DOI: 10.2478/sspjce-2023-0006

Use of Electrical Resistivity Tomography for Joint Geophysical and Geotechnical Landslide Characterization: A Case Study

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Abstract

Slope movement processes include complex soil and rock failure mechanisms. Their study benefits from a multidisciplinary approach based on a wide range of information including geological and geomorphological mapping, and geotechnical and geophysical investigations. This research paper focuses on the characterization of the Tamentout landslide that occurs in the southeast of Jijel province. The study area belongs to the Tellian domain in which the geological outcrops are dominated by Senonian formations, composed of marl deposits overlain by Numidian flysch of Aquitano-Burdigalian age, with a sloping topography ranging from 20° to 30°. The geophysical approach consists of processing the available geophysical data of resistivity, obtained by the Electrical Resistivity Tomography (ERT). This study aims to characterize the internal structure, and the changes in water saturation within the unstable mass and locate the depth of slip surface associated with this landslide. Through this work, we combined geological and geotechnical investigations with electrical resistivity tomography (ERT). This combination gave a more detailed image of the substrate geology and structure of the landslide zone. The 2D resistivity results show that the basement consists of two main formations. The first one is a highly conductive formation with a resistivity range between 2 and 25 Ωm, a depth of 0-8 m, and is interpreted as a saturated marl-clay overlaying. The second, a hard and compact formation with a resistivity range between 50 and 200 Ωm and a depth range of 8 to 40 m, was interpreted as a substrate of tellian marls. The presence of boulders of Numidian sandstone within the two formations is materialized by a very high resistivity value ranging from 500 to 1000 Ωm. The slip surface was located on the layer with low resistivity (2-25 Ωm). The precise determination of the depth of the shear zone is of vital use in implementing mitigation measures and carrying out the stabilization work of this unstable zone. Through this work, we will highlight the advantage of the combination of available results of the geological, geotechnical investigations and electrical resistivity tomography (ERT) carried out in the study area.

Keywords: Tamentout, landslide, electrical resistivity tomography (ERT), resistivity, slip surface.

1 Introduction

Landslides are complex geological phenomena that can have disastrous consequences [1, 2]. The study of this damaging phenomenon involves the application of a combined approach based on a wide range of data including geological and topographical investigations combined with geotechnical and geophysical measurements [3, 4]. In recent years, the application of

geophysical methods to landslide studies has evolved considerably [5, 6]. Due to the rugged terrain and abrupt topographic changes in the landslide areas, it was difficult to conduct such investigations. Recently, some geophysical imaging techniques based on tomography are commonly used in shallow surveys [5, 7, 8], the purpose of geophysical prospecting applied to ground movements is mainly to identify the lateral limits of the mass in motion, the slip surface in depth, as well as the imaging of the internal structure of the moving body [6, 9].

Landslides are among the most, widespread and damaging natural hazards in northern Algeria. They represent a major threat to the population, buildings, and various infrastructures in most mountainous regions [1, 10, 11]. These phenomena are frequent in the Jijel region, due to the high relief and the lithological complexity of its soils, as well as climatic conditions, which it is considered among the rainiest areas in Algeria. Among landslides in the Jijel region, there are those of Tamentout.

This study aims to the contribution of Electrical Resistivity Tomography (ERT) for the Tamentout landslide (located between the PK 42 + 260 and 43 + 050) characterization, and how geophysical information can improve our knowledge about the geometry of this sliding zone portion. This work highlights the advantage of using geological, geotechnical investigations, and those acquired from the use of electrical resistivity tomography at the study area.

2 Geographic Location and Geological Context

Djimla is a mountainous region covering an area of 65.28 km² located 45 km southeast of Jijel province (northeast Algeria). With its elongated shape, it is characterized by a steep topography, and altitudes vary from 209 m to 1548 m (Figure 1). Tamentout region is a mountain group belonging to the reliefs of Djimla. The geological, topographical, and climatological features of the region are particularly favorable for ground movements.

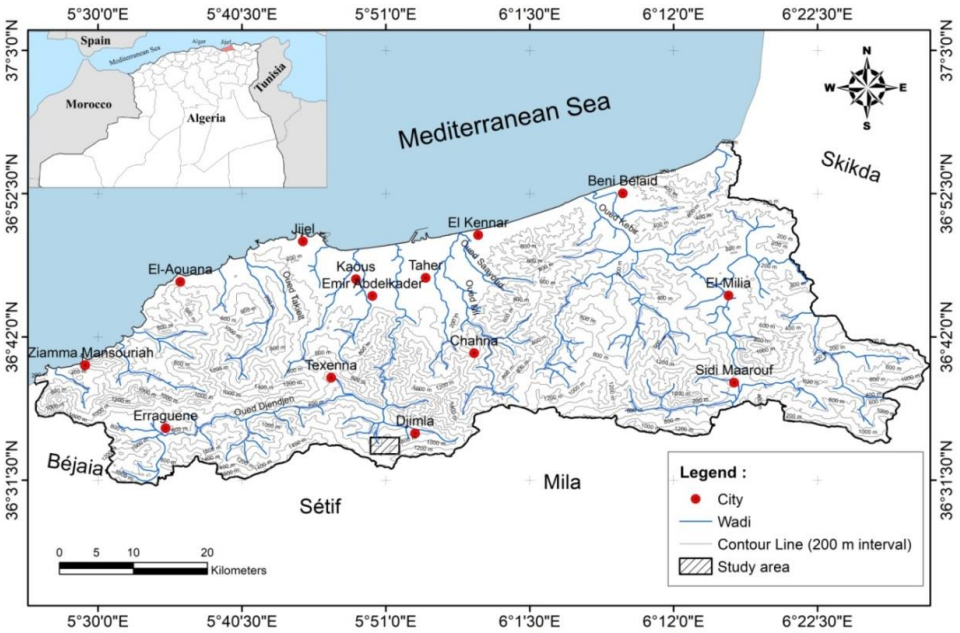


Figure 1: Geographic location map of the Tamentout landslide (Northeast Algeria)

The landslide targeted by our study is located at 5.5 km southwest of Djimla village, and 2 km northwest of the Tamentout col. Its geographical coordinates are: 5 ° 49 '26 "East and 36 ° 33' 51" North (Figure 1).
The study region had long attracted the attention of geologists. Indeed, this mountainous region is characterized by an important geological contrast (Figure 2), which became a subject of research conducted by several geologists. The Djimla region, which includes the study area, is located in the contact zone between internal and outer domain formations “crystallophyllian basement, tellian formations” [12, 13, 14].

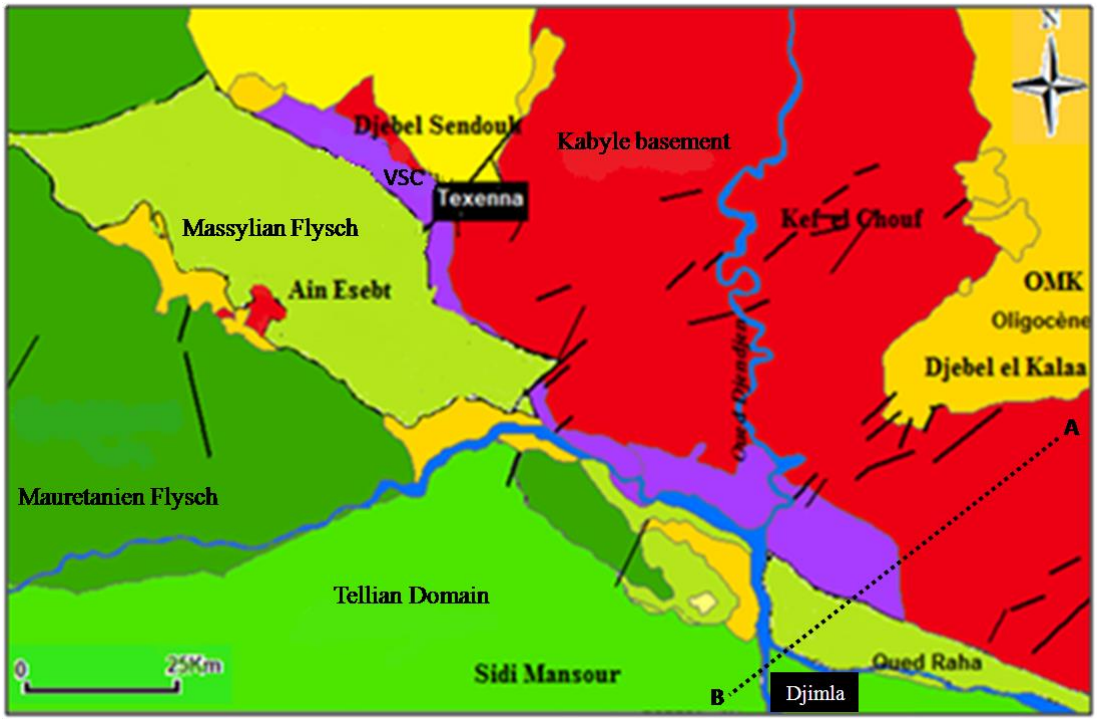


Figure 2: Geological map showing the alpine units of Petite Kabylie-Jijel region, slightly modified [13]. AB: Cross-section

The geological formations that are outcropping in the study region (Figure 3 and 4) are mainly characterized from top to bottom as follows:
- The Numidian flysch occupies the highest structural position in the Alpine structure. It is composed of three terms that are in stratigraphic continuity from top to bottom: (1) A higher term with selexites, the upper part of which reaches basal Burdigalian [12, 13]; (2) A median term formed by Numidian sandstones in thick benches, with heterometric grains and a quartz dragees, dated Aquitanian to lower Burdigalian [13, 14]; (3) A basic term consisting sub-Numidian clays, sometimes varicolored, green, red or purplish to Tubotomaculum. The Numidian formations lie in discordance on tellian formations (Figure 3) [12, 13].

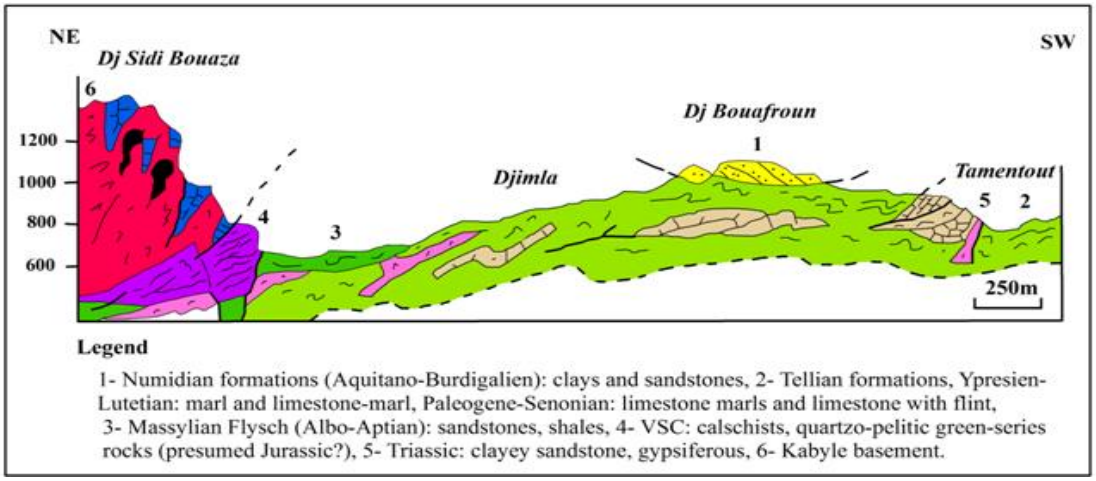


Figure 3: Geological cross-section NE-SW shows the structural feature of the Tamentout region where the landslide occurred [6]

The Tellian formations are represented in Tamentout by a group (about 100 m) of the Campanian- Maestrichtian (term1), a term from the Paleocene (term2), (term3) admitting to their summit of "Suessonian" facies limestones with flint (term4). The terms 2, 3, and 4 are between 250 and 300 m thick. On the term (4) that is attached to the Ypresian finally arrive about 80 to 100 m of black marl is observed (term 5) past lime, locally shaped yellow balls are observed and the Lutetian terminates this lithological series [13, 14].

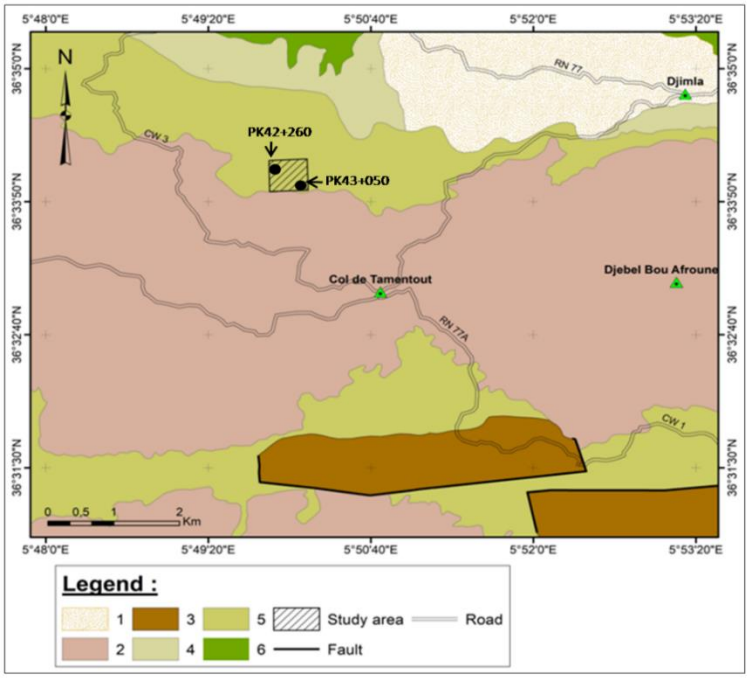


Figure 4: Geological map of the study area (Extracted from "Tamesguida" geological map at the scale 1/50.000, slightly modified [28]. 1-Quaternary: slope scree consisting, 2-Numidian formations (Aquitano-Burdigalien): clays and sandstones, 3-4-5 and 6-Tellian formations (Maastrichtian-Danian to Eocene): schistose marls and clays, schistose marls, marls, and limestone with flint

3 Causes and Landslide-Related Disorders

This slope extends in the direction of N-NE. Disorders observed in the study area are induced by the combination of several geological, hydrogeological, and geotechnical dynamics. Among the degradations observed on-site, we can cite:

- The presence of instability indices materialized by slumping bulges and cracks, also the lining trees and electrical poles down the slope.
- Very significant damage to the pavement with fissures and ground breaks, especially at the level of tectonic weakness zones.

Landslides do not usually occur as a result of a single cause. They are often observed after the occurrence of several harmful factors that initiate instabilities. This combination is at the origin of the triggering ground movement such as:

- Slope: the stability conditions of terrain being directly linked to its slope; in the study site we observed moderate to steep slopes.
- Lithology: marl-clay nature of the grounds and their permeability rate and sensitivity in the presence of water.
- Hydroclimatological and hydrological characteristics of the study region: The region of Tamentout is characterized by a mild and rainy Mediterranean climate in winter with hot and dry summer. It receives a height of rainfall ranging from 1000 to 1200 mm/year; during the cold season, hail and snow are observed mainly on reliefs exceeding 800 m altitude. The study area is well watered; due to the frequency and intensity of these precipitations, and the occasional occurrence of hail and snow on the Djimla Mountains, which is feedings potential landslide areas [6, 10, 15].
- Geologic structures: Main axes of unstable zones (presence of regional faults).
- Anthropogenic factors: Following earthworks (overload at the head of the already unstable slope, discharge in the foot removing a stabilizing stop, etc.).
- Earthquakes: According to the Algerian seismic regulation, the region of Jijel is characterized by medium seismicity (Zone IIa) with acceleration in order of 0.25 g [16].

4 Methodology

4.1 Geotechnical Investigation

In order to obtain more complete interpretation and to analyze the correlation between the lithology of the landslides and determined the distribution of electrical resistivity on the profiles; results of geotechnical tests carried out in 2016 were used [17]. The description of soil lithology is presented in Table 1 and Figure 5. These boreholes were accompanied by piezometric measurements.

Table 1: Lithological description of borehole's and piezometric measurements

Borehole N°	Depth in meter	Lithology	Water level in meter
SC1	0.00 – 08.30	marl-clay	
	08.30– 20.50	Sand-gravel clay with sandstone blocks	

PK 42+200			16.87
	20.50– 40.00	marl compact	
	0.00 – 04.20	marl-clay	
SC2 PK 42+560	04.20 – 30.00	Marl compact	18.77
	0.00 – 7.50	Sand-gravel clay with sandstone blocks	
SC3 PK 43+020	6.00 – 30.00	Marl compact	02.80

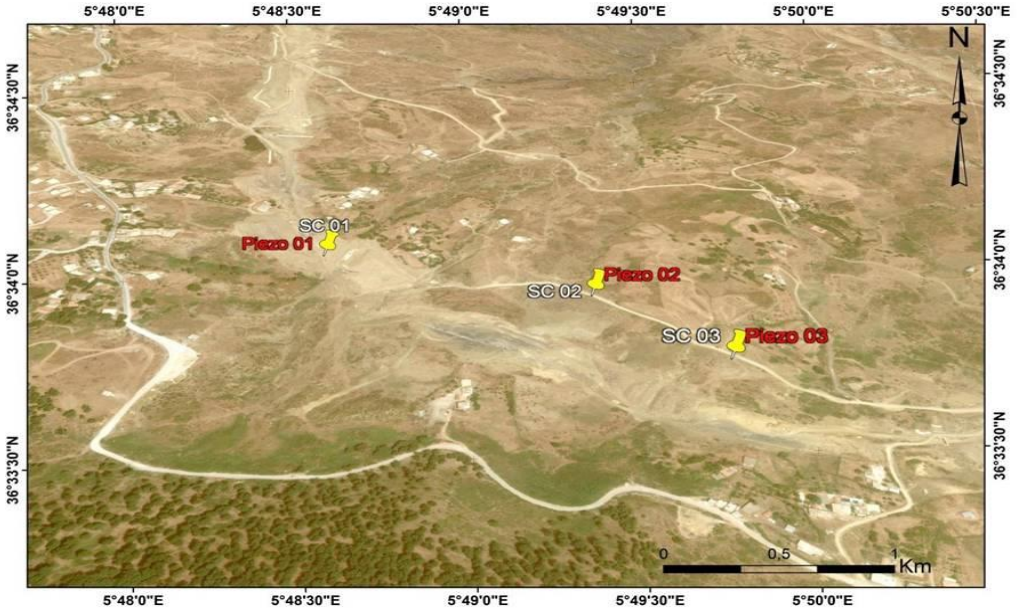


Figure 5: Location of boreholes and piezometric surveys carried out in the study area

4.2 Electrical Resistivity Tomography for Landslide Investigation

Electrical Resistivity Tomography or Electrical Resistivity Imaging is a geophysical technique derived from conventional resistivity methods used to identify subsurface soil [18, 19, 20, 21]. Electrical tomography provides high-resolution 2D, 3D, and 4D images of the basement [6, 22], [23, 24].

A set of electrical resistivity tomography profiles was carried out in the study area by the company GEOEXPLO in 2018 [25], four (4) lines of 2D resistivity surveys called RL1 to RL4 because are considered representative of the field in question was chosen for this study. These profiles were produced using a Saris / Scintrex instrument with a Wenner-Schlumberger measuring device composed of 30 steel electrodes with an electrode spacing of about 5 (m) (RL1-RL2) and 2.5 meters (RL3 and RL4) [25]. The lines RL1-RL3 were positioned northwest-southeast, while the lines RL3-RL4 were oriented northeast-southwest. The total length of profiles was varying between 130 m and 450 m and reaching around 25 m in depth (Figure 6).

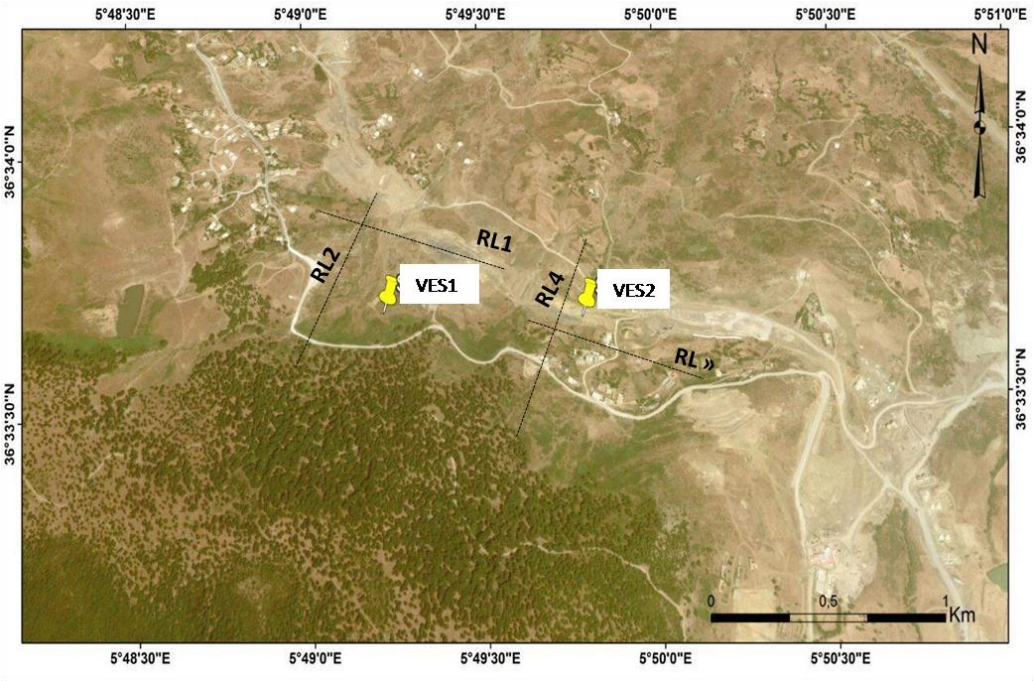


Figure 6: Locations of resistivity lines (RL) and vertical electrical soundings (VES) at the study area

5 Results and Discussion

5.1 Geotechnical Characteristics

Based on the results obtained from boreholes (Table 1 and Figure 7) show that the soil of the study area is mainly composed of a first layer represented by a friable marl-clay and/or a second layer marked by a clay with blocks of sandstone. The ensemble overlaying bedrock composed by tellian compact marls.

Table 2 lists the values of basic parameters of soils. For the type of soil encountered, the values of dry and wet densities range between 1.89-2.20 g/cm^3 and 2.18-2.42 g/cm^3, which gives dense-state formations, the water content (W) range between 6.85% and 15.20% which is characteristic of slightly wet to moist soils. The piezometric readings carried out indicated the presence of water at varying levels (Table 1). Understanding the hydrological functioning of an unstable mass is a major objective in the study of ground movements. The infiltration and circulation of water within an unstable ground can generate a progressive deterioration of the materials which will decrease the mechanical characteristics and increase the risk of triggering the phenomena of landslides.

The results of Atterberg limits tests are grouped in Table 3.

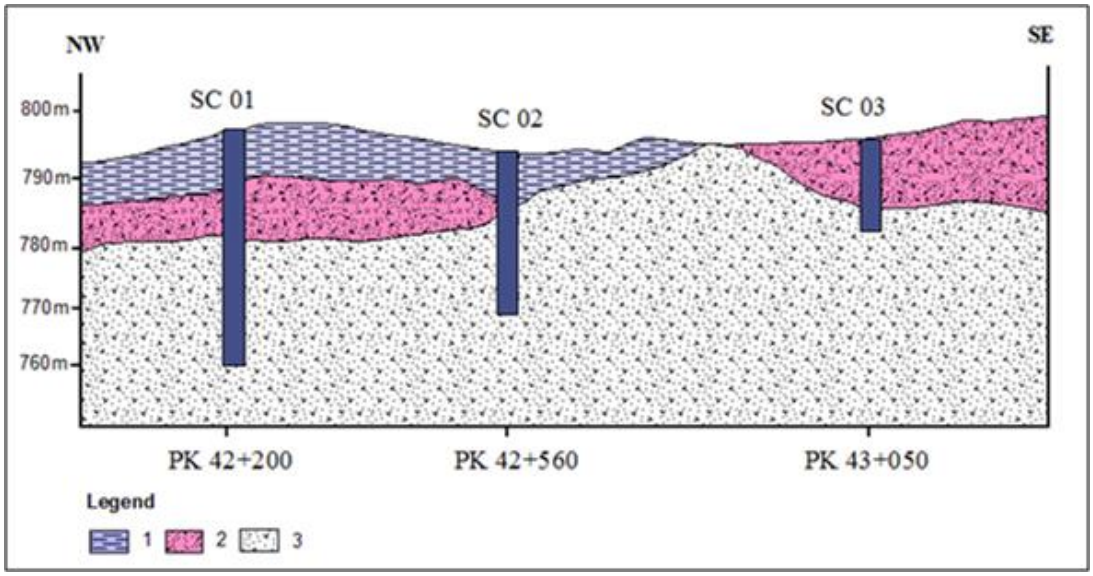


Figure 7: Lithological cross-section of the study area.1- Marl-clay, 2- gravel-clay with blocks sandstone, 3- compact marls "bedrock"

Table 2: Values on the physical parameters of soils

Borehole N°	**Depth in meter**	**Water content in %**	**Dry bulk density ρ_d in g/cm^3**	**Wet bulk density ρ_h in g/cm^3**
SC PK 42+200	35.1-35.38	6.85	2.18	2.33
	35.6-36	10.78	2.07	2.30
	36.44-36.75	8.86	2.12	2.30
	39.5-39.77	15.20	1.89	2.18
SC PK 42+560	1.30-1.57	12.20	2.16	2.42
	6.30-6.50	11.63	2.20	2.38

Table 3: Results of Atterberg limits

Borehole N°	**Depth in meter**	**Liquid Limit (WL) in %**	**Plastic Limit (WP) in %**	**Plasticity Index (PI)**	**Consistency Index (CI)**
SC PK 42+200	35.1-35.38	36	19	17	1.71
	35.6-36	32	18	14	1.52
	39.5-39.77	27	13	14	0.80
SC PK 42+560	1.30-1.57	33.81	22.06	11.75	1.84
	6.30-6.50	34.18	21.29	12.89	1.75

The liquid limits (WL) range between 27 and 36 percent, while the plastic limits (WP) range between 13 and 22 percent (Table 3). The plasticity index (PI) ranged from 11 to 17 and the

consistency index (CI) ranged from 0.80 to 1.84 percent. These results indicate that we are dealing with plastic low clay (CL) and very hard consistency.
Geotechnical tests revealed dense, slightly moist, moderately plastic and consistent soils. Marls and clays are the impermeable rocks; In other part, we note that the value of water content is very variable with depth which indicates the presence of pockets accumulation of underground water formed by gravelly-clays with boulders of sandstones which condition the setting in motion of the unstable mass. The landslide occurs in marl-clay when their water content increases significantly. Among the predominant factors for the occurrence of landslides are: 1) The low cohesion of soil, 2) The high degree of reworking, 3) Increased water content and pore pressures.

5.2 Geophysical Results

The pseudo-sections are represented at the same resistivity scale (Figure 8). The interpretation of the results was done based on resistivity ranges.
All pseudo-sections that we have selected as a part of our study show us the following:

- A change in the resistivity value indicates the change in facies; This is practically visible in all pseudo-sections.
- The appearance of saturated zones shows that the ground is very permeable in some places and shows that these areas present a preferential water circulation path.
- A line that distinguishes the boundary between two different resistivity environments. From a geological point of view, this boundary may also be a boundary between the Bed-Rock and the formations that have been displaced. The distribution of the resistivity on the different lines is as follows:

The pseudo-section ERT1 of the first profile RL1 (Figure 8a), shows the distribution of electrical resistivity at a depth of 25 meters. It shows good resistivity contrast, allowing better identification of the underground horizons and their state of stability. In this pseudo-section, the conductive formations are dominant with a high concentration in the center of the profile. These formations are characterized by a resistivity ranging between 5 and 30 Ωm, which can be attributed to saturated marl-clay, while the moderately resistant formations are scattered and located more at limits of the profile, whose resistivity values range between 50 and 100 Ωm. These resistant formations can be attributed to compact marls. The moderately resistant range located 750 m to the NW could correspond to a boulder of sandstone according to the borehole (SC01) carried out near the electrical panel.
In the pseudo-section ERT2 of the profile RL2 (Figure 8b), two lithological horizons are distinguished. A superficial horizon located at SW of the profile, and which shows a more resistant trend than the previous profile. The resistivity falls in a range between 75 Ωm and 500Ωm. This layer superimposes a second less resistant layer with a low resistivity (5-25 Ωm) on the side NE. In the center of RL2, a boulder of sandstone seems to come off and move from the SW towards NE, which can represent a slip surface on which the resistant formation outcrop in the surface can be slid.
Pseudo-section ERT3 of the profile RL3 (Figure 8c) corresponds to a conductive horizon with electrical resistivity ranging between 5 and 30 Ωm, which can be attributed to saturate marl-clay. This horizon is interspersed with moderately resistant formations, which electrical resistivity range between 50 and 250 Ωm and corresponds to compact marl. The configuration

of this resistant formation has a sliding potential on the conductive formation given the slope and shape of these two formations.

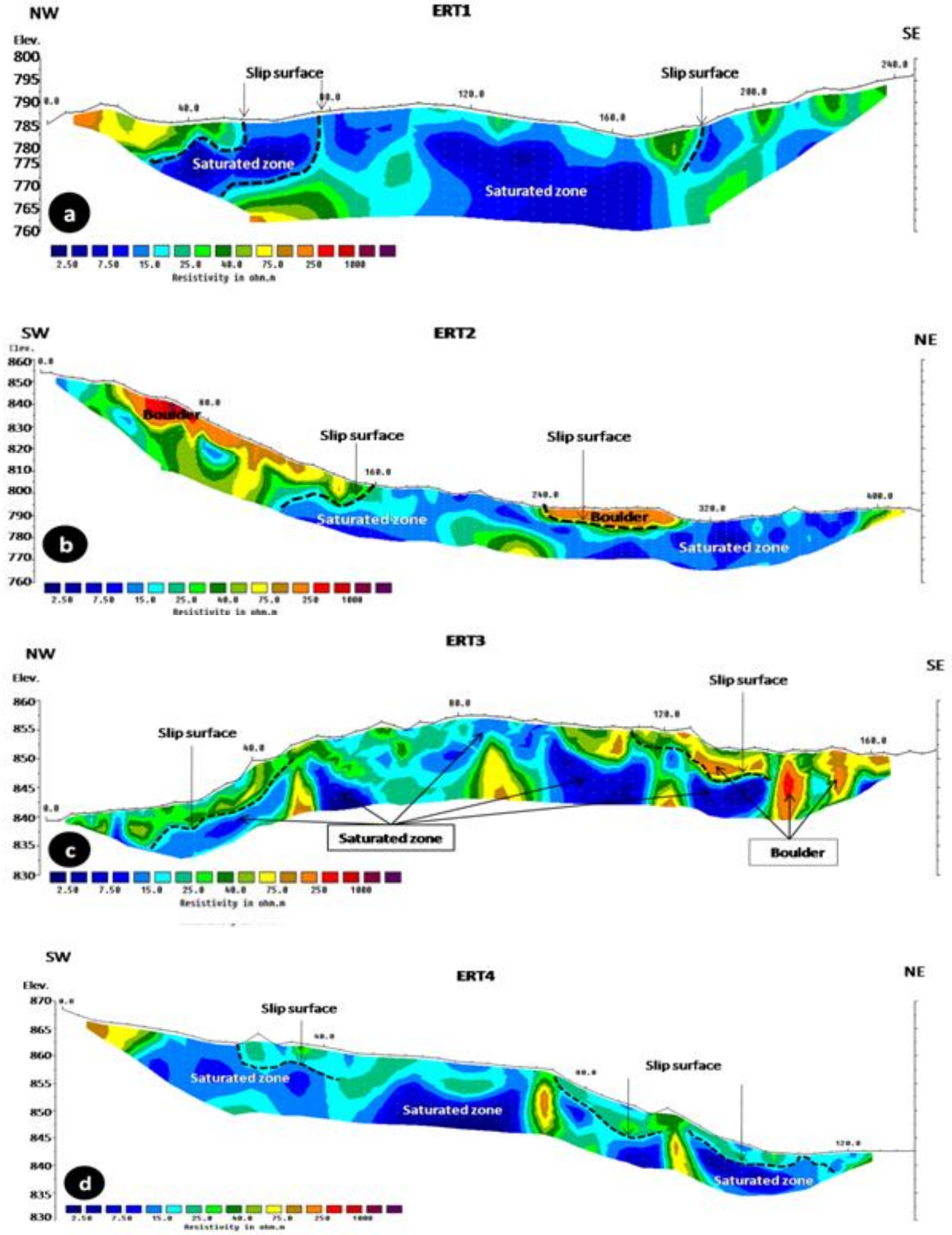


Figure 8: Pseudo-sections of RL1-RL4 lines

The pseudo-section ERT4 of the profile RL4 (Figure 8d), illustrates a large conductive horizon, its electrical resistivity ranging between 5 and 30 Ωm, which corresponds to saturate marl-clay. The resistant formation located in the SW part with electrical resistivity moderately oscillate between 50 to 100 Ωm can be attributed to compact marls, while in the NE part of the profile where the slope is presenting, a resistant formation can be attributed to compact marl-clay is highlighted with two sub-vertical intercalations separating the conductive formation, present a sliding potential of the conductive layer.

Electrical imaging made it possible to reach certain conclusions on the geometric configuration of the terrains as well as their resistivity values. In general, the sections show alternation of conductive ground interspersed with low resistant to resistant terrains with irregular shapes. Electrical resistivity values obtained were calibrated with logs of core drillings. The first resistivity range presents a conductive formation whose values of resistivity range between 5 to 20 Ωm, which can be attributed to saturate marl-clay. The second resistivity range is characterized by a resistivity ranging between 20 and 1000 Ωm. The weak resistance formations (20 to 100 Ωm) are attributed to compact marls, while the resistant formations (100 to 1000 Ωm) are attributed to boulder of Numidian sandstone. Fine soils such as clays and marls are very sensitive in the presence of water, and they are characterized by the possibility of flow due to the increase in water content. The consistency of soil varies on the water content when it increases, the soil passes successively from the solid to the plastic state, and then to the liquid state. The layer with resistivity values varying between 2-25 Ωm, is represented by clays. Layers in low values of resistivity, approximately 2 Ωm are related to higher water content. Based on data from core drill holes located near the tomography profiles, subnumidian clays are present; their thickness can reach 20 m at the level of SC1 and 7.5 m at the level of SC3. This formation covers compact tellian marl.
In particular, the active landslide material is characterized by electrical resistivity values ranging between 5 and 25 Ωm, which can be attributed to saturate zone. The slip surface is located in a depth range between 4meters (ERT3 and ERT4) and 7 m (ERT1 and ERT2). Despite varied resistivity contrasts, the ERT allowed us to define the geometry of the landslide object of our study, to identify the sub-vertical discontinuities, often corresponding to the failure surface, and to locate the zones characterized by a higher water content (saturated zones) (Figure 8).
The results obtained are correlated with the results of the research work of Bellanova et al. [26], Mezerreg et al. [20], and Pasierb [24]. We notice that the resistivity values obtained are similar, namely: the saturated zones, the values were between 3 and 20 Ωm and gradually increased in the unsaturated zones to reach values between20 and 100 Ωm. For sandstone blocks (boulder), resistivity values reach 1000 Ωm.

5.2.1 Identification of Shear (Slip) Surfaces

Generally, landslides that affect homogeneous formations can lead to variations in resistivity with mass movement in clayey layers. This can be explained by the presence of water, which is an important factor in the reduction of the mechanical characteristics of the soil, combined with the presence of a large percentage of the clay fraction [27]. For a first interpretation, the results obtained can be divided into two resistivity ranges: the first varies from 2.0 to 25 Ωm, the second range above 25 Ωm. Several authors associate this low resistivity (less than 25 Ωm) with the presence of a slip surface. In the electrical imaging profiles, a resistant formation is

shown with a resistivity varying from 50 to 200 Ωm near this formation and in places, a conductive formation is observed with a low resistivity between 2.0 and 25 Ωm, mainly due to the presence of water (saturated zone). This conductive layer with its curvilinear shape can represent the slip surface on which resistant formations can slide.
The preliminary results of this geophysical and geotechnical prospecting campaign in the study area have shown that: Electrical tomography appears to be a viable geophysical method to locate layers of low resistivity susceptible to trigger landslides. Tomography integrated with geological information has proven to be a powerful tool for the investigation of landslides.

6 Conclusion

This study is to characterize the internal structure, changes in water saturation, and the location of the slip surface of the Tamentout landslide. Analysis of the electrical tomography imaging allowed us to characterize the geometric configuration of the grounds as well as their resistivity values. The combination of slope with the morphology of conductive and resistant formations shows that the slip surface may be located at the surface of the layer with a resistivity ranging between 5 and 20 Ωm, corresponding to saturate formations.
The pseudo-section shows that the main cause of the instability is due to the presence of a saturated zone; hence drainage systems and evacuation of groundwater can be recommended as a remedy technique to stabilize this landslide. Finally, to follow the movement and its evolution, it is recommended to regularly conduct geophysical prospecting of the unstable sites. Electrical tomography should be combined with other geotechnical and geophysical methods to better identify the depth of the slip surface.
The resistivity of the 2D inversion model has been well correlated with the Tamesguida geological map. Thus, the 2D resistivity survey provided valuable information about the subsoil characteristics, in particular on slope instability.

Acknowledgments

The authors would like to thank the anonymous reviewers for their constructive suggestions. They are grateful to the Algerian National Highway Authority (ANA, Jijel) for providing the necessary data for this study.

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