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Grouting to Control Deep Foundation Settlement
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SYNOPSIS
An 18-story reinforced concrete building under construction in South Florida reached 16th floor level when significant differential settlement presented an unanticipated foundation problem. The foundation consisted of a structural mat supported by 14-in. concrete piles 24 to 75 ft long. Surprisingly, the longest piles were within the area of greatest settlement. Investigation revealed a previously undisclosed semi-cavernous zone from 120 to 175 ft below ground surface, and level surveys using deep benchmarks confirmed that zone to be the source of movement. Injection grouting first accelerated and then controlled the settlement, allowing the building to be completed on schedule. Temperature probes and weekly precise level surveys were key control devices contributing to the correction of the problem.

INTRODUCTION
During February, 1965, construction of a planned 18-story reinforced concrete building in South Florida had reached the 16th floor level when it was discovered that the pile-supported foundation mat was settling differentially, allowing the slender building to tilt. A re-survey of the positions of control points located within the elevator shaft opening at each floor level, all constructed precisely above a common point on the mat, revealed that these had each shifted westerly, in the direction of mat tilt. The bow-shaped pattern now occupied by these points, as sketched in Fig. 1, revealed that some tilting had been experienced almost from the beginning of construction, but it also confirmed other evidence that a sudden movement had occurred when the 14th floor was poured.

During that same month, the building owners retained McClelland Engineers to investigate the causes of this unexpected movement and to advise them with respect to possible remedial action. This paper presents a narrative account of the investigation, the corrective measures that were carried out, and the results obtained. To highlight some of the unique aspects of this case history and, in particular, the uncertainties that persisted throughout this operation, the case history is presented in a chronological format.

PROJECT DESCRIPTION AND STATUS, FEBRUARY 1965
The 18-story, reinforced concrete structure was constructed about 35 ft from an existing 2-story facility. Shown in plan and profile on Fig. 2, the complete development included a 2-story transition structure between the new tower building and the existing facility. The high-rise portion of the expansion is shaped in plan like a rectangle 148 ft by 95 ft with truncated corners. The building rests upon a pile-supported mat, 38-in. thick and 10,910 sq ft in area. The total design load (full dead load + reduced live load) of 41,465 kips corresponds to a uniform applied pressure of 3800 psf, exclusive of wind load.

The foundation mat is supported by 578 precast concrete piles driven with a Delmag D-12 diesel hammer. The piles were 14 in. square and designed for an allowable working load of 36 tons. All but 26 of the piles were driven to a
The length for this large group of piles was selected following a series of static load tests which demonstrated a capacity in excess of 80 tons.

In the northwest sector of the mat, the remaining 26 piles were driven to depths of 65 to 76 ft. Their added lengths resulted from application of driving criteria specifying that resistance for the last 10 ft must be at least 10 blows per ft and for the last 3 ft at least 60 blows per ft. It appeared as a paradox, in February, 1965, that these long piles were located beneath the part of the mat that had settled the most.

Prior to design, subsurface conditions had been investigated by soil borings to 100-ft depth, results of which are given by the generalized profile of Fig. 3. The surface is covered to 8 ft of hydraulically placed sand fill, fill overlies 10 to 15 ft of very weak. The groundwater level was near the surf.

By the end of February, 1965, the reinforced concrete frame had reached the 16th floor, the 15th floor slab had been poured. Exterior facing had been applied to the 14th f level, and interior partitions and ceiling were being added up to the 8th to 10th floor

settlement investigation, Feb. 24 - March 1965

Beginning on February 24, a program of pre level surveys was begun, including elevations at the base of 29 columns. The next several months, elevations at t points were determined to an accuracy of 0.001 ft and at intervals of about one week. Initial observations revealed that settlement was increasing about 0.001 ft per day.

A decision was required first whether to construction. The contractor estimated that to muster, then resume construction at a later date, an add 20 percent to the cost of the structure, further loss would arise in connection leasing agreements already signed calling building occupancy by late fall.

By March, the dead load in place was comp to be 31,100 kips, about 80 percent of expected dead load associated with comple of the building shell. Our judgement w that the settlement was probably the consequence volumetric strains and that continuation construction would not seriously alter the r of structural failure, even though settlement could be expected to accelerate. The ow accepted this judgement and its conseque and elected to continue construction with a pause.

An investigation to determine subsurf conditions to a greater depth was commenced drilling five borings that extended from 16 to 213 ft below the original ground surface at locations shown on Fig. 4. Positions of the borings were chosen to explore; surface conditions near the area of maxi foundation movement, an area which encompass all of the long piles. The other boring drill on the east side of the structure at settlement was least.

A generalized stratigraphic profile based results of the new borings is presented Fig. 5. These borings disclosed subsurf conditions to 100-ft depth that were similar those observed in the pre-construction borin An exception, found in Boring 6, was identification of a 6-in. void at 63-ft de and a 4-in. void at 65-ft depth.
Below El-110 ft, all of the new borings except Boring 8 revealed very loose calcareous sand down to El-145 to El-165 ft. Within that depth range, there was a 25-ft zone in Borings 7, 9, and 10 in which the formation soil would not support the drill pipe weight. No samples could be recovered in that semi-cavernous zone. On the east side of the building, Boring 8 indicated conditions throughout its depth, to El-165 ft, that were similar to those found in all of the borings above 100 ft. Either limestone or medium dense sand was found underlying the cavity.

During the period from February 24 to March 25, as the subsurface investigation proceeded, the average settlement increased 20 percent although the building load increased only 9 percent. We tentatively concluded that the ongoing settlement resulted from volume compression of the loose soils between El-110 and El-165 ft. Alternate remedial measures given consideration at that time included (a) selective and variable preloading of the structure to expedite settlement, with an attempt to control differential settlement, (b) underpinning, and (c) deep injection grouting. Underpinning was considered the surest but also the most expensive and time consuming alternative, and delays to the construction schedule were certain to occur. Grouting was considered uncertain in effectiveness, but it could be implemented without affecting the construction schedule. The decision was made to conduct an experimental grouting program using the holes drilled for Borings 6-10 as well as additional holes to be drilled through the foundation mat.

PHASE I GROUTING, APRIL 6 - MAY 12, 1965

Injection grouting from the top-down in seven borings between El-110 and El-170 ft was implemented to determine the effect on settlement of grouting the deep weak zones. Locations of these Phase I borings are shown in Fig. 6. Five were made west of the building, and two were drilled through the pile-supported mat.

Each boring was advanced until there was loss of drilling fluid circulation. At the level where that occurred, a grout mixture consisting of equal parts of sand and cement was pumped through the drill pipe using a surface injec-

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Fig. 3 Subsurface profile based on pre-construction borings.

Fig. 4 Mat and column layout, with post-construction boring locations.
tion pressure of about 10 to 20 psi. Pumping was usually continued until refusal but in some cases was abandoned to avoid sticking the drill pipe. After a time lapse of a few hours to allow the grout to set up, the hole was deepened and the process repeated.

Results of the Phase I program were not encouraging. The production rate, hampered by a recurring problem of drill pipe freezing up during grout placement, was disappointingly slow. The rate of settlement of the west side of the building increased from 0.001 to 0.003 ft per day, a trend that can be recognized in the plot of Column D-3 settlement, Fig. 7. The 14th floor, which had shifted laterally 1-1/8 inch prior to March (Fig. 1), reached an offset of 2-1/2 inches by April 22. These movements occurred despite the fact that building load increase during the same time period was very small.

The investigation succeeded in resolving one uncertainty during this period. This was the question as to whether the weak and semi-cavernous layer below El-110 was contributing any or all of the observed settlement. On April 24, a sectional aluminum casing with telescoping couplings at 10-ft intervals was installed to El-110 through a pile-mat opening in the area of maximum settlement, between Columns C-3 and D-3. The casing was sealed in place with a weak bentonite-cement slurry. By May 12, repeated elevation observations indicated conclusively that the entire aluminum casing was moving downward at the same rate as the mat, confirming that settlement was coming entirely from volume compression of strata below El-110 ft.

At the conclusion of Phase I grouting, the possibility that underpinning might be required still had not been set aside. Nevertheless, decision was made to make grouting succeed at all possible, and a modified and more effective injection procedure was initiated.

PHASE II GROUTING, MAY 12 - JUNE 1965

The technique adopted for Phase II was to install a 2-in. or 3-in. pipe to firm soil or rock at about El-160 ft, and then to inject grout through 1/2-in.-diameter holes formed in the pipe with a gun perforator. The first grout batch was placed through the open end of the pipe. Thereafter, perforations were made near the bottom of the pipe --- usually 2 perforations per ft over a length of 4 ft. After that section was grouted, additional perforations were made and grouted at the next higher level, and in that manner the full section lying between El-110 and El-165 ft was exposed to grout at the ten Phase II locations shown on Fig. 6. Three of the holes were west of the mat and seven were drilled through the mat.

The slurry injected into these holes consisted
was followed immediately by sufficient water to flush the grout pipe, plus an additional 10 to 15 gallons to encourage the perforations to remain open. Following a 4-hour wait to allow initial set, the process was repeated. Although refusal was frequently encountered early in the second injection period, in many instances an additional 4 to 6 cu yd was placed with little buildup of resistance. From the latter experience arose a persistent concern that much of the grout was moving outside the building area and therefore was producing little benefit.

To determine if cement hydration was occurring close to the point of injection, a program of downhole logging of water temperature in the grout pipes was initiated on May 29. Temperature logging was conducted by attaching a series of maximum-reading thermometers to a calibrated line at selected intervals and lowering the line into the hole 12 hours after grouting was completed. Observations indicated a strong rise above the 80°F ambient temperature following any injection of 5 or more cu yd. As illustrated by Fig. 8, the temperature rose in such instances as much as 40 degrees or more, and the effect extended as much as 30 ft above the injection level. Fig. 8 also illustrates as instance where temperature observations were repeated after an additional 24-hour lapse, although the customary procedure was to resume perforating and grouting on the following day.

![Diagram](image_url)
Results of the temperature logging added to our confidence that substantial grout quantities were remaining in the target zone and that continued grout applications would improve the foundation. In the meantime, continued settlement observations provided additional encouragement. As shown by Fig. 9, the rate of settlement began to decline noticeably in early June, the first favorable trend since the beginning of drilling and grouting. The average settlement rate, however, was still about 0.0023 ft per day and was judged to be too severe.

Close examination of settlement rates and their trends had made it clear, by early June, that there was always a sharp reduction in the rate of settlement whenever grouting activity ceased, even for a day or two. We concluded that the initial effect of the injected grout was to increase the vertical pressure on the foundation soils and to contribute to settlement; at the same time, we were confident that once the grout hardened, the average compressibility of the formation would be reduced. The decision was made to complete injection of grout in the remaining holes prepared for Phase II, then to halt all grouting for 1 week. On the basis of settlement trends at the end of that time, a further decision was made whether to continue to pursue the same method of correction or to resort to underpinning.

PHASE III GROUTING, JUNE 15 - JULY 15, 1965

By the end of June, the rate of foundation settlement had continued to decline. Eight grout pipes had been installed in readiness for further injections. Phase III grouting resumed on July 1, using the same procedure as in Phase II. When the injection of the last of these eight holes was completed on July 15, additional 449 cu yd of grout had been placed. During this period, the rate of movement steadily declined (Fig. 11) and was about 0.0006 ft per day by July 15. On July 16,
grouting operations were suspended, but elevation observations continued. All equipment was held in a state of readiness for still further injections in the event the settlement rate did not continue to decline as expected.

At the conclusion of Phase III, the total grout placement for all three phases was 1791 cu yd. An example of the grout distribution is given on Fig. 10, a north-south profile following a line of five grout holes along Column Line 2-A. Superimposed on each boring is a graphic indication of the amount of grout placed at each of the various injection levels.

POST-GROUTING PERFORMANCE, JULY 1965 - APRIL 1976

By August 12, 1965, the average settlement rate had decreased to 0.0003 ft per day, and settlements were progressing on both the east and west sides at almost the same rate with no significant increase in tilt. On the basis of this continued favorable trend, the Owner accepted completion of the remedial grouting and approved demobilization of all equipment.

Elevation observations of all 29 control points continued for the next several years, with the same high-level precision but with gradually reduced frequency. Results are given by the two plots on Fig. 12 which show average settlement and average settlement rate from May 1, 1965, through April 6, 1976.

Inasmuch as construction never halted, the project finished almost on schedule. The tower structure was occupied from the third floor up by mid-November, 1965, and the rest of the structure including the link building was occupied by February, 1966.

STRUCTURAL EFFECTS

Settlement contours developed from observations on the second floor on July 21, 1965, Fig. 13, show the oyster-shaped deformation of the lower floors of the structure at the time grouting was completed. Angular rotation, defined as the ratio between differential settlement of two columns and the column spacing, ranged from 1/190 to 1/230 for columns along Row C. The most severe angular rotation at that time, between Columns F-3 and F1-2A, was about 1/160.

Profiles of settlement, Fig. 14, for the pile-supported mat indicate that total downward movement, 11 years later, ranged from 4.1 to 8.3 in. at the locations of Columns D-5 and D-3, respectively. This produced 4.2 in. of tilt over a distance of 64 ft. Subsequent to about October 1965 settlement has proceeded almost uniformly. The maximum differential settlement along Column Row 3 had actually reduced by April 1976. This was a differential of 1.2 in., between Columns E and F, corresponding to an angular rotation of 1/210.

The observed differential movements are classed as severe and are very close to the limits for avoiding structural damage, according to Skempton and MacDonald (1956), Bjerrum (1963), Feld (1965), and Sowers (1979). Repeated and careful inspections of the building, however, have disclosed no structural damage beyond minor hairline cracking in concrete beams. The building is currently in use and has endured hurricanes since completion.

CONCLUSIONS

Following are some of the significant observations and conclusions based upon this case history:

1. The nearly completed 18-story building suffered large and unequal settlements due to compression of poorly consolidated calcareous sediment filling deepseated cavities.

2. Precise elevation observations of the structure and of deep benchmarks established that the source of the movement was below El-110 ft, which is consistent with the highly compressible zone between El-110 and El-165 ft as identified by borings.
3. A settlement problem associated with a cavity at such great depth is unique in the authors' experience as well as the experience of others consulted during the project, including those who conducted the original design investigation.

4. Grouting the compressible formation from the bottom-up, through gun-perforated injection pipes, initially accelerated settlement but finally controlled settlement to an acceptably small and relatively uniform rate.

5. Down-hole water temperature measurements were of importance in verifying that significant grout quantities remained within the zone of intended improvement.

6. Although the observed differential movement is considered severe from the standpoint of potential structural damage according to frequently used criteria only minor hairline cracking of concrete beams can be detected, and the structure has given good service.
ACKNOWLEDGEMENTS

The location of the building and the identity of the owner are not disclosed here, at the Owner's request. The Authors wish to acknowledge, however, the substantial contributions to operating procedures and decisions made by members of the Owner's engineering staff throughout the remedial operation. We are also grateful for the insight and recommendations provided by Dr. John Schmertman and Dr. Philip C. Rutledge who provided consultation to us during the work. The grouting contractor was The Halliburton Company.

REFERENCES


