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SYNOPSIS: Rock excavation for a 7,200-square-meter building site in Saudi Arabia intercepted a large cavity underlying approximately half the site. Relocation was impossible; therefore, a grouting program was selected to modify the site to accept the allowable design load of 2.1 mega pascals. Due to the extreme depth of the cavity, the modification was limited to a depth of 25 meters under the building.

INTRODUCTION

A new facility for the Royal Saudi Air Force (RSAF) required a building area of 7,200 square meters (8,600 square yards) to be excavated to a depth of 22 meters (72 feet). The subsurface data obtained from borings for site selection indicated that the excavation in limestone bedrock contained very small cavities, tubes and vugs of insignificant size. These would not create problems or difficulties during excavation.

Excavation, however, was interrupted at 13 meters (43 feet) depth when a collapse in the 2.5-meter (8-foot) thick rock roof over a cavity partially swallowed a D9 dozer. During this pause in excavation, a probe hole investigation was initiated to determine how extensive this cavity or a system of cavities may be. Problems during drilling limited the hole depth to final excavation grade. These 220 holes did not reveal any indication of significant voids. A ground probing radar survey followed the borehole investigation, but it was ineffective. The collapsed hole was filled with rock to provide support of the roof rock and a safer condition in the area of collapse.

Cautiously, the excavation continued over the entire site until final grade was reached. The final excavation depth defined the collapse as a vertical annulus which was dubbed "the doughnut."

Another boring program was planned along load bearing walls with 15 borings to be advanced to 15 meters (49 feet) depth and 101 borings to 8 meters (26 feet) depth. Around one of the deeper borings, which revealed a cavity south of the collapse, a group of 13 borings were drilled to determine the cavity extent. All penetrated into the cavity.

The annulus was cleaned of rubble fill which permitted visual observation. The collapse had occurred directly above the apex of a large dome of rubble rock. The vertical space over the dome was relatively uniform at about 1 meter in the east, north and west directions. The height of vertical space to the south was about 0.5 meter (1.6 feet) or less. A trench was dug from the annulus southward to where the rubble pile steepened and it opened into a large chamber up to 7 meters (23 feet) in vertical space. Its main axis started at the east end and extended to mid-point of the south excavation limit. Normal to this were two more long chambers extending southward beyond the excavation. All three chambers had long flat ceilings and near vertical sides.

After visual examinations, it was established that one continuous cavity extended underneath approximately half the area of excavation.

BACKGROUND

In recent years, cavities have often been encountered in eastern Saudi Arabia but have not been documented in literature. Lack of documentation has failed to forewarn designers and contractors of the widespread and frequent problem. Recent articles indicate that progress is being made to alert engineers of cavities and their relationship to regional and structural geology.

Prior to the design and construction of the RSAF facility, other organizations had been assigned the task of finding a location for the building. With known loading conditions, they selected a site on the King Abdulaziz Air Base in Dhahran. They planned and administered the initial subsurface investigation program of borings which indicated limestone bedrock to full excavation depth in the Rus formation without any significant cavities.

The building would exert an average dead load of 2.1 mega pascals (MPa) (22 tons per square foot, TSF) under interior and perimeter continuous bearing walls. Half of this load is a true dead load, the remainder could possibly come from a dynamic type load which may come in the life of the facility. The full allowable load would approach uniformity at about 13 to 17 meters (45 to 56 feet) into the underlying materials.

Following several boring programs and the completion of excavation, the project was at a new threshold where we started our study. Direct contact and visual observations were used to evaluate the cavity. Until these were made, it was difficult to visualize a cavity of the magnitude that was observed.

Time constraints did not permit relocation of the facility to another site. The problem was to adapt this site to support the very high loading conditions to be placed over this cavity.

SITE GEOLOGY

The King Abdulaziz Air Base is located in the Interior Platform Section of the eastern Arabian Shelf. This structural division consists of sedimentary rocks ranging from Precambrian to Quaternary in age, with the area surrounding the site consisting of Paleocene and early Eocene marl, chalky limestone, dolomite, shale and geodal quartz. The site is located near the southern end of the Damman Dome, a broad 14 km by 10 km (8.5 by 6 mile) elliptically-shaped structure oriented N30°W and which rises to an elevation of approximately 150 meters (492 feet) above sea level. It is generally thought that the Damman Dome is the result of a deep-seated salt dome intruding the overlying sedimentary rocks (J. J. Grosch, F. T. Touma, and D. P. Richards).

The RSAF site is underlain by calcarenite and calcarenitic limestones of the Rus and Damman Formation. Logs of exploratory borings drilled at the site indicate an upper unit of light gray-brown fine calcarenitic limestone exhibiting abundant solution pitting. The limestone units contain numerous small solution cavities and vugs which are generally filled with calcite near the surface and iron-stained with greater depth.

The carbonate rocks of the entire Damman Dome region are characterized by solution cavities and karstic features. In general, solution channels have developed along the major joint system oriented tangential or radially to the dome structure. Case histories of cavity sites in the Dhahran area by Grosch, Touma and Richards indicate a reasonable agreement of cavity orientations with respect to the rock structure of the dome and location to each other.

GROUND WATER

Ground water was encountered at the base of the cavity chamber underlying the excavation and was recorded in borings. The water surface elevation is in agreement with the elevation recorded in surrounding wells. Samples of the water were obtained and analyzed in a laboratory to determine its compability or limitations with the grout to be used. The temperature of water and cavity were determined to be uniformly 85°F.

All exposed surfaces in the cavity, excepting those covered with dust and rock from the collapse, were an intense black. Slight variations in the color intensity continued at the same elevation throughout the cavity. Ground water was lowered through the cavity in the early 1950's. The hydrocarbons are believed to have been deposited on the surfaces at that time. Using this phenomenon as a guide, there was no evidence of disturbance since the deposition.

PROBABILITY OF CAVITY DETECTION

Detection and evaluation of cavities by means of a standard boring program is very difficult and usually impossible. Because the borings are limited in coverage, the number needed would depend on the size, depth and location of cavities that would be critical for the project. Once a cavity is detected, the best assessment is by visual observation in person or by means of downhole cameras or boroscopes.

Considering the site and cavity size on this project, the initial and subsequent boring programs could have revealed cavity information; however, the borings were not deep enough. Drilling problems limited depths in some borings and greater depths were not deemed feasible or cost-effective. A ground penetrating radar survey also proved ineffective.

Previous experience in Riyadh, Saudi Arabia using electrical resistivity and seismic geophysical methods demonstrated that especially the seismic method had potential of locating possible cavities. The boring program that followed investigated the locations indicated by seismic to be cavities and proved there were some cavities at shallow depth. More experience is needed to substantiate the effectiveness of the method.

DESCRIPTION OF TREATMENT

Before entry into and having direct contact within the cavity, it was apparent that the cavity should be filled. Inside observations revealed a flat ceiling spanning a space on the order of 26 meters (84 feet) under the south edge of the excavation. The ceiling warped into a dome in a northerly direction going from a relatively flat dome to a rather abrupt dome in the area of the collapse. Computations proved the cavity roof needed support. Filling of the cavity would transfer load to the rock fall material in the floor of the cavity. Since none of the boring programs had provided information on material and conditions underlying the cavity, 21 additional borings were advanced to a depth of 50 meters (164 feet) below final excavation grade using rock coring methods.

Core boring was difficult. A mud-rotary drilling method was used to stabilize the hole, remove cuttings, and cool and lubricate the drill bit. There was no return of drilling fluid below about 12-meter depth. At different depths in each hole, the rock conditions required use of a casing fitted with a cutting shoe to advance the boring. To facilitate recovery of rock cores, various types of core barrels were used.

Loose fine-grained material was encountered in some of the various sized cavities. Adequate quantities were obtained in seven samples for sieve analysis which revealed a gradation of silty sand and limestone fragments. Comparable materials were observed in the space between rubble rock pieces in the south end of the cavity floor as well as in the area of the original collapse and a partial roof fall nearby.

Unconfined compression tests on twenty-four representative rock cores yielded results between 6.8 and 100.5 MPa (71 and 1,045 TSF) which averaged 50 MPa (520 TSF). These strength test results suggest the rock be classified as relatively weak to strong. The complex stratigraphy based on poor rock recovery and quality of rock made it difficult to correlate between the deep boreholes.

Cavities were detected by observing the rate of penetration, drop of the rods and pressure exerted during the drilling operations. This procedure allowed detection of vertical cavity size from 50 mm (2 inches) and larger.

Treatment necessary to adapt this site for support of the facility had to consider the following:

- o The roof rock over the cavity needed support.
- o Filling the cavity would provide roof support and apply load to cavity floor.
- o Conditions in the cavity indicated that large masses of rock had dropped many meters, some only a matter of a few cm.
- o There was no sign of rock fall in the cavity since deposition of the hydrocarbons.
- o Large rubble rock in the chamber area had been bonded at contact points by calcite. The bonding suggests long-term inactivity in rock fall.
- o The cause or origin of the cavity was very deep seated. If originating in the edge of the salt dome, it could be hundreds of meters deep.
- o The nature of the rock falls observed in the cavity led to the belief that large rock masses had dropped.
- o All voids below 15-meter depth would be water-filled.
- o The true void space in material underlying the major cavity was not known.

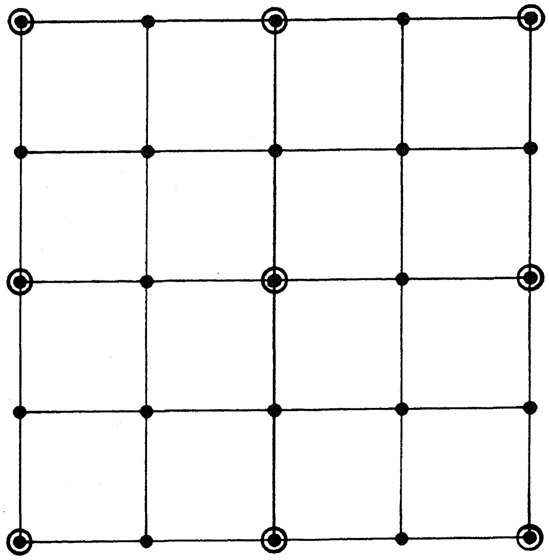
It was hypothesized that the originating cause of the cavity was very deep-seated and that a remedial program to provide needed support would be limited to a relatively shallow depth. It was decided that the most effective solution for stabilizing the ground support for the facility was to fill the original cavity (the doughnut) with concrete and to grout the cavities and fragmented rock. For safety reasons, the "doughnut" was filled with concrete under a separate existing contract, prior to development of recommendations for the grouting program.

The purpose of the grouting program was to fill openings, though not all the small interstices, in the rock down to a 25-meter depth and out to a boundary extending from the edge of the excavation at 45 degrees. This grouted mat would distribute the load and prevent the possible loss of material into underlying cavities. The primary activities included in the grouting program were as follows:

1. Drilling southern perimeter barrier grout holes.
2. Placement of southern perimeter barrier grout.
3. Drilling mass cavity fill holes.
4. Placement of mass cavity fill.
5. Drilling primary grout holes.
6. Placement of primary grout.
7. Drilling secondary (verification) grout holes.
8. Placement of secondary (verification) grout.

The initial phase of the subsurface stabilization program consisted of placement of perimeter barrier grout at the southern end of the excavation in the large horizontal chamber. Following completion of the perimeter barrier grout placement, mass cavity filling began. Shortly thereafter, vertical placement hole drilling was initiated in the northern portion of the site. This drilling was performed concurrently with the mass cavity filling operation. These holes provided additional information on rock conditions to 25-meter depth.

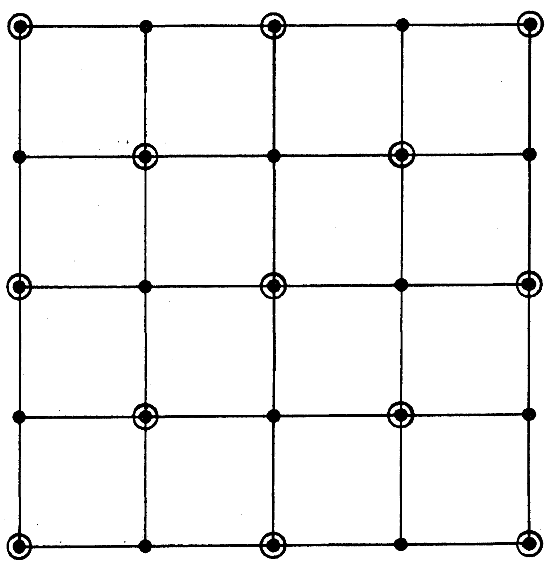
Exploratory borings and observations inside the cavity indicated that the southern and eastern portions of the site contained the most extensive voids; therefore, the primary grouting work was initially concentrated in the southeastern corner of the site. A test area was located in this corner. A first pass grout injection pattern was developed as shown on Figure No. 1. Approximately 30% of the total number of primary holes were grouted in the first pass. Injection in the remaining 70% of the primary holes (second pass) indicated that the 30% pattern was insufficient to insure adequate ground stabi-



Legend:
- ● Primary Holes on 3.2m centers
- ◉ Injection Holes in the first pass (30% of the Pattern)

Pattern shown typical of Contractor's Grid Pattern

Figure 1 Plan of First Pass Injection Holes



Legend:
- ● Primary Holes on 3.2m centers
- ◉ Injection Holes in the first pass (50% of the Pattern)

Pattern shown typical of Contractor's Grid Pattern

Figure 2 Plan of Modified First Pass Injection Holes

lization. Therefore, a modified first pass grout injection pattern was developed and used thereafter. This pattern is shown in Figure No. 2 and utilizes 50% of the full primary pattern in each pass.

The data obtained in the test area was extremely useful in assessing grouting results throughout the remainder of the site. Table No. 1 contains tabulation of partial grouting data from the test area. The quantities in this table are the recorded grout quantities placed in the test area, broken down by stage (pass) of grouting.

Significant grout takes were realized during first pass grouting in the 12.5 meters of depth immediately below the facility foundation and in the 12.5 to 25-meter depth zone. Second pass grout takes were considerably less for the upper 12.5 meters than the lower 12.5 meters.

GROUTING WITHIN THE BUILDING LIMITS

The program emphasized grouting in the vicinity of the known large cavity in the southeastern portion of the site to gain experience and to establish grouting guidelines. As grouting progressed toward the northwestern portion of the site, it was possible to identify two separate areas with differing ground conditions and differing grout takes. The line of demarcation between these two areas was quite distinct and was as shown on Figure No. 3. Segment No. 1 contained the large horizontal void and a system of smaller cavities; Segment No. 2 contained in general only small cavities and fractured rock. Grout takes in Segment No. 1 were relatively large and erratic while in Segment No. 2 they were relatively small and consistent.

In general, five conditions were utilized in the evaluation of the effectiveness of the ground stabilization and the determination of the extent of grouting required: grout quantity, location of grout quantity, grout take correlation between nearby grout holes, time required for grouting each hole, and logs of investigative borings and grout holes.

Conditions encountered in Segment No. 1 required the full verification grouting program. Several grout mixes, covering a wide range of viscosity, were evaluated for use in verification grouting and were tested in Segment No. 1. The primary grout mix was concluded to be appropriate for all primary and verification grouting.

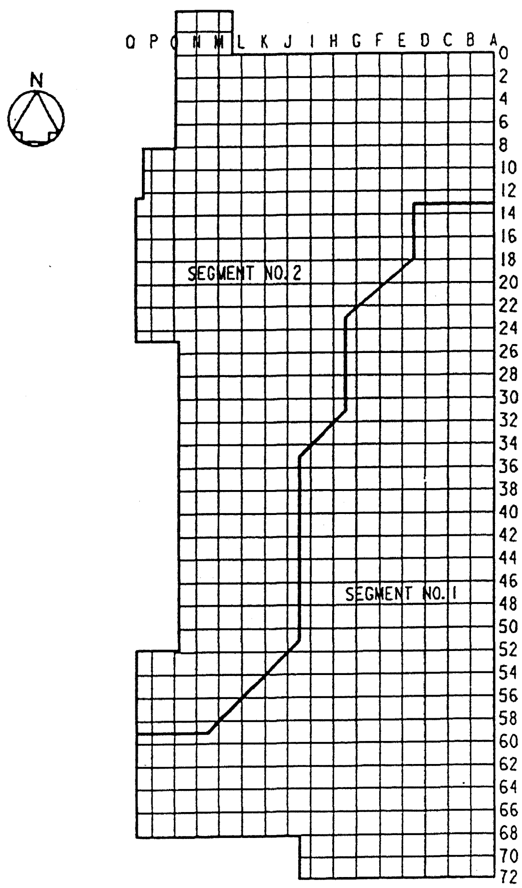
In one portion of Segment No. 1 (lines 52 to 62, Lines A to I), a number of verification grout takes were high. Careful evaluation of the data indicated that ground stabilization was accomplished in the upper 12.5 meters during the primary grouting. Some minor voids remained to be filled by the verification grouting below the 12.5-meter depth.

Use of the full primary grouting pattern in the northeastern corner of Segment No. 2 per-

TABLE 1

TEST SECTION GROUTING DATA

	No. of Grout Borings	Total Grout Quantity	Average Grout Quantity Per Boring	Percent of Total Grout Injected in Test Area
First Pass Top 12.5 meters	30	529.49m^3	17.65m^3	31.8%
First Pass Bottom 12.5 meters	30	426.19m^3	14.21m^3	25.6%
Second Pass Top 12.5 meters	69	119.12m^3	1.73m^3	7.2%
Second Pass Bottom 12.5 meters	69	588.09m^3	8.52m^3	35.4%
		1662.89m^3		100.0%



NOTE: Numbers and Letters Indicate Contractor's Grid Pattern on 3.2m spacing.

Test Section Was Inside Grid Lines 52 to 72 and A to I.

Figure 3 Plan of Segments 1 and 2

mitted evaluation of the effectiveness of first pass injection. First pass grouting was sufficient throughout Segment No. 2 and was verified by selected verification grout holes.

GROUTING OUTSIDE THE BUILDING LIMITS

Grout take data for the inclined borings was evaluated in the same manner as indicated above for the interior of the site, taking into consideration the difference in spacing at 25-meter depth. The inclined borings were at the ends of the grouting grid lines and the cluster of borings were drilled at predetermined angles. At various locations, verification borings were directed in order to substantiate ground stabilization.

An area of high grout take was encountered along the southern boundary of the site during placement of grout in the inclined holes. Full verification grouting was directed in this area and ground stabilization was indicated by the verification grouting.

COMPLETION OF PROGRAM

The subsurface grouting stabilization program began in early August of 1986 and was completed in a timely manner on February 2, 1987. The following quantities of grout had been placed:

Perimeter Barrier Grout	65.20 m^3
Mass Cavity Fill (Concrete Not Included)	3,322.44 m^3
Primary Grout	7,009.62 m^3
Secondary Grout	618.39 m^3
TOTAL Grout Quantity	11,015.65 m^3

The grouting program was completed according to the design plan and procedure.

CONCLUSION

The grouting work has bonded together a rock mass 25 meters thick. This very stiff mat bridges the unstable area and provides for a relatively uniform load distribution into underlying rock fall and the the more stable surrounding bedrock. Drilling and observation data indicates that the conditions causing the cavity and displaced bedrock has been inactive and stable for a long period of time.

This project demonstrates the need for an awareness of possible cavities in eastern Saudi Arabia, especially those not encountered during excavation. After assessing the size and depth of a cavity that would be critical to a project, one must select an exploratory method(s) to detect critical cavities under a building site.

REFERENCES

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