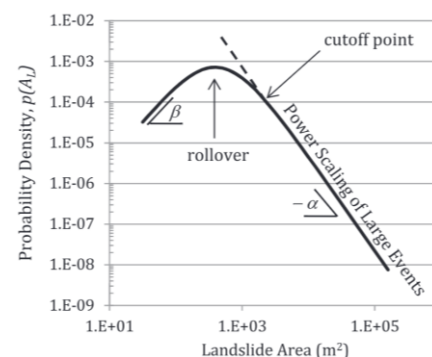


Figure 1. A representation of the probability density distribution of landslide areas. The cutoff point marks where the distribution diverges from the power-law describing larger events (Hovius and Stark 2001), while the rollover region indicates the slope change in the distribution (e.g., (BD and DL 1999))

Numerous studies have shown that the frequency of different types of landslides is not random. A statistical analysis reveals that they can be grouped according to their high frequency:

- Spatial clustering meaning that landslides often occur close to one another in specific regions (e.g., along fault lines, steep slopes, or areas with similar geology)

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(Guthrie and Evans 2004a; Liucci, Melelli, and Suteanu 2015; Qiu et al. 2019).

- Temporal clustering meaning that multiple landslides may happen within a short time frame, often triggered by the same event (like heavy rainfall, earthquakes, or rapid snowmelt) (Qiu et al. 2019).
- Geometric clustering meaning that similar shapes, sizes, or structural features appear repeatedly, suggesting common underlying processes (Gregory, 1844).

The scale of the landslides imposes different approaches (Lombardo et al. 2021; Medwedeff et al. 2020). As can be seen, landslides that occur on surfaces of the order of hectares have an average frequency compared to the others. To stabilize these landslides, which most often can be assimilated to "creep", having a small depth, and the displacement has a progressive variation towards the surface, the challenges posed to the geotechnician are major. The large surface prevents him from building support structures that act on the entire mass; prices would be onerous in this case.

For the stabilization of shallow landslides, the adoption of drainage ditch systems is a well-established method for increasing the stability factor, FS , of slopes as a result of their installation (Hutchinson 1978; Stanić 1984; Bromhead 1984). The method is accessible, being robust and relatively inexpensive engineering work. Several studies have referred to methods for establishing the hydraulic efficiency. Drainage systems through ditches are considered functional for the mitigation of shallow landslides (Hutchinson 1978; GREGORY 1844; Bromhead 1984; Meriggi and Ziraldo 2014). Hutchinson (1978) proposed the idea that the piezometric level can be obtained below the bottom of the ditch, when longitudinal ditches of 2 to 5 m depth are installed. Stanić (1984) proposed a method for calculating the increase in the safety factor of massifs with shallow landslides, as a result of the installation of shallow longitudinal ditches with a distance S . The analysis assumes a uniform degree of saturation, $S_r = 1$, and the lateral boundaries are at an infinite distance from the sliding mass. Consequently, the calculation is performed for only one of the repetitive modules of the system. In parallel, Bromhead (1984) proposed a 2D analytical solution of transient infiltration caused by buttress drains, through a Fourier solution similar to that which predicts heat flow in a solid (Tagarelli and Cotecchia 2022).

The present work analyzes possibilities for stabilizing a large landslide. in the sense of a large surface in horizontal projections and not in the sense of a deep phenomenon that would require a different approach. Solving such a problem is conditioned by the large scale at which ground displacements occur.

This dimension requires that the main emphasis be directed towards a general parameter, i.e. system solution, and not a punctual, concentrated and constrained solution in terms of dimensions, unlike the usual methods (retaining walls, sheet of piles and so on) which are approached point by point, contributing to the stabilization system as a whole.

An indirect approach to strengthen all the geotechnical indices mentioned above is to decrease the moisture content of the clay. Especially after heavy rains, the surface soil and upper superficial deposits can be saturated; by collecting groundwater, the soil passes into an unsaturated state, which means that the pore pressure goes from a positive value, in the saturated state, to a

negative pressure, conferring an apparent cohesion on one side and improving the internal friction angle. The influence of variations in the degree of saturation of soils on slopes has also been addressed in certain studies by several authors (Fredlund and Rahadjo 1993; Gavin and Xue 2008; Bittelli et al. 2012) and a similar study in the case of the city of Cluj-Napoca was presented by Battali and Carastoian (Batali and Andreea 2016).

2. MATERIALS AND METHODS

2.1 Methods of approaching slope stability according to the scale of the phenomenon

In analogy to the consequences of the scale effect defined in rock mechanics which refers to the inclusion of the scale (in the form of a size step) of the rock mass in rock mechanics, to take into account the variation in strength and behavior as the size of the rock mass or specimen changes. This effect implies that larger volumes of rock tend to be weaker than smaller volumes, and the scale effect influences the uniaxial compressive strength (UCS) of the rock, leading to adjustments in the shear strength parameters to better predict the behavior of the rock mass at different scales. The scale effect can significantly modify the failure mode, deformation pattern, and safety factor in clay slope analyses.

Slope stability analysis is a fundamental step in the geotechnical design of civil works. The approaches can be classified as follows:

- limit equilibrium methods (EQUILIBRIUM / LEM): focus on the delimitation of the potentially unstable mass and on the intuition of the geometry of the sliding surface, being the oldest and most widely used method in the practice of geotechnical engineering;
- numerical methods: discretization that include the finite element method (FEM) and other numerical schemes, combined with appropriate constitutive models, allow the determination of safety factors through resistance reduction techniques or by evaluating displacements and torsions;
- analytical methods: provide solutions in simplified contexts, being especially useful for situations with reduced moments and for superficial layers, but have limited applicability for complex configurations.

FEM analysis confirms that scale matters and influences the results (Sengani and Mulenga 2022), and some of the reasons may be the following:

- the scale of the model and the stratification determine which failure mechanism occurs and consequently layered clay slopes can present shallow or deep failures;
- the failure zone can expand or shrink as the model size increases or decreases. The deformation-dependent weakening phenomena or, clay weakening (strain softening), controls the position of the slip surface.
- logical consequence leads to the fact that within a large-scale landslide, the stabilization of a restricted portion leads to the redistribution of the efforts and deformations in their entirety. We have based ourselves on this mechanism in adopting the solutions that will be presented below (drainage of the entire mass as a general solution and the execution of the piloted retaining wall with local effect).

We can state that in clay slopes, landslides are produced on several planes (Highland and Bobrowsky 2008), and their number and is reduced the higher the consistency of the clay. The emergence of these multiple critical surfaces is favored by the existence of larger domains on the one hand, and on the other hand, spatial variability can generate several competing critical surfaces, increasing uncertainty in probabilistic analyses. Under seismic loading, large models can amplify deformations, create wave effects and thus extend failure. In the FEM analysis, the numerical boundary conditions have an influence on the redistribution of stresses and convergence behavior.

3. CASE STUDY – CÂNDEI STREET, COMARNIC CITY

3.1 Geological and geomorphological context

To analyze the methods of stabilizing a shallow, shallow but large-area landslide, we resorted to the situation of a slope (see

Figure 2) in the Curvature Subcarpathians, in the built-up area of Comarnic City. In Figure 3, it can be seen the morphological aspect of this slope and a zoning of stable vs. displaced soil.



Figure 2. Initial appearance of the slope

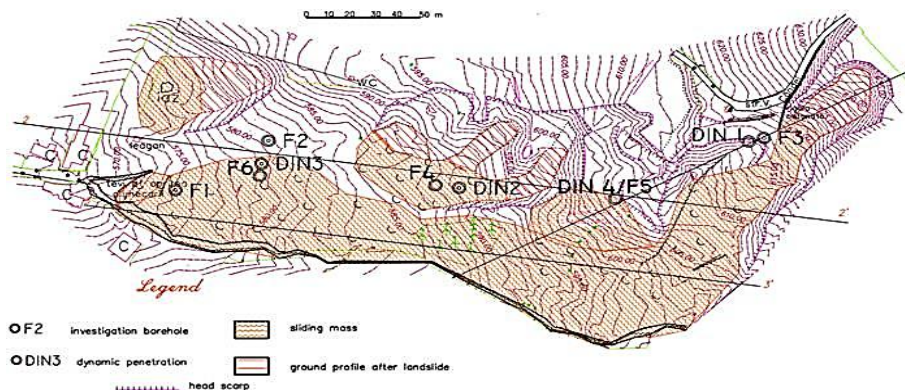


Figure 3. Situation plan

Landslides occurred on the slope delimited by Cândeii Street and extends westward to the vicinity of the national road DN1. Valea Cândeii Street was not affected by the ground movements, but may endanger road traffic in this area. The foot of the landslide occurred at a distance of approx. 100 m from Valea Cândeii Street, the landslide developing over a length of approx. 300 m (see Figure 4), the detachment line being located at a distance of approx. 400 m from Valea Cândeii Street, in the area of Gârlici Street.

The main landslide detachment face is located approximately 10 meters from Valea Cândeii Street, its base being located at a nickel difference of approximately 10 meters from the roadway. The road is asphalted and is bordered on one side and on the other by private properties.

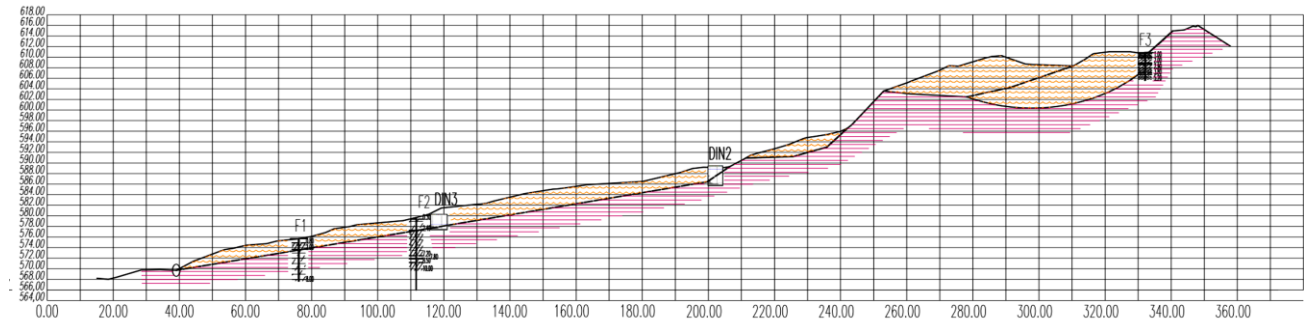


Figure 4. Geotechnical profile 2-2' (in beige the slipped mass, in magenta, the base terrain)

The Quaternary deposits have become very active with very large contractions and swellings due to the intense chemical alteration of the bedrock. The bedrock has transformed into a clayey-dusty formation of considerable thickness, sensitive to increased humidity which is the main triggering factor for landslides.

Numerous reactivations occur in the slipped mass, evidenced by friction mirrors and swollen contraction cracks, on smaller or larger surfaces. The reactivations that have occurred are mainly due to the failure of the rainwater drainage system, which has infiltrated the slipped mass which changes the shear strength of

the soil. There is no groundwater, i.e. a water table. Surface runoff water infiltrates the flood mass and causes the rocks below the flood formation to become wet.

Local reactivations can also be influenced by undeveloped torrential valleys. The infiltration of the waters towards the base of the slope torrent led to the creation of a with a large thickness of the soft sliding mass, which in some on the platform of Valea Căndei Street, the most affected by the Landslides.

From a geomorphological point of view, the studied area belongs to the Curved Subcarpathians, in the Prahova Subcarpathians subunit, more precisely the inner part of the Teleajen Subcarpathians. The general appearance is given by the rows of hills with a parallel plane, with transverse fragmentation. From a tectonic point of view, the area is composed of a series of thrust sheets, in which, on the studied site, upstream of the slide, a patch of Albian-Vraconian age appears over the native Turonian. The stratification of the bedrock, marl, coarse marl, is consistent with

the slope. The Curvature Subcarpathians are in a continuous, relatively slow uplift and these "neotectonic movements", associated with clayey rocks, create a greater dynamic of landslides.

4. DIMENSIONING OF THE WORKS

The investigation of the ground was carried out through geotechnical drilling with continuous rotary core drilling and was completed with dynamic penetrations to estimate the depth of the slipped shaft. From the samples collected in the drillings, laboratory analyses were performed (natural humidity, particle size, plasticity-consistency, residual shear strength, free swelling). The results of the laboratory tests are shown in Table 5.

The force on the supporting structure was calculated using the slice method (see Figure 6). When the soil is undrained, the calculation showed that the slope is unstable, and the pressure on the retaining structure is 83.6 kN/m.

Borehole 1													
position	clay	d ₁₀	U	W _f	W	W _c	I _p	I _c	φ'	c'	φ' _{res}	c' _{res}	FSI
[m]	%	mm	-	%				-	°	kPa	°	kPa	%
displaced material [-4.50 m]	25.8	0.000505	15.84	24.9	30.5	76.58	51.68	0.88	3.73	20.19	3.97	0	116.67
	25.8	0.001151	6.95		31.21								123.33
	32.4	0.00097	8.25		33.22								
	average												
	28.00	0.000875	10.35	24.90	31.64	76.58	51.68	0.88	3.73	20.19	3.97	0.00	120.00
undisturbed ground [-8.00 m]	33.5	0.000185	9.75		17.66								157
	42.6	0.000107	6.8		15.62								
	29.6	0.000214	8.4		12.09								
	average												
	35.23	0.000169	8.32		15.12								157.00

Borehole 2													
position	clay	d ₁₀	U	Wf	W	Wc	Ip	Ic	φ'	c'	φ'res	c'res	FSI
undisturbed ground [-10.00 m]	%	mm	-	%				-	°	kPa	°	kPa	%
	10.3	0.001724	3.66	25.3	16.46	77.82	52.52	1.21			7.4	0	
	19.6	0.000936	6.75		14.24								
	19	0.000743	8.51		13.67								
	12	0.001217	5.16		11.61								
	average												
	15.23	0.001155	6.02	23.42	14.00	71.10	47.69	1.20			7.75	0.00	

Borehole 3													
position	clay	d ₁₀	U	W _f	W	W _c	I _p	I _c	φ'	c'	φ' _{res}	c' _{res}	FSI
[m]	%	mm	-	%				-	°	kPa	°	kPa	%
displaced material [-4.10 m]	22.4	0.000862	12.76	15.21	18.61	32.69	17.49	0.44			12.3	0	
	16.2	0.001134	10.58		27.5								
	19	0.001076	10.69		24.62								
	31.3	0.00162	11.55		30.29								
	48.34	31.65	0.57		10.5								
	average												
	22.23	0.001173	11.40	15.95	25.19	40.52	24.57	0.51			11.40	0.00	
undisturbed ground [-5.20 m]					30.33								
	average												
					30.33								

Borehole 4													
position	clay	d ₁₀	U	W _f	W	W _c	I _p	I _c	φ	c	φ'	c'	FSI
[m]	%	mm	-	%				-	°	kPa	°	kPa	%
displaced material [-2.40 m]	20.2		3.64		35.32								
	average												
Undisturbed ground [-1.40 m]				25.45	33.85	70.87	45.42	0.82					
	average												
				25.45	33.85	70.87	45.42	0.82					

Borehole 5													
position	clay	d ₁₀	U	W _f	W	W _c	I _p	I _c	φ'	c'	φ _{res}	c _{res}	FSI
[m]	%	mm	-	%				-	°	kPa	°	kPa	%
displaced material [-3.40 m]	30.5	0.001683	3.75	13.5	22.18	42.64	29.14	0.7					
	26.6	0.001457	4.31	22.96	41.86	64.68	41.73	0.55			8.8	0	
	average												
	28.55	0.00157	4.03	18.23	29.47	53.66	35.44	0.63			8.80	0.00	

Borehole 6													
position	clay	d ₁₀	U	W _f	W	W _c	I _p	I _c	φ'	c'	φ _{res}	c _{res}	FSI
[m]	%	mm	-	%				-	°	kPa	°	kPa	%
displaced material [-3.00 m]					52.63								
	27.1	0.001589	3.97	26.22	45.37	53.74	27.5	0.31			9.9	0	
	average												
	27.10	0.001589	3.97	26.22	49.00	53.74	27.50	0.31			9.90	0.00	

Table 5. Laboratory analysis centralizer

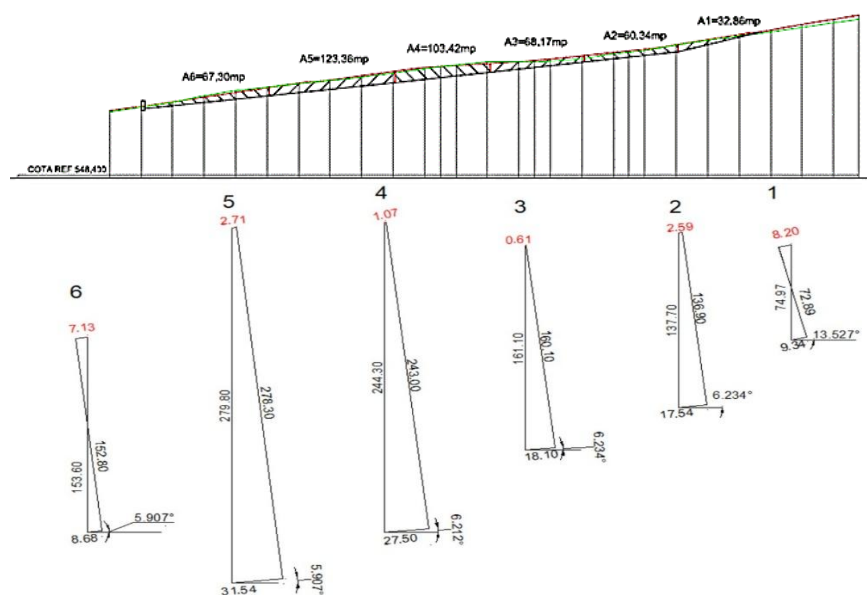


Figure 6. Slope stability analysis

Based on granulometric analysis, and more specifically on the effective diameter d_{10} , an average value for the permeability coefficient of the landslide mass was adopted using Hazen's formula. Therefore, the hydrogeological properties values (deduced from granulometric analyses and observations on the collected runoff) are as follows:

- filtration coefficient $K_f = 0.1$ m/day;
- drainage coefficient (dehydration coefficient) $k_c = 10\%$;

- specific flow rate $q_{sp} = 2.0$ m³/h/m;
- static groundwater level $H = 2.0$ m
 - water level height on the walls of the drain channel $h = 0.3$ m

The aim of those designed works is to increase stability mainly by reducing the water content, as being known that there is a direct relation with the shear strength as it shown in figure 7a -

7b. To estimate the extent of the influence zone of the drainage works performed in the phreatic aquifer horizon, the working hypothesis is taken into account that the functions of as a

drainage ditch and the calculation relationship specific to this type of work will be applied.

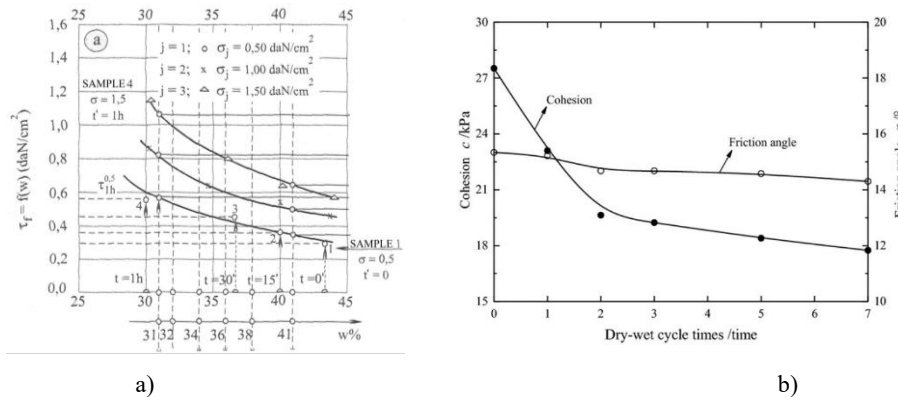


Figure 7. a) Example of shear strength vs. water content in the case of a direct shear test of an alluvial clay (Stanciu and Lungu 2006), b) Measured cohesion and friction angle of the weak soil as a function of the dry-wet cycle (Xu et al. 2021)

For a conservative calculation, if the radius of influence of the ditch is unknown, the discharge can be calculated assuming an experimentally established mean slope, I_0 of the depression curve is:

$$I_0 = \frac{H-h}{R} = 0.15 \quad (1)$$

then:

$$Q_t = L \cdot K_f \cdot (H + h) \cdot I_0 \text{ [m}^3/\text{day]} \quad (2)$$

For the values assumed above, the flow per linear meter of drain will be $0.00345 \text{ m}^3/\text{day}$, which means that for a total length of 1277 m, the total discharge will be $4.4 \text{ m}^3/\text{day}$. According to observations made in the water discharge areas, the total

discharge was estimated to be $0.0001 \text{ m}^3/\text{sec}$, which means $8.64 \text{ m}^3/\text{day}$, which covers the total discharge with a safety factor.

For an unpressurized aquifer, placing the drain at a certain distance from its bed implies replacing the parameters H and h with H_0 and h_0 as follows (see Figure 8):

$$H_0 = 1.3 \cdot F \quad (3)$$

and

$$h_0 = H_0 - s \quad (4)$$

where:

- F is the thickness of the water layer to the bottom of the drain,
- s is the descent of the hydrostatic groundwater level.

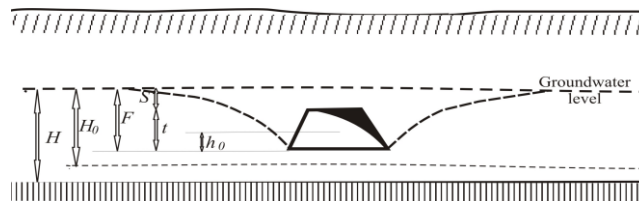


Figure 8. Location of a drainage gallery in an unpressurized aquifer

The relation for the radius of influence used (R) has the following form:

$$R = \sqrt{\frac{3 \cdot H \cdot K_f \cdot T}{K_c}} \quad (5)$$

where:

- H - hydrostatic level height, m;
- K_f - filtration coefficient, m/day;
- T - drought duration, days;
- K_c - drainage coefficient (dewatering coefficient).

Considering the values of the hydrogeological characteristics of the groundwater horizon presented above and taking into account the drainage process related to a period of 30 days, the radius of influence of drying will be approximately 18 m. The decrease in water content leads to an increase in resistance. The decrease in water content leads to an increase in the shear strength of the soil, i.e. both the friction angle and the cohesion. The result of the experimental research can be seen in figures 7a and 7b, taking into account, of course, other factors. It can be estimated that at

an average reduction in humidity of 5%, the shear strength increases by about 20 kPa or 4 - 6° of the internal friction angle. Starting from these mechanical and physical parameters of the ground, the stresses in the buttresses and in the piles were calculated. Each buttress is based on two piles with a diameter of 600 mm and a depth of 9 m.

Consequently, the steps taken to reduce instability were as follows:

- remodeling the geometry in the form of slopes of maximum 1 to 4 and intermediate berms, i.e. systematizing the slope for its stabilization by modifying the geometry in the form of slopes and intermediate berms; since there is a layer of kneaded topsoil on the surface of the slide, which is not good soil for filling, it will be removed to a thickness of 30 cm, after cleaning the soil affected by the works of trees and shrubs. The slope inclination will be made so that the slope is maximum 1:4, the length is 25 m, and the width of the safety berm is at least 3.0 m (see Figure 9). The upper part of the ground will be leveled, and the cracks will be filled with waterproof material.

- A drainage network throughout the landslide to increase geotechnical characteristics (see figure 10).
- A system of buttresses on piles to protect Valea Căndei Street and nearby houses.
- A concrete ditch with thresholds to limit the speed of water flow on the stream.
- A gabion retaining wall on the upper part of the landslide.
- An anti-erosion protection by weeding the slope and planting trees.

5. DISCUSSION

Considering the extension of the landslide in plan and in depth, the general stability of the slope can be regained by an action on the triggering factors, in particular by reducing the infiltration and flow of water on and in the slope. Consequently, after analyzing the triggering factors of the lamella, in order of their weight, we proposed to act within the limits of reasonable material costs. This approach aims to reduce the use of concrete-intensive or high-cost technologies, taking into account the current land use and the limited development potential of the affected area, despite its central urban location. There is no doubt that the land should be rehabilitated for construction. The analysis of the slope stabilization options started from an indicative calculation in three successive hypotheses. The ground mass was discretized on a section that was estimated to be the most dangerous.

The stability of the slope was analyzed under existing conditions, which obviously led to an unsatisfactory result, the safety factor, calculated by several methods, being 0.52 - 0.53 (see Figure 11b). It was considered a restoration of the geometry of the slope, in which the earth masses were redistributed in the sense of compensating the active prisms, which generate instability, with the passive ones, which contribute to the generation of moments and stabilizing forces.

An important aspect of the analysis in this hypothesis is the management of surface waters, which due to the existence of a continuous slope, will no longer stagnate and subsequently infiltrate into the ground. As a result of the reduction in seepage, the soil humidity will decrease, the groundwater level will drop, and the unsaturated soil area with negative pressure will expand, providing an additional stability fraction. In this hypothesis, we improved the soil shear strength parameters in our analysis. The safety factor increased significantly to 0.72 - 0.75 (see Figure 11c).

In the next stage of the analysis, several support systems (piles rows) were added, however, in relation to the entire analyzed surface, their effect was minimal, almost insignificant (see Figure 9d). As a result, the adopted solution was mainly based on restoring the slope geometry, adapting and directing surface runoff and on creating a drainage system on the entire slope. Punctually, near the foot of the sliding mass, a local support system represented by a piled concrete wall was adopted.

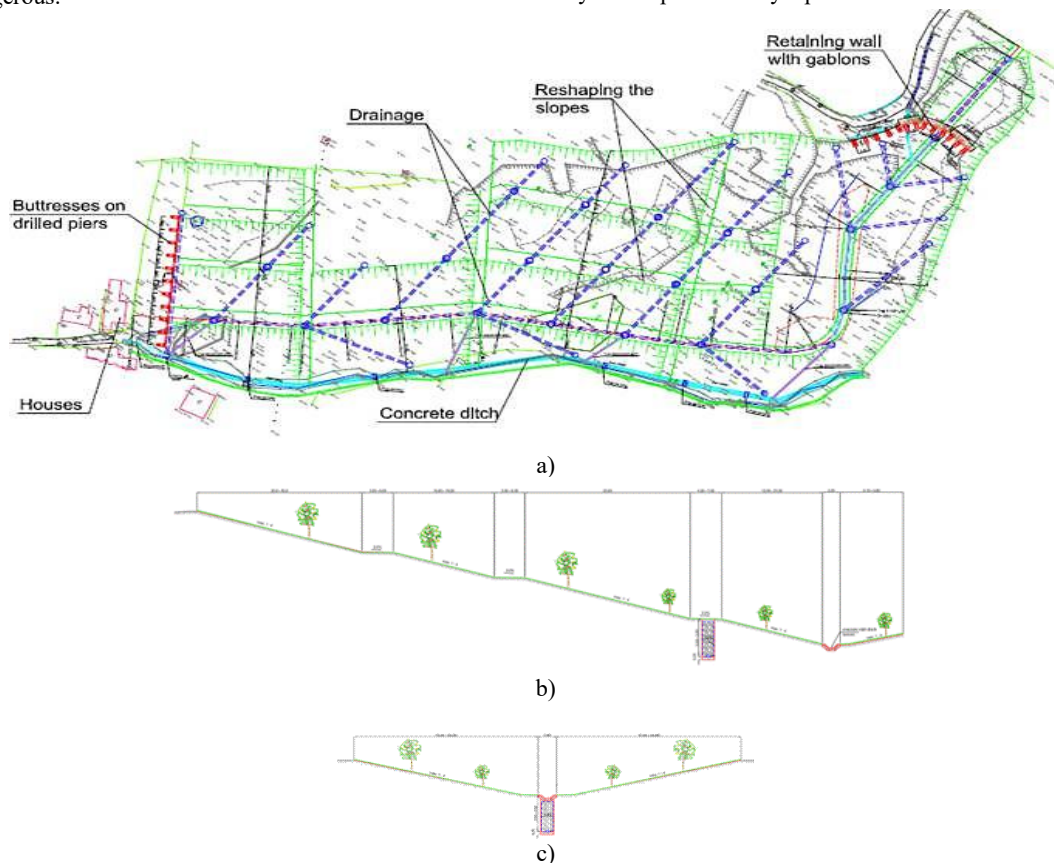


Figure 9. Designed plan (a) with longitudinal (b) and transversal profile (c)



Figure 10. The layout of the drains and manholes (D1, D2,...) in which the flow rate was estimated

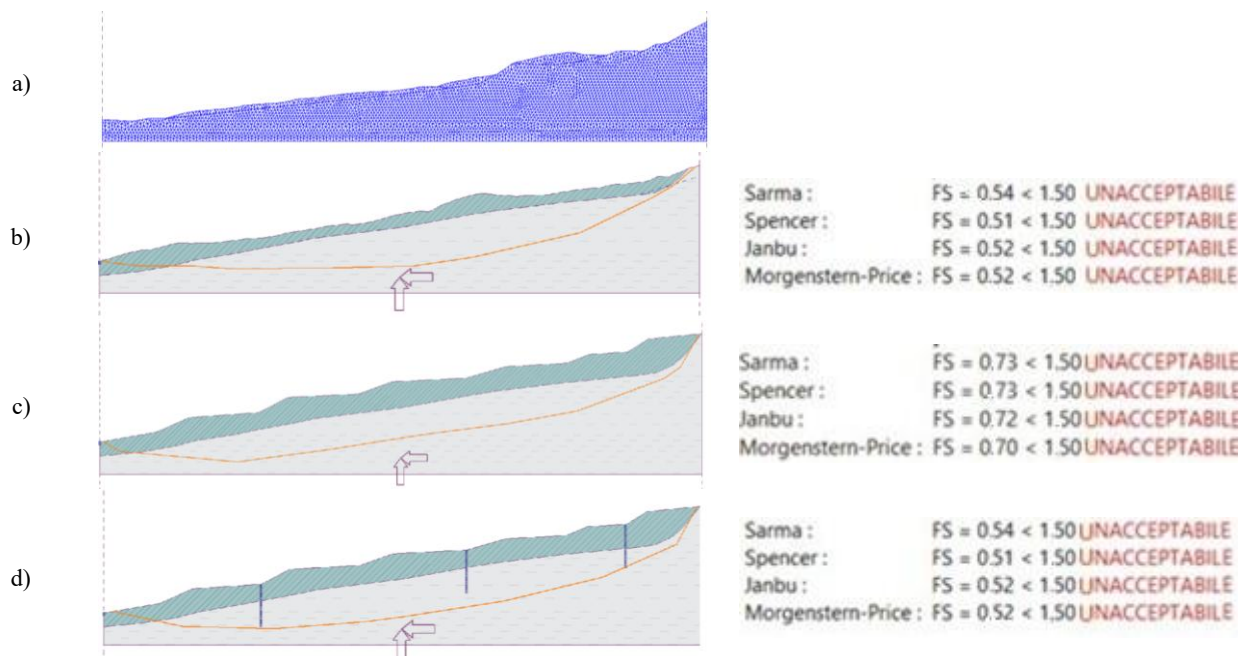


Figure 11. Analysis of slope stability in the three analyzed variants; a) slope discretization; b) stability analysis in the initial situation; c) stability analysis in the case of slope drainage; d) stability analysis in the case of drained slope and with successive support systems

Since the analysis presented above showed that even in the hypothesis of carrying out these interventions, the safety factor remains sub-unit, therefore unsatisfactory, we considered that the proposed works are absolutely necessary under any conditions, have minimal costs, and their effect has a significant latent potential. For the values assumed above, the flow per linear meter of drain will be $0.00345 \text{ m}^3/\text{day}$, which means that for a total length of 1170 m, the total estimated discharge will be $0.168 \text{ m}^3/\text{h}$ ($4.03 \text{ m}^3/\text{day}$). According to the observations made in the water discharge areas, the total discharge was estimated to be $0.212 \text{ m}^3/\text{h}$ ($5.09 \text{ m}^3/\text{day}$), which covers the total discharge with a safety factor (see table 12).

Drained segment	Total drainage length in the sector	Estimated flow rate [mc/h]	Measured flow rate [mc/h]
D1-D2	327.53	0.047	0.072
D2-D3	255.64	0.037	0.04
D3-D4	265.54	0.038	0.04
D4-D5	321.42	0.046	0.06
TOTAL	1170.13	0.168	0.212

Table 12. Table of measured flow rates

6. CONCLUSIONS

In the case of landslides in clayey deluvial sediment deposits extended over large areas of the order of hectares, a scale effect can be taken into account, which, analogously to the scale effect applied to rocky massifs, leads to a reduction in the stability of the entire massif compared to the characteristics restricted to the samples collected from the site.

Any analysis made in advance by a method no matter how sophisticated can only lead to indicative results. The investigation of a large area, varied in topography, cannot be exhaustive, because there are limitations of cost and time, and as a result the analytical modeling of the terrain will always be susceptible to additions, improvements or eliminations.

The approach to these types of challenges is done in stages, initially applying inexpensive methods, which however affect the entire surface; restoring the geometry of the slope by uniforming the slope, redistributing the earth masses, then by correctly

managing surface waters, capturing and directing them to a controlled outlet.

Subsequently, after evaluating the results through visual or instrumented monitoring of the slope, complementary methods dictated by the new conditions can be applied.

Point support works, retaining walls, rows of piles, sheet piles, etc. have a local effect, negligible compared to the entire phenomenon in the case of recent ground instabilities over large areas.

As a result, two years after the beginning of the project's works, the area seems to be stabilised as its can be seen in fig. 13.



Figure 13. Site images after stabilization works

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