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GEOPHYSICAL, GEOTECHNICAL, AND SPELEOLOGIC ASSESSMENT FOR KARST-SINKHOLE COLLAPSE GENESIS IN CHERIA PLATEAU (NE ALGERIA)

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Abstract: Several sinkhole collapses were occurred in the many sites in urban areas and/or their rural periphery; in NE Algeria, in the last few years. The abrupt collapse causes damages to properties, infrastructures, and even lives. The most spectacular oneoccurred in February 2009 inside the Cheria city, Northwest of Tebessa department, with a diameter of more than a hundred meters. This abrupt collapse is due to a sudden rupture of the roof of a large underground karst cavity. It caused panic-stricken among the population living near the crater. In order to investigate the origin of this phenomenon, we combine several geophysical and geotechnical methods, such as Ground Penetrating Radar, Electrical Resistivity Tomography, Standard Penetration Test, Mechanical Drill Core, Cave Survey Photogrammetry, etc. It appears that each method may provide specific information. Their comparison allows to precise the results itself, the limits and the application field of each. Consequently a number of open karst voids and disturbed areas were detected in the study area. The results show that sinkholes originate from two different processes: a brutal collapse of karst voids located at shallow depth, by agravitational effect especially building surcharge on top of limestone. And progressive piping and erosion of the thick gravel cover, especially after storms making large depressions. The drawdown of the aquifer following intense pumping could have accelerated these processes. The extension plans of the study area could be established with this methodical acquaintance of the underground conditions of the karst cavities such as: occurrence, depth, geometry and dimensions.

Keywords*:* GPR, ERT, SPT, Cave Survey, Photogrammetry.

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INTRODUCTION

In many regions of world, movement of ground (MG) caused damages in the natural and built environment. It may occur in various forms as terrain collapses (sinkholes, pinnacles, cavities, etc.), landslides and rock falls, etc. Such events highlight the need of effective MG exposure mitigation strategies for urban areas (Carbonel et al. 2015; Sakhel et al. 2017). The sudden collapse of loose deposits overlaying underground solution cavities in karstic limestone areas constitutes a severe natural phenomenon in MENA zone (Hadji et al. 2013; 2016; 2017). It constitutes a real challenge for civil engineers as it affects severely buildings and networks. Their creation is due to a soil bridges gap where sediment has been washing into solution enlarged fractures. Over time, the void migrates upward through the soil. After the bridge thins, a sudden collapse often plugs the drain and erosion will, after many years, transform the collapse into a more bowl-shaped sinkhole (Fig. 1a). Up to date, only some researchers have approached this problem in Northeast of Algeria (Fehdi et al. 2011). Each has addressed a different side of the problem. Baali et al. (2015) have mapped the susceptibility of karst cavities collapses as a natural hazard. Whereas Azizi et al. (2014) have studied these cavities as a hydrogeological hazard.

A number of methods for assessing sinkhole collapses and karst genesis using analytical approaches have been proposed in mining and geotechnical engineering literature (Paine et al. 2009). Geophysical used techniques includes ground-penetrating radar (Nouioua et al. 2013), gravimetry (Kaufmann and Romanov, 2009), seismic reflection and refraction (Miller and Steeples 1991), electric resistivity tomography (Redhaounia et al. 2016), and magnetic susceptibility difference (Balkaya et al. 2012), or a combination of them (Carbonel et al. 2014). This study addresses the problematic of karst sinkhole collapse in Cheria area. This phenomenon threats more than 75,000 habitants in this common. It caused severe damage to houses and networks. In the last two decade, two major events occurred in this region. One occurred inside Drâa Douamis rural area (50 m, in diameter), whereas the second arises in Harkat Bouziane urban area (100 m, in diameter) (Fig.1b, c). In that of the city, no lives were lost, but the residential quarter, which included more than hundred houses, was destructed. Cracks appeared first on the walls of buildings followed by a sudden collapse and opening of underground cavities whose existence was not even suspected. It remained uninhabited lest potential future collapses were assessed. Nevertheless the drilled water wells in the region have encountered several metric voids until 50 m of depth (Nouioua et al. 2013). The main conditions that controls sinkhole genesis are lithology (fractured chalky limestone) as predisposition factor and the rapid draining of the water table as triggering factor. The collapse is due to a sudden rupture of the roof of a large underground karst cavity developed in the Eocene limestone, which forms the substratum of the Cheria syncline under the Quaternary cover. Their mechanisms passes through three main steps: first karstic caves develops at greater depth according to gradual baselevellowering. Then the loose soil cover are by piping or suffusion, eventually making slow subsidence. If cavities in the limestone are large enough, or become so, collapse can evolve to a sinkhole. The problem of sinkhole collapse in Cheria region has been monitored as part of a program agreement " PHC Tassili ".

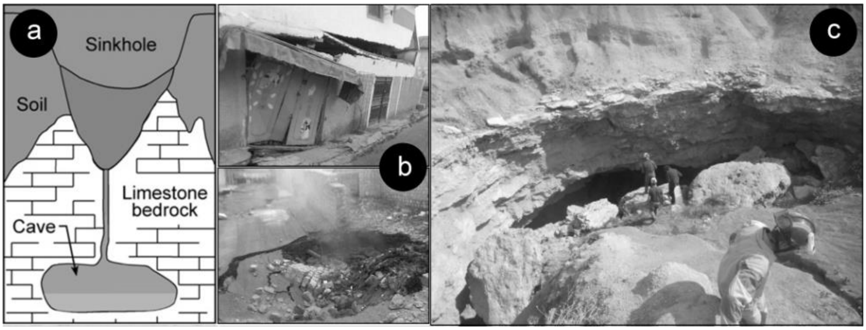

Fig. 1. a: Scheme of sinkhole formation, b: The sinkhole collapse in Harkat Bouziane urban area; c: The sinkhole collapse in Drâa Douamis rural area

GEOGRAPHICAL, GEOLOGICAL AND HYDROGEOLOGICAL SETTING

The community of Cheria (35° 16′ 13.0″ N? 7° 45′ 07.09″ E) is located 47 km SW of the chief town of Tebessa department, NE Algeria (Fig.2). It is 267 km^2, and includes 75 344 Hab. (2008) with a density of 282 hab./km^2. The plateau of Cheria has a triangular shape. It belongs to Chott-Melghir endoretic watershed, which covers 722 km². Its altitude varies between 1000 to 1200m in the middle of the basin and it is surrounded by jebel Doukkane (1550m) and j. M'Taguinaro (1712m) (Baali 2007).

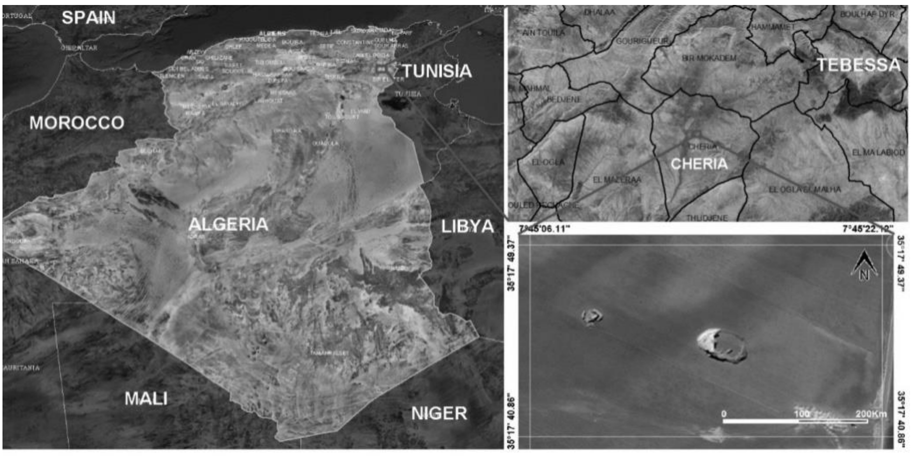

Fig. 2. Geographical situation of the studied area

The plateau is characterized by a syncline structure , which axis is sinking towards SSW (210°). It consists of a succession of sedimentary formations, with Campanian marls, surmounted by Maestrichtian limestone, as well as the fractured and karstified Eocene limestone covered by discordant Mio-Plio-Quaternary deposits composed of a silt, sand, and gravel (Fig.3).

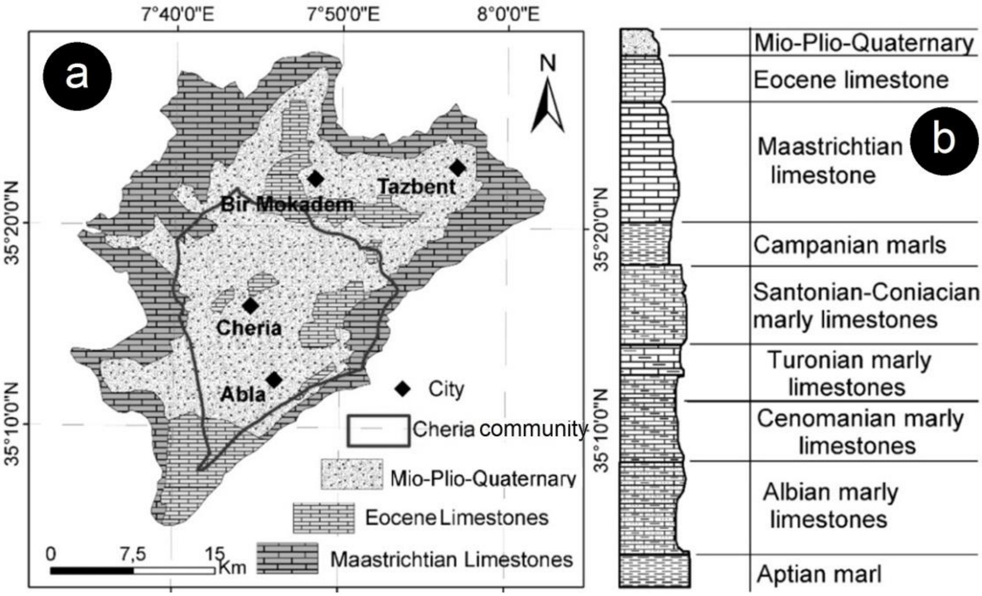

Fig. 3. a. Simplified geologic map of Cheria plateau; b. Stratigraphic column of the studied area

The basin is dissected by three major fractures sets with NE-SW, NW-SE, and N-S directions. The drainage pattern of the basin is not well developed and is controlled by these fractures. In the Chérea basin, areas where tectonic fracture networks pre-exist allowed the water circulation. This, led to the formation of fractured and fissured corridors that will constitute drains favors for groundwater. Drilling log confirms that Eocene limestones are affected by fracturing and karstification. Chamekh et al. (2014) found that the directions of the main underground and surface flows depends closely on the Eocene limestone cracks direction. Neo-tectonic, lithologic and morpho-structural factors play a decisive role in the karstification process in the plateau.

The climate has the main impact in the presence of Karst morphology. Rain, mechanical erosion, are the dominant factor; in most other lithologies, plays a lesser role. The climatic setting of the study region is summarize in the table (1) computing the main parameters. In the "karstification" process, the carbonate rocks are formed by solvation according to the following chemical reactions:

dissolution of carbon dioxide: $CO_2 + H_2O \leftrightarrow H_2CO_3$

aqueous dissociation of carbonic acid: $H_2CO_3 + H_2O \rightarrow H_3O^+ + HCO_3^-$

acid attack of carbonates ("limestones"): $H_3O^+ + CaCO_3 \leftrightarrow Ca^{2+} + HCO_3^- + H_2O$

balance sheet equation: $CO_2 + H_2O + CaCO_3 \leftrightarrow Ca^{2+} + 2\ HCO_3^-$

Tab. 1. Potential evapotranspiration and the water balance in the study area

Month	P, mm	T, °C	I	K	ETP, nc	ETP, c	ETR	RFU	DA
Sep	47.40	20,8	8.65	1.03	93.06	95.3	47.4	0.0	47.9
Oct	28.34	16,81	6.26	0.97	65.41	63.5	28.3	0.0	35.1
Nàv	17.88	10,64	3.12	0.86	30.77	26.6	17.9	0.0	8.7
Dec	20.99	6,74	1.57	0.85	14.65	11.8	11.8	9.1	0.0
Jan	17.86	6,40	1.45	0.87	13.46	11.7	11.7	15.3	0.0
Feb	13.57	6,86	1.61	0.85	14.96	12.8	12.8	16.1	0.0
Mar	22.8	10,23	2.95	1.03	28.76	29.9	29.9	9.0	0.0
Apr	27.68	12,64	4.07	1.09	40.81	45.1	36.7	0.0	8.4
May	32.05	18,26	7.10	1.21	74.75	90.7	32.1	0.0	58.6
Jun	18.18	23,34	10.28	1.21	112.24	136.7	18.2	0.0	118.5
Jul	11.06	26,54	12.49	1.23	138.58	171.5	11.1	0.0	160.4
Aug	20.27	25,16	11.54	1.16	126.61	147. 0	20.3	0.0	126.7
Total	278.10	15.36	71.09	-	754.06	842.5	278.1	-	564.4

The region is characterized by an N-S flow direction and a very prominent exploitation area in the center. Rainfall significantly affect piezometry. The recharge zone (bordering the sector), are formed mainly by fractured Eocene and Maastrichtian limestones (Fig. 4).

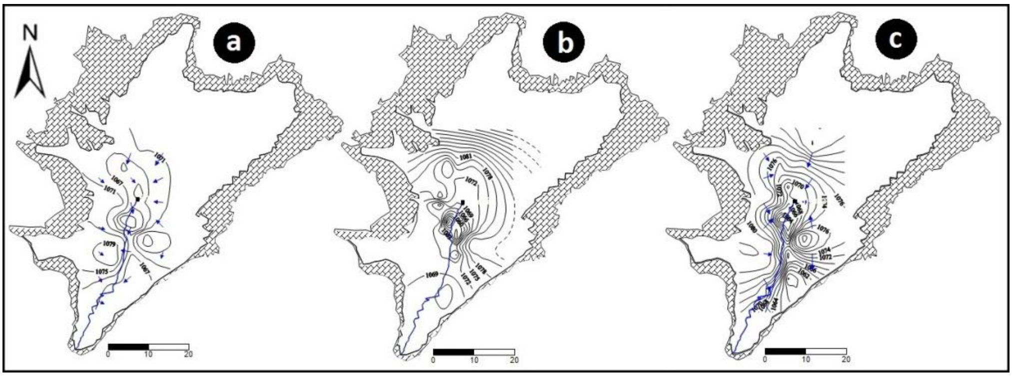

Fig. 4. Piezometric map of the study area, a. Sep. 2002; b. Sep. 2005 c. Feb. 2005

The water level is lowered for the period between 2000 and 2005 which can be explained by the drought that affected the region. The variation in water level is irregular, which can be due either to temporary recharge or overexploitation and lack of precipitation.

MATERIAL AND METHODS

To investigate the nature and the geometry of the study area basement, several geophysical and geotechnical recognition methods were implemented. The results of these methods have been integrated to find the best method of recognition of this hazard in order to serve as a basic document for the extension of the city of Cheria.

Geophysical methods provide information on the geological model, which allows precise zoning of the measured anomalies to be linked to the cavities. Boreholes are then implanted, they allow to locally controlling the assumptions emitted on the model by the geophysical methods. The most appropriate methods in the urban areas are Surface Seismic Wave, Ground Penetrating Radar, Micro-gravimetry and Slingram. It was with difficulty that ERT could be made in an urban site where pavements had to be destroyed to implant the electrodes. The GPR was used on both sites (Drâa Douamis and Harkat Bouziane). 20m-deep carrot drill holes were performed in close proximity to Standard Penetration Testing locations.

The accessible cavities of Drâa Douamis were investigated with a Speleological Cave Survey. ERT often applied for karst-sinkhole exploration problems (Redhaounia et al. 2015). GPR is also used in mapping of bedrock horizons (Beauvais et al. 2004). ERT method provides greater depth information than GPR, but it is less manageable and does not give unique interpretations. Both ERT and GPR are affected by the geological and environmental noise. It is, however, useful to combine the two methods for providing comprehensive coverage of the investigated sites and for optimising the survey results.

ELECTRICAL TOMOGRAPHY

2D inversion techniques are practical to determine the data-setlimitation and resolution. Electrical tomography profile was measured across the area, using SARIS Scintrex resistivity device by a Wenner configuration with a=2m and 9 levels detection of underground cavities by combining electrical investigation. The total length of the profile through the collapsed site is 80 m. The method is based on measuring the electrical potential between one electrode pair (M-N) while transmitting a direct current between another electrode pair (A-B).

GROUND PENETRATING RADAR (GPR)

GPR is a non-destructive method that produces vertical cross-section images of the shallow subsurface. The resulting image style (radar Gram) seems very close to seismic reflection profiles. GPR acquisition is based upon the propagation, reflection and scattering of high frequency electromagnetic waves. The survey was carried out using radar equipment consisting of a SIR-3000 radar central unit Conducted by a 400Mhz antenna. The carriage is provided with a thumbwheel, the position of each anomaly is given relative to the starting point. Nine profiles with 145m of total length were conducted in Drâa Douamis site (Fig. 5).

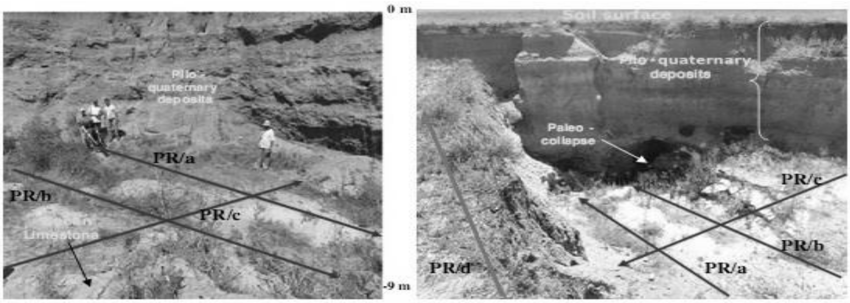

Fig. 5. GPR lines in the two collapses

CAVE SURVEY

Any survey which deals with caves requires a detailed maping of the cavity. Our research has, therefore, carried out a great deal of survey work. However, the use of numerical modeling has made it possible to represent survey data in appropriate ways. Cave survey consists of recording distances, inclinations, and orientation of a succession of segments. Additionnal informations, such as width, height, profile and shape of the passages are sketeched in a notepad. The definitive geometry of the cavity is established only at the surface return, from the notes taken underground. The necessary equipment is a "Leica DistoX" device that record the 3 basic measures. Measurement data are then injected into "Visual Topo" open source software as an input grid. Wich is probably the most commonly used cave survey software in Algeria, and can be download for free.

CORE DRILLING

Core drilling is the most accurate recognition means, but also the most expensive. It consists of drilling by driving a hollow cylinder into the ground with continuous rock sampling. This type of drilling is done only when it is necessary to know precisely the rock, its structure and / or to make precise measurements such as physical and mechanical tests. It is a relatively slow operation; the progression is limited by the size of the cylinder of by the corer or of the drill string. In Harkat Bouziane site, 15 drill holes were drilled to a depth of 20m. Beside (at 2m) a point of dynamic penetrometer was implanted.

STANDARD PENETRATION TEST (SPT)

The Dynamic SPT is a geotechnical survey that involves penetrating into the ground a standard sampler (a rod). Under the blows of a hammer with a weight P and a height of H, falls in free fall on the sampler tool. Three measurements are made by counting the number of strokes necessary to each time for obtaining a penetration of the tool and until refusal (stem not go any further). This test has various advantages, such as reduced cost and that it can be carried out on any field. In Harkat Bouziane site, 13 SPT, were carried out until refusal, at depths ranging from 4 to 8 m.

RESULTS AND DISCUSSION

DRÂA DOUAMIS AREA

The 2D inversion profile (Fig. 6) clearly maps the sinkhole structure in the underground of the studied site. The limits of cavities can be seen as smaller locally resistive zones within the basin-shaped zone. These cavities are characterized by high resistivity values especially for the first and the second. A prominent, highly resistive feature (350–400 Ω m) is visible below station positions. This feature appears to have adepth extent of 3–6 m. Large resistivity contrast shows an anomaly probably in response of an air-filled cavity. The relatively high resistive zone on the left side of the illustration (below station position 22 m) could be the response of a further not deep cavity which could be filled with clay. There are, however, no surface features indicative of the existence of a subsurface cavity. The bedrock is resistant corresponding to Eocene limestone situated at a depth of 10 m. The resistivity of the limestone varies between 400 and 500 Ω m. The clays have a resistivity of about 10–40 Ω m. The two resistant peaks centered on the stations at 40 and 50 m of about 2.5 m depth represent a zone of highly resistant gravel.

The studied sinkhole area has been developed on a Plio-Quaternary deposit, locally under 10m thick, whose deposits have been affected by syn-sedimentary subsidence caused by the dissolution of the karstic bedrock.

Radar signals are plotted in the form of 2D cross section, with the abscissa, the distance at the origin, and on the y-axis, the estimated depth of investigation through the di-electric constant. Zero is at the origin of the profile. The depth is given from the surface of the ground. GPR data for these profiles are shown in figure 7 an overall horizontal geometry. Indeed, with the same equipment on the roof of the first collapsed limestone, which is more homogeneous and resistant soil, several anomalies have been detected that probably correspond to cavities. The presence of a cavity is characterized by an amplification of the signal and a reversal of the polarity when positioned on the cavity. Concerning fractures, the signal appears as a sharp and linear interface.

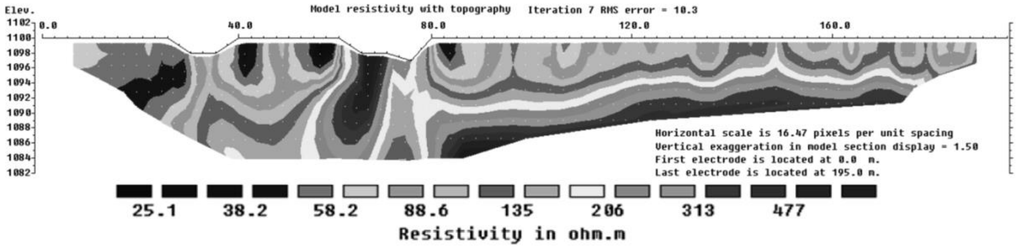

Fig. 6. The result of 2D inversion of Wenner array data from the study area

The first profile PR/a shows a cavity located 10 m from the beginning of the profile and 0.5 m deep. The radargram also shows a signal of decompression zone from 11 m to the end of the profile probably corresponding to a fracture with a depth ranging from 1.1 to 0.6 m. The second profile PR/b shows a cavity at 2.2 m from the starting point and 50 cm deep. Moreover, the signal shows a field much more heterogeneous than the previous profile.

According to these results, third profile (PR/c) has been conducted crossing previous (PR/a and PR/b) profiles. The radargram shows a heterogeneous soil in the first 6m with the presence of several cavities.

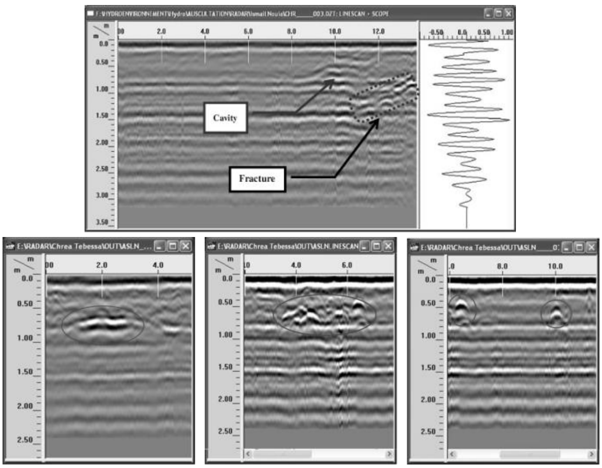

Fig. 7. GPR profiles radargram showing cavities and fractures

The speleological cave survey has made it possible to determine the underground topography of DrâaDouamis caves, which are accessible by the small sinkhole (big collapse: 35°17' 45.56"N, 7°45'10.19"E, altitude 1095 m, small collapse: 35°17' 49.37"N, 7°45'06.11"E, altitude 1096m, depth 26 m, lenth 210 m) (Fig. 8).

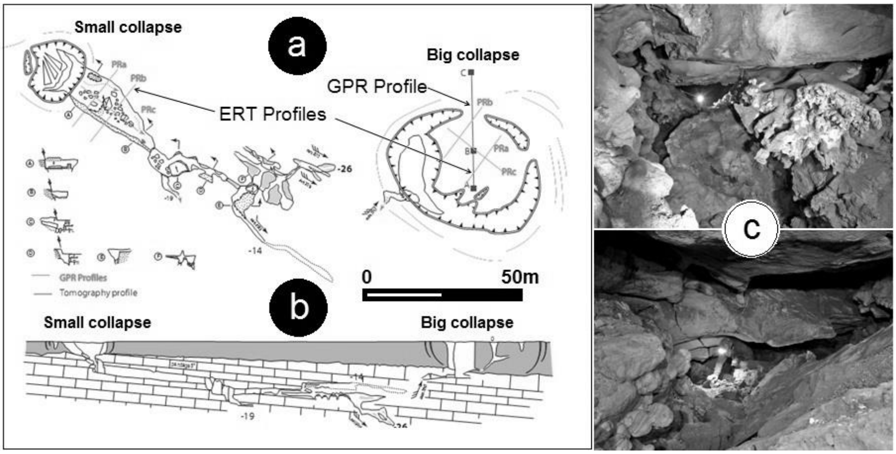

Fig. 8. a. Plan view of Drâa Douamis caves with location of the GPR lines;
b. The profile of the cave; c. The inside of the small sinkhole (Audra, 2014)

CHERIA CITY AREA

By combining the results of the electric tomography with the core drilling carried out in Harkat Bouzaiane site, we have obtained several combinations. The tomography detected voids which correspond to high resistivity of the order of 200 Ω m to 1200 Ω m (Fig. 9a).

The 15 drill holes drilled throughout the neighborhood (Harkat Bouziane) are coupled with Standard Penetration Test points. Their combination provides a good correlation. It confirms the mediocre stability of the underground of the district (Fig. 9b).

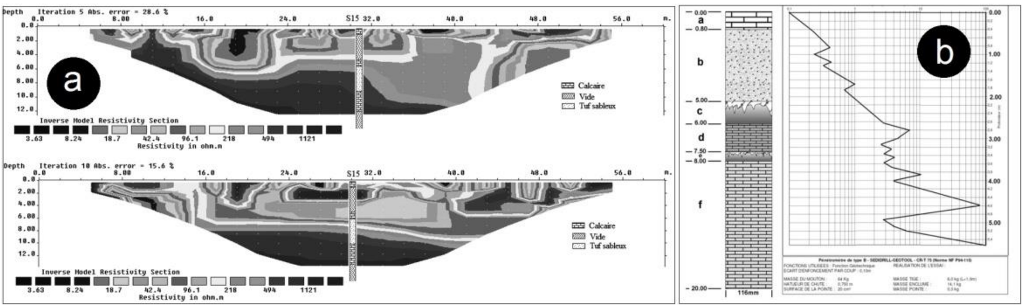

Fig. 9. a. Tomography profile in Cheria city. b. Log drilling of a core drilling S2
and Standard Penetration Test profil

CONCLUSION

We have demonstrated that, the formation of cavities is due to a soil bridges gap, where sediment has been washed into karst voids. Over time, the void migrates upward through the soil. After the bridge thins, a sudden collapse, often plugs the drain and erosion will, after many years, transform the collapse into a more bowl-shaped sinkhole. The geophysical surveys have determined the extent and the geometry of the sinkhole structure. The electrical resistivity profiles, have provided valuable information on the subsidence structure and distribution of the stratigraphic units at greater depths. The tomography gives interesting and precise results, but its implementation is delicate in an urban site. The GPR profiles carried out showed good penetration of the signal and made it possible to demonstrate several abnormalities likely corresponding to cavities. The GPR gives interesting results, in the case of Cheria city which is built directly on the limestones substratum, but in rural site results are less interesting because of the interference due to the clay contents in alluvial deposits layers.

The speleological survey determined the underground topography of Drâa Douamis caves by making direct measurements of underground topography. The drill holes are costly alone, however their combination with the SPT provide very effective results in the study of urban expansion. Photogrammetry gives interesting results and presents an effective technique with interesting return costs. This method is intended to be used for land planning, when only limited subsurface information is available. The evaluation is performed on the basis of the expected final thickness of the overload soil and the anticipated range of soil void or dome diameters.

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