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Slope failure characterization: A joint multi-geophysical and geotechnical analysis, case study of Babor Mountains range, NE Algeria

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Abstract

Purpose. The research purpose is to apply an original combined approach to the study of landslide occurrence in the Tarzoust region, based on geophysical approaches. This is extremely important because landslides damage roads and buildings in many parts of North Africa, especially in the city of Tarzoust, NE Algeria. Significant slope failures have resulted in serious disasters in the region.

Methods. In this study we use Vertical Electric Soundings (VES) and Seismic Refraction Method (SRM) for underground exploration, as well as Electrical Resistivity Tomography (ERT) to support the latter two methods.

Findings. The clayey nature of the terrain is confirmed, very often covered by a mantle of superficial colluvium formations. The depth of the bedrock and shear surface has been precisely determined. The ERT reveals that the terrain has already experienced instability in the past.

Originality. The originality of this study is in the combination of data from various sources and different approaches for the purpose of planning the deployment and use of land.

Practical implications. Our approach has proven that the combination of geological and geotechnical data with geophysical deterministic methods can help engineers and decision-makers in land management. Our recommendations consist of topographic, inclinometric and piezometric monitoring for slip development and the effectiveness of reinforcement measures for new housing, and equipment programs for regional planning.

Keywords: *slope failures, tomography, resistivity, seismic refraction, substratum*

1. Introduction

Natural disasters damage human lives and property around the world [1]. Each time we find ourselves unable to do anything, faced with recurring phenomena [2]. In the Mediterranean basin, both landslides and earthquakes cause severe bodily functional and structural damages [3]. The assessment of these geologic hazards is the key to any mitigation strategy for this problem that hampers development efforts[4]. Landslides occur when masses of rocks, soil material, or muddy flow move down a slope, caused by disturbances in the natural stability of a slope. Several authors from Europe and Africa have stated that when field and environmental conditions play in such a way that predisposition and triggering factors act simultaneously, landslides can become extremely catastrophic [5]-[7]. To study landslide occurrence in a hilly region, a number of direct and indirect methods can be used [8], [9]. The direct approach requires field and laboratory data as well as a safety factor calculation using one of the well-known stability analysis techniques such as the limit equilibrium and finite elements methods [10]. Their disadvantage is that the information is provided in a specific location and assessment of the spatial distribution of safety factors is not economically efficient, since a large number of samples and tests are required in the affected area [11], [12]. These techniques would allow landslides to be assessed at some scattered locations, giving an idea on the stability state, but an additional geophysical study would be an ideal tool to deal with this difficulty [13].

Natural and anthropogenic landslides have caused earth failures leading to the damage of buildings and infrastructure such as transportation facilities and pipelines in many hilly regions of Algeria. In the Babor mountain range and adjacent areas, such as the Neogene El Milia basin, landslides of various type and sizes often take place. They have caused several disturbances, such as the tilt between buildings in the city of Tarzoust. These instabilities developed over time with variable velocities despite the installation of 3 m deep draining trenches and 10 m deep micro-piles. Last but not least, a seismic event that occurred in Mila on August 07, 2020, with a magnitude of 4.9 degrees, caused several landslides, damaging the mines and urban sites of the main city of Mila (Fig. 1).

Geophysical methods such as Vertical Electric Sounding (VES), Electrical Tomography, Seismic Refraction, or Ground Penetration Radar (GPR) are research tools adapted to the ground instability study [14].

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(a)

(b)

Figure 1. The earthquake induced disturbances on August 7, 2020 in Mila with a magnitude of 4.9

They are effective tools for characterizing landslides while reducing the use of more expensive and costly methods. In the case of landslides, they can characterize the internal land structure and the position of moving masses [15]. Geophysical techniques are also used to identify the geometry and characteristics of underground cavities, based on the contrast of physical properties such as density, magnetic susceptibility, electrical resistivity, and conductivity, which vary between the different layers and crossed materials. In general, this is an efficient means to trace the evolution of karstic terrains [16], [17]. Nevertheless, a particular geophysical method may not be suitable for all types of mass movement processes. A careful choice of a method or a combination of several methods is necessary, taking into account local geological and structural parameters, as well as the type of mass movement. Currently, geophysical methods are widely used to detect different types of underground anomalies.

Our research is aimed at applying an original combined approach to the study of landslide occurence in the Tarzoust region. In this research, geophysical surveys include Electrical Resistivity Tomography (ERT), Seismic Refraction and Vertical Electrical Sounding (VES).

2. General setting

The city of Tarzoust is located on the northeastern side of the El Milia Neogene basin, 57 km southwest of the main city of the Jijel province, between 06° 17′ 7.44″ longitude E and 36° 45.2′ 62.08″ latitude N, along the national road RN43 between Jijel and El Milia. The site covers a surface area of 12 ha (Fig. 2).

The study area is influenced by major multidirectional regional tectonic events (NS, EW, NE-SW and NW-SE) [18]. These tectonic events have caused the formation of the El-Milia Neogene basin and played an important role in the Triassic uplift (in particular, in the Bellara outcrop).

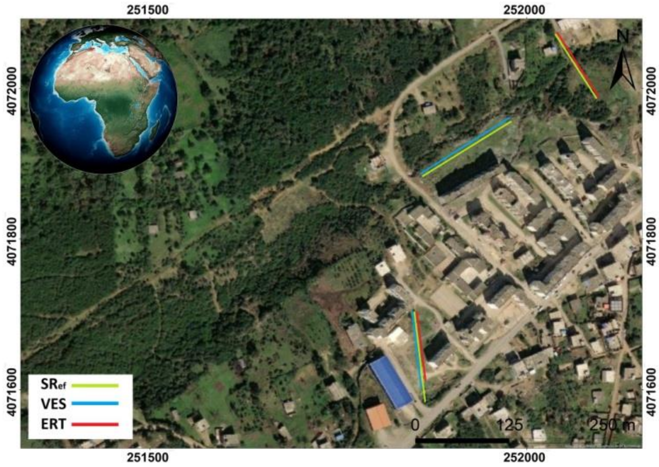


Figure 2. Geographic location of the study area

Moreover, these tectonic events later reactivated as strike-slip faults and affected the Miocene formations, which is clearly seen in the El-Milia microgranitic formations. The NS tectonic events (normal fault) are identified on the sandstone layer (Fig. 3) [19]. Several formations accumulate at the study site, namely a fractured and diaclase massive sandstone formation of Aquitanian age, overlaying a clay formation; these latter are distinguished by Sub-Numidian clay of the Upper Oligocene age.

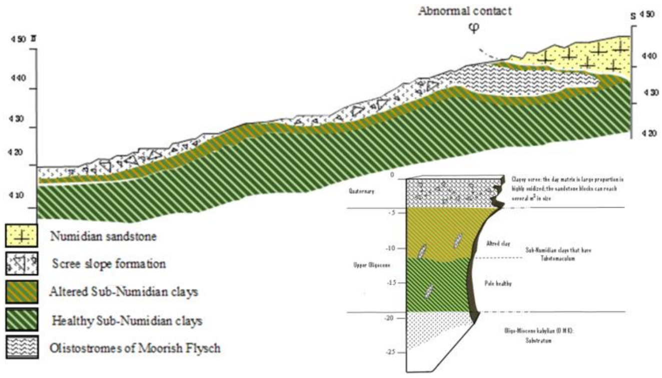


Figure 3. Geological cross section in the study area

At several points of the site, the Sub-Numidian clays are covered by a mantle of scree slope; clay matrix abundant in large proportion; sandstone blocks are coarse, porous and can reach several cubic meters in size. This altered zone reaches 20 m in the middle part of the urban site. The site is exposed to water infiltration and seepage as the overlaying sandstone is highly porous and receives a considerable amount of rainfall. Groundwater is shallow (0.5 to 1 m) and comes to the surface in winter and spring. The general flow is SW/NE direction.

3. Initial data and methods

Many authors have applied geophysical techniques to delineate the sliding surface, hydrogeological regime, or to monitor landslides [20]-[23]. In our study, we have combined two methods: VES and SRM. The main objective is to determine the lithology of the study site, given a precise subsoil structure, to define the piezometric level and the substratum depth. Therefore, we decided to complete and confirm the results obtained by ERT (Fig. 4).

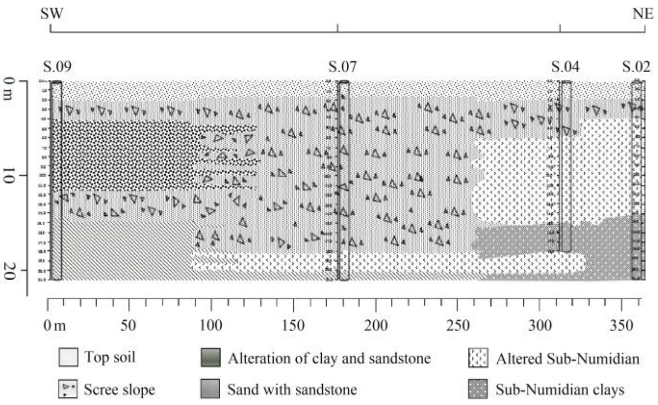


Figure 4. Lithofacies correlation, passing through S9, S7, S4 and S2 sounding

3.1. Investigation by VES

The VES is one of the most widely used geophysical methods for shallow-depth prospecting. Being quick and easy to perform and interpret, it exhibits a wide range of values that are sensitive to various factors such as the lithological subsoil nature [24]. For this survey, a Schlumberger-type sounding is performed at the location of electrical panels and seismic profiles; the profile characteristics are shown in Table 1.

Table 1. Characteristics of VES profiles

	Orient	Length	Began	End	Obs
P_1	NW-SE	140	252131 4071953	252037 4072065	Overlap 2 cables
P_2	N-S	140	251881 4071877	252014 4071945	

3.2. Investigation by SRM

Unlike seismic reflection surveys, which are rarely used in landslide studies, seismic refraction is widely used in engineering geology to determine the bedrock depth. It has been found to be applicable for landslide studies, as shear and compression wave velocities are generally lower in disturbed soil mass than in undisturbed soil. M^c Cann and Forster [25] presented several case studies based on the use of seismic refraction to locate undisturbed bedrock below the upper moving mass. Data acquisition is based on the interpretation of the first arrivals of seismic waves. In order to acquire two seismic profiles (P_1 and P_2), the Summit/X/Stream/Pro device of DMT.l with Reflex W seismic refraction interpretation software (Sandmeier Scientific - Germany) is used, which allows to arrange and download different shots from their geometry (Table 2).

Table 2. Characteristics of seismic profiles

	Orient	Length	Began	End	Obs
P_1	NW-SE	120	252131 4071953	252037 4072065	Overlap 2 cables
P_2	N-S	120	251859 4071592	251828 4071684	

3.3. Investigation by ERT

The ERT method provides a high-resolution image of the subsoil for terrains with a complex geological structure. It has been proven to be useful for a variety of problems, including pollution of coastal aquifers, mapping hydrogeological systems, or studying landslides [26], [27]. The results obtained seem to be fairly significant [28]. In our study, the SARIS of Scintrex device with Res 2Dinv, a program for automatic 2D reversal of apparent resistivity data, the electrical streamers with five electrode sockets spaced 5 meters apart, and steel electrode stakes are used to acquire three profiles of electrical imagery (P_1, P_2 and P_3). The first two profiles (P_1 and P_2) have a length of 145 m; the third one (P_3) is 95 m long. The geometrical characteristics and orientation of the profiles made are given in Table 3 and the different profiles are shown in Figure 2.

Table 3. Characteristics of ERT profiles

	Orient	Length	Began	End	Obs
P_1	NW-S	145	252131 4071953	252037 4072065	Overlap 2 cables
P_2	NW-SE	145	251881 4071877	252014 4071945	
P_3	N-S	95	251859 4071592	251828 4071684	

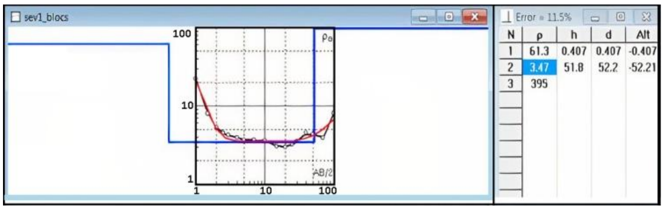
4. Results and discussion

In many cases, information on the geological depths and lateral continuity of sliding surfaces cannot be obtained by drilling or geological surveys. Fortunately, a geophysical study can complete the subsoil parameter dataset for a better understanding of the physical behavior of the slope [29].

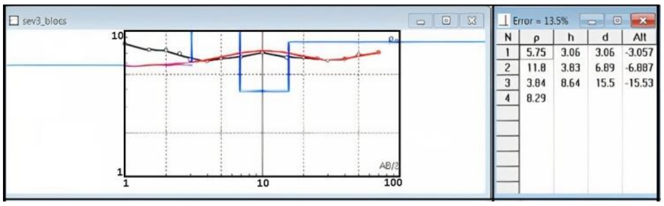
4.1. Vertical Electrical Soundings (VES)

The first VES_1 (Fig. 5a) has allowed to draw a transverse geophysical section on the scree slope object of the study and shows a thin and resistant layer. On the other hand, a conductive layer is widely represented by its thickness of more than 52 m; it is represented by a very low resistivity, about 3-7 Ohm.m. This is a mass reworked from crushed wet and conductive clays. At a depth of 52 m in the middle of the slope, some traces of bedrock are detected, which indicates the extent of underground disturbances on which the buildings are located. In addition, the resistivities are too low from 2 to 3 Ohm.m, which indicates the presence of gypsum.

(a)



(b)



(c)

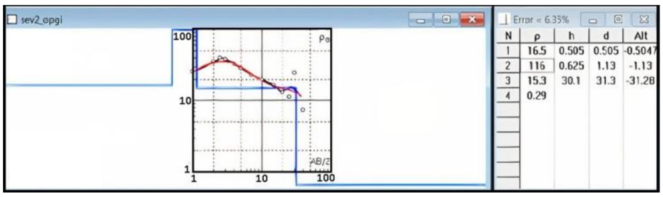


Figure 5. Electrical vertical cross-sections: (a) VES_1; (b) VES_2; (c) VES_3

The implemented cross-section of correlation lithofacies, passing through the corresponding sounding S_9, S_7, S_4 and S_2 (Fig. 4), clearly confirms the reworked state of the ground, as well as the abundance of sandstone blocks of different sizes, giving false penetrometric refusals at low depths.

The second VES_2 (Fig. 5b) shows two distinct layers. The first layer is relatively more resistant with a resistivity of 30 Ohm.m. The thickness of these has not been precisely determined, and another more conductive layer is more than 32 m deep. This is consistent with our electrical panels, which indicate the existence of a sound, consolidated layer.

To determine the sub-terrain in all these measurements, the last VES_3 (Fig. 5c) is placed longitudinally relative to the others; it is 140 m long. The section shows a single conductive layer with an average resistivity of 5 Ohm.m; its depth is about 16 m.

4.2. Seismic Refraction Profiles (SRM)

P_1 profile: The seismic P_1 profile is oriented to SE-NW direction. The section for the "P" compressive wave highlights three distinctive velocity ranges: the first range is with a velocity of 190 and 730 m/s and a thickness varying from 2 to 6 meters; the second range is with a velocity of 970 and 1380 m/s and a thickness varying from 7 to 17 meters; the third range is with a velocity of 1990 and 3420 m/s. The results obtained for recording compression and shear waves are given in Tables 4 and 5.

Table 4. Digital results for P_1 profile "P wave"

Shot point	V_1 [m/s]	V_2 [m/s]	V_3 [m/s]	H_1 [m]	H_2 [m]
TD 2-5	315	1245	2800	3	13.5
TC-G 6-7	330	1175	-	2.5	15.5
TC-D 6-7	360	1175	2640	2.5	15.5
TC-G 12-13	190	1010	2240	-	17
TC-D 12-13	185	970	1990	-	17
TC-G 18-19	430	1255	3420	2	16
TC-D 18-19	380	1255	-	2	16
TR+2.5	730	1380	2610	6	7

Table 5. Digital results for P_1 profile "S waves"

Shot point	V_1 [m/s]	V_2 [m/s]	V_3 [m/s]
TD	165	340	–
TC-G	70	200	355
TC-D	70	245	695
TR	250	325	–

Profile P_2: the seismic P_2 profile is oriented to NW/S. The results obtained for recording compression and shear waves are given in Tables 6 and 7.

Table 6. P_2 Profile digital results "P waves"

Shot point	V_1 [m/s]	V_2 [m/s]	V_3 [m/s]	H_1 [m]	H_2 [m]
TD	670	1385	2670	5	5.5
TC-G	460	1235	–	3	7.5
TC-D	510	1135	–	3	7.5
TR	750	1195	3185	3	9.5

Table 7. P_2 Profile digital results "S waves"

Shot point	V_1 [m/s]	V_2 [m/s]	V_3 [m/s]
TD	195	340	860
TC-G	160	320	–
TC-D	165	295	–
TR	265	465	780

The geo-seismic section for the compressional waves highlights three distinct velocity ranges, namely, the first range is with a velocity of 460 and 750 m/s and a thickness varying from 3 to 5 meters, the second range is with a velocity of 1135 and 1385 m/s and a thickness varying from 5.5 to 9.5 meters and the third range varies between 2335 to 2670 m/s. The seismic and Hodochron cross-sections of P and S waves of the first profile are shown in Figure 6. The results of the seismic profiles confirm the heterogeneity and the presence of a reworked zone.

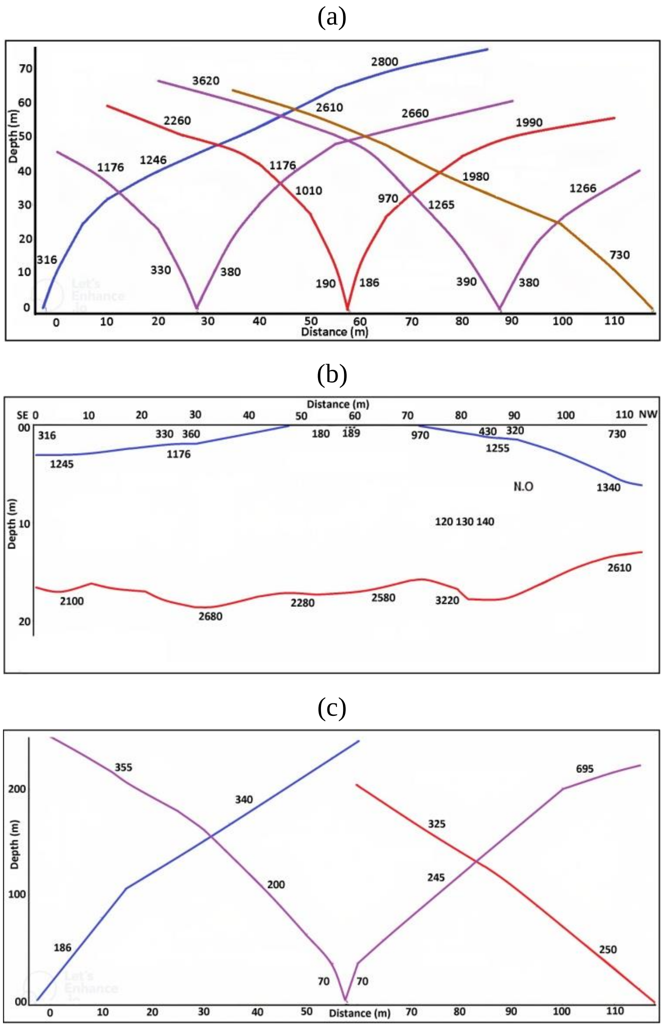


Figure 6. Left: Seismic and Hodochron cross-sections of P and S waves of the P_1 profile

4.3. Electrical Resistivity Tomography (ERT)

The profile is located in the middle of the studied landslide. The pseudo-section P_1 is almost occupied by a wide blue area, which is fairly conducive (Fig. 7a); it corresponds to a low resistivity not exceeding 15 Ω.m; this corresponds to a reworked, crushed and unstable layer of clay colluvium, defined as a scree slope, which explains the refusals obtained at shallow depths (0.6-2.0 m) by dynamic penetrometer test during the geotechnical study. It is sufficiently wet and saturated to allow water circulation and to decrease electrical resistivity. This zone is 17 m deep along the main axis, but it is reduced along the sides of instability. The tomographic profile is between 10 and 13 meters thick in the east. This depth is informative about the degree of instability in the vertical direction. This zone is very heavily landslide, and various disturbances in the building can be observed on its surface.

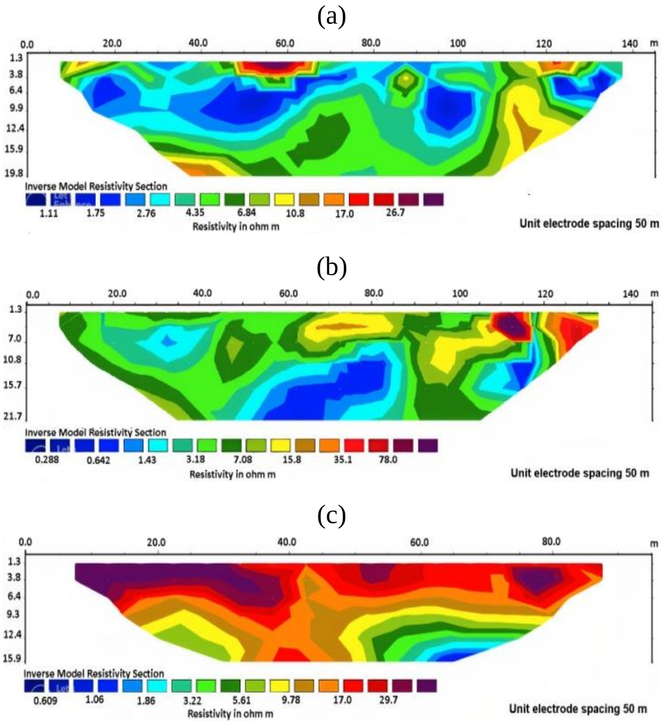


Figure 7. Geo-electrical sections: (a) P_1; (b) P_2; (c) P_3

The high porosity of these soils clearly indicates that we are dealing with the presence of loose soils that enhance both water infiltration and seepage. The shear angle can be represented by a dark blue range, representing a paleo-channel whose axis is inclined from NE to SW. The experience has shown that for several superficial landslides, saturation is the key element. Below lies a relatively more resistant horizon rising from a depth of 13m in the eastern part of the profile. This layer is above the horizon from 20 to 45 Ω.m, and behaves electrically as a compact and consolidated material. It is not highly recommended to identify it as a substratum because it can be the ubiquitous sandstone blocks in the subsurface.

As for the P_2 profile parallel to the direction of motion (Fig. 7b), its pseudo-section shows a depth of 24 m with a predominance of a conductive range that corresponds to a reworked clay matrix. It carries blocks of metric sandstone, which are represented by a resistivity of the order of 40 Ω.m from a depth of 7 m.

Finally, the P_3 profile (Fig. 7c) is made upstream of the affected buildings. The pseudo-section indicates a depth slightly exceeding 18 m over a transept length of about 95 m. The resistivity values vary between 0 and 60 Ω.m. Two underground horizons are distinguished: a superficial horizon that is relatively more resistant, and another deep conductive horizon. The first horizon is characterized by a higher resistivity, from 20 to more than 60 Ω.m; it could correspond, according to the nearest penetrometer log, to areas of Numidian sandstone-clay sheet, which outcrops in the surrounding massif, whose thickness does not exceed 10 m. The second one is rather a conductive horizon, represented by the blue range in Figure 7b and having a lower resistivity, not exceeding 10 Ω.m; it corresponds to clay-dominated colluviums that are moist and sufficiently reworked to increase groundwater circulation resulting in a significant drop in the subsoil resistivity.

Therefore, the terrain is stable on the surface, but instead causes instability indices at depth. This is informative about the deep nature of instability.

5. Conclusions

Refusals obtained by dynamic penetrometer test at shallow depths (0.6 to 2.0 m) during the geotechnical study indicate the presence of sandstone blocks that form the scree slope rather than bedrock. The poorly structured image of the different underlying layers or boundaries between less net layers and the reworked state of the subsoil clearly indicate that the site has already undergone difficult sliding periods in its history, although it does not exhibit any manifestation or significant indication of instability on the surface. Based on these results, the continuous evolution of instability can be explained by the fact that the undertaken remedial measures are designed to ensure that the sliding plane is located at a maximum depth of less than 10 m. Unfortunately, the bedrock is much deeper and can be up to 50 m deep, and the soil above it has undergone sliding most of the time and has therefore been reworked and saturated with water.

Our recommendations consist of topographic topographic, inclinometric and piezometric monitoring for slip development and the effectiveness of reinforcement measures for new housing, and equipment programs for regional planning. It is highly recommended to develop geophysical, geotechnical and geological reconnaissance plans (projected earthworks, ground plans, etc.) first. We find it interesting to expand the focus of our research to the Numidian formations, which appear to be causing instability problems.

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Визначення характеристик обвалення схилу: спільний мультигеофізичний і геотехнічний аналіз, дослідження на прикладі гірського хребта Бабор, північно-східний Алжир

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Мета. Вивчення зсувної активності в районі Тарзуста шляхом застосування оригінального комбінованого підходу на основі геофізичних підходів для серйозних техногенних катастроф у регіоні.

Методика. У цьому дослідженні використано вертикальне електричне зондування (VES) і метод сейсмічної рефракції (SRM) для підземної розвідки, а також електротомографію специфічного опору (ERT) для підтримки останніх двох методів.

Результати. Виявлено, що відмови, отримані динамічним пенетрометричним випробуванням на малих глибинах (від 0.6 до 2.0 м) під час проведення інженерно-геологічних досліджень, свідчать про наявність блоків пісковика, що формують схил осипу, а не корінних порід. Підтверджується глинистий характер місцевості, дуже часто покритої мантією поверхневих колювіальних утворень. Точно визначено глибину залягання корінної породи та поверхні зсуву. ERT показує, що в минулому місцевість вже зазнавала нестабільності. Запропонований підхід довів, що поєднання геологічних і геотехнічних даних із геофізичними детерміністичними методами може допомогти інженерам та особам, які приймають рішення в землеустрої.

Наукова новизна. Оригінальність цього дослідження полягає в поєднанні даних з різних джерел і різних підходів визначення зсувної активності з метою планування засвоєння й використання земель.

Практична значимість. Запропоновано рекомендації, що складаються з топографічного, інклінометричного та п’єзометричного моніторингу розвитку ковзання й ефективності заходів з укріплення нових житлових будинків, а також програм обладнання для регіонального планування.

Ключові слова: *обвалення схилів, томографія, опір, сейсмічна рефракція, субстрат*