Application of Microgravimetry to Assessing Collapse Risk in Carbonate Sinkhole Areas, Cheria Basin, Northeast of Algeria

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Abstract: This study presents the results and the interpretation of a microgravity survey realized in the MChentel zone near Cheria tone situated in the Northeast Algerian. The microgravity survey, made during April and March, 2016, allowed the obtaining of 614 measures distributed on the whole zone of study. The gravimetric data were measured by means of a gravimeter relative GNU-KC 444 were used with location and the height of stations with centimetric precision by pocket GPS and an electronic theodolite type Qeo FET 420 k. The gravimetric data measured on the ground were connected with a reference gravimetric station situated near the zone of study. On the scale of the zone of study, the gravimetric data show a decrease of the values of the anomaly of Bouguer between both collapses. This trend implies probably an effect of karstification which would explain the decrease of the values of the anomaly of Bouguer by going to the center of the studied zone. The interpretation of gravimetric data shows the presence essentially of two negative zones, they present a deficit of in-depth mass which can be 30 meters.

Key words: Microgravity survey, MChentel, Bouguer anomaly.

1. Introduction

Geophysics provides a multidimensional suite of investigative methods that are transforming our ability to see into the very fabric of the subsurface environment [1]. Geophysical prospecting methods have proved a very useful tool for determining the location and size of cavities below the surface [2].

The detection and characterization of underground cavities represent an essential technical and scientific stake in the process and setting up risks prevention plans related to ground movements. Scientific research on geophysical techniques aiming to detect, locate and characterize the underground cavities at depths ranging between ten and a few hundred meters is still a matter of debate and remains more than ever of topicality. Indeed, for this range of depth, the majority of these techniques presents a lack of resolution and requires being adapted to investigate site and wanted target, namely delineation and the characterization of the abandoned underground works and the overburden [3].

The use of the geophysical techniques, such as the microgravity and the electric resistivity, for the detection of the underground cavities is not a new approach. During the last 20 years, published applications recall the potential of these techniques to...
detect and locate shallow cavities (depth < 100 m) in various geological and mining contexts [5-9].

Microgravimetry is one of the most effective geophysical methods as far as its ability is concerned to detect and delineate underground cavities and passages [8, 10-12]. Microgravity survey is a non-invasive geophysical method for the delineation of subsurface density variations. A microgravity survey consists of making sensitive gravity measurements at discrete points on the ground surface [4]. Spatial changes in gravity are referred to as gravity anomalies and are directly related to subsurface features with a measurable density contrast [13-15]. The microgravity survey technique is a powerful cavity location method. Because a void represents a mass deficiency in the subsurface, a small reduction in the pull of the Earth’s gravity is observed over the cavity, which is called a negative gravity anomaly [5].

In 2001, a huge sinkhole opened in MChentel in the north east of Cheria City. Its diameter was 20 m and 5 m depth. Over the next 12 months, a new sinkhole opened in the same development, with diameters ranging from 15 to 20 m, and from 4 to 6 m depth.

At this time, the phenomenon starts to affect the security and the economy of the population. The collapse is due to a sudden rupture of the roof of a large underground karst cavity. Karst cavities are in fact widespread in the Eocene limestone forming the upper formation under the quaternary cover in the Cheria syncline [16].

The surveyed area around the two sinkholes is approximately 14,700 square meters (210 per 70 meters) in which 614 gravity points were located, and arranged as a square grid of 5 per 5 meters.

2. Description of the Study Area

The study area is a part of a narrow plain which forms a small portion of the Plio-quaternary of Cheria basin. The study area is located between X (386785 and 386590) and Y (3906510, 3906645). The region is bounded by Edalaa basin to the West and El Ma El abiod catchment area to the East, by the Hamammet-Tebessa-Morsott trough fault to the North and by Tlidjen basin to the South (Fig. 1).

Annual precipitation in the study area ranges between 350 and 400 mm, and thus the area is considered to be a semi-arid area. Temperature can rise in the summer to 45 °C. This situation of dryness accentuates the drawdown of water resource especially during the last decade because the renewal of this resource is very weak [17].

3. Geological and Hydrogeological Setting

Approximately 5 million years ago during the Neogene Period (Miocene series) the Cheria basin (North of Algeria) started to subside. It is a part of a narrow trough which forms a small portion of the great Mio-plioquaternary tectonic depression of Cheria [18, 19]. The basin is entirely filled by marine sediments of Upper Cretaceous age. The bedrock is made up of marly rocks of the Danien Tertiary age and marly limestone rocks of Cretaceous age [19, 20]. The survey area investigated in the present study is from the Eocene formation, which is known locally as the Cheria Limestone formation. This formation is mainly made up of limestone which is overlain by quaternary alluvial deposits, composed of gravel, sand, silt and clay [21].

The Eocene limestone Aquifer System is considered to be one of the most significant and potable groundwater aquifer in the Cheria basin [16, 22]. The perennial water available in the study area is from the Eocene limestone aquifer. The Marly-limestone bedrock forms the boundaries of the groundwater reservoir [16, 22]. The thickness of the Eocene limestone aquifer increases towards the central part of the basin [23], it is considered as a broadly closed system, as it has natural boundaries to the east and southeast formed by the Djabel Achour and Dokkan and is bounded to the south by Djabel Zora and Boukammech and west by Djebel Kamell and Djabel El Abtine and North by Djabel Troubia and Djabel Tazbent.
Karst processes are one of the most important factors affecting the study area. Cover-collapse sinkholes, even though an apparently sudden phenomena, are the result of complex processes that occur through a succession of steps in terrains characterized by a soluble (karst) bedrock covered with a more or less thick and loose sedimentary cover, normally ranging in thickness between a few metres and approximately 30 m (Fig. 2). They normally form in recharge areas of covered karst terrains [24], but can also develop, under certain circumstances, in areas of groundwater recharge [25]. Under-ground drainage through the epikarstic zone towards deeper lying karst conduits or along enlarged joints and mantled karren shafts (wide enough to enable turbulent flow) connected to the overlying sediments allows downward and lateral transportation of material by gravity or by seeping water. This downward erosion of covering sediments into the epikarst is called “ravelling” [24]. In many cases this is not a purely natural phenomenon, but
appears most often to be accelerated by anthropogenic activities such as pumping and constructing, as clearly demonstrated by numerous case studies published in *The Proceedings of the Multidisciplinary Conferences on Sinkholes* [24].

4. A Conceptual Model of Sinkhole Formation

The diagnostic landform of karst is the closed depression formed where the ground surface has been eroded around an internal drainage point into the underlying limestone (Fig. 2). These depressions are labelled dolines by geomorphologists, but are generally known as sinkholes by engineers [26]. They are classified into six types (Dissolution sinkholes, Collapse sinkholes, Caprock sinkholes, Dropout sinkholes, Suffosion sinkholes and Buried sinkholes) each with its own discrete mechanism of formation.

Fig. 2  Diagrammatic and photograph representations of the dropout sinkhole.
(a) A. C. waltham and P. G. Fookes, 2003 [26];
(b) Study area.
The studied area stretches over 14,700 m² with altitudes ranging from 1,090 to 1,096 m above sea level. From time to time, steep-walled circular collapses open up in the area. Since 2001 up to now, two collapses have been reported. Their size ranges from 35 to 45 m in diameter. The two collapses are also known as cover collapse sinkholes (Dropout sinkholes type). They are formed in cohesive soil cover (Mio-plio-quaternary) where percolating rainwater has washed the soil into stable fissures and caves in the underlying limestone (Fig. 2). Rapid failure of the ground surface occurs when the soil collapses into a void that has been slowly enlarging and stoping upwards while soil was washed into the limestone fissures beneath [27, 28].

5. Field Investigation

5.1 Microgravimetry and Topographic Surveys

Microgravity observations were made on a 70 m × 210 m grid with a spacing of 5 m in one only phase from February to March in 2016 (Fig. 3). Local coordinate system was used with the starting point at...
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(point 01, profile 01 Fig. 4) located in the south-east part close to study area (Fig. 4). Globally, 614 points were positioned, measured and distributed on 42 profiles with length of 70 m. Each measured station position had been determined with a sufficient accuracy in horizontal and vertical directions. Elevations of measured points have been determined by means of technical levelling with the instrument Fennel Qeo420K in a closed loop (starting from the base station). The loop error was ±0.001 m and in the case of such a small error, obtained elevation values have not been adjusted. The map of measured elevations is displayed in Fig. 4.

Gravity data were collected using the relative gravimeter GNU-KC 444. The instrument has a quoted standard field repeatability of less than 6 μ Gal. The corrections of Earth tides, tilts of the measuring system, temperature changes and a long-term drift were implemented automatically during the measuring process. For a correct determination of the short-term drift, the base station readings were recorded every hour during the survey on a selected base station (located at 10 m in the south of the first point of measurement on the profile No. 01). Repeated readings on 123 control stations (i.e., 20 percent from the total number of points) were taken as a part of the survey, which provided the root-mean-square error of less than 4 μ Gal.

Fig. 4  Location and numbering of topographic and gravimetric profiles on the altimetric map of the study area.
5.2 Data Processing

In the interpretation of microgravity surveys the relative variations in the local gravity field are important. Therefore, the data do not need to be corrected to the absolute gravity. Elevation and Bouguer corrections (with a density of 2.35 g/cm³) were applied to all gravity values. Since the topography of the study area is flat, no topographic correction was applied.

The method of regional-residual separation is the graphical method, which is suitable for data recorded over a grid. The gravity field was observed surrounding a particular grid point. In this manner, at all grid points a new grid is generated, which is contoured to obtain the residual anomaly map representing shallow sources. This method is dependent on the grid size adopted for averaging the surrounding values, and therefore depends considerably on the individuals experience in dealing with gravity anomalies, and the nature of the problem for which the survey is conducted.

6. Results and Discussion

6.1 Complete Bouguer Anomaly

The data of the complete Bouguer anomaly (Aمبر) vary from 220.281876 to 220.801051 mgals and the average is 220.446147 mgals. The map of the complete Bouguer anomaly (Fig. 5) showed space variability was well organized like the distribution of topographical survey (Fig. 4). The values of the complete Bouguer anomaly increase at the two ends of the map (North-East, South-West) with a variability about 0.40 mgals. Low values being observed in the sector located between two collapses and more precisely in the sector of the low altitude.

Fig. 5  Complete Bouguer anomaly map of the study area.
The map of Fig. 5 underlines a gravimetric zonality reflecting the characteristics of underground in the part center of the map. According to local geology, this would be explained by the presence of the more important karstic cavities in this part of the MChentel area according to the studies passed on this area. Note that according to the scientific literature, the karsts and the cavities underground generally have low densities by contributions the densities of the sedimentary formations of the area have (1 g/cm³ if the empty cavity).

6.2 Residual Anomaly

The data were processed and corrected using the procedures outlined in Butler [11, 29, 30]. A density of 2.35 g/cm³ was used for the Bouguer and terrain corrections based on density measurements on near-surface soil and rock samples from the study area. A total of 614 stations are near the two sinkholes. Fig. 6 is resulting residual gravity anomaly map for the basic 5 m grid data set and for all the data (including 5 m grid data), respectively, after removal of a planar regional field determined by graphical method. This map was created by the grid subtraction in the Surfer software (Surfer 11). For further interpretation, the area bounded by a rectangle (Fig. 1) was used. The main feature, clearly noticeable in the final residual Bouguer anomaly map, is a negative anomaly located in the apse, with amplitude exceeding -0.01 mgal (The two zones bordered by the yellow color in Fig. 6). One of the possible interpretations of this negative anomaly is the existence of underground cavities.

Fig. 6  Residual anomaly map of the study area.
6.3 Derivatives Maps

Two types of gravity-gradient maps were generated from the MChentel area microgravity survey data. The familiar ring and center point (spatial filtering) techniques were utilized to compute first (vertical gradient) and second derivative maps from the gravity data. These techniques were used for this site for two reasons: (1) to investigate the application of the techniques to small-scale surveys for improved resolution and the determination of residual gravity maps; and (2) because the known cavity system is clearly three dimensional. Since the techniques are familiar and standard, details about their formulation and use will not be given.

The first and second horizontal derivatives following X and Y directions maps in Figs. 8 and 9 were produced using a transform due to Fourier [11, 13, 31-33]. This technique is sometimes referred to as successive derivative of the potential method, since it is designed to produce a map closely resembling a residual gravity map.

The comparing of the first and second horizontal derivative maps following X and Y directions in Figs. 8 and 9 with the residual gravity map in Fig. 6, the similarity is evident except the two zones bordered by the yellow color in Fig. 6 (residual gravity map). The vertical derivative technique is a more objective procedure than the inspection or graphical techniques, and it can be advantageously applied to microgravity survey results when it is difficult to recognize the proper scale regional field. Fig. 10, the first and second vertical gradient, was produced using a transform due to Fourier. The transform does not have coefficients chosen to produce smoothing as in the residual gravity. Thus, in principle, the first vertical derivative map should have greater resolution than the second derivative and residual gravity map. All of the anomaly features identified on the residual gravity map can be seen on the first derivative map; however, the spatial extent of given anomalies is generally less on the first derivative map than on the residual gravity map. Also, some anomalies observed as single features on the residual gravity map seem to be resolved into two or more features on the first derivative map (the first and second derivatives for three directions X, Y and Z), such as the first negative anomaly between the two sinkholes in Fig. 6 (residual gravity map) along the south-west boundary of the survey area.

In order to compare and evaluate the features of the derivatives and residual gravity maps, two north-south profile lines were selected for study. The 22 north-south profile lines (Fig. 4) were chosen due to the interesting negative anomaly centered at (22, 13) and because it is representative of areas at the site about which nothing was known prior to verification. All eighteen profiles show the negative anomaly feature between profile line (22, 13) and (35, 28) (Fig. 4). The gravity profile suggests that there might be two closely spaced subsurface features causing the anomaly (or at least a significant change in shape, size, or density contrast of the feature). The second derivative map shows essentially the same information as the residual gravity map. The first derivative profile, however, clearly resolves the anomaly into two negative anomalies centered at the (22, 13) and (35, 28) profiles lines. The results of interpretations confirmed the presence of a significant cavity feature at this location which varied in dimension and depth laterally.

Qualitatively, all eighteen profiles in Fig. 6 are similar. The smoothing inherent in the second derivative procedure is evident in the subdued nature of the highs and lows corresponding to the limestone pinnacles. The first derivative profile in this case, however, is nearly identical to residual gravity profile in delineating the top of limestone topography and detecting the known cavity (see Figs. 8 and 9).

In the map of the first derivative of the residual anomaly according to the authors find the two negative anomalies (I) and (II) (Figs. 6 and 7). Anomaly (I) is
Fig. 7  The vertical derivative maps of the residual anomaly.
Map 01: residual anomaly of order 01.
Map 02: First vertical derivative of the complete residual anomaly of order 01.
Map 03: Vertical second derivative of the complete residual anomaly of order 01.
Fig. 8  The horizontal derivative maps according to x.
Map 01: Residual anomaly of order 01.
Map 02: First horizontal derivative of the residual anomaly following x.
Map 03: Derivative horizontal second of the residual anomaly following x.
Fig. 9  The horizontal derivative maps following y.
Map 01: Residual anomaly of order 01.
Map 02: First horizontal derivative of the residual anomaly following y.
Map 03: Horizontal derivative second of the residual anomaly following y.
a more important intensity by contributions of the second anomaly. The map of residual anomaly obtained starting from higher order (derivative second) shows the same zones of anomalies but their intensity is varied from an order to another. The anomaly remains like a trace by contributions of second anomaly to disappear completely. Knowing that more order large more the anomaly is decreased, one can deduce that the two anomalies were located at a low depth and the speed of variability always remains weak with worthless following axis Z.

The second derivative watch much best match the trajectory of the variability of the karstification phenomenon and its extension on two axes (OX) and (OY). The intensity of the anomaly remains always positive as axis (OZ) in zone (II) and more developed the zone (I) where an anomaly negative was found on an important surface by contribution at the same zone for a second derivative following Z knowing that the major anomaly about axis (OX) that axis (OZ).

6.4 Extensions of the Residual Anomaly

For better identification of the generating sources of the anomalies, we applied to the map of Bouguer anomaly the filter of prolongation to various heights of 10, 50, 70, 80 and 100 meters (Fig. 10). It is noticed that starting from the height of prolongation of 70 meters the two anomalies (I) and (II) stamp themselves; it indicates the shallow deep characters of the two anomalies.

The application of differences between the prolonged maps to different heights (Fig. 10) makes it possible to specify these results:

- Between 10 meters and the surface of ground: The near total of energy is preserved in this slice, the same anomalies (I) and (II) (coloured by violated color) already quoted are found.
- Between 10 and 50 meters: Quasi energy especially is little changed in level of the anomaly (II). This little change found on the surface of this anomaly indicates in this slice of prolongation closer to the centre of gravity of the anomaly (already calculated to be 26,775 m).
- Between 50 and 60 meters: The energy of the anomaly returns in an initial state of slice (from 10 to 50 m), which indicates its beginning of distance per contribution to the centre of gravity of the two anomalies.
- Between 60 and 70 meters: The two anomalies grow blurred, which confirms the not very major character of the two anomalies (shallow deep of the two anomalies).

6.5 Comparison between Drilling and Microgravimetric Surveys

With a careful field acquisition, the gravimeter was shown to be adequate for shallow subsurface target location in karstified limestone. Considerable emphases were placed to the data processing, especially to the evaluation and delineation of the shallow cavities, which could produce false negative signals and deform the interpreted Bouguer anomaly field.

Drillings of water in the Cheria basin (Table 1) indicates an average thickness to the karstified limestone of the Eocene from 25 to 35 meters, the residual anomaly (the gravimetric answer of all that is above twice the depth of limestone of the Eocene; approximately of 70 meters) is given by the subtraction of regional anomaly (the field prolonged to the top with an altitude of 70 m) and also calculation maximum depth of the anomaly given is 55 m <d> 65 m [19, 23]. This depth is confirmed by the prolongation of our complete Bouguer anomaly.

Fig. 6 shows the residual anomaly result of the subtraction of regional of the Bouguer anomaly. The part of the anomaly attenuated (coloured by violated in Fig. 10) by the prolongation is represented in the residual anomaly. According to the development of Jacobson (1987), this residual is the gravimetric answer of the distribution of density until the depth equals to 30 meters (Z/2). The residual anomaly takes values between (-0.000211) and (-0.126958) milligal.
Fig. 10  Maps of the complete Bouguer anomaly after extensions 10, 50, 60, 70, 80 and 100 meter upwards.
Table 1  Drillings of water in the Cheria basin.

<table>
<thead>
<tr>
<th>Well N°</th>
<th>508</th>
<th>510</th>
<th>512</th>
<th>517</th>
<th>534</th>
<th>JK8</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total depth (m)</td>
<td>51</td>
<td>29.15</td>
<td>30.6</td>
<td>20</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>Depth of limestone roof (m)</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1.10</td>
<td>0</td>
<td>11</td>
</tr>
<tr>
<td>Thickness of limestone (m)</td>
<td>51</td>
<td>29.15</td>
<td>30.6</td>
<td>18.9</td>
<td>100</td>
<td>89</td>
</tr>
<tr>
<td>Depth of the karstified zone (m)</td>
<td>19.7-23</td>
<td>20-20.05</td>
<td>19.7-23.3</td>
<td>5.1-19</td>
<td>44-45</td>
<td>15-27</td>
</tr>
</tbody>
</table>

Table 2  Characteristics of the two anomalies zones.

<table>
<thead>
<tr>
<th>Anomaly</th>
<th>Zone I</th>
<th>Zone II</th>
</tr>
</thead>
<tbody>
<tr>
<td>X Coordinates of the center of gravity of the anomaly</td>
<td>3,906,627</td>
<td>3,906,675</td>
</tr>
<tr>
<td>Y Coordinates of the center of gravity of the anomaly</td>
<td>3,906,627</td>
<td>3,906,675</td>
</tr>
<tr>
<td>Maximum length of the anomaly (m)</td>
<td>44.968</td>
<td>46.76</td>
</tr>
<tr>
<td>Maximum width of the anomaly (m)</td>
<td>33.862</td>
<td>19.12</td>
</tr>
<tr>
<td>Total scope (m)</td>
<td>133.481</td>
<td>119.594</td>
</tr>
<tr>
<td>Total surface area (m²)</td>
<td>1,153.114</td>
<td>639.356</td>
</tr>
<tr>
<td>Radius of the anomaly (m)</td>
<td>19.163</td>
<td>14.269</td>
</tr>
<tr>
<td>Depth of the center of gravity of the anomaly (m)</td>
<td>41.640</td>
<td>26.755</td>
</tr>
<tr>
<td>Amplitude of the anomaly (mgal)</td>
<td>-0.09</td>
<td>-0.09</td>
</tr>
</tbody>
</table>

The interpretation of all gravimetric documents shows the presence primarily of two negative zones of anomaly, the characteristics of these zones and anomalies are defined in Table 2.

Significant negative anomaly was obtained from the final residual Bouguer anomaly map. Euler deconvolution and system of source equivalent [34, 35] provided approx. positions and depths to the anomaly source. The shape and depth of possible crypt were estimated using 3D density modelling. The results show that the crypt could be situated approx., from 25 to 40 m under the surface of the study area (depth of centre of gravity of the anomaly). Finally, we can claim, based on the qualitative (shape and amplitude of the anomaly) and quantitative (3D Fourier transform and 3D density modelling) interpretations, that the presence of medieval crypt in the apse of the church is highly probable. However, it must be accompanied by the 3D electrical resistivity tomography measurements.

7. Conclusion

The microgravity technique at the MChentel area is shown to be a very effective and non-destructive tool to detect and delineate shallow, complex cavity systems. Familiar spatial filtering techniques were applied to the dense grid of gravity stations to produce first and second vertical and horizontal derivative maps. Suitable selection of ring radii and coefficients in a first and second derivative equation successfully produced a map which compares quite well with residual gravity maps produced by the usual regional-residual separation procedure (graphical method).

The microgravity survey of the study area successfully detected the main water-filled cavity system (complex karstified cavities systems). This paper has presented an example of microgravity data collected in MChentel area in Cheria basin in order to map out the possible subsurface void features.

References


