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ABSTRACT

The sub-surface geology of the Project Site, in at least six out of a total of eight Zones, are characterized by presence of highly to moderately weathered and fractured Limestone formation. This is generally encountered at a depth ranging from surface to 1.50 meter. However, there is yet another dimension to this geology. A typical characteristic of this bedrock is the presence and occurrence of numerous small to large Cavities, Sinkholes and/or Limestone Solution Channels, which are often found to be filled with clay/silt/sand.

A serious program was undertaken to map all these Karstic features. An extensive "Cavity Search Probing" was conducted under footprints of each building to ensure the competence of the strata below. The probing was done using "Pneumatic Driving" of a Rock Probe into the bedrock using a Wagon Drill, with compressed air to clean the hole as it advanced. Semi-Rigid Raft Foundation was used to circumvent the Cavities & Sinkhole problems at the Site.

This paper focuses on the experiences vis-à-vis the above and brings to light the Case History leading to managing and circumventing the Sinkholes & Bedrock Cavities at the Project Site per se.

INTRODUCTION

This Case history pertains to the Project Site of Prince Abdullah Military City situated approximately 12 Km west of the city of Hofuf in Al-Hassa, an oasis in the Eastern Province of the Kingdom of Saudi Arabia. The Project Site is riddled with underlying bedrock cavities. These findings for the subject Site have been documented in a number of Reports including those done by US Army Corps of Engineers in 1978 covering a large portion of the Site, another Report in 1992 by a Geotechnical Consultant for a small portion of the Site [Dames & Moore, 1992]. Finally yet another Report, this time done as per the revised Master Plan, by the main Contractor of the Project.

The Karstic Features encountered at the Project Site are best described as: Collapse Sinkholes, Subsidence Sinkholes, Dropouts and Bedrock Cavities. A serious program was undertaken to detect & map the bedrock cavities at the Site. Detailed Geotechnical Investigation program carried out at the Site, for the purpose, included drilling a large number of Bore Holes, excavation of Test Pits, In-Situ Testing & Sampling of overburden soil by Standard Penetration Tests (SPTs) and coring in the bedrock strata. In addition, measurement of Core Recovery & Rock Quality Designation (RQD) was done. Also included were, testing representative samples of subsurface materials in the Laboratory. In addition, an extensive "Cavity Search Probing" was also conducted under the footprints of each building to ensure the competence of the strata below. The probing was done using "Pneumatic Driving" of a Rock Probe into the bedrock using a Wagon Drill, with compressed air to clean the hole as it advanced.

These exploration & probing helped in mapping the "Karstic Terrain" at the Project Site. The information also helped in preparing schemes for the treatment of the same and in the subsequent construction of the Project.

Semi-Rigid Raft Foundation was used in view of the Karstic problems at the Project Site. This foundation system is known as quite rigid to bridge over the underlying cavities and hence became the ultimate choice for the same.

OVERVIEW OF KARST PROBLEM

The term "Karst" is applied to characteristic topography that is formed on carbonate rocks such as, limestone, dolomite, magnesite or gypsum, and other rocks by dissolution. This term is derived from the geographical name "krs" from part of the Karst Terrain in Slovenia.

A Karstic Terrain is generally characterized by presence of well developed Solution Channels, Caves, major Springs, Sinkholes, and a highly irregular weathered bedrock surfaces with Cavities. Sinkholes are the principal geologic hazard in Karst Terrain for obvious reasons. They can damage structures, drain ponds & lakes, and allow direct infiltration of groundwater contamination.

Sinkholes are "Closed Depressions" in the land surface that are formed by solution of near-surface limestone & similar rocks and by subsidence or collapse of overlying surficial material into underlying solution Cavities. Sinkholes generally tend to form when infiltrating acidic water is in contact with limestone for a long time. The process that creates a Sinkhole is slow and continuous. However, the effects of the Sinkhole at the ground surface may occur either catastrophically all of a sudden. The two distinct Sinkhole are: i) Collapse Sinkhole and ii) Subsidence Sinkhole, respectively.

Collapse Sinkholes occur when the solution of the limestone, creates a vertical cavern or throat beneath the ground surface. At first, the soil at surface may be strong enough to bridge the cavern. With time, the cavern will continue to widen and the bridging soils will finally collapse. This is what most people have heard about in media regarding Sinkholes. Subsidence Sinkholes occur when the soil above the limestone formation is relatively granular. In this case, as the limestone erodes, the soil above it fills the voids. This is called raveling; when the soil continues to ravel into the limestone voids, the ground surface begins to subside, forming a Sinkhole.

Another Karstic features are Solution Voids. These may occur from surface water percolating into the joints of an exposed limestone layer. With time, they may be filled up with loose sandy deposits, which can hide their presence. In some instances, these may actually be of cavernous nature. However, they may also be like a network of solutionally widened channels, popularly known as "Serpentines".

Sinkholes vary in size depending on the thickness of the overlying stratum. If the overlying stratum is relatively thick, it can span a larger cavern. The cavern must grow larger in order to cause a collapse. Sinkholes can reach sizes that can swallow entire structures, as well [Steven, J. G. 1992].

The process of forming Cavities or Caves is very slow. It all begins with rain. As rain falls through the atmosphere, it absorbs a small amount of carbon dioxide. It gathers additional carbon dioxide as it moves through the soil. Water mixed with carbon dioxide is weak carbonic acid solution. As this solution of water and carbon dioxide seeps through the cracks & crevices, it dissolves the soluble rock and forms Cavities and Channels. The great size & beauty of limestone caves have made them features of public amazement and wonder. In the US, 130 caves are open for public, and about 13 national parks contain caves. The world's longest cave is perhaps Kentucky's Mammoth Cave, which has more than 240 Km of accessible passages. Gouffre Berger Cave in France descends at least 1,100 Km below the surface and is the deepest cave yet explored by man. In Saudi Arabia also, there are numerous caves that attract people here in large numbers. The notables amongst them are in Hofuf (in the Eastern Province) and in Al-Kharj area near Riyadh [Lange, A. L. 1977].

KARSTIC TERRAIN AT THE PROJECT SITE

Geologically the Project Site is characterized by Hofuf and Dam formations. The principal feature of Hofuf Formation is the vast areas of gravels of quatzitic origin and stones/pebbles of igneous and metamorphic rocks. The base of the Hofuf Formation is at the contact with calcareous rocks of the Dam Formation. The top is at the upper limits of the exposures of the Al-Hofuf, commonly an old duricrust-covered surface.

The Dam Formation comprises pink, white and gray marl, and red green, and olive clay with minor interbeds of sandstone, and chalky limestone. Continental deposits of conglomerate, sandstone, sandy limestone, sandy marl and sandy shale of the Hofuf Formation overlie Dam Formation. The upper beds consist of sandy, fresh water, limestone.

The varieties of Karstic Terrain encountered at the Project Site per se are described as Solution Channels, Bedrock Cavities, Subsidence Sinkholes and Collapse Sinkholes [RGME 1998].

More precisely, the major part of the Site Karstic condition can be described as "Mantled Karst Terrain". A Mantled Karst Terrain is the one where the limestone is overlain by notable thickness of unconsolidated sediment. The overburden can be marine sand, clay, glacial sediments, or thick residual soils. However, in case of the Project Site, the overburden largely consists of silty sand with limestone fragments and calcareous clay. The thickness of this cover above rock, in general, does not extend to more than one meter, except in some bore holes where the same has been observed to exceed 1.5 meter.

Research has shown that the solution of limestone takes place beneath this cover of sediment, although solution features may have begun developing before the overburden was deposited. To understand how and why these Sinkholes develop and how to deal with their effects, one must understand the "hydrogeologic" process occurring in the "Epikarstic Zone", meaning the zone surrounding the overburden: rock interface.

Hofuf, where the Project Site is located, is an oasis and is characterized by presence of many known springs called "Ayyoon-al-Moya", meaning water springs. The solutioning of the subsurface limestone and formation of the Solution Channels & the Cavities, are largely attributed to the acidic action of these very springs.

At the Project Site, Sinkholes identified ranged from "small dropouts" or simply trenches to large sized (about 2-m wide) irregular depressions. At some places, luckily outside the buildings, some cave like holes were found which had multi-lateral solution channels like features. Some of the pictures of these Sinkholes, discovered at the Project Site, are attached.

PRINCIPLES OF SINKHOLE INVESTIGATION

About one-fourth of the earth's crust is known to be underlain by rocks that are susceptible to solutioning activity. Globally, reports of problems encountered with construction on Karst sites are numerous. Like wise existing structures have also experienced damages from the sudden collapse of solution cavities, which were previously undetected.

Comprehensive subsurface investigations are obviously needed when important structures are to be located in Karstic regions. However, it also remains a fact that detecting potential Solutioning Activity, Cavities or Sinkholes, that have not yet affected the ground surface can be relatively difficult. The traditional geotechnical investigation consisting of drilling boreholes may not detect them because a borehole samples only a small area. Experience has shown that using borings is only 10 % to 20 % accurate in terms of locating Cavities or Sinkholes.

Investigation of Sinkhole potential begins with studying the local geology & hydrogeology and mapping Sinkholes that have occurred in the project vicinity. For large-scale Site Investigation, both surface geophysical methods and boreholes will have to be employed. The usual strategy should be to use surface methods for initial reconnaissance (Anomaly Detection) and to use borehole methods for detection and delineation. That is, when anomalous responses are recorded during the Surface Surveys, the zone in question should be drilled and sampled to provide observations for the purpose of evaluation.

Various approaches to investigating Karstic features are:

- Aerial & Satellite Photography
- Backhoe Trenches
- Drilling boreholes
- Modern Geophysical Techniques

Aerial & Satellite Photography

Aerial surveys are useful technique for locating potential Sinkholes. Historical air photos may show large-scale areas of subsidence that can help identify smaller-scale localized Sinkholes. They are traceable from the ground but is more convenient from the aerial survey [Steven, J. G. et al.1992].

Backhoe Trenches

Backhoe can explore easily & quickly a relatively large area. Trenches done this way can expose near-surface solution voids or Sinkhole throats. However, they can not completely replace information obtained from a borehole.

Drilling Boreholes

Test borings are an important part of Sinkhole or Cavity investigations. The holes are drilled to the bedrock even if this requires drilling to a much greater depths than would be necessary, otherwise. Standard Penetration Tests (SPTs) are usually conducted as the bore advances. This helps in knowing the strengths of various sediment layers. The data is used to draw subsurface cross-sections that helps in inferring about the presence or absence of Sinkhole or Cavity associated features.

Geophysical Surface Surveys

A number of such techniques are currently in vogue that can locate Cavities & Sinkhole. The idea behind such techniques is to probe the subsurface without disturbing the ground surface. This is done by generating a wave, which when propagated through the soil, reveals anomalies. This can be investigated to find if the same is the presence of Cavities or not.

All these methods either have Cavity detection capability or can provide data useful to the cavity detection process. A research on the subject provides an insight about the merits & demerits of these methods [Cooper, S. S. et al. 1988].

Based on the same research the following are the guidelines.

a) Surface Reconnaissance Surveys include the following:

Electrical Resistivity: Can be used for both shallow and deep investigations. Considerable operator skills required for data interpretation.

Seismic Fan Shooting: It is labor intensive. Suited for shallow depth investigations. Interpretation of results is simple.

Seismic Wave Form: Rapid, economical, simple in execution & interpretation Viable only for shallow investigations.

Microgravimetry: Labor intensive, skilled operator required for both data acquisition and interpretation.

Ground Probing Radar: Very rapid, virtual real-time graphic interpretation. Best suited for shallow investigations.

Pole-Dipole Electrical Resisivity: Labor intensive data acquisition & interpretation, requires skilled operator.

Standard Refraction Seismic: Widely used but cannot detect cavities below top of refracting layer; has limited utility.

Spontaneous Potential: Rapid & economical. Used only for the special case of flowing water-filled Cavity systems.

b) High-Resolution Surveys encompass the following:

Crosshole Radar: Good results when subsurface materials have high dielectric constant that is little or no clay present.

Acoustic Resonance: Good for mapping shallow-depth Cavity systems when cavity interior is accessible.

Refracted Wave Form Seismic: Rapid, suitable only for shallow-depth investigations.

SINKHOLE INVESTIGATION AT THE SITE

The Project Site is divided into 8 Zones and is spread over an area of about 6 Sq. Km. The geotechnical investigations at the Site consisted of: first, a Preliminary Reconnaissance Investigation followed by a Detailed Investigation for each of the 8 Zones. Before the Preliminary Reconnaissance Investigation (done in March 1998) for the Project Site, there were two investigations done already by different agencies at two different periods. Table: 1 represents the scope of work for the various investigations performed at the Project Site.

Table: 1 Scope of Investigations at the Project Site

Year	Boreholes With SPTs	Test Pits	Cavity Probing
1978	not available	not available	not available
1991	38 nos. up to 8 M	66 nos max. 2.2 m	219 nos. up to 6 m
1998	25 nos. up to 6 m	10 nos max. 2.0 m	detailed probing done

All these investigations at the Project Site established that the bedrock essentially consists of light brown, fine grained, highly to moderately weathered and jointed Limestone. The Total Core Recovery (TCR) of the underlying rock strata was found in the range of 27 % to 100 %, exceeding 50 % in general. The Rock Quality Designation (RQD), however, was recorded between 0 to 100 %, though it was generally less than 20 %. A typical characteristics of this limestone, noted in all the reports, is occurrence of numerous small cavities within the underlying limestone bedrock. The reports recommended carrying out a detailed Cavity Probing at the Locations of foundations (under the footprints of the facilities) subsequent to excavation during the construction stage. This should be achieved by drilling probe holes to a depth of a minimum of one and a half times the width of foundations.

Before the commencement of constructions at the Project Site a more detailed Investigation was also carried out; this time in each of the eight zones, as mentioned above. The zone wise scope of Investigations is represented in Table: 2.

At the Project Site, the following techniques were used for studying the regional geology & hydrogeology, detection and mapping of potential Sinkholes and Cavities.

- Trenches and Test Pits
- Drilling Boreholes, and
- Cavity Probing using pneumatic driving of Probe.

Extensive data was obtained through Trenches/Test Pits and Boreholes that gave clue of presence of underlying bedrock Cavities. A detailed Cavity Probing was, however, made under the footprints of each facility in order to ascertain the presence or absence of the cavities, before going ahead with pouring of foundations. A total of 5,610 nos. of Probe holes (in 166 facilities in 06 zones) were performed. This included an additional 219 nos. around the problem areas in 18 nos. of facilities. The Cavity search program was very detailed & extensive. The Probing was carried out by means of pneumatic driving of a rock probe into the rock using a Wagon Drill. Compressed air was used to clean the hole as advanced. The time of penetration of probe through each consecutive depth of 20 cm was carefully recorded which indicated the resistance of rock to penetration. In case of occurrence of cavity/loose zones in underlying strata, the time for penetration records will be comparatively small. A duration of less than 10 seconds for 20 cm penetration is considered the presence of loose zones, while in case of cavity, there will be no resistance to rock penetration and it occurs all of a sudden.

During the course of this operation, the following were noted very minutely:

- Time taken for 20 cm penetration
- Air escape in the finished boreholes
- Sudden fall of drill rod
- Boreholes, where time was 10 seconds or less

When the last three observations were noted in any bore, the probing was repeated around them until either presence of cavity was detected or some reasonable explanations were found for the same. In case of cavities, the same was back filled with grout. Excavations were also done, around these problem probe holes, to expose the Sinkholes or Cavities.

Table: 2 Zone-wise Scope of Investigations at the Project Site

Zones	Boreholes With SPTs	Test Pits	Cavity Probing
# 1	79 nos. up to 10 m	nil	Details of cavity probing shown in table: 3
# 2	69 nos. up to 10 m	nil	
# 3	43 nos. up to 12 m	nil	Expansive Clay Zone
# 4	07 nos. up to 15 m	nil	Details of cavity probing shown in table: 3
# 5	28 nos. up to 7.71 m	nil	
# 6	54 nos. up to 06 m	nil	
# 7	54 nos. up to 06 m	nil	
# 8	54 nos. up to 12 m	nil	Expansive Clay Zone

This probing was followed by a Report certifying competence of the strata to sustain the expected building loads before the foundations were poured. Table: 3 represents the actual number of Cavity Probing made for the problem facilities (in all the 6 zones) with the exception of two zones where expansive soils were encountered. This table show additional Probe holes made for 08 nos. of the problem facilities (out of a total of 18 nos.) to ascertain the presence or absence of any cavity. In some of these selected facilities, cavities were detected and treated accordingly.

TREATMENT AND REMEDIAL MEASURES

The treatment of Karst related features could entail methods, which can be as varied as the Cavities and Sinkholes themselves. If the "throat" of a Sinkhole is located, a commonly used treatment involves excavating the overburden soils to expose the opening in the rock surface.

The throat is then plugged or covered with an inverted filter, and the excavation backfilled. If the throat cannot be located, or the depth to rock makes exposing the rock surface impractical, a less effective treatment is normally used.

If a throat is identifiable but the depth to rock is excessive, the excavation base could then be capped with concrete and/or the entire area covered with a geotextile. In case where no throat can be identified, and the depth to rock is excessive, feasible treatment may be limited to excavating soft or organic materials, laying a geotextile over the area and backfilling with clayey soils. Table: 4 list some of the common concepts of treatment of the subject problems.

Table: 3 Cavity Probe holes in problem Facilities

Item	Facility Name	Floor Area, m²	Nos. of Probes	Additional Probes *
1	5B-030-1	319	28	15
2	5A-040-1	929	45	16
3	5A-080-1	1,407	106	17
4	6A-085-1	1,630	103	13
5	5A-130-1	609	32	12
6	1B-244-1	1,979	60	22
7	2E-312-2,3	1,921	96	10
8	2D-330-1	1,718	58	10

* additional probing done to ascertain presence/absence of Cavity

Table: 4 Application of Remedial Sinkhole Treatment

Types of Remedial Treatment	Types of Karst Problems	
	Subsidence/ collapse	Drainage/ flooding
BRIDGING		
Rock Pads	X	X
Rock Backfill (Plugs)	X	
Grouting	X	
Concrete Structures	X	X
Geofabrics	X	X
Gabions	X	X
Lime Stabilization	X	
ARTIFICIAL COLLAPSE		
Dynamic Compaction (in soils)	X	
Blasting & Excavation (in rock)	X	
DRAINAGE		
Paved Ditches	X	X
Curbing for Embankments		X
Doline Clean-Out & Protection	X	X
Overflow Channels		X

Legend: X denotes common application

The treatment and remedial measures to address the Sinkhole & Cavity problems at the Project Site, however, varied as per the specific Site conditions. This can be grouped as: i) during Leveling & Grading ii) during Foundation Construction, and iii) during External Works Construction, like Roads, Water Supply, Sanitary Sewer, Storm Water Drainage, and other items related to Landscaping & Irrigation Works.

Leveling & Grading: After proper stripping of the Site, the exposed subgrade in the building and pavement areas was carefully proofrolled with a 7-ton pneumatic tired vehicle. This was done to enhance detection of unsuitable soil conditions and incipient dropouts. This exercise did pay the dividend and at some places pockets of dropouts were exposed & detected. These weak points were treated by various methods, including grouting and Bridging. Bridging included making use of rock pads & rock backfill together with use of geo-fabrics, etc. Efforts were also made during rough grading works not to push debris or soil into depressions that might mask evidence of Sinkhole activity. Large pan scrappers were used to move the soil and heavy traffic loading were monitored to reveal soft areas or dropouts. At some locations, multiple passes of this heavy equipment did result in dropouts, revealing voids or incipient Sinkholes. These were then treated by excavating and backfilling with grouts.

Foundation Construction: The Sinkholes and Cavities were mostly found outside the footprints of the facilities, except for some including 7E-010-1, 1F-030-1 & 5A-200-1. In these, large open-mouthed Sinkholes (about 5m x 4m x 3m deep) were found right inside the footprint. These were over excavated to expose the extent of the cavities and later were treated by means of Compaction Grouting. This new technique was developed in the USA and is defined as, “the Grout injected with a slump less than 25 mm”. In this, normally a soil-cement with sufficient silt sizes, to provide plasticity, is used which develops internal friction. The grout generally does not enter soil pores but remains in a homogenous mass that gives controlled displacement. Normal Grout was also used to fix the problem in this particular facility. Some were also rock backfilled using bridging technique.

In the other 8 facilities, listed in Table: 3, there was suspect presence of Cavity or Sinkholes because of low time recorded for 20 cm penetration of probes during Cavity Search Probing. Additional probes were therefore made to ascertain the fact. In most cases the time recorded for the additional probes did not record less than 10 seconds, except for two facilities namely: 1B-244-1 and 5B-030-1.

In the facility 1B-244-1, deep excavations were required to be made for Service Pits and Hydraulic Lift Pits. These additional probing, with time record of less than 10 seconds implying presence of Cavities, were close by. It was decided, therefore, to over excavate the localized area for inspection of the subsurface Cavities. Excavation exposed the cavities with some lateral solution channels as well. These were thoroughly cleaned and later treated with a combination of two methods: i) by Compaction Grouting of the vertical cavities, and ii) by Bridging using boulders and geotextiles to close the mouth of the lateral solution channels. There were some cavities & solution channels situated at a distance outside this building also. These were partly exposed to the surface and partly deep-seated. These were also treated, more or less, in the same manner. In facility 5B-030-1more or less similar situation was encountered, and the same was addressed in the like manner

External Works: Most Cavities, Sinkholes, Dropouts and Solution Channels were found at the time of rough grading and during the execution of external works. Very few were actually found under the footprints of the building. They were found in road works, excavation for Trapezoidal Channels (storm water disposal), sanitary sewer lines and ponding area for Reverse Osmosis of Water Treatment Plant.

These were treated using a variety of methods, depending on the nature of the Karstic Feature. However, the subgrade of roads were generally treated with simple slurry grouts and geotextiles. The road ditches were paved, especially in areas of suspect Sinkholes. Some lateral solution channels (serpentine) were found on the sidewalls of the trenches for the sanitary sewer lines. These were treated by: rock backfill (plugging) and by raising masonry or concrete structures to block the mouths of the lateral solution channels. At some places, geotextiles were also used. During excavation of long storm water Trapezoidal Channel, a number of Sinkholes, Cavities & Dropouts were found. They were largely treated by grouting & by rock backfill. Large Cavities and Sinkholes found during excavation for ponding area of R. O Plant was also treated using Compaction Grouting and by Rock Plugging.

PERFORMANCE OF THE TREATMENT

These treatment works, at the Site, are at least 4 years old. In between, these have seen through many a changing/alternating seasons, from extreme heat to rain. No report of any problem, whatsoever, have been noticed.

FOUNDATION CONSIDERATIONS

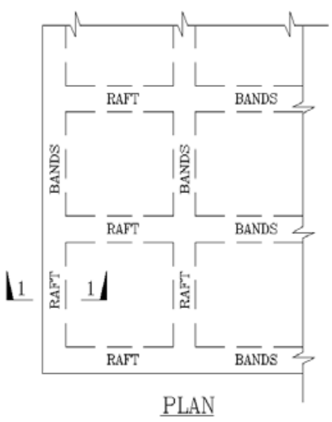
Experts on the subject agree that even with the best methods and designs, construction in Karst Terrain is certainly not risk free. However, the risk posed by them warrants that some solution is found that reduces the risks at a feasible cost.

The solution in vogue are outlined as follows [Sowers, 1984].

- Optimize the location on the Site
- Treat defects that are present
- Use modified shallow Foundations
- Use Deep Foundations
- Minimize future Activation

Use of Modified Shallow Foundation is a viable option to deal with the Karstic problems, as far as medium sized buildings are concerned. The use of such foundations entail: i) creating a footing that spans or bridges over the cavity ii) constructing a Mat Foundation that is rigid enough to minimize deflections that may occur due to Sinkhole formation beneath it.

Semi-Rigid Raft Foundation, adopted for the Project Site, is a proposition. It is a Mat like foundation with thickened edges or Raft Bands. This was used in the Project to circumvent the problems of Cavities and Sinkholes at the Site. This is rigid enough to bridge over the Cavities. PCA-MATS was used to analyze & design the same. As per the Geotechnical Report a Bearing Capacity of 150 KN/m² was used to design the Foundations. A comparatively low value of Bearing Capacity was recommended keeping in mind the weathered conditions of the rock and the Karstic Terrain. A typical detail of the subject system is attached as Fig: 1.



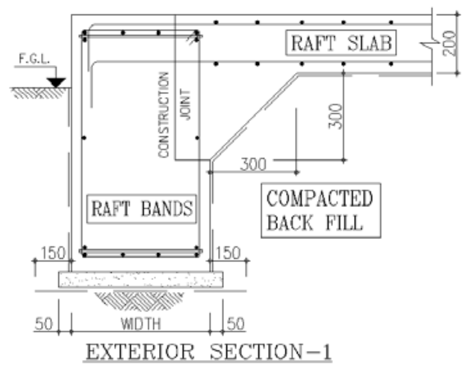


Fig: 1 A typical Section of Semi-Rigid Raft Foundation

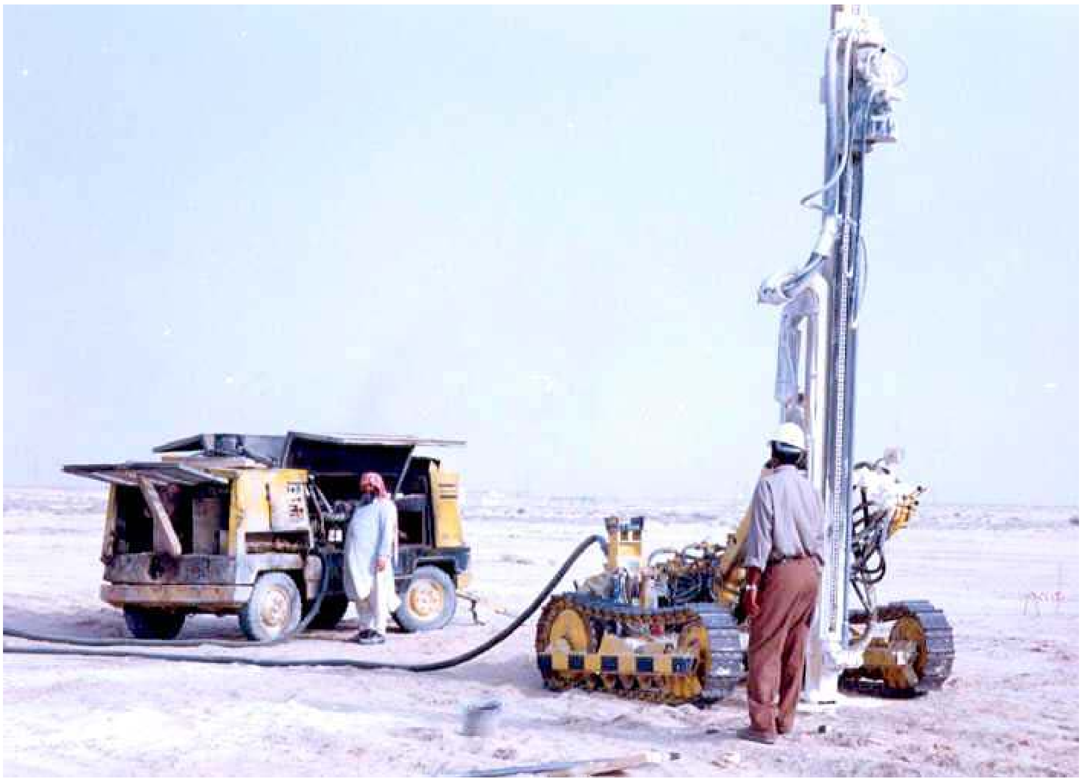


Plate: 1 Cavity Probing in progress at the Site

Plate: 2 A Typical Sinkhole at the Site

CONCLUSIONS

- The Project Site in Hofuf was encountered with presence of Karstic Terrain.
- An extensive investigation program was run to detect delineate & map the bedrock Cavities, Sinkholes, Dropouts & the Solution Channels.
- This comprised drilling of 316 boreholes, 10 nos. of test pits, & 5610 Cavity Probe Holes under the footprints of 166 nos. of facilities in 06 zones.
- The Cavity Probing was carried out by means of pneumatic driving of a rock probe using a Wagon Drill. Compressed air was used to clean the hole as advanced.
- Karstic features at the Site were mapped. Treatment measures were undertaken. Most of the Cavities & Sinkholes were treated by grouting, using geotextiles at some places. Some of them were remedied by using a new Compaction Grouting technique. Some were also rock backfilled (plugged) using the Bridging technique. In utility trenches, the Cavities & the lateral Solution Channels were fixed by erecting masonry and/or concrete structures. The ditches along the roads were paved.
- The treated Karstis features, at the Site, are performing satisfactorily well and there is no report of any problem since past more than four years or so.
- Semi-Rigid Raft Foundation, a rigid & shallow type of foundation, was used. Experts recommend such footings because of their ability to bridge over the Cavities.

ACKNOWLEDGEMENTS

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Plate: 3 Preparation being made for Treatment of Sinkhole at the Site

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