Karst limestone foundation geotechnical problems, detection and treatment: Case studies from Egypt and Saudi Arabia

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Abstract— Three selected areas in Egypt and Saudi Arabia have been chosen as pilot sites for studying the karst foundation problems. On a world scale, the dissolution of carbonate rocks creates extensive karst landforms that can be very difficult ground for civil engineering projects.

Geologically the observed caves, sinkholes and open fractures at El Minia-Maghagha Plateau (Upper Egypt) are belonging to the Middle Eocene limestone unit of Minia and Samalut Formations. Most of the observed karst caves and sinkholes are structurally controlled by major faults and joints which have NW-SE trend. The engineering classification of this karst foundation bedrock (as per Ford and Williams, 1989) is class K III.

The limestone foundation bedrocks at the northwest part of Riyadh city are composed of dolomite Limestone (Sulaiy Formation of Cretaceous age) and highly fractured limestone and evaporite (Arab Formation of Jurassic age). The engineering classification of this karst foundation bedrock is class K IV. The limestone foundation bedrock at the eastern part of Al Ahesa city is composed of fractured limestone (Hofuf Formation of Miocene-Pliocene age). The engineering classification of this karst foundation bedrock is class K IV.

Detection of Karst limestone foundation bedrock (caves, sinkholes and open fractures) in the three studied sites has been conducted by using geological and geophysical studies. The geological studies include detailed geological and geomorphological mapping for the three sits .The geophysical studies include 2D Electrical Resistivity imaging survey for northwest part of Riyadh city and GPR-2D Electric Resistivity survey to the eastern part of Al Ahesa City. The geological and geophysical surveys for the studied sites represent good approach and guide for projects foundation design and treatment.

Karst limestone foundation bedrock treatments have been used in several worldwide projects and include engineering fill, engineering fill and geosynthetic materials, concrete filling and cement grout low pressure injection. El Minia-Maghagha caves under the new constructed settlement areas have been treated by using high slump concrete filling. Northwest Riyadh City and Eastern Al Ahesa Citiy foundation treatment are conducted by using engineering fill, high slump concrete filling and low pressure cement grout injection.

Index Terms— **Karst limestone, foundation problems, GPR, 2D Electrical Imaging, detection and treatment**
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1 INTRODUCTION

Karst features occur primarily in limestone and dolomite rock masses. They include cavities, sinkholes and open fractures. Dissolution landforms develop best in competent, fractured rocks whose intact unconfined compressive strength generally ranges between 30 and 100 Map. Low strength (weaker) limestone, chalk and unlithified carbonate sediments lack the strength to span large cavities, and develop limited suites of karst features that are generally smaller than those in stronger limestones (Jennings, 1968 and Kannan, 1999).

Karst limestone foundation bedrock worldwide problems create serious construction problems and effective costs due to insufficient understanding of karst features during the design phase. A full understanding of the nature of karst as well as the method of surface and subsurface detection are very important to avoid the risk of sudden collapse of constructed buildings.

The studied Karst limestone foundation bedrock are located in three localities (Figure1), namely El Minia-

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Maghagha plateau, northwestern part of Riyadh City and eastern part of Al Ahesa City. These karst foundation bedrocks have several engineering problems related to construction process, project time schedule as well as project cost impact. The main objectives of this article are classifying the encountered karst foundation bed-rocks according to Ford and Williams (1989) engineering classification, introducing the optimum methods for detection these karst features and engineering treatments of these features.

Figure 1: Google Earth Satellite Image showing the locations of studied areas (1-Minia - Maghagha Plateau, 2-Northwest part of Riyadh City and 3- Eastern part of Al Ahesa City).

2 Karst limestone morphology:

The Karst geomorphology is a distinctive terrain developed on soluble rocks (carbonates and evaporites) with landforms related to efficient underground drainage. Disrupted surface drainage, sinkholes and caves, open fractures and pinnacles are the main diagnostic features that characterize these types of landforms. The geometrically complex natural cave passages create uniquely difficult ground conditions for civil engineering (Sowers, 1996 and Waltham et al, 2003). Solid limestone of high bearing capacity is interspersed with open and sediment-filled voids as well as pinnacles at shallow depth that complicate foundation design, homogeneity, integrity and excavatability. The unpredictability of these features under the proposed engineering project increase the problem for the ground engineer.

The three studied areas with karst limestone foundation bedrock have average compressive strength of 30 Mpa which is favorable to form relatively large size caves, sinkholes and open fractures of average cross-section diameter not less than 3m.The main geomorphologic features observed in the studied areas include pinnacled rockhead, buried sinkholes, caves and fissured rockhead (Figures 1, 2 and 3).

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3 Stratigraphy of studied karst limestone sites:

3.1 El Minia – Maghagha plateau karst limestone: El Minia - Maghagha plateau lies east of the Nile River and it is mainly composed of Middle Eocene carbonate rocks (Bishay, 1961, Said, 1962 and Philip et al. 1991). The oldest exposed unit is El Minia Formation which is composed of white hard cavernous and fossiliferous limestone and chalk intercalated with thin beds of sandy, cherty and clayey limestones. El Minia Formation is conformably overlain by Samalut Formation which is composed of snow white moderately hard cavernous, fossiliferous limestone. These two Middle Eocene units are characterized by karst geomorphology of shallow and deep caves, open fractures and connected old drainage channels (figure 1). Most of site observed caves and sinkholes are controlled by the major faults and master joints oriented NW –SE (Abdeltawab et al. 1991, Abdeltawab, 1994 and Abdel-Meguid et al.1998).

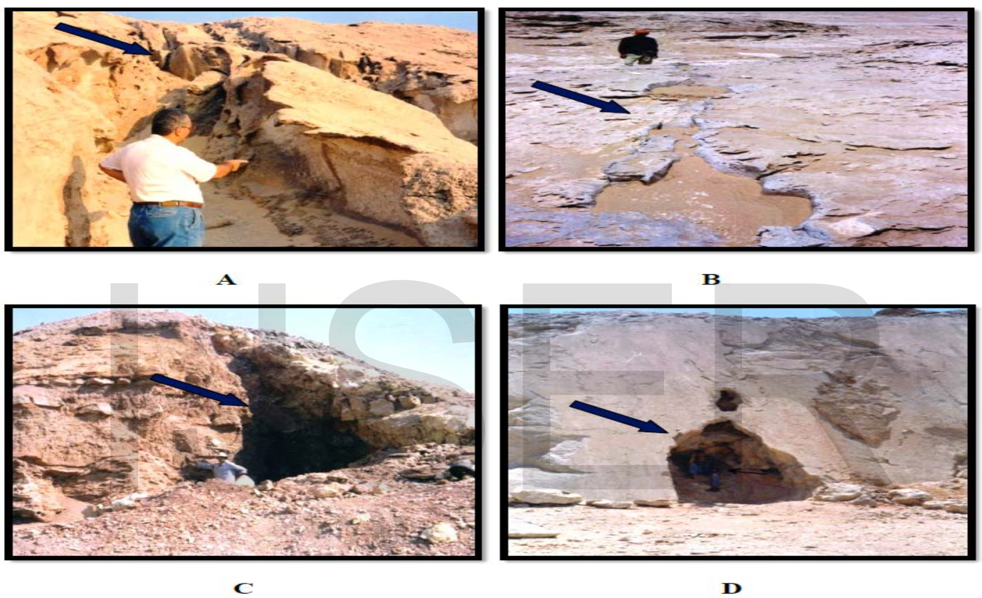

Figure 2: El Minia- Maghagha Plateau karst limestone, A - Process of solution and erosion along existing joints (fissured rockhead) , B –Group of sinkhole top circular opening along N300˚ trending Joints, C-Large size well developed caves and D- Solution caves at NW trending normal fault at El-Minia El-Gidida City.

3.2 Riyadh Karst Limestone: At the northwest part of Riyadh city there are two units of limestone bedrock which have high potentiality of karst caves, sinkholes and open fractures. The first unit is exposed as NW-SE limestone belt at the eastern side of Riyadh city and is named as the Sulaiy Limestone Formation of Cretaceous age (Geologic map of Riyadh Quadrangle, 1991). The Sulaiy Formation is typically composed of compacted limestone with few thin calcarenite beds. In outcrop this formation shows slumping features in its lower beds exactly like those features which found in the Arab Formation. The higher beds, however, are unaffected by slumping and are moderately strong, forming erosion-resistant, well-defined steep scarp slopes. Cavities and sinkholes are likely formed in the lower beds of this formation at the contact with the Arab Formation rather than the in upper beds as they made up mainly of compacted limestone.

The second karst unit belongs to the Jurassic limestone of Arab Formation. This Formation is outcropping as NW-SE trend of limestone belt on the west side of Riyadh City. The Formation is mainly made up of limestone

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and evaporites. The Arab Formation is the main rock unit underlying the City of Riyadh. It is considered the most susceptible to the development of solution cavities. This could be attributed to either the dissolution of evaporites or the nature of the limestone which may be found in the form of limestone boulders in an extremely soluble matrix of softer dolomitic limestone. The limestone unit is thin bedded and highly deformed by slumps and looks like brecciated rocks (Figure 3).

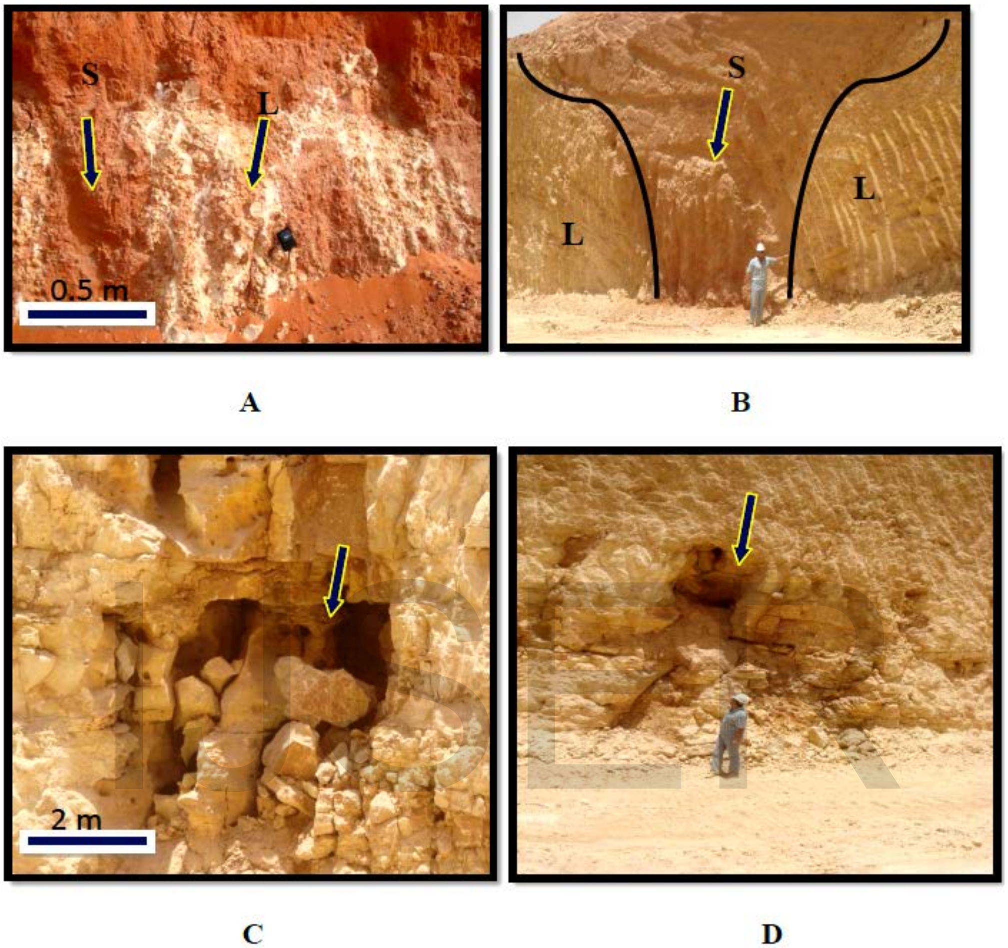

Figure 3: Riyadh city foundation bedrock, A - Karst limestone pinnacles (L- limestone and S is sandstone), B - Karst buried sinkhole filled with weakly cemented sand, C and D solution caves affecting the foundation bedrock.

3.3 Al Ahesa karst limestone: The eastern part of Al Ahesa city is mainly founded on limestone bedrock which has high potentiality of karst caves, sinkholes and open fractures. The main unit affected by karst geomorphic features is the Hofuf Formation which belongs to Miocene-Pliocene ages. The Hofuf Formation consists dominantly of white to light grey, massive, calcareous marl and sandstone with intermittent horizons of soft, reddish to yellowish brown marl and clay. The study area has famous tourist caves and sinkholes (Jabal Al Qarah) which is located approximately 13 km east of Al Ahesa city. These caves and sinkholes are developed in the calcareous sand, marl and clay of the Hofuf Formation. The eastern edge of the Jabal Al Qarah, close to the cavity entrance, is interpreted to be bounded by several north-south trending high-angle normal faults with throws up to 10 m (Hussain et al. 2006).

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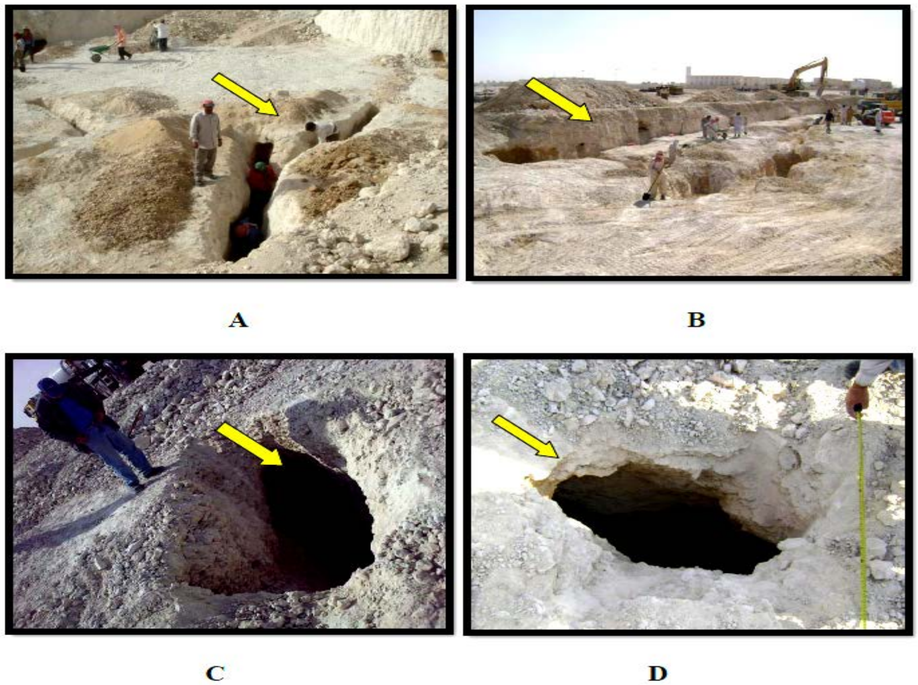

Figure 4: El-Ahesa foundation bedrock showing the occurrences of caves and open fractures (A - B, karst caves and fractured filled with silty clay materials and C - D are empty shallow caves).

4 Engineering Classification of Karst Ground:

Ford and Williams, 1989 provide an engineering classification of karstic ground conditions which represents simplified guidelines to the potential variation in landforms and ground cavities that may be encountered in civil engineering works on karst. This classification divides the Karst ground into five classes. The five classes provide the basis of an engineering classification that characterizes karst in terms of the complexity and difficulty to be encountered by the foundation engineer. The geomorphologic characteristics of the five classes as per Ford and Williams, 1989 classification can be summarized as follows:

- K I: Only in deserts and periglacial zones, or on impure carbonates, sinkholes rare, rockhead almost uniform; minor fissures; low secondary permeability, Caves are rare and small; some isolated relict features.
- K II: Minimum in temperate regions, small suffusion or dropout sinkholes; open stream sinks, many small fissures, Fissures are widespread in the few meters nearest surface, Caves are many and small (size less than 3m across).
- K III: Common in temperate regions; minimum in the wet tropics, many suffusion and dropout sinkholes; large dissolution sinkholes; small collapse and buried sinkholes extensive fissuring; relief less than 5m , loose blocks in cover soil, extensive secondary opening of most fissures, caves are many (size less than 5m across at multiple levels).
- K IV: Localized in temperate regions; normal in tropical regions, many large dissolution sinkholes; numerous subsidence sinkholes; scattered collapse and buried sinkholes, Pinnacled; relief of 5-20m; loose pillars, extensive large dissolution openings, on and away from major fissures, caves are many (size greater than 5m across at multiple levels).
- K V: Only in wet tropics, very large sinkholes of all types; remnant arches; soil compaction in buried sinkholes, tall pinnacles; relief of greater than 20 m; loose pillars undercut between deep soil fissures ,

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abundant and very complex dissolution cavities, numerous complex 3-D cave systems; galleries and chambers (cave size greater than 15m across).

5 Engineering classification of the three studied karst limestone areas:

5.1-El Minia- Maghagha Plateau: The limestone units of this plateau have many suffusion and dropout sinkholes; large dissolution sinkholes; small collapse and buried sinkholes, extensive fissuring; relief less than 5m , loose blocks in cover soil, extensive secondary opening of most fissures, caves are many (size less than 5m across at multiple levels). The strength parameters after Abdeltawab, 1994 are as follows:

- El Minia Formation, average unconfined compressive strength = 39Mpa and Young`s modulus = 32 Gpa
- Samalut Formation, average unconfined compressive strength = 39Mpa and Young`s modulus = 32 Gpa.

The karst limestone of El Minia-Maghagha Plateau can be classified as per Ford and Williams, 1989 engineering classification as Class K III.

5.2- Riyadh City : The limestone units at Riyadh city have many large dissolution sinkholes; numerous subsidence sinkholes; scattered collapse and buried sinkholes, pinnacled (Figure 3) ; relief of 5-20m; loose pillars, extensive large dissolution openings on and away from major fissures, caves are many (size greater than 5m across at multiple levels). The average strength parameters of Riyadh City foundation bedrock after Alawaji et al. (2006) are as follows:

- Average unconfined compressive strength = 30 Mpa
- Average Young`s modulus = 40 Gpa

The karst limestone encountered at Riyadh city can be classified as Class K IV (Ford and Williams, 1989 engineering classification).

5.3-Al Ahesa City : The limestone units at Al Ahsa city have many large dissolution sinkholes; numerous subsidence sinkholes; scattered collapse and buried sinkholes, pinnacled (Figure 3) ; relief of 5-20m; loose pillars, extensive large dissolution openings, on and away from major fissures, caves are many (size greater than 5m across at multiple levels). The average strength parameters of Riyadh city foundation bedrock (after Site Investigation Report SAFCO, 2008) are as follows:

- Average unconfined compressive strength = 32 Mpa
- Average Young`s modulus = 24 Gpa

The karst limestone encountered at El Ahesa city can be classified as Class K IV (Ford and Williams, 1989 engineering classification).

6 Detection of Caves and Sinkholes:

Karst limestone foundation bedrock caves, sinkholes and open fractures have been studied by several methods. These methods can be classified into geomorphologic studies and measurements, geologic mapping and geophysical survey. The most effectives and applicable methods used to detect the karst anomalies in the three studied sites can be summarized as follows:

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6.1-Geological mapping: Studying the main geologic units of the project foundation bedrock from the available published geologic maps, geologic papers and reports give a very good starting for assessment of the expected karst foundation problems. Also preparing detailed geologic map for the proposed projection including lithologic description, joints, fractures and fault zones will facilitate the predict the distribution of these karst units laterally and with depth. The geologic desk studies and mapping represent the first phase of geotechnical site investigation program. The geologic studies represent the most economic and quick method for predicting and evaluating the risk of karst foundation bedrock. The geological studies that have been done for the three sites give very strong criteria on the existence of karst foundation bedrock hazards. Based on the geologic criteria the project designers added new items for the project cost that includes detection of karst features under the proposed buildings as well as treatment of these detected karst features.

6.2- Ground Penetration Radar (GPR) Survey: Ground penetrating radar (GPR) techniques have been progressively developed and used for several types of engineering foundation problems. Karst limestone caves, sinkholes and open fractures can be successfully detected in dry areas by using GPR surveying. The basic idea of GPR is to transmit and receive electromagnetic waves of wide spectrum frequencies (100 MHZ to 500 MHz) and processing the received waves to detect the shallow underground anomalies as caves and sinkholes. The karst limestone foundation bedrock at the eastern part of Al Ahesa city was surveyed by GPR profile grid using electromagnetic waves with frequency ranges between 100 MHz and 500 MHz .The processed data indicate the presence of shallow caves and open fractures (Figure 5). The detected GPR anomalies have been verified by using mechanical probing to determine the accurate depth and to start with the treatment process.

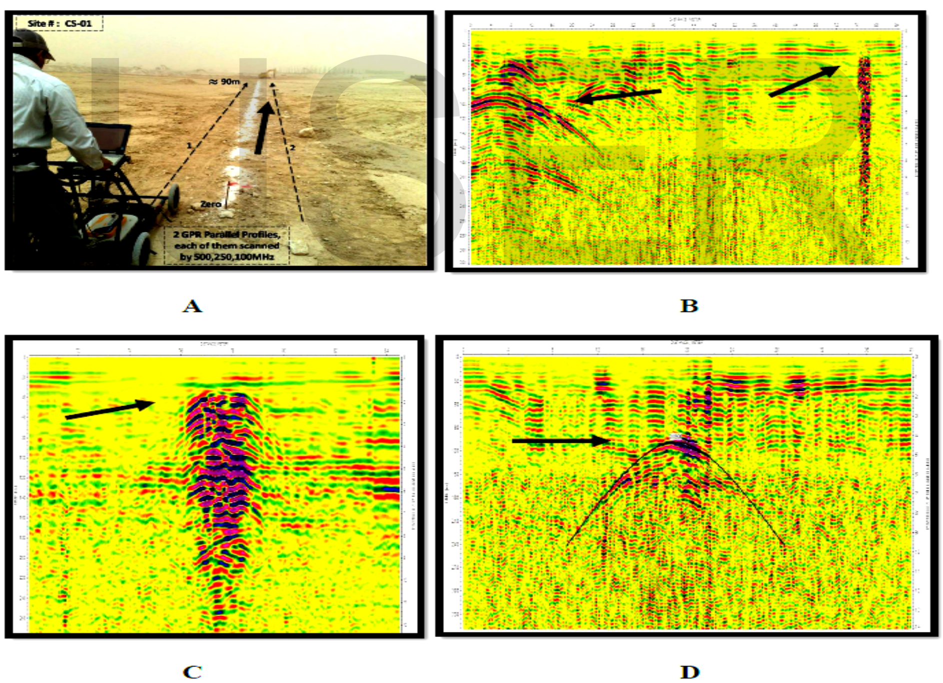

Figure 5: Eastern part of Al - Ahesa city GPR karst limestone survey. A – GPR apparatus setting out at profile line to start survey, B- open fracture and cave at 3m depth , C – Cave extended from 3 m to 10m depth and D, cave at 5 m.

6.3- 2D Electrical Resistivity Survey: The objective of using the 2D electrical resistivity imaging is to detect any suspected anomaly or any lithological variations such as: cavities, soils, layers and water conditions. Two dimensional (2D) electrical resistivity imaging was conducted at Riyadh and Al-Ahsa projects to map the subsurface structures. The surveying process was acquired using the Winner-Schlumberger configu-

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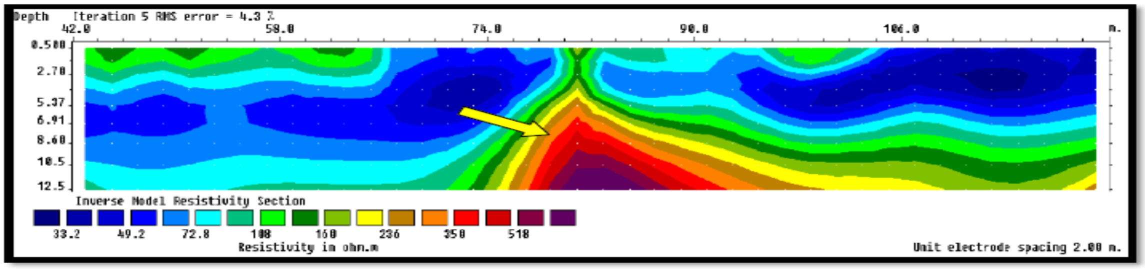
ration with different lengths but with constant 2 m interval electrode spacing. Some of the obtained 2D electrical imaging profiles at the two sites (Riyadh and Al Ahesa) are shown in Figures 6 and 7.



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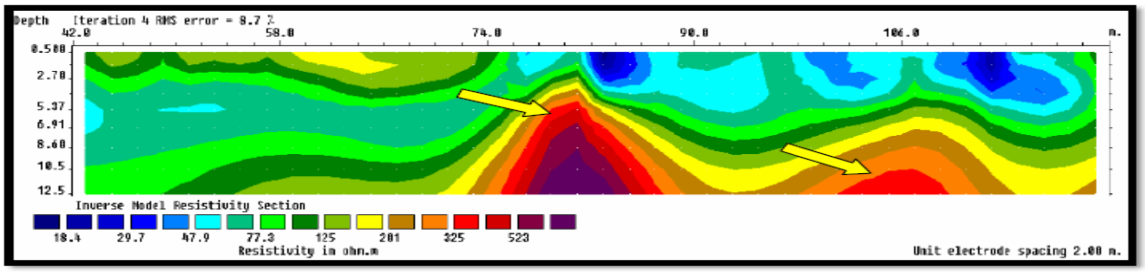

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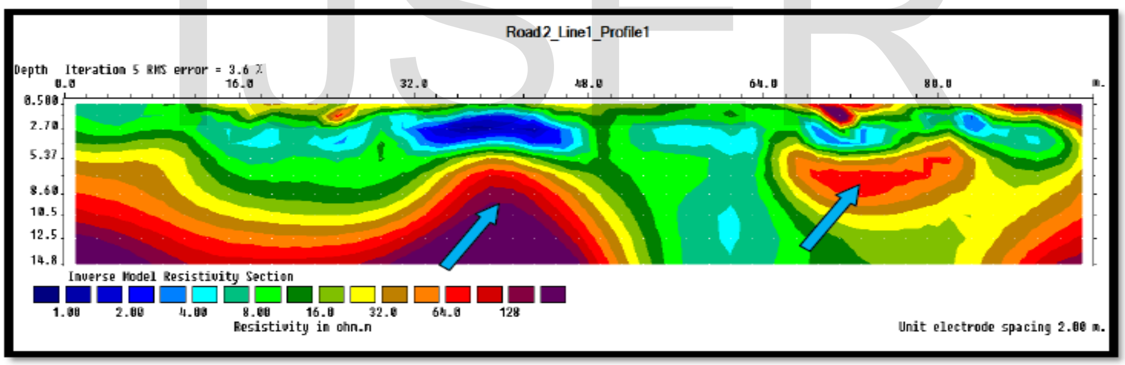
Figure 6: Northwest part of Riyadh city project 2D electrical resistivity imaging lines A and B showing the detection of the subsoil karst features. The marked arrows indicate high resistivity zones of empty caves.



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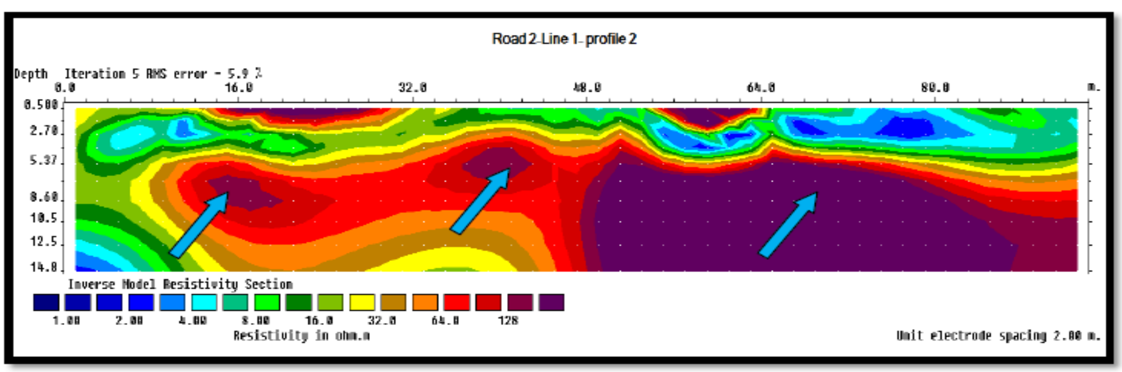

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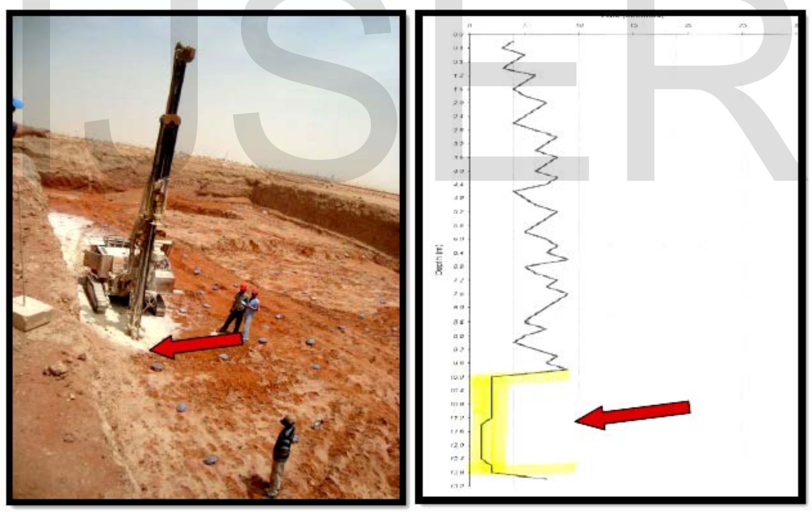
Figure 7: Eastern part of Al Ahesa city 2D electrical resistivity imaging Lines A and B showing detection of subsoil karst features. The marked arrows indicate high resistivity zones of empty caves.

6.4- Borehole lithological logging and Fluid circulation Monitoring: The detailed phase of site investigation that can help in detecting the karst foundation bedrock is boreholes continuous coring and sampling the foundation bedrock. Critical monitoring of the lithologic variation of core samples as well as the condition of cooling fluid loss will give good criteria about the depth of caves and open fractures. Most of the executed boreholes in the studied area indicate large quantities of drilling fluid loss. The site supervision geologist records the depth of water loss and its quantity to give one of the most important criteria for karst limestone foundation bedrock. All executed boreholes along the studied three sites indicate the presence of drilling fluid loss at depths ranging between 3m and 10 m.

6.5- Mechanical Probes: Mechanical probes using pneumatic percussive drilling with probehole diameter of 50 mm. The mechanical probes are representing the final and more accurate tool for detecting the depth of caves and sinkholes by critically observing the rate of drilling in relation to the depth. The caves and sinkholes zones usually have abrupt decrease in the recorded drilling time and sudden drop of drilling pipe. The mechanical probe and result curve are showing in Figure 8. The studied sites mechanical probe holes have dual function (karst feature depth determination and treatment by bumping concrete or cement grout through the probe hole).



A B

Figure 8: Mechanical propping for detecting caves and sinkholes in limestone foundation bedrock covered by Quaternary cemented sand (A is probe machine and B is probe curve (time-depth relation) showing caves at depth at 10 m).

7 <u>Caves and Sinkhole Treatments:</u>

The karst limestone caves, sinkholes and open fractures cause severe damage for buildings worldwide and the main target of site investigation geotechnical programs are to evaluate, assist and determine the vertical and lateral distributions of these foundation problems and to adopt the most economic solution for treatment. Several engineering methods have been used in several worldwide projects and include engineering fill, engi-

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neering fill and geosynthetic materials, concrete filling and cement grout low pressure injection. The most recorded cases of karst treatment are depending on concreting and cement grout injection filling. The author has reservation on using concreting and injection work for filling the caves and open fractures in the areas that have shallow groundwater aquifer. The concreting and injection work will close all underground drainage channels and also will pollute the groundwater aquifer. The three studied sites have been treated by using concrete filling and cement grout low pressure injection. The process of foundation bedrock treatment can be summarized as follows:

- At the final excavation level, any cavities/fissures and solution channels encountered at rock surface or slightly below rock surface shall be exposed, trimmed, cleaned and then filled with engineering fill materials if the cave and sinkhole size can be properly compacted to minimize the expected risk of fill material settlements (Figure 4A and B).
- The near surface narrow open fractures, caves as well as the solution channels less than 1m width can be treated by manual cleaning the silt and loose material then filling with high slump concrete (Figure 9 c and D).
- The relatively deep (greater than 2m depth) caves and sinkholes can be treated by high slump concrete or cement grout low pressure injection (Figure 9 C and D).
- Deeper-seated cavities are treated by pumping a cement-grout or cement-sand grout mixtures through injection packer system fixed on the top of probe holes (Figures 9 A and B). The grouting will be started with the specified grout mix until completely fill the cave and achieve refusal under maximum 2 bar pressure. In the case of multiple cavities in any drill hole, treatment should proceed from the lowest cavity and completed for that cavity before proceeding to the next higher cavity.

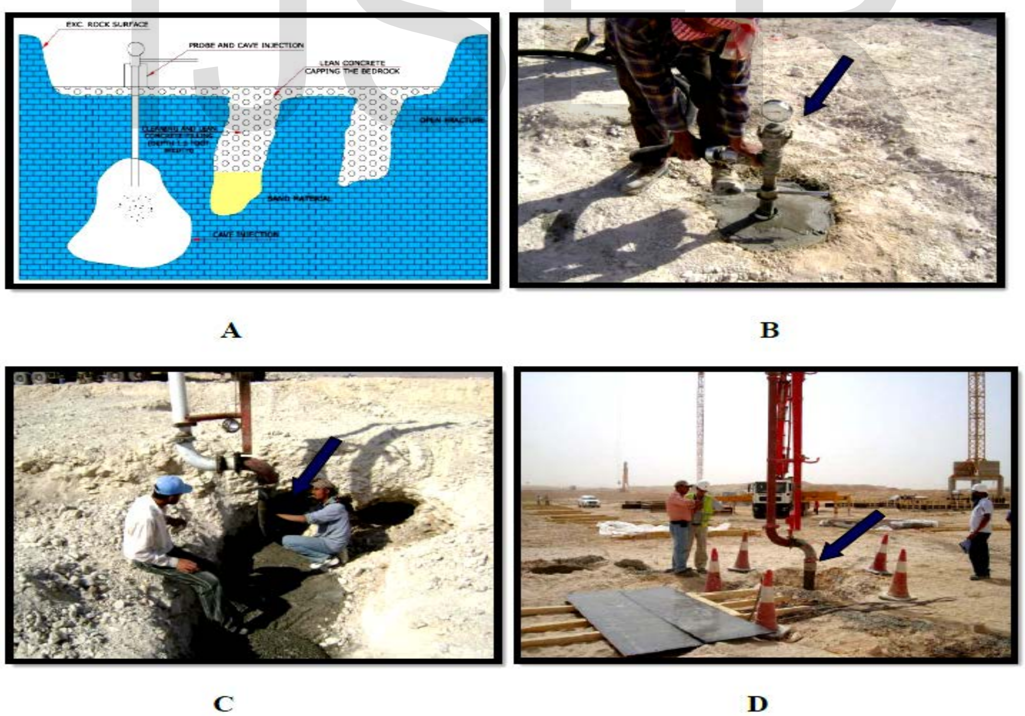

Figure 9: Karst foundation bedrock treatments, A and B cement grout injection, C and D high slump concrete filling.

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Conclusions:

The three studied sites (El Minia-Maghagha Plateau, Riyadh and Al Ahesa cities are representing good cases for karst limestone foundation bedrock problems. Collaborative desk studies between the geotechnical engineer, engineering geologist and geophysical consultant will give a very sound conclusion for evaluating and detecting the foundation bedrock karst features. The lessons that can be achieved from this study are as follows:

- Geologic and geomorphologic desk studies should be done prior any site geotechnical investigation phase.
- The obtained geologic and geomorphologic maps are used as a guide for geophysical survey task to minimize the effort and cost.
- GPR and 2D electrical resistivity imaging give very good detection for the karst features (caves, sinkholes and open fractures).Ground penetration radar (GPR) cannot work in areas of high water content or shallow groundwater aquifers.
- The geophysically detected anomaly can be easily verified by mechanical probes.
- Karst feature treatment can be classified into compacted engineering fill, engineering fill with geosynthetic materials as reinforcement, concrete filling and cement grout filling.
- For sites that have shallow groundwater aquifer it is prefered to minimize the use of concrete filling and cement grout to avoid affecting the channel way of the ground water. In this case we can use coarse aggregate as engineering fill materials.

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