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Detection for severe caves and sinkholes in non-clastic rock type using GPR technique

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ABSTRACT
This study examines the application of Ground Penetrating Radar (GPR) to the detection of severe caverns and sinkholes in non-clastic rock formations. Due to the presence of vertically sloping bedrock, cavities, and sinkholes, geotechnical engineers face significant challenges when designing and constructing foundations in karstic formations such as limestone. The territory under investigation is located close to the Giza limestone plateau, the northern side of which has experienced severe stability issues. The ground-penetrating radar (GPR) method was used to identify the presence and extent of exposed caves and caverns in the studied region. The research area's geological and geomorphological background is explored, including the creation of primary and secondary caves, as well as solution caves generated by the breakdown of soluble rocks like limestone. Data collecting, processing, and interpretation procedures used in the GPR survey are described. GPR survey findings revealed the existence of a severe cave and many minor sinkholes in the studied region. GPR has shown to be a useful and efficient tool for determining geometric karst features in the subsurface, helping to a better evaluation of the dangers associated with this geological environment.

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1. Introduction

Geotechnical engineers have faced a number of difficulties while designing and building foundations in limestone formations because of the rock's karstic characteristics, including its steeply inclining bedrock, slime zone, cavities, and sinkholes existence. The establishment of foundations in such extremely erratic ground conditions requires careful planning and execution of the work, beginning with preliminary subsurface investigation, followed by detailed subsurface investigation, analysis, design, and continuing all the way up to the construction stage, where continuous feedback is essential for the satisfactory performance of the foundations. In this type of geological context, soil subsidence and cavity collapse can pose a social and economic hazard, which is exacerbated by the urbanisation of these cities (Waltham et al. 2005).

Several geophysical techniques, such as geoelectrical resistivity, gravity, magnetic, and seismic instruments, can be used to determine the lithology and structures of the subsurface (Azeem et al. 2014; Abdelazeem et al. 2020; Araffa et al. 2020). Ground Penetrating Radar (GPR) has been proven to be the most effective geophysical instrument for identifying geometric karst characteristics in the subsurface, despite the large number of geophysical studies conducted on karst terrains around the world. Whereas, the GPR method has been effective in mapping subsurface caverns and sinkholes in karst environments and has been contributed to a better assessment of the risks associated with this geological environment (McMechan et al. 1998; Zisman et al. 2005; Kruse et al. 2006; Sevil et al. 2017; Mohamed et al. 2019; Hussain et al. 2020).

In Cairo, the verticalisation of urban spaces as a result of higher living standards and the construction of tall buildings in urban areas, as well as the progressive expansion of land use, have affected the natural environment, as is the case with karst terrains on the west bank of the Nile River. These urbanisations are vulnerable to geological threats presented by events that cause subsidence and caverns beneath the newly expanded zones. This is exactly happened at the research site, where open caverns were accidentally uncovered in the limestone rock at a specific position during excavation for one of the metropolitan communities being developed along the Alexandria-Cairo desert road, as shown in Figure 1. This location is near to the Giza limestone plateau, as

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Figure 1. Examples of founded caverns that were uncovered on the construction site during excavation.

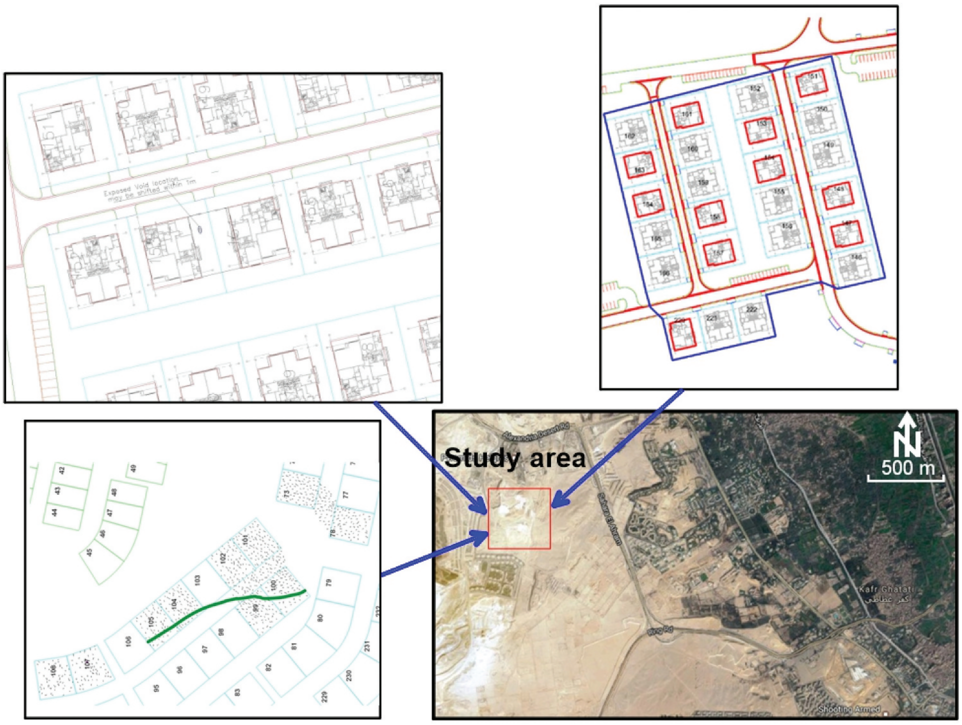

Figure 2. The location map of the study area near the Giza limestone plateau, the northern side of which has encountered significant stability issues.

depicted in Figure 2, a portion of which has severe stabilisation issues on its northern side. In order to detect the existence and extension of the exposed caves and caverns in the studied area, GPR technology was employed.

2. Geological and geomorphological setting

The geology of the study region is distinguished by a palaeozoic-aged rock basement. Above this foundation lies an ancient limestone made of clayey limestone. Tertiary sediments are found above that, including alluvium gravel and sand, as well as Sandstone, Limestone, and Clay (Figure 3).

The lithology of the rocks and geologic structures in the studied area plays a crucial role in the formation of their topographic and geomorphologic characteristics. The Nile valley is composed primarily of alluvial deposits derived from Pleistocene deposits and Pliocene bedrock, with a well-developed thickness of approximately 2 metres. They have a light grey appearance and a very delicate texture. They are composed of sand, sediment, and gravel with a reddish hue. Middle Eocene Tertiary sediments are the earliest deposits in the study area.

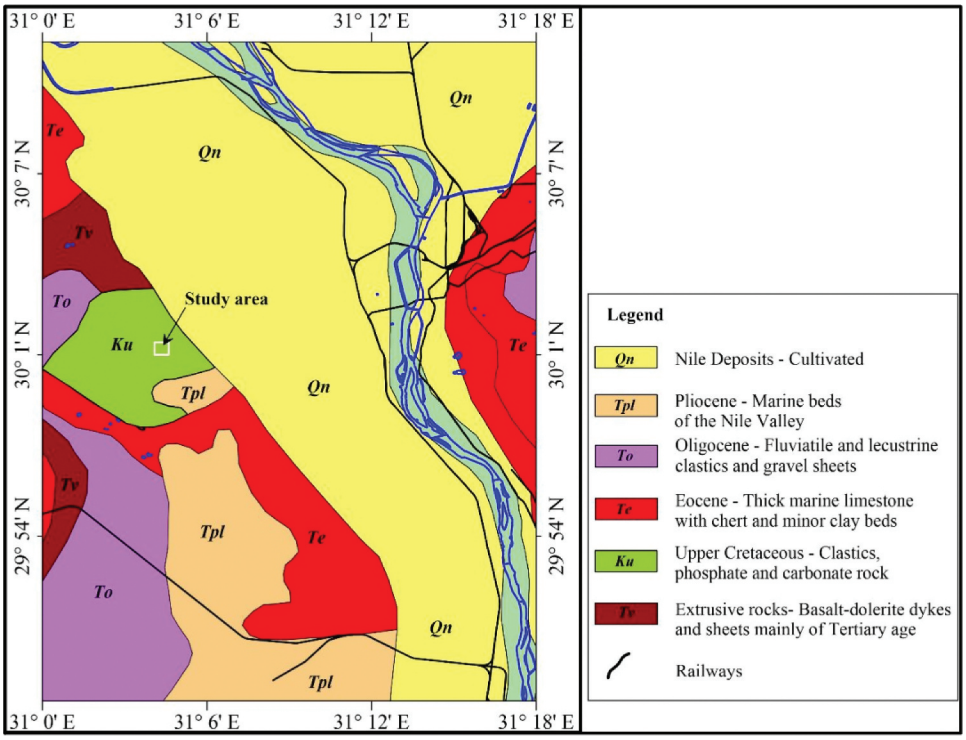

Figure 3. The geological map was derived from EGS, 1981 showing the distribution of limestone formations that are vulnerable to cavities and sinkholes due to the karstic properties of the rock.

During the Tertiary, a significant sedimentary cycle, the transgressive-regressive development, took place, which is reflected in the general organisation of deposits. Any hole in the ground that is big enough to prevent portion of its interior from being illuminated by direct sunlight is considered to be a cave. A cavern is a specific kind of cave that forms in soluble rock. Caverns may be formed as a consequence of the deposition of minerals called speleothems.

According to their origin, caves can be divided into two categories: primary and secondary. The formation of primary caverns, including volcanic tunnels and coral caves, occurs during the solidification of the host rock. The formation of secondary caverns follows the deposition and consolidation of the host rock. The majority of caverns fell into the second category. Solution cave is the subcategory of cavern-classified caverns. They result from the dissolution of soluble rocks, such as calcium carbonate rocks (limestone), calcium magnesium carbonate rocks (dolomite), calcium sulphate dehydrates rocks (gypsum), and salt (halite). The host rock in the current investigation is limestone. However, the conditions for other soluble minerals are essentially identical. Because the dissolution of limestone occurs in bedrock beneath the surface, a cavern cannot acquire an entrance. Most entrances are formed after the formation of a cavern. Entrances may be the result of natural erosion, roof collapse, or accidental discovery during quarrying, tunnelling, or other ground works (Chamberlain et al. 2000).

3. Methodology

GPR is a useful tool for finding tiny caves and fissures in karstic environments (Collins et al. 1994; Conyers 2012, 2013, 2015, 2016). In dry or fairly moist solid rocks, the GPR survey is considered more convenient. The GPR technology works by sending radar waves into the ground and then capturing the signals that return to the surface. The cavern zones on the received waves are distinguished by high-amplitude reflectivity patterns, and the polarity of the individual reflection traces is reversed (polarity shifts). The GPR geophysical method was used in the present research to discover near-surface concealed caverns under the investigated region. Global Navigation Satellite System (GNSS) observations have been carried out to measure the position of GPR profiles and points. The accuracy of the measured positions reached to sub-millimetre.

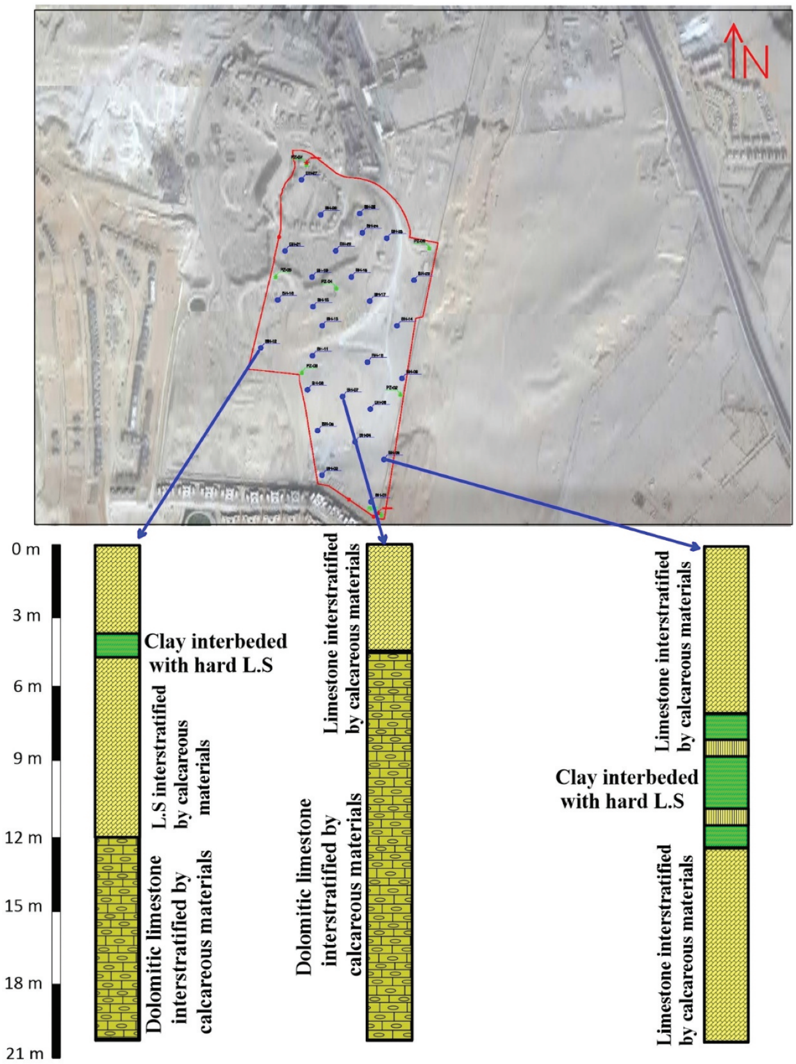

Figure 4. Drilled boreholes in the study area.

3.1. Soil description

For a detailed understanding of the subsurface soil composition in the study area, series of boreholes were drilled. These boreholes provided valuable insight into the geotechnical features present in the area, revealing the existence of two distinct types of limestone with varying depths. Dolomitic limestone was identified at greater depths, while fragmented limestone was found closer to the surface.

The fragmented limestone layer located closer to the surface is characterised by block-like structures containing numerous closely spaced fissures and fractures, as depicted in Figure 4. Furthermore, it was observed that these limestone layers were intermixed with calcareous material and had a yellowish-white appearance. During the drilling process, there were instances where fluid circulation was lost, indicating the potential presence of cavities or fractures at certain subsurface levels.

In addition to the limestone layers, a clay layer with a thickness of approximately 6.0 metres was discovered at a depth of around 7.30 metres in an existing borehole. Thin clay layers with a thickness of approximately 70 cm were also found interspersed within the limestone layers. These findings provide valuable information on the subsurface soil composition in the study area and can aid in future geological investigations and construction projects.

3.2. GPR scans and analysis

Based on two phase measurements, a total of 299 GPR profiles were measured to cover the area of study using 200 MHz monostatic antennas and applying time window 200 ns, with 32 scans per metre, and 512 samples per scan (Figure 5). The measurements of the profiles were taken using the same survey parameters in order to identify the existence of subsurface cavies, fractures, and joints.

Figure 5. The GPR scan with SIR 4000 and Mala systems using 200 and 250 MHz antennas during acquisition.

The GPR data were processed using algorithms from the REFLEX 7.0 suite in order to eliminate the noise signal and improve the signals representing the embedded characteristics. A number of processing procedures, such as static correction for the ground zero level, backdrop removal to make it easier to recognise the embedded infra-structure, band-pass 2D filtering to get rid of the noise and achieve clear portions, and automated gain control (GC), were used. By conducting GPR over an exposed cave in the research region, the velocity that was utilised for time/depth conversion was determined, and it was found to be 0.1 metres per second (as shown in Figure 6). In order to make the GPR scanning procedure easier, the research area was split up into numerous sections, each of which was roughly rectangular in shape and measured around 30 by 30 metres (see Figure 7). The GPR scan was carried out with a line spacing of 1 metre for each scan segment that was obtained.

As the main geological rock unit in the study is marl limestone, which includes clay continents, the results of GPR profiles revealed the existence of high attention and reflectors zonation in subsurface which are clay formations. Furthermore, there are surficial joints and voids distributed in several directions which are proposed to be not connected to each other, as well as, the voids were originally a clay zone that formed by dissolved the clay content due to the effect of chemical reactions and dissolving process. The below GPR profiles were measured across exposed void to determine its extension in depth as well as its lateral distribution. The void extended to 6 metres depth, with major length 60 cm and width 25 cm.

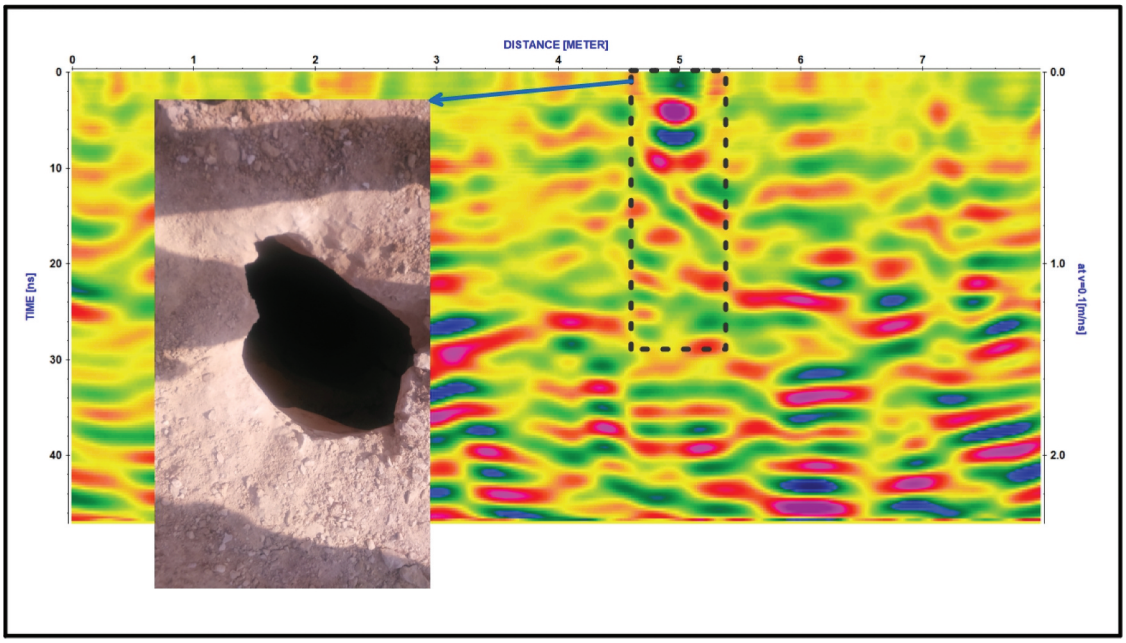

Figure 6. The exposed cave in the study area.

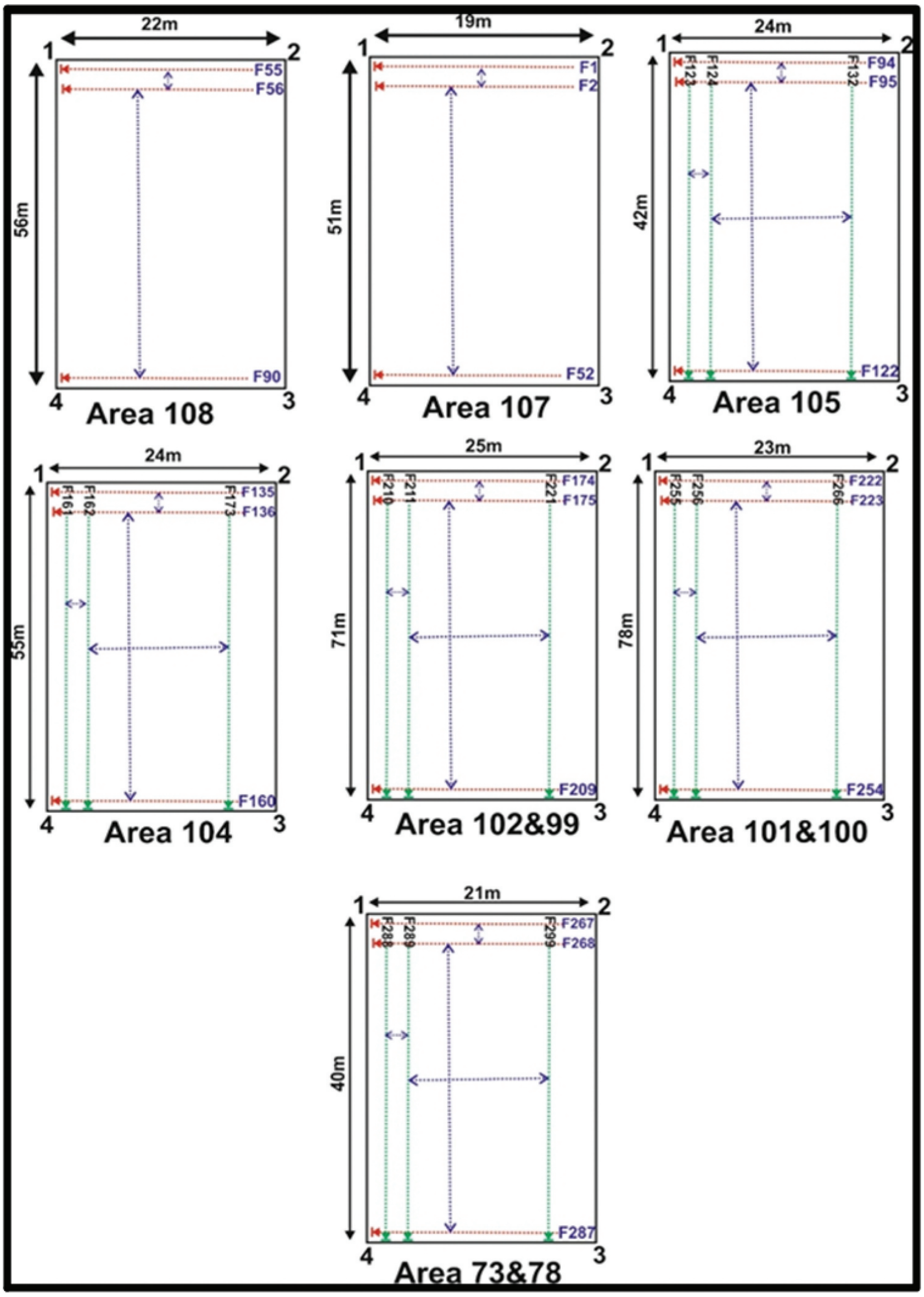

Figure 7. Example of dividing of each scan segment in the study area.

The results of GPR characterised subsurface rock in the scanned area into three geological, sedimentological, zones. Weakly compact limestone which has thickness varies between from 30 cm up to 1 metre and it is found as upper layer or zone. The second zone is compact limestone which is thought to vary between 1 metre up to 2.5 metre and it is found as intermediate layer. Moderately compact limestone which found from 2.5 metre and extended for deeper depths. Figure 8 illustrates the GPR profile and the derived interpretation for fractures and joints in the cliff edge.

4. Results and discussion

The Ground Penetrating Radar (GPR) technique was used to investigate the exposed caves in the limestone rock at the study site. The GPR survey was conducted in dry and moderately wet solid rocks and the GPR data processing revealed several anomalies in the

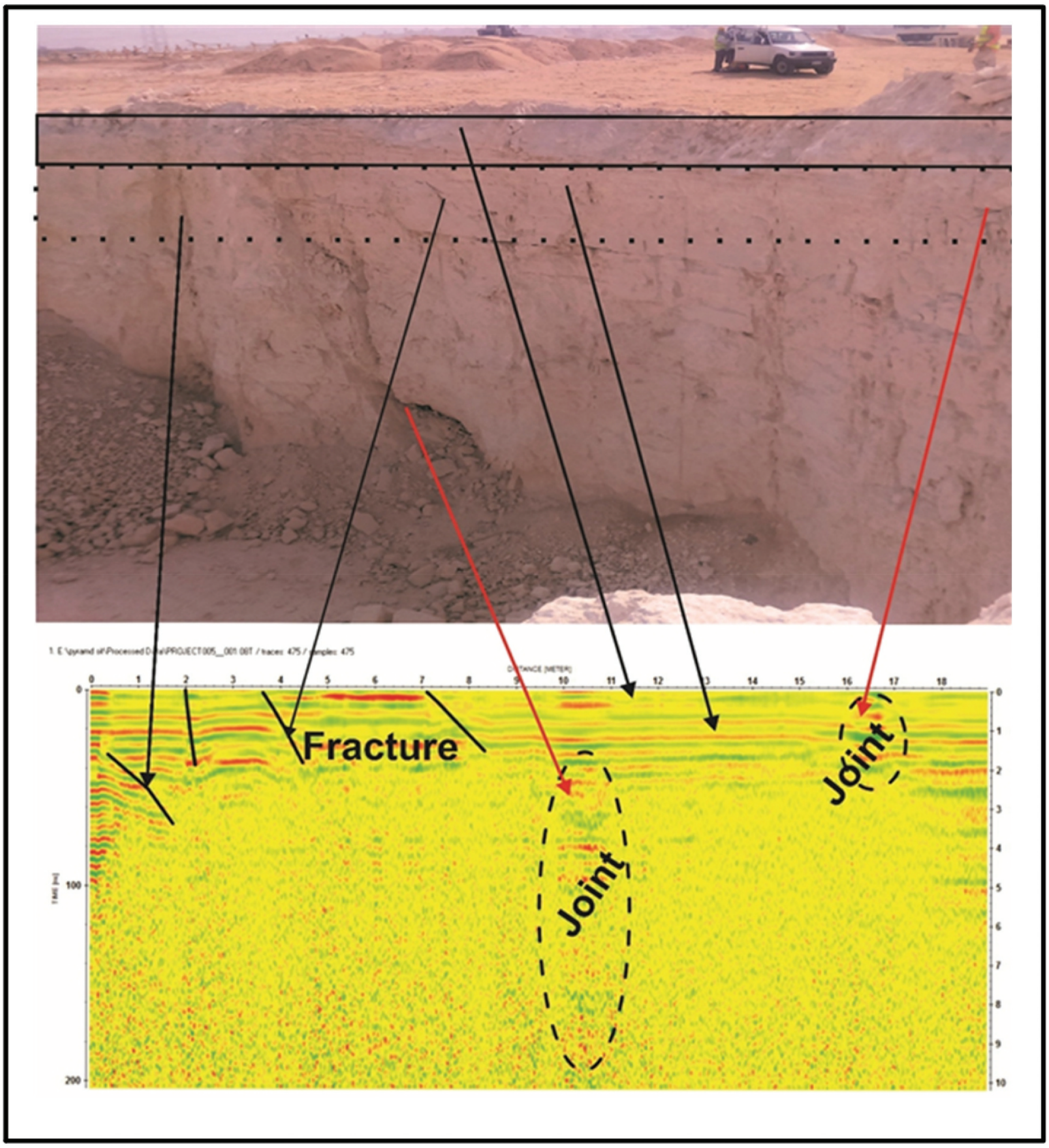

Figure 8. Surface exposure correlation of measured data.

subsurface that corresponded to the presence of underground cavities. Furthermore, the GPR profiles showed that the exposed caves were part of a larger cave system extending beneath the study area and representations of these results are shown in Figures 9, 10 and 11 respectively. The GPR survey identified two main zones of interest, Zone (A) and Zone (B). Zone (A) showed strong reflections at a depth of 3–6 metres, indicating the presence of a large underground cavity. This zone was located directly beneath the exposed caves and was found to extend towards the east and west of the study area. Zone (B) showed moderate reflections at a depth of 6–9 metres, indicating the presence of a smaller underground cavity. This zone was located to the south of Zone A.

The GPR survey also revealed the presence of fractures and fissures in the subsurface, which could have resulted from the karstic nature of the limestone rock. These fractures and fissures were found to be concentrated in the vicinity of the underground cavities. The results of the GPR survey provide valuable information for the design and construction of foundations in the study area. The identification of the underground cavities and fractures will help in avoiding potential

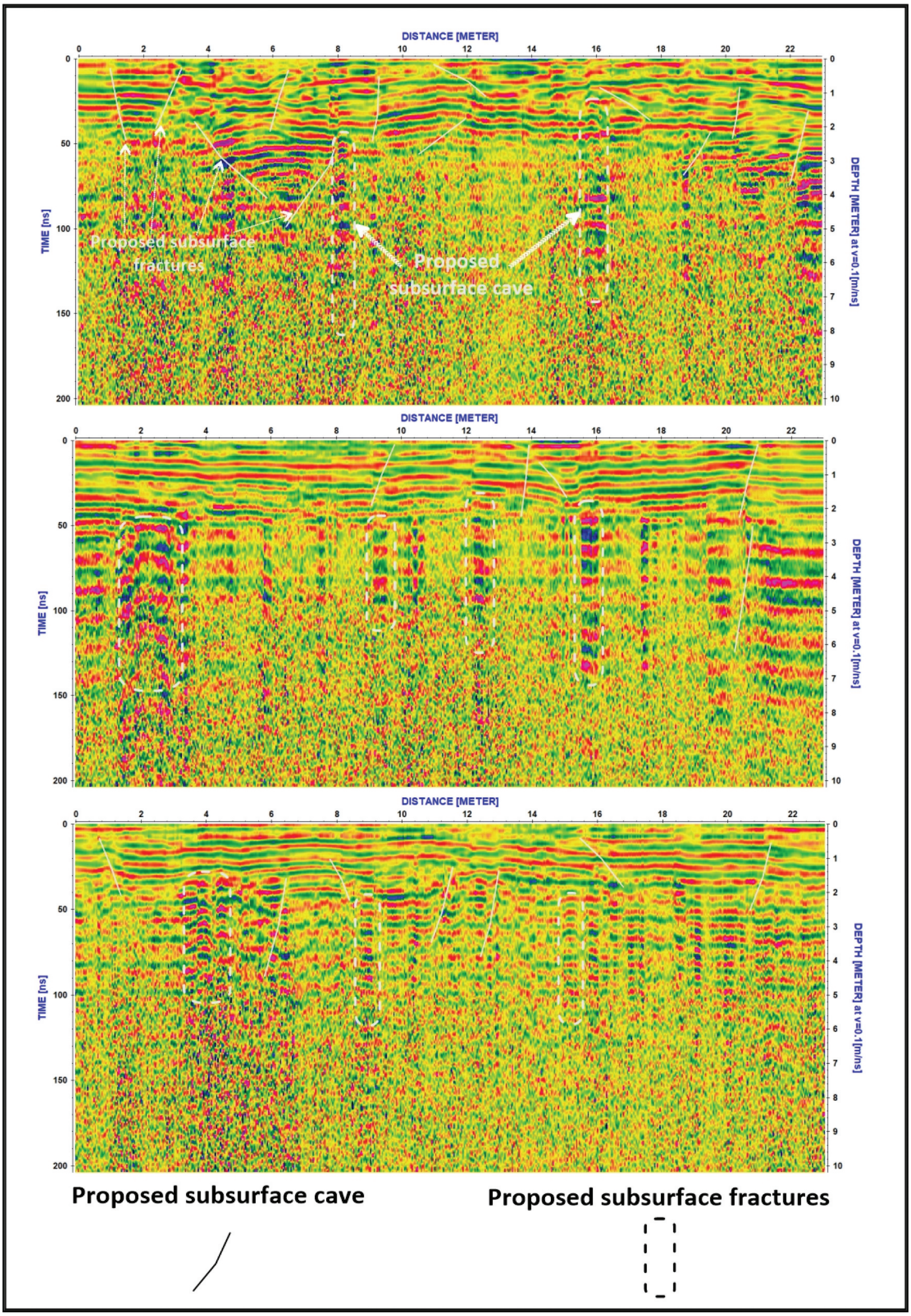

Figure 9. The 2D results of GPR scan with 200 MHz antenna.

hazards associated with the karstic environment, such as subsidence and cavernous. The hazards based on the GPR results due to caves and fractures portion in limestone are located in the east and is extended to the west side part. The GPR survey also provides a cost-effective method for mapping underground cavities and fractures, which can be used to assess the geological risk of karst terrains in urban areas.

In conclusion, the GPR technique has proven to be an effective geophysical tool for identifying

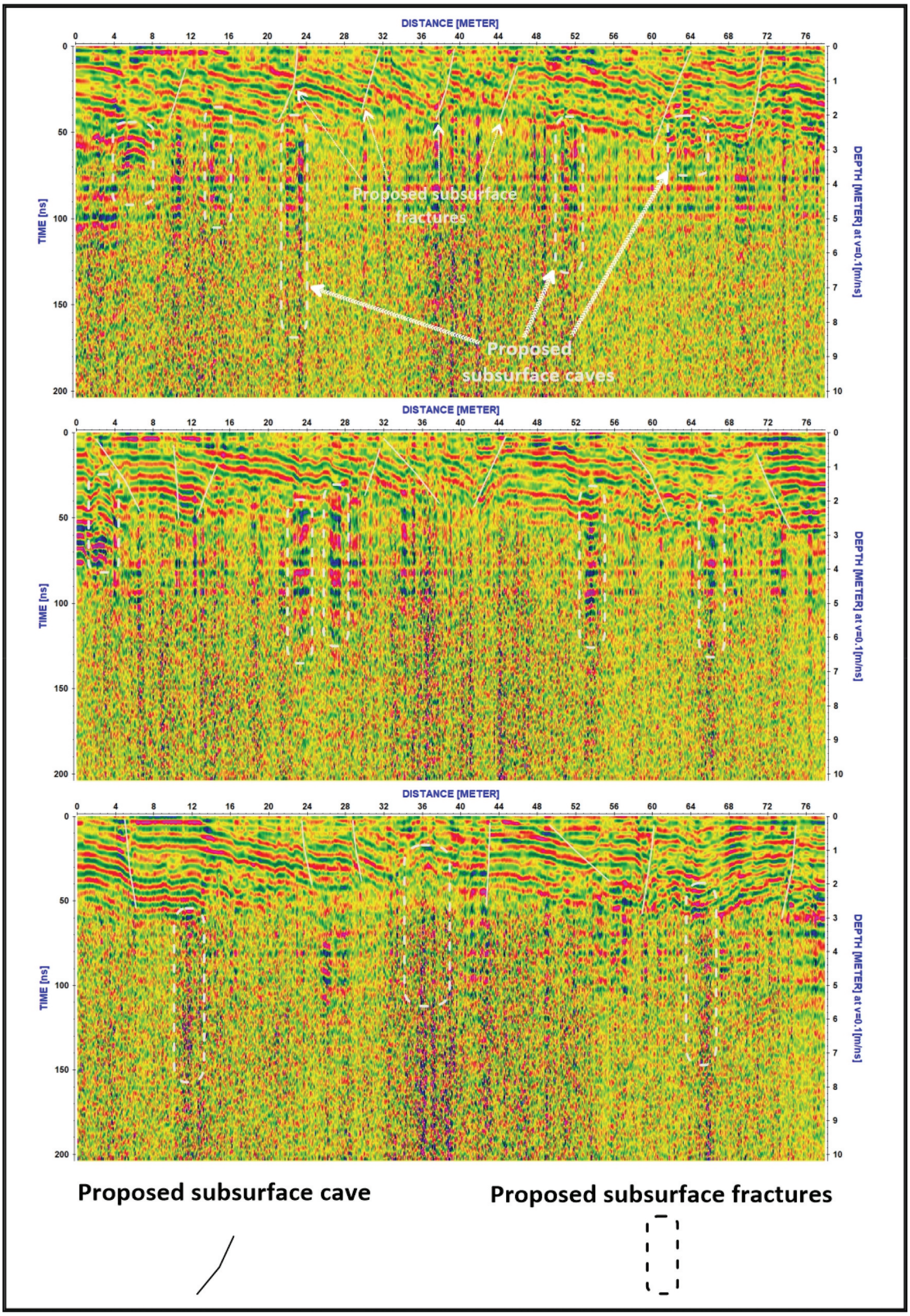

Figure 10. The 2D results of GPR scan using SIR 4000 and 200 MHz antenna.

underground cavities and fractures in karst terrains. The results of GPR survey conducted at the study site have provided valuable information for the design and construction of foundations in the area. The study highlights the importance of conducting subsurface investigations, analysis, and design for the satisfactory performance of foundations in highly erratic ground conditions.

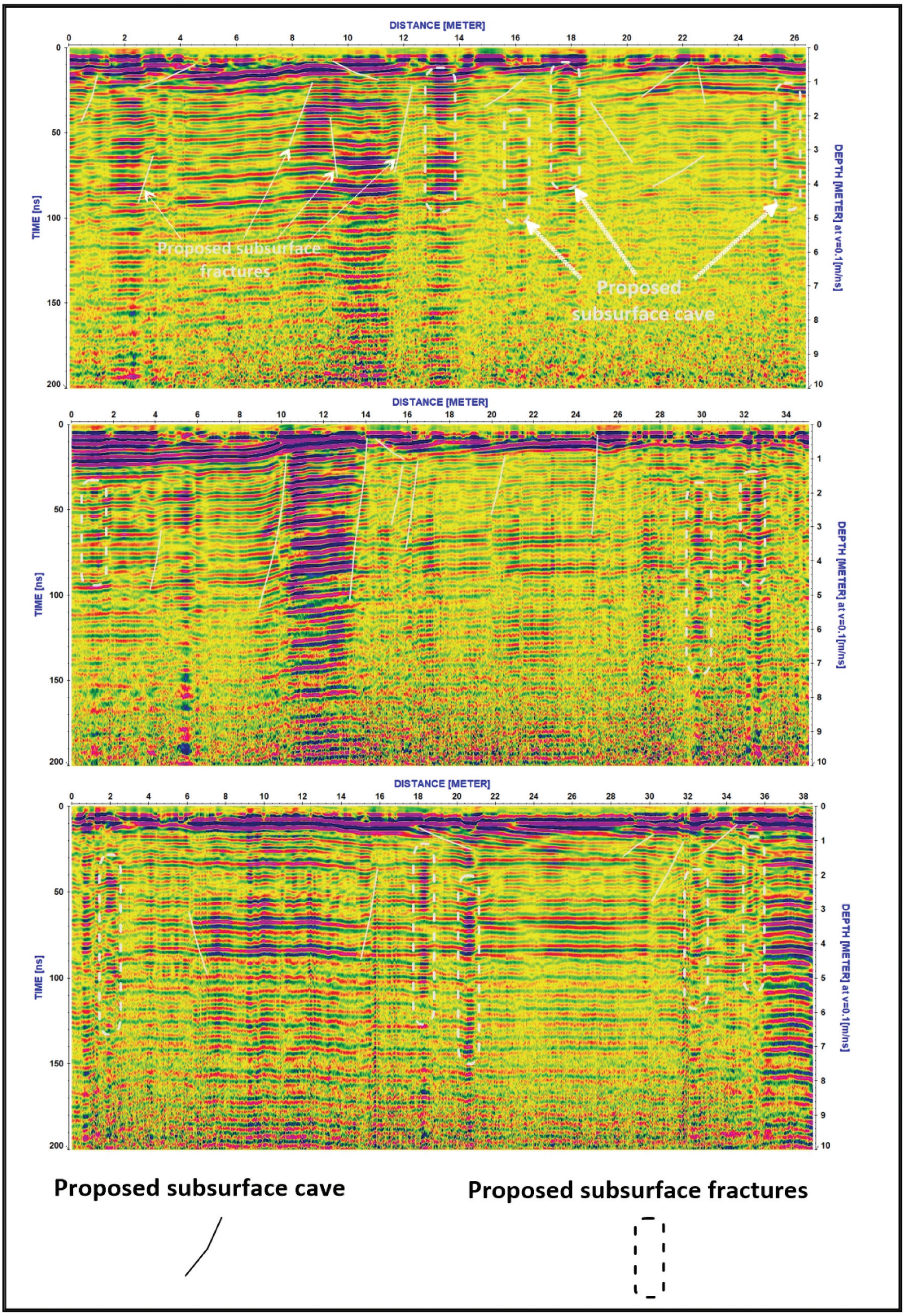

Figure 11. The 2D results of GPR scan with MALA system and 250 MHz antenna.

5. Conclusions

The GPR technique was used to detect underground cavities and sinkholes in limestone formations in the study site in Cairo, Egypt and the GPR survey covered an area of 700 m × 500 m using 200 MHz and 250 MHz centre frequency antennas. The results of the GPR survey showed clear reflections from the top and bottom of the limestone bedrock, as well as from the anomalies corresponding to the underground cavities and sinkholes. Based on the analysis of the measured GPR profiles in the study area, it can be concluded that the lithology succession comprises three types of limestone with varying degrees of compaction from the surface level to a depth of 9 metres. The uppermost layer or zone is weakly compact limestone, followed by a layer of compact limestone and a moderately compact limestone layer at greater depths. Fractures and cracks are observed in the compact limestone layer due to hard compaction, while joints appear in the moderately compact limestone layer due to soft compaction. The configuration of fractures and joints suggests that they are tectonic structures resulting from the stresses and strains of the earth rather than hydrothermal structures in limestone. Additionally, the data showed that the distribution of fractures and joints rates increased towards the East. The findings of the GPR survey demonstrate the effectiveness of the GPR technique in detecting underground cavities and sinkholes in limestone formations, which is valuable information for geotechnical engineers in designing and building foundations in karst terrains.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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