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MULTISOURCE DATA INTEGRATION TO INVESTIGATE A 3D LANDSLIDE MORPHOLOGY AFFECTING AN URBAN AREA: CASE OF BORDJ BOU NAAMA (WEST ALGERIA)

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Abstract: Situated in the northern part of Algeria, Ouarsenis is one of several area affected by landslide phenomena. Indeed, 60 houses, a stadium and a lot of sports infrastructures are affected by the landslides. In this perspective, we have chosen a model of landslide with an area of 166 700 m^2 affecting the southern part of the Bordj Bou Naama city. In order to characterized the landslide structure, we used multisource data (geological, topographical, geophysical and geotechnical). For modeling the 3D landslide surfaces we used three geometric models which are generated from different techniques of interpolation as Inverse Distance Weight (IDW), Minimum Curvature (MC) and Kriging (KO) and applied to the same input data set. The root of the mean square error (RMSE) and visual appearance of the morphology are used to select the best model. Indeed our results show that the KO represents the best model that gives a good result. Quality control is also performed to ensure that the model is suitable for hydro-mechanical modeling. This model show that the total volume of soils moved is ~$9.8 * 10^5$ m^3, in which the volume of geological levels is 828 500 m^3, 143440 m^3 and 11 434.32 m^3 respectively for the embankments, colluviums and Brown shale. The bleu shale is far from to be affected by this landslides, indeed the deepest zone that the rupture area affects is located at 12 m of depth. These results seem to be very important in order to plan remediation work in this area.

Keywords: *Ouarsenis, landslide, geophysics, modeling, lithological interface, 3D surface rupture*

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1. INTRODUCTION

The culminating zone of Ouarsenis is part of the external Tell chain of Algeria; it is located about 170 km SW of Algiers (Fig. 1a). The study area is smaller and not

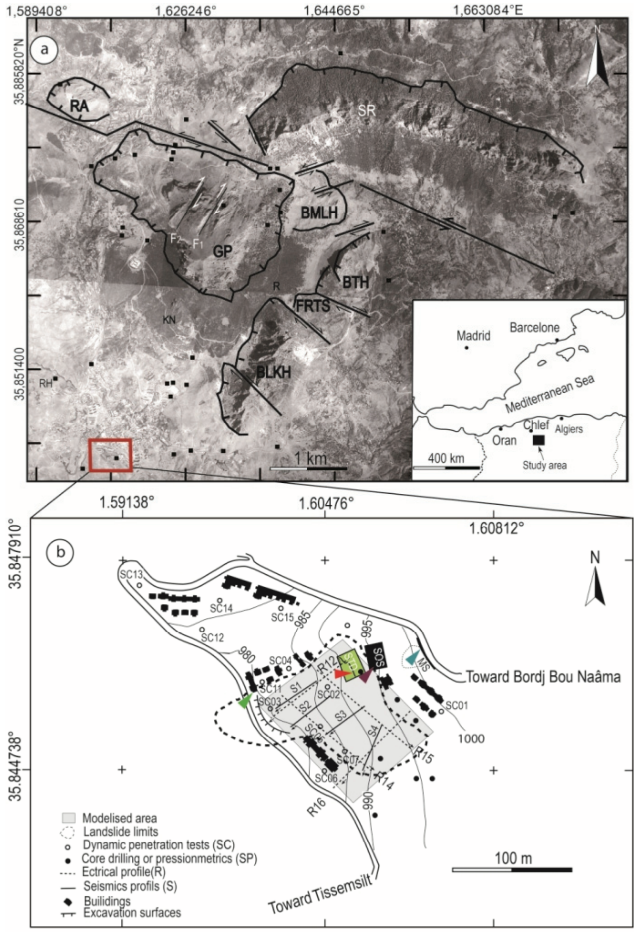

Fig. 1. Location maps of the study area, a: photo-map extracted from aerial photos composed of 20 images at 1/20 000 (Universal Transverse Mercator) *UTM* WGS84) showing the location of the study area, the black lines show the tectonic structures located in the study area, the small black squares show the location of landslides listed in the vicinity of inhabited areas, the large black square indicates the location of the landslide studied in this work. The abbreviations BLKH, FRTS, BTH, SR, GP and RA represent respectively the mountains Belkhreit, Fartas, Batha, Sra Abdelkader, Grand Pic, and Rokba Atba. These abbreviations are used for the rest of the text, b: map of implantation of mechanical soundings, tomographic profiles and seismic profiles in the affected area. STD, SOS and MS represent, respectively, Stadium, Omni-sport hall and retaining wall. The colored arrow represents the damage caused by the landslide event (Please see Fig. 5)

exceeds 0.25 km^2 in area; however it is represented by the higher mountains in the western of Algeria. Indeed, in this region the Grand Pic (GP) culminate at 1985 m, Sra Abdelkader (SR) 1760, Belkheiret (BLKH) 1620 m And Rokba Atba (RA) at 1160 m. Fartas (FRTS) and Batha (BTH) are smaller and not exceed 1100 m in altitude. This area is very affected by landslide phenomena; one of these biggest landslides affects an urban area that includes buildings and various infrastructures (Fig. 1b).

In this area, the slopes are the seat of a considerable transfer of materials among which we can mention: (i) rock fall which is the habitual phenomena that the local population can see every times (Fig. 2a), (ii) gully erosion triggered along the hills slopes (Fig. 2b) and (iii) landslides triggered especially in winter and spring. Landslides is the most widespread phenomena in our study area, affecting inhabited areas or various infrastructures (roads, buildings, bridges, etc.) (Fig. 2c).

Fig. 2. Photos showing several gravitational instability forms: a) Rock fall in the northern hills of the Grand Pic Mountains, with F, ZB and ZE are, respectively, Fault, Rupture zone and Accumulate area, b) a several landslide affecting the river banks, dashed lines represent the ruptures areas. Landslide affecting a road with a lot rupture area represented by white dashed lines in downstream (c) and other cracking zone in the Road top () affecting even the protection dispositive (Gabion) (d)

The Ouarsenis area is considered as one of the most important areas in Algeria where we can study these movements of open skyline. Almost all the types of landslides are present, we can cite for example: (i) a rotational landslides that are most widespread with surface ranging from 501 424 to 16 670 m² and which are characterized by a curve rupture surface in depth (Fig. 3a), (ii) a debris flows afectecting roads thus

Fig. 3. Different types of landslide affecting infrastructures (Roads, buildings and other infrastructures), a) rotational landslides, b) debris flows, c) and d) translational landslides extended on a hundreds of meters, e) and f) represents pictures of high magnification of landslides taking in photo c) and d)

causing their inaccessibility during whole months (Fig.3b), (iii) a translational landslide characterized by linear surface in depth and that can reach a surface of 12935 m^2 (Fig. 3c) and which the sliding surface is very long (Fig. 3d), and (iv) solifluction characterized by a slow flow, along a slope, where the surface soil is subsaturated with water, especially in cold climates on a constantly frozen subsoil. Vegetation can interfere to some extent with soil flow, as the roots hold the top layer. This phenomenon is poorly represented in areas where the vegetation cover is very dense (Fig. 3e, f).

The case of landslides studied in this article degraded degraded homes and a sports complex in Bordj Bou Naâma city in March 2006.

We chose to study this landslide for several practical reasons: (i) its ease of access and, (ii) the data availability (a seismic and tomographical profile, mechanical soundings and geotechnical analyzes of the soil). These data were revealed by various studies (technical report, construction), and were available to us. This landslide is oriented NE/SW affecting a more or less oval surface up to 166 700 m^2, it extends over a length of 173.6 m and a width of about 127.3 m, the difference in level of the affected area varied between 974 and 948 m, on a slope of 15% (Fig. 1).

The research initiative conducted in this work is focused on three fundamental objectives: (i) understand the hydrodynamic process in the landslide, (ii) estimate the volume of moving land and (iii) characterize the morpho-structural model of the rupture area at depth and this from geophysical data. These results may serve as a basis to oppose the decision of local authorities who like to install a new building in this affected zone.

2. GEOLOGICAL SETTING

The Ouarsenis area is characterized by facies of Mesozoic age (Calembert 1952, Mattauer 1958; Farès Khodja 1968; Benhamou 1996). These formations are represented by: (i) competent materials which form the frame work of this mountainous area, in particular dolomitic and limestones of Jurassic age, which are locally associated with marl-limestones and sometimes sandstones (Mattauer, 1958) and (ii) ductile materials, either marl-limestone (Neocomian) or flyschs (Albian and Aptian) in which marls of schistoid character alternated with centimeter quartzite levels. To the southwest of Ouarsenis, the flyschs provide a very important recovery of the underlying Jurassic formations. This facies are in the form of blue shale, the upper levels of which are altered into brown schist by weathering action.

The Ouarsenis area is represented by a much accentuated orography characterized by a steep geomorphology resulting from a recent tectonic polyphase process (Calembert 1952; Mattauer 1958; Zaagane et al. 2015; Zaagane et al. 2016; Lepretre et al. 2018; Frizon de la Motte et al. 2015). The essentially horizontal movements due to tangential stresses have generated lines of tectonic weakness along which the

Jurassic limestone strata pierce Albo-Aptian ductile formations (Zaagane et al. 2016).

This tectonics is probably old and taken up by recent episodes of age probably (Zaagane et al. 2016). These tectonic episodes are at the origin of the exhumation of these mountains at the origin of the exhumation of these mountains. Indeed, these movements created rugged areas represented by steep slopes sometimes exceeding 80°, for example the southern slope of Sra Abdelkader. These slopes are represented by a ductile Cretaceous material which covers the limestone framework of Jurassic age.

Compressive tectonic stresses are at the origin of an initial deformation stage. This exhumation is done along the major NE–SW or E–W fault lines and along the deep detachment surfaces ensured by Triassic complex (Calembert 1952; Mattauer 1958). The ductile formations form a delacered material belonging to tectonic nappes. The curvilinear faults the extremity border of the structural entities; they are marked by Triassic uplift which contains xenoliths belonging to the Paleozoic basement (Mattauer 1958). The Cenozoic lands are located to the north and south of the culminating zone.

The dip of the overlying formations are oriented generally perpendicular to the tectonic contacts. The Dogger and Malm formations are oriented N60° with an average dip of 70° SSE at Rokba Atba, they become ~N20° in the southern massifs (BLKH, FRTS and BTH). In the Sra Abdelkader Mountain, the same formations are strongly inclined ~70° towards the South and oriented almost to the East (Calembert 1952). At the Grand Pic, formations ranging from Lower Liassic to Lower Cretaceous are almost horizontal with a slight eastward tilt. However, low altitudes have very friable ductile formations with oblique inclination towards the SW. The incision of the valleys shows the oldest formation represented essentially by flysch.

2.1. LANDSLIDE EVENT HISTORY

In 2005, on the football stadium situated in the sportive complex of Bordj Bou Naama city, was built in 1990 at a cost that exceeded millions of dinars. In 2006, three lines of sub-parallel cracking oriented N140° appears. These lines prefigure future ruptures zones.

In the first trimester of 2006, the phenomenon has been aggravated after a very important rainfall (99 mm in January, 93 mm in February and 100 mm in March), mostly accompanied with snowfall. A rupture area occurs at the contact between the superficial formations and the Albo-aptian flyschs. In the surface, the movement of material is accompanied by rotational landslide, indeed the three cracking line transforms to three rupture area spaced at 6.6 m and 8.2 m, of which the two summits are the most marked (ZR1 and ZR2) (Fig. 4a).

In March 2006, rains and snow melt fed the high mountains with water. The flow of water in downstream has developed a gradual destabilization of materials. This caused: (i) the soil bulging in the direction of the movement of the material and affecting even the road joining Bordj Bou Naâma to Tissemsilt by causing their intense cracking, (ii) the partial destruction of the stadium grounds and their enclosure (Fig. 4b) and (iii) the variable degradation from one building to another located downstream of this landslide, taken in the lateral shear lines (cracking and swelling of the walls in the direction of the slip and even the partial destruction of the plaster roof of some houses) (Fig. 4c).

The sport hall was also affected, but slightly, especially the climb of the stairs (Fig. 4d). This phenomenon has worsened following anarchic work. Indeed, earthworks

Fig. 4. Disorder in the frames related to the soils moved: a) stadium ground affected by two surfaces of rupture (RA_1 and RA_2), the white arrows and the drawn white lines show the failover related to these ruptures surfaces of, the dash lines at the top of the photo shows the tilting of the wall, b) the white arrow shows the degradation of the stadium, the black arrow shows the direction of flow of the destabilized materials, c) degradation by bulging of the retaining wall by the movement from the ground, black arrow always indicates the displacement sense, and d) buildings of the 60 housings city being in the lateral shear lines, white arrow indicates an intense cracking in the walls, black arrow always indicates the flow direction

have been launched to set up a platform which will be the seat of a new building. During these works, a more or less remarkable water infiltration was observed from the first works. This flow of water and in the presence of marl could cause damage which could go to the total destruction of the newly constructed block.

The preliminary study conducted highlighted the following triggers:

(i) Abundant rainfall.

(ii) The digging of pits for the construction of new buildings between the city of 60 homes and the oldest city (Fig. 5). The superficial formations have been destabilized although the slope is not steep. Following the movement of land, the construction of these buildings has been postponed. No pit is visible on the Google Earth image of June 8, 2010 (Fig. 3), however, the work then resumed: pits (Photo 2, taken in December 2012), then foundations (image of July 29th, 2013), the image of February 20th, 2018 shows buildings that are starting to come out of the ground. This anarchic work has accelerated the process of moving the soil to where the buildings are located (Fig. 5).

(iii) The presence of soft material (colluviums and marl) favorable to this type of instability.

Fig. 5. Google earth quick looks showing the landslide area and also the anarchic work that lead to the installation of a multi-storey apartment building: a)–d) are different satellites images dating of 08/06/2010, 09/12/2012, 29/07/2013 and 20/02/2018, respectively. For the abbreviations please see the Fig. 1b

3. MATERIALS AND DATA

The data used in this study come from geomorphological, geotechnical and petro-physical approaches.

Each data is geo-positioned (geographical coordinates *X* and *Y*). The *Z* dimension varies in the same location depending on the considered element: topographic surface, interfaces between layers, contrasts of electrical resistivity and contrasts for deep seismic wave velocities. The data is transformed into digital maps (rasters) and correlated thereafter in a Geographic Information System (GIS).

3.1. GEOLOGICAL DATA

The surface geology is interpreted from an investigation during field investigation and consultation of geological maps. This information can be classified according to two very distinct axes: (i) the lithological nature of superficial formations and (ii) the structural aspect (layers dip, joints, fractures and folding) (Table 1).

When layers dip is consistent with the slope this fact is favorable to instability. Indeed, contact between the two superficial formations (colluviums) and underlying (blue schist) is favorite an intense circulation of fluids especially because the impervious hydrological features (Table 1).

Table 1. The type of data sources and relevant survey techniques used in this work, these data are used to provide information on the landslides geometry

Data types	Techniques types	Information types	Extension	Resolution
Geomorphological	Aerial photographics	externe	2D	$20*10^{-3}$ m
	Satelitte images	externe	2D	$1,5*10^{+1}$ m
	Aster DEM	externe	2D-3D	30 m
	DEM made from topographic map	externe	2D-3D	2,5 m
	topographic mapping	externe	2D	$25*10^{-3}$
Geological	Géological mapping	interne	2D	10^{-3} m
	Boreholes stratigraphic logs in non destructive drilling	interne	1D	10^{-1} m
Geotechnical	pressiometric tests	interne	1D	10^{-2} m
Petro-physical	seismic refraction tomography	externe	2D-3D	10^{-2} m
	electrical resistivity tomography	externe	2D-3D	10^{-2} m
	borehole logging	interne	1D	10^{-2} m
Others	various field observations, already interpreted data	externe	2D	variable

In all cases the extrapolation of the dip and the azimuth of the interface (flat stratification) between the stable badlands and the moving mass is used to estimate in the firstlythe direction of a possible displacement of landslide (Cornforth 2005).

3.2. GEOMORPHOLOGICAL DATA

In the field, various indications (cracking at the level of the rupture zone, slumps, shearing on the sides of the sliding, bossing, inclination of electricity poles and trees, disturbances with the installations) make it possible to delimit the sliding zone and to evaluate the of displacement.

Field observations were supplemented by the identification of morphological features, from Google Earth images, high-resolution aerial photographs, a digital terrain model (DTM extracted from a topographic map at 2.5 m of resolution) (Mckean, Roering 2004; Eeckhaut et al. 2005) and ancient documents (topographic maps, photographs and scientific documents).

The area affected by the landslide is shown in Fig. 4. Downstream, it extended below the road that leads to Tissemsilt, between the city of 60 housing and the oldest city of 2005 (which was confirmed by the technical services of Daïra de Bordj Bou Naâma) (Table 1).

3.3. GEOTECHNICAL DATA

The geotechnical surveys show the existence of four lithological levels: embankments, colluviums, brown shale and blue shale (Fig. 6).

Shale are inclined in the same direction as the topographic slope (towards the SW), but with a lower angle (8.5°). This arrangement is conducive to the instability of surface formations, indeed, the infiltration of deep water being blocked particularly in contact between colluviums and shale (Table 1).

The top of colluviums is the interface C1. These materials are directly exposed at the surface to the meteorological conditions sometimes in absence of embankments (Sounding SC7). They are based on either blue shale (SC2) or brown shale (SC1). The C2 interface separates colluviums from brown shale, it's observed in the surroundings of the geotechnical soundings (SC1). The limits characterizing the limits between altered (Brown sahle) and conserved (blue shale) is deisgned by the C3 interfaces. This one can never been seen in the geotechnical surveys.

For the record, we say that some penetration tests, static and/or dynamic, have been carried out for the acquisition of information on compressibility, shear and water saturation. The results are not reported here.

These data are mainly represented by in-situ measurements through holes made in the landslide area (mechanical tests) or in depth (static or dynamic penetration tests) (Table 1). These data provide a crucial asset to complete the geological uncertainties especially in depth (Cornforth 2005, Bichler et al. 2004) (Fig. 6).

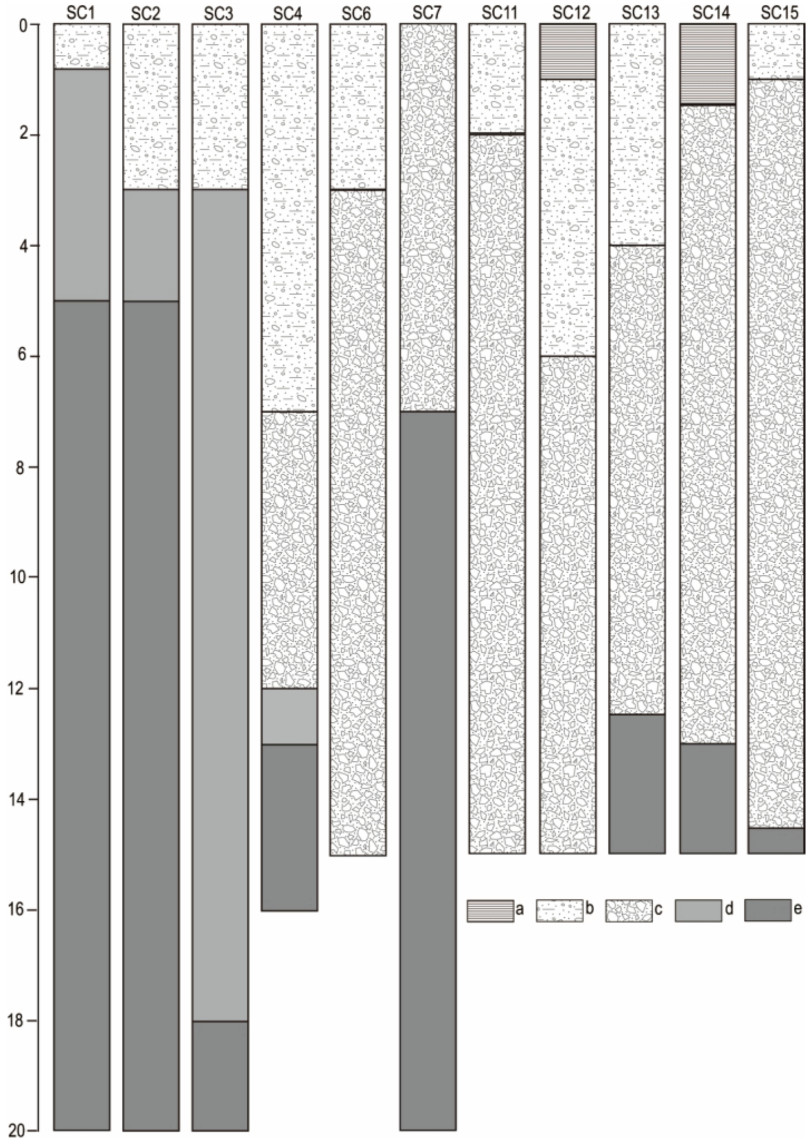

Fig. 6. Lithological columns from mechanical soundings located in the study area:
1 – topsoil, 2 – embankment, 3 – colluviums, 4 – Brown shale, and 5 – compact blue shale,
for the localization of these columns please see Fig. 1b

3.4. PETRO-PHYSICAL DATA

Petro-physical properties are used to determine the linear continuity of geotechnical and geological levels at depth. In the case of our study, two types of methods were used:

3.4.1. ELECTRICAL TOMOGRAPHY

The equipment consists of a TERRAMETER resistivity meter (SAS 1000/4000) equipped with a high-definition internal computer, a current converter and 64 injection

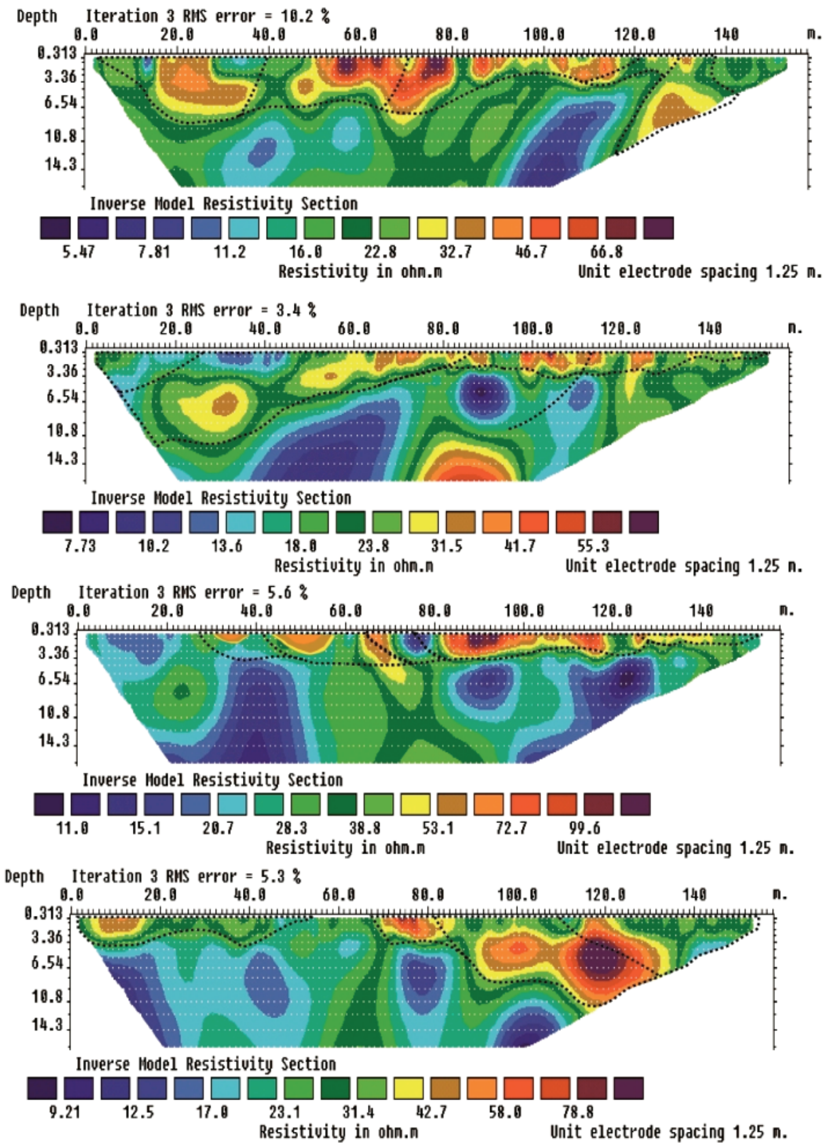

Fig. 7. Example of interpretations of electrical resistivity tomography (ERT) data along the profiles from the top to the bottom of this figure respectively Lr12, Lr14, Lr15 and Lr16, crossed in the study area, property contrasts in the ERT allow to detect the In-depth interface, the root mean square error (RMSE) are also shown

and current-receiving electrods spaced from each other by approximately 2.5 m over a total length exceeding 160 m (Fig. 7, Table 1).

Electrical tomography is widely used in the exploration of large-scale landslides. The main objective is to delimit the unstable surface (Malet 2003; Apel 2006; Travelletti, Malet 2011). Data acquisition in the field is done on cross profiles. These are profiles R14 and R15, oriented NE-SW and distant from 100 m, and profiles R12 and R16, oriented NW-SE with identical spacing.

After treatment, the results obtained provide two-dimensional color contrast images that indicate, for each profile, the changes in the physic propriety of lithology especially the humidity as a function of the wave propagation velocity (Fig. 7).

On the study site, both shale and wet surface formations exhibited a resistivity of 10 to 30 ohms/m, while values ranged from 30 to 70 ohms/m for shallow surface formations.

3.4.2. SEISMIC REFRACTION

Seismic refraction classifies formations as a function of the propagation velocity of seismic waves. The interfaces between the layers of different materials are determined from the time of the travel wave in the ground. We worked on the primary waves P (compression or longitudinal waves).

Four profiles with 20 m of lenght oriented NE-SW, spaced 5 m apart were studied. The equipment includes a multi-channel, TERRALOC MK6 seismograph with an internal computer with high precision programs, twelve vertical geophones connected to a model SM4 14 HZ seismic braid, twelve horizontal geophones spaced 5 m apart and connected to a seismic braid similarly type and a source of seismic energy. The measurements collected were processed with the software (Rock-Works 15).

After treatment, the results obtained provide two-dimensional images that indicate, for each profile, the lithologic formations limits as a function of the propagation velocity of the waves. The results have been compared to those of the mechanical soundings.

In the absence of information on transverse waves (S), the available seismic data do not allow to directly obtain a spatial representation of the interfaces.

4. METHODOLOGY

4.1. DATA EXTRACTION

The data used in this study are from heterogeneous sources (CAUMON et al. 2009). The data distributed in the study area are characterized by a planar positioning in (X, Y

geographical coordinates), only the factor Z varies relating to: (i) limits of the lithological levels listed on the various mechanical soundings, (ii) the lithological levels limits characterized the electrical resistivity contrasts and (iii) contrasts corresponding to the velocities of the seismic waves. It is important to note that the different data sources are listed in the same study site but with different positions.

After data acquisition in several field campaigns, we organized our data using different methods and techniques.

For the mechanical soundings, we adopted an easy and effective technique, indeed, for each sounding; we replaced the lithological data which correspond to the different lithogical levels (embankments, alluvium, brown shale and blue shale) by the values of interfaces that correspond to them. The data are directly integrated into the database, the principle is to convert the thicknesses of layers into depth value and to relate them to the topographic point where the mechanic sounding was conducted (Cornforth 2005; Bichler et al. 2004). Then, the altitudinal position of each interface (Ci) separating two lithological levels is represented by the value:

$$Ci = Alt - Ep.$$

Where Alt is the altitude of the sounding position and Ep is the total thickness of the materials above Ci (Fig. 4).

This database has been interpolated and represented as a raster map. Each map shows the layout of the interface separating two different lithological levels for example (C1 = interface separating embankment and colluviums).

(i) For the electrical tomography data, we have first drawn the line separating the two different geophysical levels which correspond to the stable part and the sliding part. The strategy adopted in this study is based on the fact that more land is waterlogged less the resistivity is lower.

(ii) The resulting line has been converted to digital data, indeed every two meters we have given the depth of this line relative to the surface plot. The deeper the drawn line, the higher the value. Finally a database has been developed and includes (X, Y position and the value of the depth). This method was repeated for the four profiles (Lr12, Lr14, Lr15 and Lr16).

(iii) The seismic data was just used to compare the boundaries of the formations obtained by the mechanical soundings and the interfaces obtained by the seismic method. These same data are correlated in a Geographic Information System (GIS).

4.2. CHARACTERIZATION OF THE INTERFACES GEOMETRY

The topographic surface affected by the landslide is not necessarily homogenous with geometry as the interfaces C1, C2 and C3. The first encloses a zone of bossing due to the accumulation zone linked to the downstream part of the landslide, the second are more or less parallel because these layers are related a sedimentological process. The different formations are characterized by varied mechanical and geotechnical properties, including penetration, pressure meter and shear (straight and triaxial) information.

In-situ geotechnical tests show two different lithological facies. In the first layer, the interface C1 separates the embankments from the colluviums. The set is inclined towards the SW. The shear surface identified from tomographic data, at depths between 5 and 19 m, is founded in either of the two superficial units, or even in the underlying shale (Fig. 8a, b).

- The second layer starts from the second interface (C2), which marks the contact between the colluviums (superficial formations) and the brown shale. This unit, from 2 to 16 m thick, is considered friable to plastic and is partially impervious. Results of the compressibility tests at boreholes 4 and 11 shows a consolidation pressure between 0.73 and 2.37 bars; a coefficient of settlement between 17 and 29.9%; and a swelling coefficient of 4.11 to 5.59%. The C2 interface coincides perfectly with the contrast limit for seismic waves: 1680–1230 m/s in S1. However, in the superficial materials this value is 403 m/s for (embankments and colluviums) (Fig. 8c, d).

The shear tests (rectilinear CU, rectilinear UU and triaxial UU) performed on samples from the colluviums layer show cohesion values of between 0.16 and 0.51 bar, with the exception of a triaxial test where the value is very high (1.82 bar). An important geotechnical characteristic is determined in the laboratory; this is the internal friction angle. In the case of colluviums, it is ranged between 9.6 and 18.6°.

These measurements showed that this unit is characterized by a very large displacement. It is associated with the so-called "deposit zone". In addition, the old torrent channel may be partially filled by significant thicknesses (several tens of meters) of colluviums deposits and embankment before the occurrence of the landslide event.

- The substratum associates two levels of the same lithological nature but different color: (i) the higher level consists of brown shale with a thickness of 8 m to 17 m and (ii) the lower level, consists of greyish to bluish shale. In situ shear tests show a cohesion between 0 and 0.6 bar for straight shear (CU and UU), however this cohesion is much higher (1.82 bar) for triaxial shear. The angles of internal friction are between 9° and 22°.

After the onset of the landslide event, a geophysical campaign was set up. The main objective was to spatially expand the geotechnical and geological data (Schmutz et al. 2009; Grandjean et al. 2007; Meric et al. 2007). Interfaces C1 and C2 cannot be detected, but a significant contrast of the resistivity (ERT) has been observed ERT > 32 Ωm in the upper part, and ERT < 32 Ωm deeper (Figs. 7a, 5b).

In comparison with the data from the mechanical soundings, it turns out that the fracture surface highlighted is located at the lower limit of the layer of colluviums. Upstream, in the bulges of the material accumulation zone, muddy flows were observed with a strong flow of fluids. This finding coincides exactly with highly conductive areas at the LR 14 and LR 16 of tomographic profiles (Fig.7). These zones have a relatively weak resistivity, even if it remains below 70 Ωm/cm, indicating areas saturated with water (Fig. 8).

- In general, it is difficult to create a lithological reference from the electrical tomography because of resistivity that is too weak, less than 70 Ω/cm. We are therefore in the presence of highly conductive materials, weakly consistent but rich in water at the time of measurements in February 2008 (Fig. 7).

The lithological profiles made from the mechanical soundings orthogonally arranged on the landslide zone, reflects a normal superposition with respect to the surface topography, however, this lithological progression shows in depth a curvature of slope oriented NW/SE.

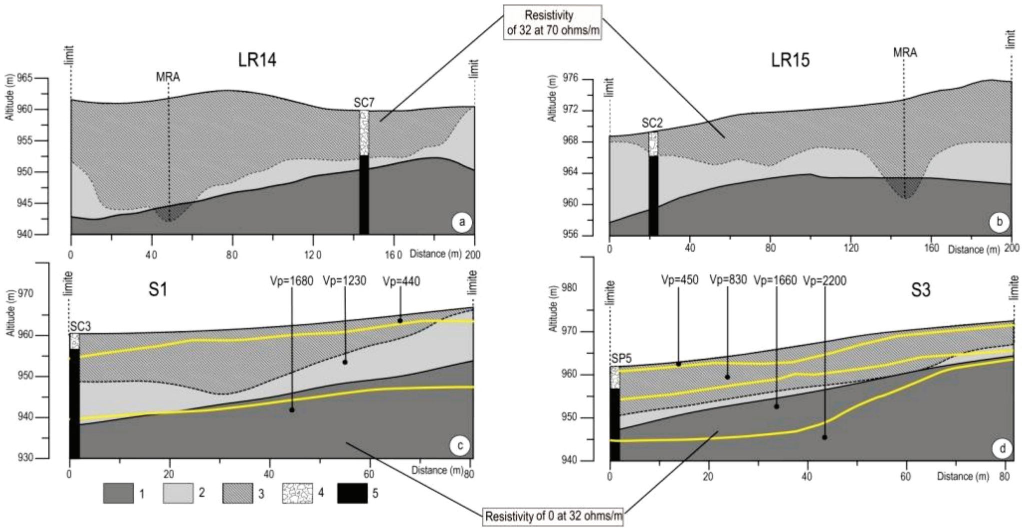

Fig. 8. Crossing of resistivity (ERT) data and mechanical soundings after interpolation:
a) 2D profiles showing the unstable set with a peak located at 50m from the starting point of (LR14), MRA indicates the maximum breaking area, SC7 indicates the mechanical sounding,
b) still shows the assumed surface of rupture with MRA located at 150 m from the profil beginning (LR15), SC02 indicates the mechanical sounding, c), d) correlation between the tomography data (3), seismic (yellow lines) with velocity envelopes (Vp) p waves and lithological from mechanical soundings (1 and 2) for 4 and 5, For more details, I refer the author to Fig. 3

4.3. THE INTERPOLATION OF THE DATA

Several methods are used in the interpolation of geographic data. Among the topographic interpolation algorithms, the kriging method is generally the most suitable (Declercq 1996; Aguilar et al. 2005; Jongmans, Garambois 2007; Olivier, Thierry 2008). Recents studies have shown that there is not entirely an objective rule for selecting an appropriate interpolation algorithm, as it strongly depends on the characteristics of (i) the surface and (ii) the distribution of the input data points and on precision of the data (Travelletti et al. 2011; Arnaud, Emery 2000; Aguilar et al. 2005; Chaplot et al. 2006; Fisher, Tate 2006; Schmutz et al. 2009; Kalenchuk et al. 2009).

In this study, three types of interpolation were used: (i) (KO ordinary Kriging): which is the simplest kriging algorithm, the input data is assumed to be stationary, without any drift (Burgess et al. 1981; Bancroft et al. 1987; Marinoni 2003; Travelletti et al. 2011) (Fig. 9); (ii) Inverse Distance Weight (IDW) has the principle of estimating elevation at unknown location using distance and values at known points in the vicinity based on the assumption that each data point influences the resulting surface to a finite distance (Travelletti et al. 2011; Chaplot et al. 2006; Van Den Eeckhaut et al. 2005) (Fig. 9); and (iii) Minimum Curvature (MC) is based on the smoothing of two line segments defined by the balanced tangential method using the ratio factor (RF) (Sowers, Royster, 1978) (Fig. 9).

Before using these models, we calculated experimental variograms in a single different preferred direction, namely 71°, 31° and 28°. The study of variograms shows the adaptation of the spherical model. The length and the scale have been adjusted graphically so that the theoretical model passes through the scatter plot (in the middle) (Fig. 10).

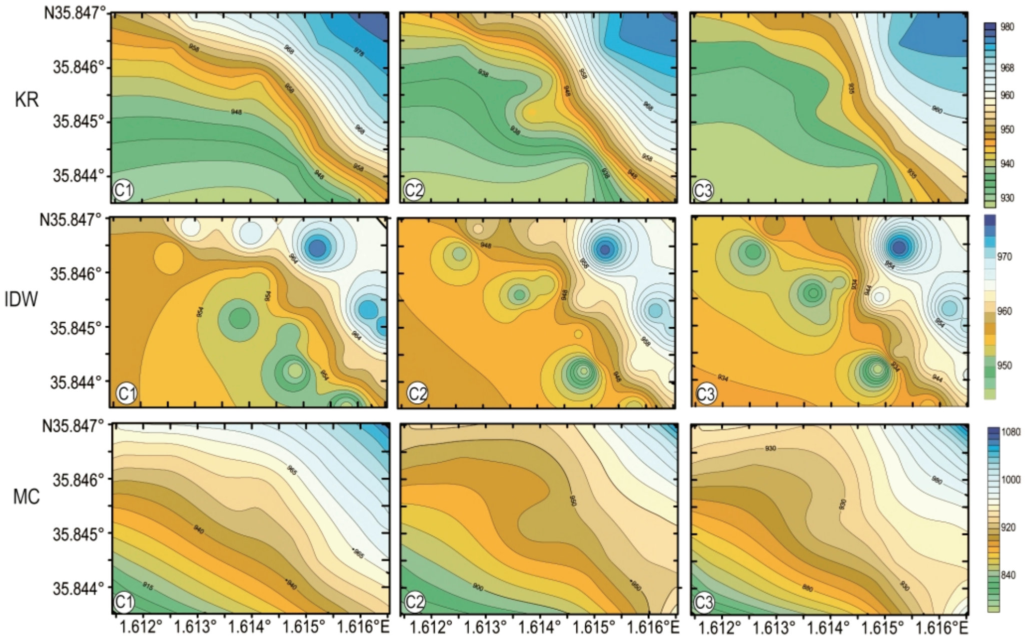

Fig. 9. Maps representing the interfaces C1, C2 and C3 modeled from the data of the mechanical soundings: a) maps obtained by interpolation in Kriging (KO), b) maps obtained using the IDW method (Inverse distance Wight), and c) maps obtained by interpolation using the method of minimum curvature

5. RESULTS AND DISCUSSION

The investigative technique proposed in this study is based on the analysis of multi-source heterogeneous data. The main objective of this method is to construct a 3D geometric model for the sliding zone that affected the stadium ground in an urban area (Bordj Bou Naâma). The information related to the different facies or the rupture surface is extracted from the 2D images, these processed data are distributed homogeneously along the profile lines (seismic refraction and electrical resistivity).

The interpolation of the data with the KO method seems to be best adapted to the geotechnical characteristics of the lithological surfaces of the landslide zone (Fig. 9). Indeed, the 3D geometry of the lithological interfaces resulting from the interpolation by the MC method shows artifacts probably related to the smallness of the area (Fig. 9). The interpolation by IDW shows, for its part, geometries whose altitude is exaggerated, especially upstream of the landslide zone. This exaggeration is obvious, the lower interface (C3) being able to exceed the topographic surfaces visualized by the DEM (Fig. 9). The data from mechanical soundings is a major element for the construction of lithological interfaces (C1, C2 and C3) in 3D (Fig. 9). Dips layers towards

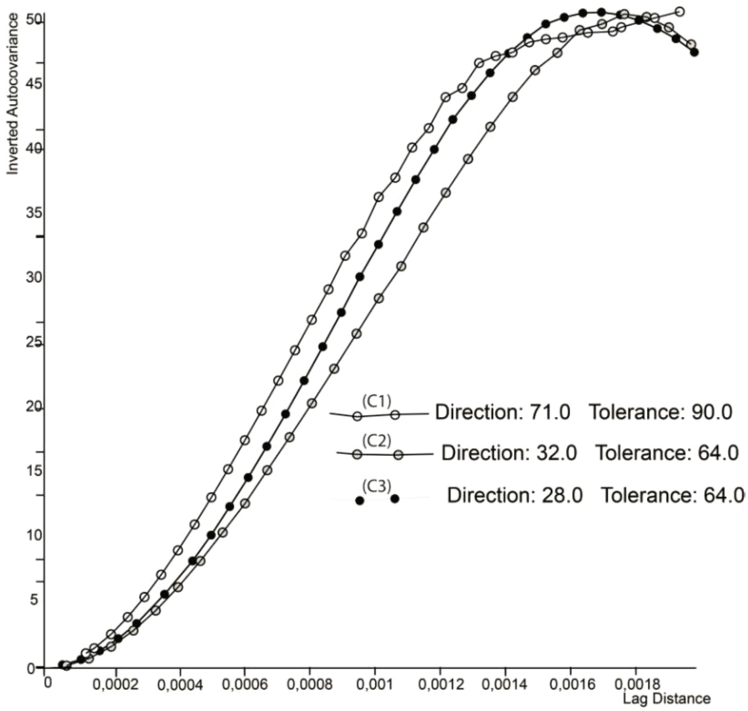

Fig. 10. Directional variograms plots with different Tolerance and direction for the three interfaces (C1, C2 and C3)

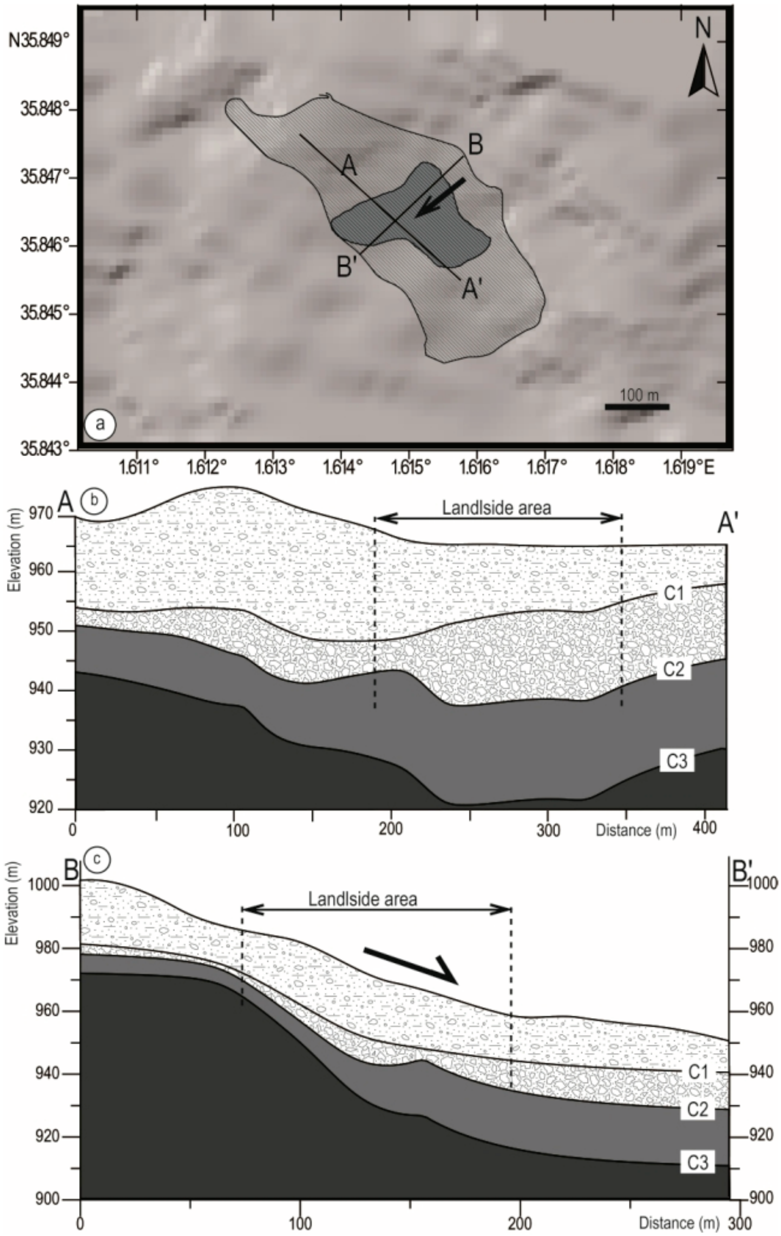

Fig. 11. Cross-sections obtained from maps: a) maps MNT shows the location of profiles AA′ and BB b) profiles AA′ showing a kind of depression filled mainly by superficial formations (Colluviums and embankments), c: BB 'profiles showing the contact between the surface formations and stable underlying domain (Shale), the arrangement of the layers conform to the direction of water flow, C1, C2 and C3 respectively indicate the interfaces between the different formations; 1 – embankment, 2 – colluviums, 3 – brown shale, 4 – blue shale

the SW shows an irregularity which could be linked to a fault (see Fig. 10b). This finding is consistent with the direction of nearby fractures, including the Belkheiret Fault (N140°) (Fig. 10a, b). The oldest geometric form of the area was a very open valley, in particular a tributary of the Grand Oued (Marzoug) which overlooks the western facade of the Bordj Bou Naâma city. Although the V-shape of the valley is neither very well identified in the ERT profiles but badly in the seismic profiles in the downstream part of the destabilized zone, brown shale and colluviums deposits is at the origin of the filling of this oldest valley beyond the city of 60 homes (Fig. 11a, c).

At the top of the formation of colluviums, the interface so-called C1, can sometimes outcrop on the surface because of the absence of embankment. Since in the other parts, this formation (colluviums) which is represented by the interface (C2), can be on contact directly with the blue shale (Sc2) or on the brown shale (Sc1). In this area, the shale constitutes the stable substrate. The interfaces are sub-parallel with a central slope break, these interfaces meet at the top. Indeed, the interfaces C1, C2 and C3 are respectively at 11 m, 20 m and 43 m in the central zone (from the altitude 970 m), however, this depth becomes less important in the upstream part of the affected zone with respective depths 16 m, 19 m and 26 m (reference point 964 m) (Fig. 12).

The 3D shear surface geometry is elongated into N243° direction; it shows a slight tendency towards the SSW, the BB′ profile shows a small valley filled mainly by the overlying formations surmounting the blue shale. The line following this valley shows a pit oriented towards the SSW, this observation is proved by the oral comments of population, indeed the investigation on ground showed that there was a oldest valley which was filled later by natural and anthropogenic works (the installation of city of 60 homes), respectively, colluviums and embankment (Fig. 12).

The interaction between (i) external topographic surface, (ii) the fracture surface (modeled from petro-physic data) and (iii) the first interface (C1) revealed a volume of $8{,}3*10^5$ m^3 only for the first sub-unit embankments, this represents a 84.25% of the total of moved soils. The second sub-unit (Colluviums) is slightly affected with a volume of $1.4*10^5$ m^3, which represent 14.58% (Table 2) (Fig. 9). The depth-modeled fracture surface affects the second interface (separating the colluviums and the brown shale) only partially in the upper part of the landslide. This part is probably related to the depth extension of the shear planes which affected even these underlying materials, however the embankment and colluviums are less affected than shallow formations (Table 2). The breaking surface that affects the stadium field is composed of two levels of breakage, the first reaching a depth of 4 m, however the second can go up to 6 m in depth (Fig. 11). For the sake of explanation that the interface C2 is at 5 m from the surface (SC02), the crossing between the deep shear surface and the interface C2 only has a slight interaction of a volume of $1.1*10^4$ m^3, this represents only 1.16% of the total volume of the slipped mass (Fig. 9).

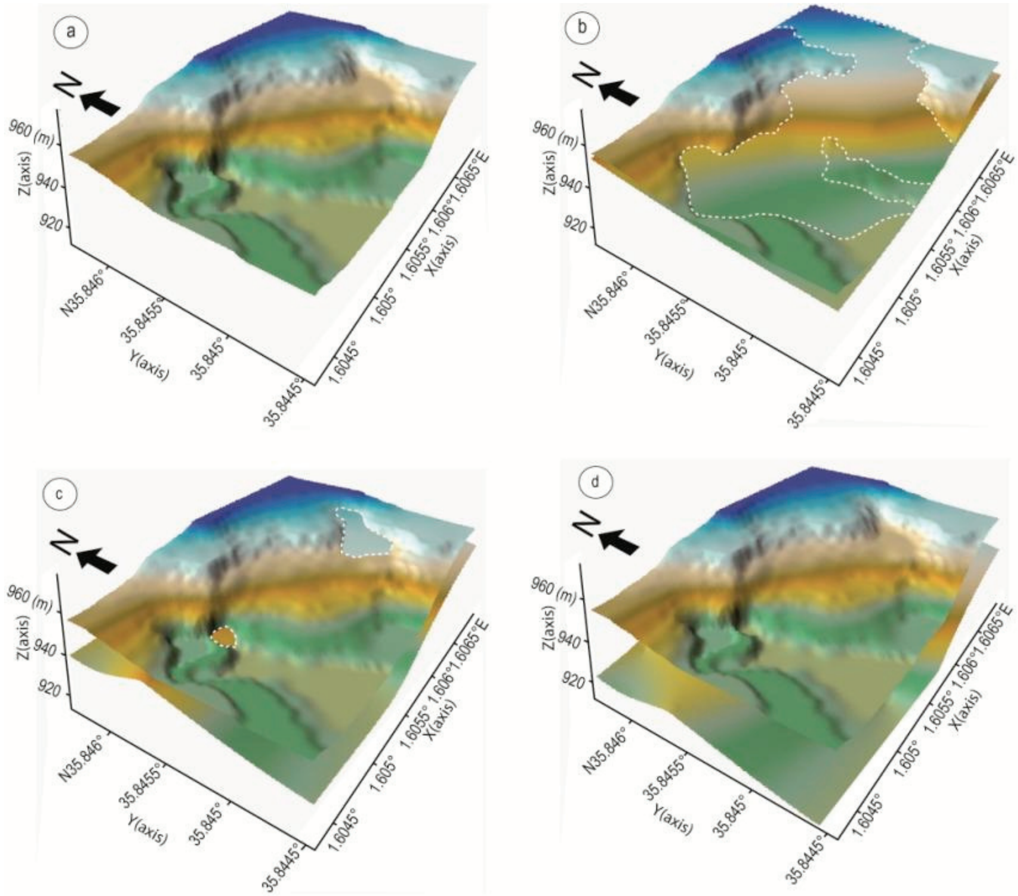

Fig. 12. Figure showing the interaction of the modeled rupture area of landslide and the interfaces modeled from the mechanical soundings: a) 3D model representation showing the geometry of modeled rupture surface in depth, b) crossing of the rupture surface (RA) with the first interface C1 showing a large part of mobilized land consists only of embankment and a significant part of the colluviums, c) crossing of the fracture surface with the second interface C2 showing a slight interaction, therefore a minimal part of brown shale affected, d) no interaction between the fracture surface (RA) and the C3 interface. White dashed dashes indicate crossing surfaces with different interfaces

The C3 interface is located below the rupture surface; this means that blue shale is not affected by the deep shear surface (Table 2, Fig. 12).

The drainage zones of the water are mainly in the C1 and C2 interfaces, this finding is in agreement with the LR14 and LR15 tomographic profiles located orthogonally on the shear plane generated by the landslide. At a depth of ~10 m we can see an area of high conductivity mainly linked to a super-saturated zone in water. The water underground flow is, therefore, not neglected especially the remediation work proved the stagnation of water levels of the city of 60 housings.

Table 2. Geometric information related to the interaction of the fracture surface with the C1, C2 and C3 interfaces

Interface	Lithology	Alt (max)	Alt (min)	EP (avg) [m]	*S* [m^2]	*V* [m^3]	%
	Embankments	988	966	16	51800	828500	84,256
C1	colluviums	976	952	5	28688	143440	14,58
C2	Brown shale	974	940	3	3811,44	11434,32	1,164
C3	Bleu shale	968	920	/	/	/	/

Alt (max) – maximum altitude, Alt (min) – minimum altitude, EP (avg) – average thickness affected, *S* – area in m^2, *V* – volume of materials affected in m^3, % – percentage of volumes affected related to the total volume.

With the 3D geometric model it was possible to estimate the volume of the lands slipped to ~$9.8*10^5$ m^3. The identification of the fracture surface generating this slip by electrical tomography is in agreement with the other cases identified (curved surface indicating rotational landslide). Contrary to what has been previously reported, the slipped lands are represented only by the superficial colluviums, but the morpho-structural model shows that even the underlying layer of shale is only partially affected by this movement. The presence of a surface flow (6 m) ensured by impervious geological layer, the plastic lithological nature of the superficial materials and layers dip of the 15° in favor of the direction of flow are responsible for this instability event.

6. CONCLUSION

A better understanding of the style and mode of non-tectonic deformation can be of crucial importance. Indeed, in the case of landslides, better understanding the deep structure of the landslide is more essential than important in order to consider the remediation solution to be carried out. In the case of our study, the geometric 3D model of the interfaces (C1, C2 and C3) showed a dip of lithological layers in the same direction of soils movement. The geometry of the landslide surface is characterized by a curved surface in depth with superimposed, continuous and sub-parallel layers.

With this 3d geometric model, it was possible to estimate the volume of the mobile mass at $9.8*10^5$ m^3, high percentage of which is represented by the two superficial formations (embankments and colluviums) 84.26%. Shear related to ground motion may have affected the roof of the altered formation of brown shale. The geometry of the failure surface (shear) is derived firstly from indirect data (ERT) which provides relatively subsurface imaging associated with direct data from geotechnical soundings. With this imagery, we have also detected the interaction of the rupture surface of landslide with the lithological interfaces (C1, C2 and C3). Consequently, this lead us to notice that the shearing surface which separate the sliding soils on the stable part is much deeper, it even affects the 3rd interface (brown shale). This movement is triggered following the interaction of several factors: (i) the slope is much important at the level of the city of 60 homes and the removal of the natural stops in foot due to uncontrolled earthworks during the realization of this building, (ii) the absence of a drainage system on the study area and (iii) and the action of geological and geotechnical factors including the punctual presence of layers of particular characteristics, the lithological facies of the soil constituted by colluviums on shale inclined in the same direction of the flow and the roof of the shale with a significant slope as it is schematized in the modeled profiles.

The result of this work may be essential in helping local authorities to decide. Indeed, through the models of the fracture surface in depth, civil engineers can thus design a retaining wall which can be dug beyond the fracture surface which exceeds 19 m in some places.

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