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Adjustable Columns Control Settlement of Structure

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SYNOPSIS A five-story precast concrete building was to be built on 10 to 130 feet of mixed cohesive and bouldery engineered fill. The initial estimates of total and differential settlement of shallow foundations for the structure were considered intolerable. After evaluating several options, it was concluded that providing a means of adjusting the building columns to "relevel" the structure as the foundations settled was the most cost-effective approach to the problem. The observed settlements were different than originally estimated, and some unanticipated settlement and adjustment problems did occur. However, the approach was successful and cost effective.

INTRODUCTION

During 1979 plans were developed using a "fast track approach" for the construction of a five-story glass and precast concrete commercial structure occupying an area approximately 130 feet wide by 580 feet long. The proposed Expo-Mart being built by the Oxford Development Company as a supplemental development of the Monroeville Mall in Monroeville, Pennsylvania was to have parking on the lower two levels, exhibition space on the upper three levels and an existing two-lane highway passing through the middle of the lowest level. The proposed structure had total design column loads of 810 kips for interior columns and 405 kips for exterior columns. The 105 columns were spaced at approximate 30-foot centers and the exterior of the top three levels of the Expo-Mart was to be a continuous glass enclosure. The above-grade portions of the lowest level and the second level were to be exposed columns with no exterior walls. Prefabricated metal pannels would enclose some areas. A two-level parking garage having approximate plan dimensions of 240 by 260 feet was to be attached to the main structure. The upper parking level was to be a concrete slab supported with 56 columns at approximate 30-foot centers. The lowest level of both structures was to be a soil-supported asphalt pavement.

The site of the proposed construction sloped gently to the northwest as shown on the plan in Figure 1 from an approximate high elevation of 1050 feet (USGS datum) at the southeast corner of the main structure to a low of about 1020 feet at the northwest corner. Final grade of the lowest level for parking sloped gently to the northwest from approximate elevations 1045 to 1035. Thus, the southeast corner was to be built in an area of about 5 feet of excavation and the footings in the northwest corner were to be built over about 12 feet of new fill as shown in Section A-A in Figure 1. The attached parking garage to the southwest was to be built mostly in an excavated area.

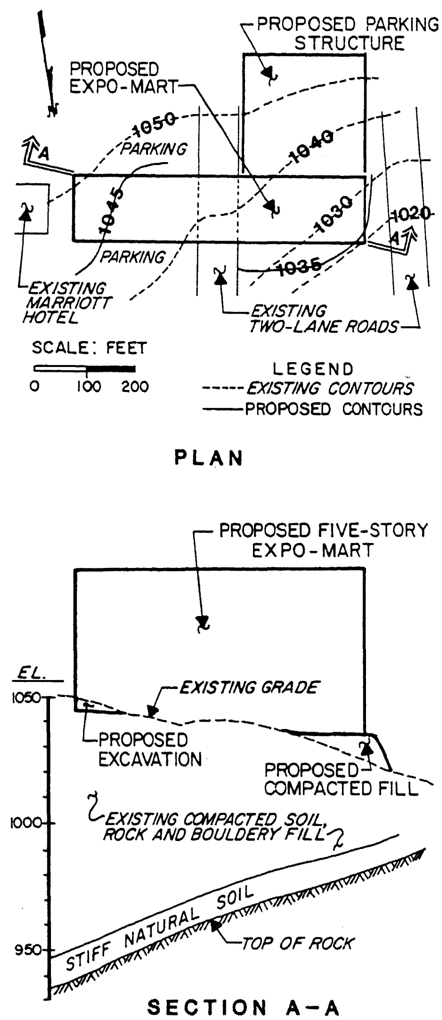

Fig. 1. Plan and Section of Proposed Expo-Mart

SUBSURFACE CONDITIONS

Based on knowledge of previous grading activities for the Monroeville Mall, as well as borings for the proposed construction, it was known that the proposed Mart and adjacent parking structure were underlain by 10 to 130 feet of generally stiff or dense compacted cohesive soil and rock fill. This fill had an average standard penetration "N" value of 18 blows per foot. The fill resulted from excavation of residual soil, limestone, shale and sandstone primarily from the Pittsburgh Formation of the Monongahela Group when a nearby hilltop was removed to below the level of the Pittsburgh Coal (base elevation at about 1080 feet) for construction of the Mall. The fill which had been in place for about 10 years was known to contain randomly located boulders several feet in diameter.

Natural soils below the fill were generally stiff residual soils about 10 to 20 feet thick which were underlain by shale, sandstone and limestone of the Casselman Formation of the Conemaugh Group (see Section A-A, Figure 1).

SETTLEMENT ESTIMATES

An initial attempt was made to determine if shallow foundation support by the existing fill was technically feasible. It was assumed that settlement of the existing and proposed fills due to their own weights and settlement of the existing fill due to the weight of new fill were complete prior to the construction of new foundations. The design loads were refined by the structural engineer for settlement estimating purposes. The sustained column loads (100% of dead loads plus an estimated 30% sustained live loads) for estimating settlements of the Mart structure were 525 kips for interior columns and 264 kips for exterior columns. The respective loads for the attached parking structure were 96 kips for interior columns and 72 kips for exterior columns.

GAI had data on the compressibility of the compacted soil and rock fill that had been developed at the time of construction of the adjacent 14-story Mariott Hotel. Settlement estimates and observations for that structure which was built over similar compacted fill on a partially floating foundation indicated that the compacted fill could be characterized as overconsolidated with a recompression index of 0.05 and an initial void ratio of 0.5. These values along with a soil wet unit weight of 130 pounds per cubic foot were assigned for analysis purposes. The ground water table was more than 40 feet below existing grade and was out of the range of influence of shallow foundations.

Various configurations of strip and spread footings supported on the existing and new fill were analyzed for the Mart structure using Terzaghi's classical consolidation theory (1967). Strip footings ranged from 5 to 18 feet in width with net stress increases of 910 to 1830 pounds per square foot. Square footings ranged from 8 to 16.5 feet in width with net stress increases of 2000 to 4000 pounds per square foot. The minimum total and differential settlements for adjacent interior columns supported on 18-foot wide strip footings with net stress increases of 910 pounds per square foot were estimated to be 1-1/2 and 1-1/4 inches, respectfully. The same values were estimated at 1 inch and 3/4 inches for exterior columns.

The design team consisted of the owner (Oxford Development Company), the architect (James S. Pedone, and Associates), the structural enginee (Gensert Bretnall Bobel) and the geotechnical engineer (GAI Consultants, Inc.). The design team concluded based on data published by Leonards (1962) and judgement regarding the proposed structure that tolerable settlement criteria for the proposed structure should be set at a maximum of 1-1/2 inches total settlement and 3/4 inches differential settlement for adjacent interior columns and 1 inch total settlement and 1/2 inch differential settlement for adjacent exterior columns. Thus, using the most optimistic analysis configurations and assumptions, the estimated settlements of shallow foundations for the Mart supported on the existing and new fill were not considered tolerable.

OPTIONAL FOUNDATIONS

Several options to reduce anticipated column settlements to within the established acceptabl limits were considered. The least cost alternative was lowering the entire structure one leve so that the lowest level would become a basement. The estimated settlements for this approach were tolerable; however, this approach was rejected for esthetic and architectural reasons.

The possibility of overexcavation of the existing compacted soil and rock fill and replacing it with well compacted relatively incompressibl select and uniform granular backfill was investigated. It was found that 6 to 8 feet of the backfill would be required below the shallow foundations to limit estimated settlements to tolerable amounts.

Grouting of the fill to reduce settlements was rejected because the permeability of the fill was too low.

Deep foundations other than drilled piers were rejected because the boulders in the fill would prohibit penetration to the desired depths. Drilled piers extending to rock were considered technically feasible because boulders could be penetrated or removed by this technique. However, this approach was estimated to be costly considering the anticipated slow rate of installation due to the presence of the boulders.

GAI offered a final option that was a relativel novel approach for a structure of this type. The basic approach was to design the columns with permanent adjustable column bolts near the bases so that the columns could be adjusted upward with removable hydraulic jacks as the foundations settled to prevent excessive differential settlement of the structure. (The Eiffel Tower in Paris has a somewhat similar system.) This approach was considered technically feasible if properly implemented with an accurate program of surveying and column adjustments. Based on the observed settlements of the adjacent Marriott Hotel, it was estimated that column adjustments might be required for two years after construction.

The estimated costs of the various alternatives prepared by Turner Construction Company (the construction manager) with inputs from the design team showed that the column jacking approach was the most cost-effective of the technically feasible and architecturally acceptable alternates, and this approach was selected by the design team for construction. It should be noted that the structure lent itself to easy adaptation to this approach since most of the columns on the lowest level were to remain exposed which provided easy access for surveying and adjustment.

ESTIMATED FOUNDATION SETTLEMENTS AND COLUMN JACKING DETAILS

Once the column jacking approach was selected and settlement of the footings or new compacted fill no longer governed the design, the design gross bearing pressure for the shallow foundations was increased to 8 kips per square foot for total loads. This value was selected to provide an adequate safety factor against a bearing capacity failure while minimizing the size of the footing required to support the column loads. Estimated settlements of the foundations were based on the compressibility parameters of the existing fill. The estimated settlements for sustained net stress increases of about 5000 pounds per square foot ranged from 1/2 inch for a 3-foot by 3-foot corner garage footing to 2-3/4 inches for a 10-1/2-foot by 10-1/2-foot interior Mart footing. The structural engineer ultimately provided approximately 6 to 8 inches of adjustment capability into each column.

Four column bolts were incorporated into each column as shown in Figure 2, approximately 2 to 3 feet above the finished grade of the lowest asphalt-paved parking level. The bolts were designed to carry full column loads and sufficient space was provided for temporary insertion of one or two Simplex hydraulic flat jacks for raising the columns.

It was anticipated that several months would be required to place most of the dead load of the structure, and the rate of anticipated foundation movement was estimated to be small on a weekly basis. Consequently, surveying of foundation and column settlements was to be conducted weekly during construction and column jacking was to be done when required. The frequency of surveying was to be reduced as the rate of settlement slowed. Survey measurements were to be correct to the nearest 1/8 inch.

The criteria for when adjustments were to be made was set at 1/2 inch differential movement between adjacent interior columns and 3/8 inch differential movement between adjacent exterior columns. These values were set below the established tolerable values to provide time to accomplish the adjustments prior to exceeding the established tolerable values. Adjustments were to be made gradually by raising the columns with the jacks and concurrently tightening the lower supporting column bolt nuts so that failure of the hydraulic jacks would not result in a sudden drop of the column.

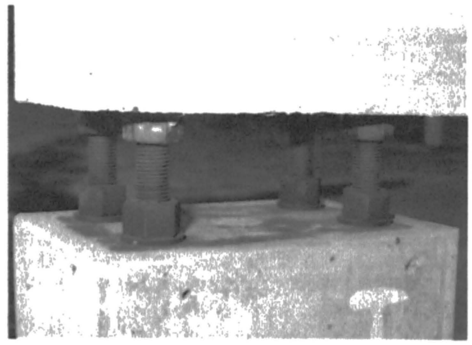

Fig. 2. Typical Column Adjustment Bolts

OBSERVED SETTLEMENTS

Primary Dead Load Case

Site grading and foundation construction for the Mart occurred during the winter and spring of 1980. It was recognized during site grading that the compaction of the new fill placed in wet winter conditions would not be adequate if the new fill were required to support conventional spread footings. However, the schedule dictated that the fill be placed during the winter, and the adjustable columns permitted a relatively compressible fill to be used to support the structure.

Each footing excavation was observed and probed with a 3/4-inch rebar driven with a sledge hammer in several locations. Refusal normally occurred at a depth of about one foot or less. Soft zones were found in some excavations along the western end of the Mart structure. These soft zones were overexcavated and replaced with well compacted backfill. The presence of several soft zones in the new fill near the western edge of the building indicated that inadequate attention had been given to compaction procedures near the edge of the fill.

Initial survey reference marks were established near the tops of the 105 spread footing piers extending above grade from the footings for the Mart structure in late April 1980 and for the 56 piers for the attached parking structure during July through September 1980. The application of the dead load of the structures occurred over approximately six months and was essentially complete by late October 1980.

The survey data collected through October 1980 indicated actual foundation settlements ranging from 0 to about 6 inches with average settlements of about 3/4 inches. All of the footing piers with the exception of nine settled less than or equal to the predicted amounts. During this period, several of the columns were jacked and the differential settlements of the columns were maintained within the established design limits.

Unanticipated Conditions

Two distinct "soft spots" in the fill were detected after footing columns were in place and structural loadings were being applied. The northwest exterior corner foundation settled about one inch and rotated excessively when only a small percentage of the dead load was in place. Investigation by drilling showed that a random soft zone in the new fill placed for this project was within the zone of influence of the footing. This soft zone had an average "N" value of 8 blows per foot. The original 5.5 foot square footing was exposed and releveled, the space between the footing and the subgrade was grouted, and the footing was enlarged to a 12 foot square to prevent future excessive settlement and tilting.

The footing that ultimately settled nearly six inches under the primary dead load case near the southwest corner of the Mart structure demonstrated a suprising aspect of the jacking operation. During August 1980 when the attempt was being made to raise the column by jacking, the pier was actually forced into the ground about three times as much as the column was raised. Subsequent investigation showed that another previously undetected soft zone having an average "N" value of 8 blows per foot was present within the zone of influence of the footing. This soft zone was present within the old fill placed during the grading for the original mall development many years prior to this project. However, this soft zone did not entirely explain the behavior observed during jacking. Consequently, the hydraulic jacks were calibrated and load data was subsequently obtained for several columns during jacking. It was found in some cases that the rigidity of the structural frame was actually imparting a load near the completion of jacking as much as 50 percent larger than the dead load. As a result of this discovery, measurements indicated that the footing that had settled nearly six inches had actually been preloaded to the anticipated full sustained dead and live loads. Tilting was not excessive and little additional loading was anticipated. Consequently, the column bolts for that footing were extended; however, no additional repairs were required. The jacking procedure was, therefore, revised to include load measurements and upper bounds as a percentage of column dead load during jacking.

Long Term Settlements

The most recent survey of the structure was made in May 1983 essentially 2-1/2 years after the primary dead load of the structure was in place. The pattern of the settlement data with time indicated that all movements were greater than 95% complete. The data indicated that total settlements ranged from 0 to 8-1/2 inches with a maximum differential settlement of about 6 inches occurring between adjacent column footings. The average footing settlement was 1 inch. The data showed that 65 percent of the settlements occured in the first six months during construction, 30 percent occurred during the next two years and the remainder thereafter

A definite pattern of settlements could be related to the engineered fill supporting the footings. Those footings supported only by the old engineered fill placed during the original site grading for the Mall settled a maximum of 2-1/2 inches and an average of 1/2 inch. None of these footings settled more than predicted and, thus, the parameters and procedures used t predict settlements of those footings agreed well with the upper limits of the observed movements.

The footings supported by the new engineered fill placed for this project which also had an average "N" value of 18 blows per foot settled significantly more than those supported by the old fill. The average settlement of the 28 footings supported by new fill (exclusive of th two footings over "soft zones" in the old and new fill) was about 3 inches and the range was to 6-1/2 inches. The ratios of the observed to the predicted settlements for those footings ranged from 0.5 to 3. Thus, the new fill was considerably more compressible than the old fil and the parameters used in the settlement estimates were unconservative for the new fill. Figure 3 shows the frequency distribution of th ratio of the observed to predicted settlements for all of the footings.

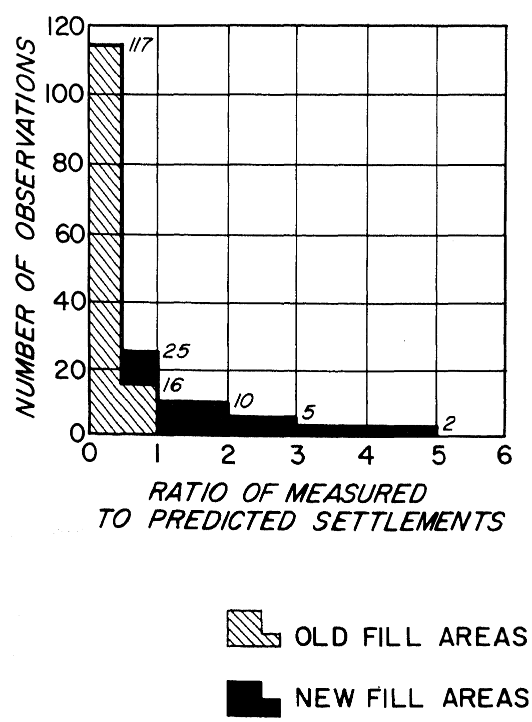

Fig. 3 Frequency Distribution of Ratio of Measured to Predicted Settlements.

CONCLUSIONS

The project described herein typifies the difficulties inherent in predicting movements for foundations supported by mixed soil and rock engineered fills. The foundation settlement data showed that some structural distress would have been likely had this type of structure been built on conventional spread footings with no means of adjustment. The approach and parameters used to estimate settlements for the old fill were reasonably reliable; however, random soft areas precluded total faith in the predictions. Random soft zones could possibly have been detected and corrected in advance; however, this would have required drilling and sampling each foundation location.

The method of column adjustment used to prevent excessive differential settlement of the structure worked well and maintained the structure within the established tolerable column settlement criteria. It permitted the use of shallow foundations with design gross bearing pressures of 8 kips per square foot. It also permitted timely site grading of mixed cohesive soil and rock fill during wet winter conditions. This approach was conservatively estimated to have saved $250,000 in foundation costs on this project.

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