INNSPUB

Journal of Biodiversity and Environmental Sciences (JBES)
ISSN: 2220-6663 (Print) 2222-3045 (Online)
Vol. 21, No. 4, p. 70-80, 2022
http://www.innspub.net

RESEARCH PAPER OPEN ACCESS

Landslides activity investigation in the Babor Mountain Chain: A combined approach for Tarzoust Site, Northeastern Algeria

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Article published on October 15, 2022

Key words: Slope failures, Tomography, Resistivity, Seismic refraction, Substratum

Abstract

Landslides harm roads and structures in many parts of Algeria; especially in Tarzoust city; where spectacular slope failures occurs since spring 2004, causing serious disasters in the region. Our methodology uses the Vertical Electric Soundings (VES) and the Seismic Refraction Method (SRM) for the underground prospection, and the Electrical Resistivity Tomography (ERT) to support the last two methods. The result confirms the clayey nature of the terrain very often covered by a mantle of superficial colluvium formations. The depth of the bed rock and shear surface were precisely determined. ERT reveals that the terrain has already undergone instabilities in the past. Our approach proves that the combination of the geological and geotechnical data with geophysical deterministic methods can helps engineers and decision-makers for land management.

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Introduction

Landslides are considered among the most perilous natural phenomena threatening humans and their physical environment. In addition to material damage, they cause tragic human losses throughout the world (Fell 1994, Zillman 1999, Glade *et al.,* 2005, Gadri *et al.,* 2015; Hadji *et al.,* 2017a, b; Dahoua *et al.,* 2017; 2018; Anis *et al.,* 2019).

Einstein (1988) stated that when field and environmental conditions play in a way that predisposition and triggering factors act simultaneously, landslides can become extremely disastrous (Hadji *et al.,* 2013, 2014a; Zahri *et al.,* 2016; El Mekki *et al.,* 2017; Tamani *et al.,* 2019).

To study landslide occurrence in a given area, several approaches can be used. The direct methods, where field and laboratory data are required and a safety factor is computed, using one of the well-known stability analysis techniques such as limit equilibrium, finite elements (Zeqiri *et al.,* 2019).

However, they provide information at a specific location and it is not costly effective to evaluate the spatial distribution of safety factors as a large number of samples and tests in the affected area are required (Chengpeng Ling *et al.,* 2016; Achour *et al.,* 2017; Hadji *et al.,* 2016; Manchar *et al.,* 2018).

These techniques would allow an assessment of landslides at some scatered locations which gives an idea of the stability state of the area but a complementary geophysical study would be an ideal tool to deal with this difficulty (Mahdadi *et al.,* 2018).

In the Babor mount-chain and its neighbouring such as the Neogene basin of El Milia, landslides of variable type and size often take place (Karim *et al.,* 2019). They caused several desorders such the tilt between buildings in Tarzoust city. These instabilities evolved over time with variable velocities despite the installation of draining trenches of 3m depth and micro-piles of 10 m depth (Fig. 1).

Fig. 1. Induced disorders in 660 collective housing, in Tarzoust city.

Geophysical methods, such as Vertical Electric Sounding (VES), Electrical Tomography, Seismic Refraction, or Ground Penetration Radar (GPR) are investigative tools adapted to the ground instability study (Deparis, 2007). They constitute an effective tool to characterize landslides, while reducing the use of more expensive and costly methods (Feregotto *et al* 2010). In case of landslides, they can characterize the internal land structure and the situation of the moving masses (Cardarelli *et al.,* 2008; Göktürkler *et al.,* 2008; Bievre 2010; Rouabhia *et al.,* 2012; Grandjean *et al.,* 2013; Rais *et al.,* 2017). Geophysical techniques are also used to identify the geometries 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 (Fehdi *et al.,* 2014; Redhaounia 2015).

In general, it is an efficient means to follow the evolution of karstic terrains (Miller and Steeples 1991, Kaufmann and Romanov, 2009; Balkaya *et al.,* 2012; Nouioua *et al.,* 2013; Hames *et al.,* 2014; Carbonel *et al.,* 2014; Redhaounia *et al.,* 2016; Mokadem *et al.,* 2016; Mouici *et al.,* 2017). Nevertheless, a particular geophysical method may not be suitable for all types of mass movement processes. A careful selection of a method or a combination of several methods is necessary, considering the local geological and structural parameters and the type of mass movement (Hadji *et al.,* 2014a, b). Currently, geophysical methods are commonly applied for the detection of different types of underground anomaly (Hamed *et al.,* 2014, 2017a, b, 2018).

Our work aims to apply an original combined approach to the study of landslide occurence in the Tarzoust region. In this study, the geophysical study involves Electrical Resistivity Tomography (ERT), Seismic Refraction and Vertical Electrical Sounding (VES).

Tarzoust city is located on the northeastern side of the Neogene basin of El Milia, at 57 km southwest of the chief-town of 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).

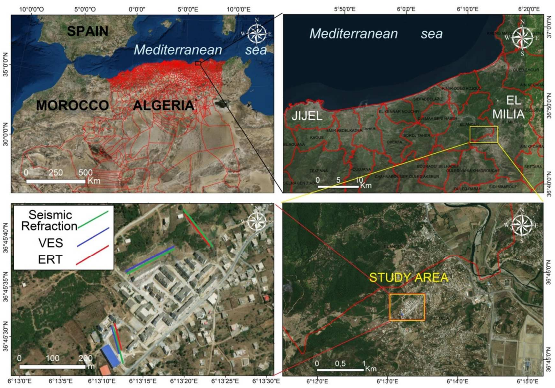

Fig. 2. Geographic location of the Tarzoust city.

The study area is affected by major multidirectional regional tectonic events (NS, EW, NE-SW and NW-SE) (Bouftouha, 2005). These tectonic events have caused the setting up of El-Milia Neogene basin, and played an important role in the Trias uplift (notably the Bellara outcrop). Moreover, these tectonic events were later reactivated as strike-slip faults and affected the Miocene formations, as it is well illustrated in the El-Milia micrograniti formations. The NS tectonic events (normal fault) were identified at the sandstone bed (Fig. 3a) (Demdoum *et al.,* 2015).

The study site cumulates several formations, namely a fractured and diaclased massive sandstone formation of Aquitanian age, overlaying a clay formation; these latter are recognized by Sub-Numidian clay of Upper Oligocene age (Fig. 3b). In several points at the site, the sub-numidian clays are covered by a mantle of scree slope; the clay matrix is abundant in large proportion; the sandstone blocks are coarse, porous and they can reach several cubic meters in size. This altered zone reach 20 m in the middle part of the urbanized site. The site is subject 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 surface during winter and spring times. The general flow is SW/NE direction.

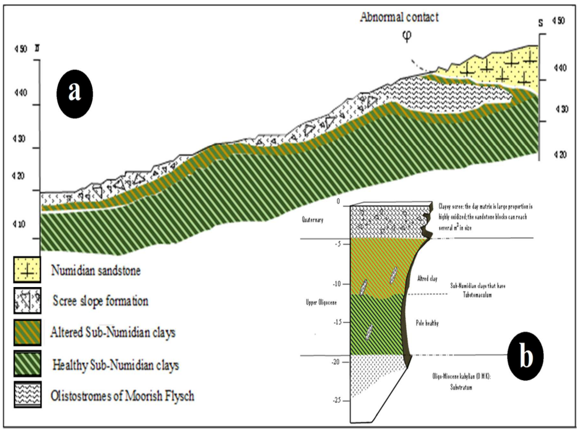

Fig. 3a. Geological cross section in the study area. b: Stratigraphic column of Tarzoust city.

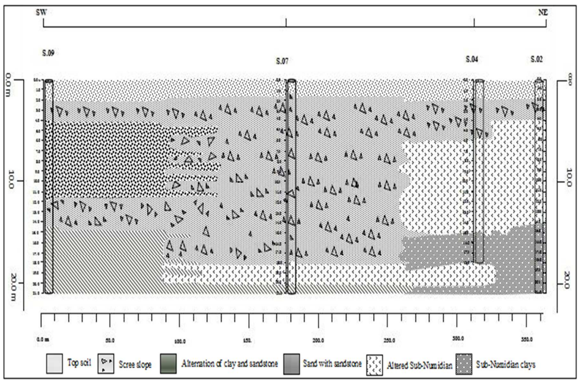

Fig. 4. Lithofacies correlation, passing through S9, S7, S4 and S2 sounding.

Material and methods

Many authors have applied geophysical techniques to delineate the sliding surface, the hydrogeological regime, or to monitoring landslides (Park 1998.; McCann and Foster, 1990, Havenith *et al.,* 2000; Hack, 2000, Lapenna *et al.,* 2003, 2005; Bichler *et al.,* Colangelo *et al.,* 2006; Friedel *et al.,* 2006; Sastry *et al.,* 2006, 2007, Jomard *et al.,* 2007; 2008; Mondal *et al.,* 2007, 2008; Erginal *et al.,* 2009; Piegari *et al.,* 2009; Perrone *et al.,* 2014; Besser *et al.,* 2018). 3D and 4D ERT (Chambers *et al.,* 2011;

Wilkinson *et al.,* 2010; Schmutz *et al.,* 2009 ; Göktürkler *et al.,* 2008; Jongmans and Garambois 2007; Friedel *et al.,* 2006; Lebourg *et al.,* 2005; Hamad *et al.,* 2018a, b) and fast 2D (Bichler *et al.,* 2004; Perrone *et al.,* 2004; Yang *et al.,* 2004; Lapenna *et al.,* 2003, 2005; Lebourg *et al.,* 2005; Drahor *et al.,* 2006; Sastry *et al.,* 2006, 2007, 2008; Mondal *et al.,* 2007). In our study, we combined two methods: VES and SRM. The main objective was to identify the study site's lithology, with a precise sub-soil structure, to define the piezometric level and the substratum depth, therefore, we decided to complete and confirm the results obtained by the ERT, (Fig. 4).

Investigation by VES

The VES is one of the most widely used geophysical methods in shallow-depth prospecting (Telford *et al.,* 1990; Reynolds, 1997). For 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 nature of the sub-soil (Telford *et al.,* 1990; Jongmans *et al.,* 2007). For this survey, we performed 3 Schlumberger-type sounding at the location of the electrical panels and seismic profiles; the characteristics of the profiles are shown in Table 1.

Table 1. Characteristics of VES profiles.

Type		Orientation	Length: (m) %	Beginning (x), (y)	End (x), (y)	Observations
Electrical VES Schlumberger	P1	NW-SE	140	252131 4071953	252037 4072065	Overlap of 2 cables
	P2	N-S	140	251881 4071877	252014 4071945	Overlap of 2 cables

Investigation by SRM

In contrast to seismic reflexion surveys that have rarely been used in landslide studies (Bruno and Marillier 2000, Ferrucci *et al.,* 2000, Bichler *et al.,* 2004), seismic refraction is widely used in engineering geology to determine the bedrock depth. It has been found applicable for landslide studies as shear and compression waves velocities are generally lower in the disturbed soil mass than in the non-affected soil. M^{c} Cann and Forster (1990) 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 (Kearey *et al.,* 2002; Zahri *et al.,* 2017). In order to acquire two seismic profiles (P_1 and P_2), we used Summit/X/Stream/Pro device of DMT.l with ReflexW seismic refraction interpretation software (Sandmeier Scientific - Germany) which allows us to arrange and load the different shots with their geometry (table 2).

Table 2. Characteristics of seismic profiles.

Type		Orientation	Length (m) %	Beginning (x), (y)	End (x), (y)	Observations
Seismic refraction	p1	NW-SE	120	252131 4071953	252037 4072065	Overlap of 2 cables
	p2	N-S	120	251859 4071592	251828 4071684	/

Investigation by ERT

The ERT method (Loke and Barker, 1996; Giano *et al.,* 1997) provides a high- resolution image of the sub-soil for terrains with complex geological structure. It has been proven to be useful for a multitude of problems, including pollution of coastal aquifers (Frohlich *et al.,* 1994), mapping of hydrogeological systems (Ramirez *et al.,* 1993, Coppola *et al.,* 1994, Gallipoli *et al.,* 2000), or for the study of landslides (Mahmut G. Drahor *et al.,* 2006, Hamza Reci *et al.,* 2013, A. González-Díez *et al.,* 2017). The results obtained seem to be fairly significant (Chabaane *et al.,* 2017). For our study, the SARIS of Scintrex device, with Res 2Dinv, program for automatic 2D reversal of apparent resistivity data, the electrical braids with five electrode sockets spaced 5 meters apart and steel electrode stakes were used to acquire three profiles of electrical imagery (P1, P2 and P3). The first two profiles (P1 and P2) have a length of 145 m; the third one (P3) is 95 m length. The geometrical characteristics and orientation of the profiles produced are given in table (3) and the different profiles are shown in fig. (2).

Table 3. Characteristics of ERT profiles.

Type		Orientation	Length:(m) %	Beginning (x), (y)	End (x), (y)	Observations
ERT	P1	NW-S	145	252131 4071953	252037 4072065	Overlap of 2 cables
	P2	NW-SE	145	251881 4071877	252014 4071945	Overlap of 2 cables
	P3	N-S	95	251859 4071592	251828 4071684	/

Results and discussion

In many cases, the information on the geological depths and lateral continuity of sliding surfaces cannot be obtained through drilling or geological investigations. Fortunately, the geophysical study can complete the dataset of the subsoil parameters for a better understanding of the physical behavior of a slope, (Godio *et al.,* 2001).

Vertical Electrical Soundings (VES)

The first VES_1 (Fig. 5a) has allowed to draw a transverse geophysical section at 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 very low resistivities, about 3-7 *ohm.m*. This is the reworked mass from crushed wet and conductive clays.

At a depth of 52 m, any trace of tne bedrock was detected in the middle of the slope, which indicates the extent of the underground disorder on which the buildings are located. In addition, resistivities are too low from 2 to 3 ohm.m, which clearly indicates the presence of gypsum.

The realization of a cross-section of correlation lithofacies, passing through the respective sounding S9, S7, S4 and S2 (Fig. 4), clearly confirms the reworked state of the ground as well as the abundance of sandstone blocks of different sizes that give false penetrometric refusals at very low depths.

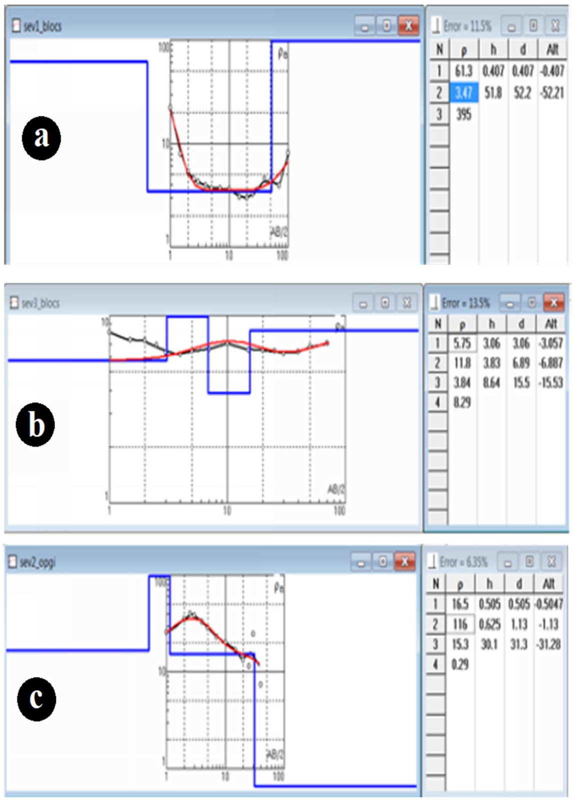

Fig. 5a. VES_1 electrical vertical cross-section. b: SEV_2 Vertical electrical cross-sections. c: VES_3 Vertical electrical cross sections.

The second VES_2 (Fig.5b) shows two distinct layers. A first layer is relatively more resistant with a resistivity of 300hm.m, whose thickness has not been precisely determined, and another more conductive layer with a depth exceeding 32 m. This is consistent with our electrical panels, which indicate the existence of a sound, consolidated layer (consolidated Sub-Numidian clays).

To define the sub-terrain in all these dimensions, the last VES_3 (Fig. 5c) was placed longitudinally relative to the others; it is 140 m long. The section shows a single conductive layer with an average resistivity of 50hm.m; its depth is about 16 m.

Seismic Refraction Profiles (SRM)

P_1 Profile: The seismic profile P1 is oriented to SE-NW direction. The section for the compressive waves "P" highlights three distinctive velocity ranges: the first range with a velocity comprised between 190 and 730m/s that has a thickness varying from 2 to 6 meters, the second interval with a velocity between 970 and 1380m/s that has a thickness varying from 7 to 17 meters and the third range between 1990 and 3420 m/s. The results obtained for the compression and shear waves recordings are given in tables (4) and (5).

Table 4. Digital results for P1 Profile "P wave".

Shot point	V1 [m/s]	V2 [m/s]	V3 [m/s]	H1 [m]	H2 [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 P1 profile "S waves".

Shot point	V1[m/s]	V2 [m/s]	V3 [m/s]
TD	165	340	-
TC-G	70	200	355
TC-D	70	245	695
TR	250	325	-

Profile P2

The seismic profile P2 is oriented NW/ S. The results obtained for thecompression and shear waves recordings are given in tables (6) and (7):

Table 06. P2 Profile digital results "P waves".

Shot point	V1 [m/s]	V2 [m/s]	V3 [m/s]	H1 [m]	H2 [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

The geo-seismic section for the compressional waves highlights three distinct speed velocity ranges, namely the first range with a velocity between 460 and 750 m/s and a thickness varying from 3 to 5 meters, the second with a velocity between 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 two profiles are shown in fig. (6).

Table 07. P2 Profile digital results "S waves".

Shot point	V1 [m/s]	V2 [m/s]	V3 [m/s]
TD	195	340	860
TC-G	160	320	-
TC-D	165	295	-
TR	265	465	780

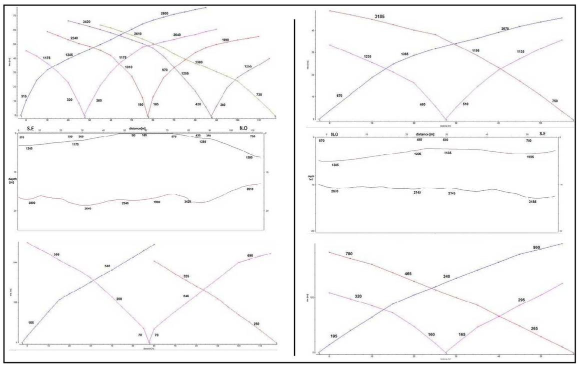

Fig. 6. Left: Seismic and Hodochron cross-sections of P and S waves of the P_1 profile. Right: of Seismic and Hodochron of the P and S waves of the P_2 profile.

The results of the seismic profiles allowed us to confirm the heterogeneity and the presence of a reworked zone.

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. 7, a); it corresponds to low resistivities not exceeding 15 *Ω.m*; this corresponds to a reworked, crushed and unstable layer of clay colluvium, which is defined as scree slope, which explains the refusals obtained at shallow depths (0.6-2m) by the dynamic penetrometer test during the geotechnical study. It is sufficiently wet and saturated to allow water circulation and to decrease electrical resistivities. This zone is a 17m deep along the main axis, but it is reduced on the sides of instability. The tomographic profile is about 10 to 13 meters thick in the East.

This depth is informative about the extent of instability in the vertical direction. This zone is very invaded by landsliding, where we could observe, at its surface, various disorders in the building. The high porosity of these soils clearly indicates that we are in the presence of loose soils that increase both water infiltration and seepage. The shear angle can be represented by the dark blue range, which is representative of a paleo-channel, whose axis is inclined from NE to SW. For several superficial landslides, the experience has shown that saturation is a key element (Benaissa *et al.,* 1989, Bougdal 2007, Bougdal *et al.,* 2013). Below comes a relatively more resistant horizon that rises from 13m of depth in the eastern part of the profile. This is a layer above a horizon of 20 to 45 Ω.m, which electrically behaves like a compact and consolidated material It is not highly recommended identifying it as a substratum, because it can be the ubiquitous blocks of sandstone in the sub surface.

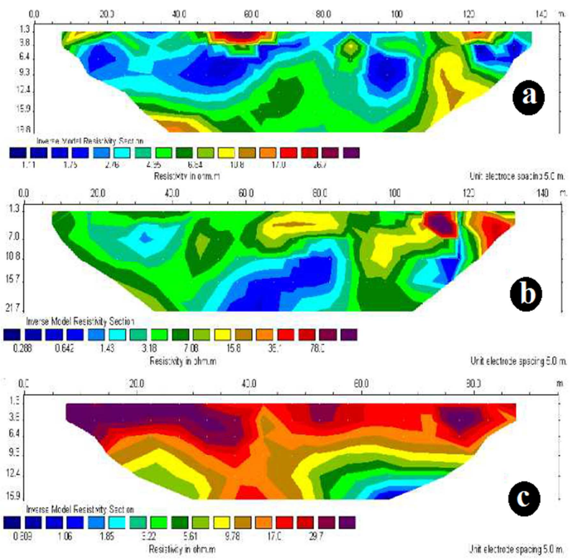

Fig. 7.a. geo-electrical section. P_1.b: Geo-electrical sections P_2.c: P3 geo-electrical section.

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

Finally, the profile P_3 (Fig. 7, c) was carried out 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 more than 60 Ω.m. Two subground horizons are individualized: a superficial horizon that is relatively more resistant and another deep conductive horizon. The first horizon is illustrated by higher resistivities, between 20 and more than 60 Ω.m; it could correspond, according to the nearest penetrometer log, to parts of Numidian sandstone-clay sheet, which outcrops in the surrounding massif, whose thickness does not exceed 10 m. The second is rather a conductive horizon represented by a blue range in the fig. (7, b) and having lower resistivities not exceeding 10*Ω.m*; it corresponds to clay-dominated colluviums, moist and sufficiently reworked to increase groundwater circulation, inducing a considerable fall in the resistivity of the subsoil. The terrain is therefore stable at the surface but instead gives rise to indices of instabilities in depth. This is informative about the deep nature of instability.

Conclusions and recommendations

Our work add new information about the actual depth of the bedrock in the study site that exceeds 15 m. The refusals obtained by the dynamic penetrometer test at very low depth (0.6 to 2m), during the Geotechnical study indicates that we are in the presence of sandstone blocks that are forming the scree slope and not the bedrock. The poorly structured image of the different underlying layers or the limits between the less net layers and the reworked state of the subsoil clearly indicate that the site would have already undergone complex sliding periods in its history, although it did not exhibit any manifestation or significant indication of instability at the surface. Based on these results, the continuous evolution of the instability can be explained by the fact that the undertaken remedial measures were designed on the assumption that the sliding plane is at a maximum located in a depth less than 10 m. Unfortunately, the bed rock is much deeper and can be 50 m deep and the soil above it is most of the time has undergone slippage and therefore reworked and saturated with water.

Our recommendations consist of a topographical, inclinometric and piezometric monitoring of the evolution of the slip and the effectiveness of the reinforcement means for new housing and equipment programs for regional planning. It is strongly recommended that geophysical, geotechnical and geological reconnaissance plans (projected earthworks, ground plans, etc.) get developed first. We find it interesting to expand our research focus on the Numidian formations that seemingly are likely to cause instability problems.

Acknowledgements

The authors would like to acknowledge the technical support of the direction of town planning and construction of the Jijel province, the International Association of Water Resources in the Southern Mediterranean Basin, and the staff of CTC/East and the National Housing and Construction Laboratory/Rouiba/Algers for providing the data needed to carry out this work. We are grateful to the anonymous reviewers for their review and critics that led to the improvement of the manuscript.

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