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Slurry Trench Wall Replaces Structure Underpinning

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SYNOPSIS Construction of the Charles Center Station of the Baltimore Metro required a cut-and-cover excavation 66 feet (20 m) deep in a major street in the central business district of Baltimore, Maryland. Several high-rise buildings were so close to the excavation that it was necessary to remove portions of the spread footing foundations which extended into the proposed station excavation. The contract documents required that the spread footings adjacent to the excavation be underpinned using steel pipe piles jacked to end bearing on bedrock. When it was apparent that difficulties in installation would result in substantial delays in project completion, the piles were deleted and a redesigned concrete slurry trench wall was constructed to confine the soil beneath the adjacent building foundations. Instrumentation data and visual observations indicated that the concrete slurry trench wall was successful in controlling settlement of the adjacent buildings to acceptable limits.

INTRODUCTION

Underpinning of building foundations located adjacent to deep open cut excavations is often accomplished by the installation of piles jacked to bearing on suitable material below the bottom of the excavations. Such a procedure was proposed on the Baltimore (Maryland) Region Rapid Transit System (Metro) to support high-rise commercial buildings located adjacent to the excavation required for construction of the Charles Center Station.

However, when construction began, it soon became evident that installation of the contract-specified piles would be a difficult, slow and costly operation. It was decided, therefore, to eliminate the installation of piles beneath the spread footing foundations of the adjacent buildings, and to construct a support of excavation system consisting of a concrete slurry trench wall which would be sufficiently rigid to limit foundation settlement to acceptable values.

This paper describes the construction of the concrete slurry trench wall which was used to replace the originally proposed pile underpinning. Data from an extensive geotechnical monitoring program are presented to indicate that the concrete slurry trench wall successfully confined the soil beneath the spread footing foundations so that the settlements which occurred were less than or approximately equal to the anticipated settlements which would have occurred had the originally conceived pile underpinning been employed.

THE PROJECT

The Maryland Mass Transit Administration completed construction of Phase I, Section A of the Baltimore Metro in November, 1983. Phase I, Section A consists of a dual track rapid transit line approximately 8 miles (12.8 km) in length, half of which, in the central area of Baltimore, is underground with the remaining half either at-grade or on structure above ground. Figure 1 indicates the alignment of

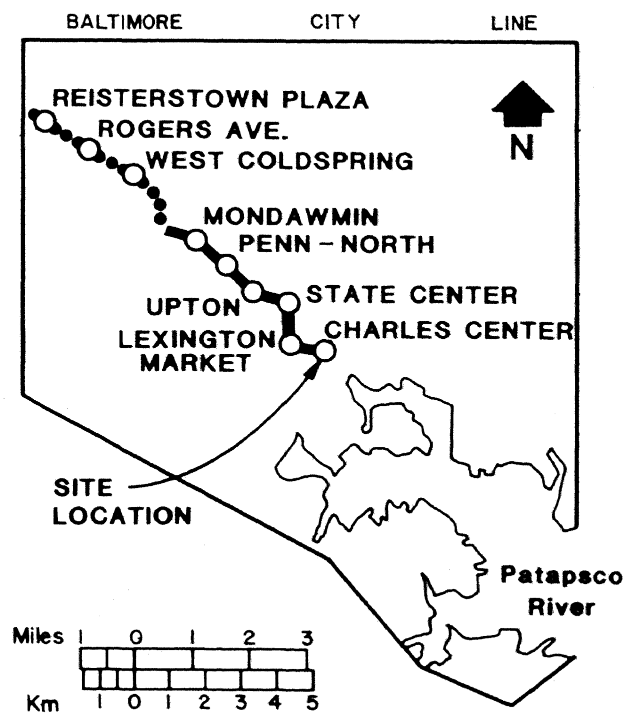

Figure 1. Location Plan showing alignment of Section A of Baltimore Metro.

the project with the underground portion indicated by the solid line and the above ground portion indicated by the dotted line.

The Charles Center Station is the terminus of the Baltimore Metro in the central business district. Construction of the Charles Center Station required making an excavation 66 feet (20 m) deep and approximately 920 feet (280 m) long in Baltimore Street, a major east-west street and the location of the City's principal shopping and financial district. The 60-foot (18-m) width of the station structure required the excavation to extend virtually from face to face of the buildings situated on the north and south sides of Baltimore Street. These buildings include two hotels and several high-rise office buildings, the most prominent being the 34-story Maryland National Bank, a Baltimore landmark. Figure 2 is a photograph looking east along Baltimore Street showing the street as it appeared during the initial phase of construction of the Charles Center Station. Because of the requirement that traffic be maintained on Baltimore Street during the construction period, it was a contract specification that the excavation be decked over for its complete length and width.

Bids for construction of the Charles Center Station were received on June 9, 1977, the low bidder being Intercounty Construction Corporation of Hyattsville, Maryland in the amount of $32 Million. Notice to proceed was issued on January 3, 1978 followed by the beginning of work on utility relocations and underpinning of the front footings of seven of the principal buildings adjacent to the proposed excavation. It quickly became evident that the installation of the underpinning piles would be extremely difficult, and in June, 1978 underpinning of the spread footing foundations by the jacking of piles to end bearing on rock was stopped, except at the Hilton Hotel, where the installation of the planned 12 piles was later completed. The decision was made at that time to delete the pile underpinning from six of the seven buildings and to redesign the originally planned concrete slurry trench wall so as to increase its strength and rigidity. Installation of the redesigned concrete slurry trench wall commenced in February, 1979, at the east end of the excavation and, proceeding westward, was completed in February, 1980. Station excavation of the planned 182,000 cubic yards (138,000 cubic meters) of soil followed construction of the slurry trench wall, and was completed in January, 1981. Construction of the concrete station was completed in the Summer of 1982, followed by backfilling over the top of the Station and replacement of utilities and the permanent street pavement.

Figure 2. View looking east along Baltimore Street during construction of Charles Center Metro Station.

SUBSURFACE CONDITIONS

The Charles Center Station is situated approximately 2.5 miles (4.0 km) southeast of the boundary of the Coastal Plain Physiographic Province with the Piedmont Physiographic Province. This boundary is generally coincident with the northwest limit of the unindurated Cretaceous sediments which overlie the residual materials and rock of the Piedmont Province.

At the Station site, the sedimentary soils are primarily silty sand and gravel, encountered to depths below street level ranging from 48 to 60 feet (14 to 18 m). Ground water was encountered at an average depth of about 33 feet (10 m). Standard Penetation "N" values in the granular deposits were generally 100 blows over less than 6 inches of sampler penetration.

The Cretaceous deposits overlie a 30-foot (9 m) average thickness of residual materials transitional between soil and rock. These materials were derived from in-situ decomposition of the parent rock and are typically described as ranging from very hard, cohesive soil-like material to partially decomposed rock. The more soil-like materials were generally penetrated by soil sampling techniques with "N" values ranging from 17 to more than 100 blows per foot of sampler penetration. The base of the transitional zone consists of a thin layer of more rock-like materials which requires coring for sampling.

The underlying parent rock was encountered at depths below street level ranging from 75 to 100 feet (23 to 30 m). The parent rock at the Station site is undifferentiated crystalline rock of suspected Cambrian age, commonly classified as interlayered gneiss and amphibolite. This rock, when relatively unweathered, is capable of safely supporting design loads of more than 100 tons per square foot (9.6 MPa) with negligible settlement.

SUPPORT OF EXCAVATION AND ADJACENT BUILDINGS

Underpinning

As originally required by the contract documents, the support of excavation system was to consist of concrete slurry trench walls braced by struts extending across the excavation along approximately two-thirds of the length of the excavation, with the remainder of the cut retained by predrilled soldier piles, timber lagging, and internal bracing. The contractor had the complete responsibility for design of the system, which was specified to be supplemented by underpinning the front row of footings of the major buildings located adjacent to the cut-and-cover excavation. The specified method for underpinning these footings was to jack steel pipe piles from beneath the spread footing foundations to bedrock or, in the case of the Hilton Hotel, to specified tip elevations below the bottom of the Station excavation, not necessarily to bedrock. The pipe piles were 12 3/4 inches (324 mm) in outside diameter with a wall thickness of 1/2 inch (13 mm), and, when installed to bedrock and filled with 4000 psi (28 MPa) concrete, would develop design load capacities of as much as 100 tons (890 kN).

The seven structures that were specified to be underpinned are shown in Figure 3. All seven of these structures were founded on spread footings on silty sand and gravel with a maximum soil loading of 4.0 tons per square foot (0.38 MPa) except at the B&O Railroad Building where the maximum applied unit loading was 6.0 tons per square foot (0.58 MPa). Underpinning of the front row of footings of these structures was to be accomplished by jacking a total of 277 pipe piles to the bedrock surface, with the number of piles beneath each footing being a function of the total column load. The spread footings of the seven buildings were located at depths below street level ranging from 11 feet (3.4 m) at 101 East Baltimore Street to 33 feet (10 m) at the Maryland National Bank. After underpinning pits were excavated and braced by timber lagging, as many as 13 piles were to be installed beneath each footing in 4-foot (1.2 m) lengths through the sedimentary and residual soils and the decomposed rock to bedrock capable of safely supporting bearing pressures of as much as 113 tons per square foot (10.9 MPa).

Despite the extremely dense nature of the granular soils and the presence of cobbles, jacking the steel pipe piles was considered by the Final Designer to be a practical approach to underpinning, although progress was anticipated to be slow. The high cohesive strength of the residual soils also impeded progress, but the most serious impact was caused by difficulties in advancing the piles through the thin layer of decomposed rock overlying the relatively unweathered bedrock. The piles could penetrate the decomposed rock only after the inside of the pile was excavated and the hole advanced below the pile tip by a drop-hammer churn bit.

At a very early stage of the underpinning, with only about 3 percent of the piles installed, the contractor indicated that his progress was considerably slower than the construction schedule provided for, and that installation of the underpinning as designed would result in substantial cost overruns and delay in completion of the project.

Slurry Trench Walls

The Mass Tansit Administration acknowledged the contractor's difficulties, and initiated the design of a modified support of excavation system which would substitute for underpinning piles specified to extend to bedrock. The underpinning of the Hilton Hotel was to be performed as originally required. A joint effort on the part of the General Consultant, Final Designer, Construction Manager, and Administration resulted in a redesign of the originally planned concrete slurry trench

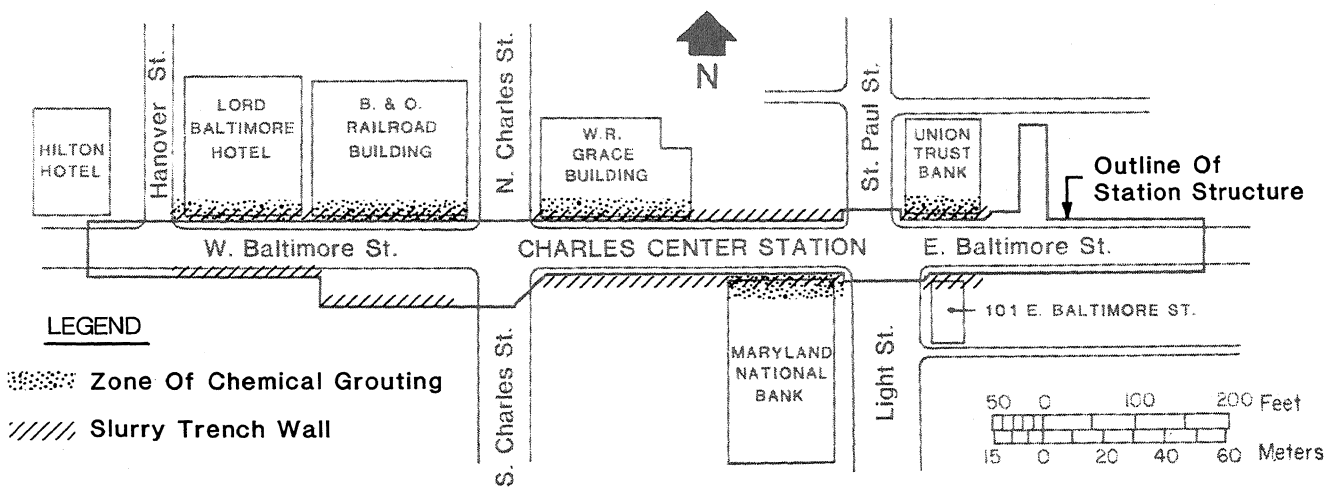

Figure 3. Charles Center Station Site Plan, showing limits of chemical grouting and slurry trench walls.

walls. The redesign would provide an excavation support system sufficiently rigid to minimize lateral deflections and consequent settlement of the adjacent spread footing foundations. This system included 24-inch (610-mm) thick concrete slurry trench walls, reinforced with embedded steel H piles, with internal bracing concentrated at the locations of lateral surcharge loads caused by spread footing bearing pressures. It was estimated that this system would limit structural settlements during construction of the cut-and-cover station to amounts that could have been anticipated had the structural underpinning been employed in conjunction with the contract required concrete slurry trench wall support of excavation.

There were four variations in the redesigned concrete slurry trench wall, all of which were to be excavated to 5 feet (1.5 m) below the bottom of the Station structure. The section used for the majority of the total 1500-foot (460-m) length of concrete slurry trench wall consisted of 8-foot (2.4-m) wall panels excavated between primary soldier piles predrilled to 10 feet (3 m) below the Station foundation, with intermediate piles installed midway between the primary piles. This same design section, but without the intermediate pile, was used over very limited lengths at one cross-street intersection. A 12-foot (3.6-m) panel length was used at three locations, totaling a wall length of approximately 450 feet (140 m), with all piles set 4 feet (1.2 m) center-to-center in the excavated slurry trench. The fourth slurry wall design section was used for a continuous wall length of 146 feet (45 m), with all piles also installed at 4 feet (1.2 m) on centers in the slurry trench panels excavated in 8-foot (2.4-m) lengths. Not all of the excavation was supported by slurry trench walls, as the easternmost 225-foot (70-m) length of the excavation, the end walls, and cross-street intersections were retained by soldier piles and timber lagging (see Figure 3).

Figure 4 is a cross-section through the excavation showing the support of excavation system as installed and the stratification of the materials at the project site. Reference to this figure shows that at the location of the Maryland National Bank, there were six strut levels, counting the deck beam as the top strut level. At this location a portion of the spread footing foundation of the bank building was removed, since it extended into the space to be occupied by the support of excavation system and the Metro Station.

Grouting

The width of the subway station, with respect to the distance between buildings along Baltimore Street, was such that in a number of cases the spread footing foundations of major buildings extended into the area to be occupied by the concrete slurry trench wall and the Station excavation. Therefore, prior to excavating the trench for the concrete slurry trench wall, it was necessary to cut off as much as 24.9 percent of the spread footing foundations supporting the front column line

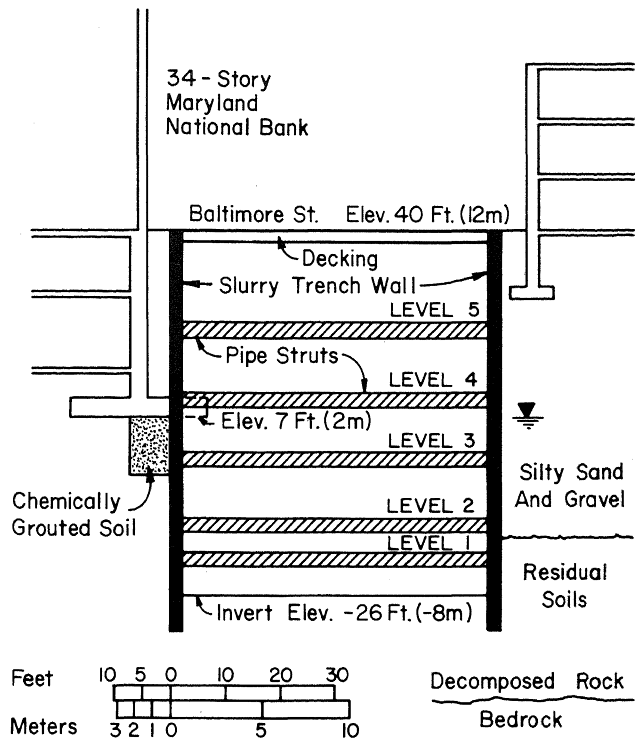

Figure 4. Section through the Station excavation at the Maryland National Bank.

of five of the buildings originally specified to be underpinned. These buildings included the Union Trust Bank, the Maryland National Bank, the W. R. Grace Building, the B&O Railroad Building, and the Lord Baltimore Hotel (see Figure 3). The bentonite slurry used as trench backfill during excavation was not considered to be solely able to prevent loss of ground caused by the action of the excavator bucket or by sloughing of the granular soils subject to bearing pressures as high as 6 tons per square foot (580 kPa). Therefore, prior to slurry trench excavation, the granular soil adjacent to the Station walls to depths of 10 to 15 feet (3 to 4.5 m) below the footings of the five buildings was stabilized by chemical grouting using a sodium silicate grout. The desired effect of the grouting was to impart to the sands and gravel a cohesion of 50 to 100 pounds per square inch (350 to 700 kPa).

The construction sequence first involved excavating to the tops of the spread footings so that grout pipes could be installed through the footings, except at the Union Trust Bank, where utility ducts and manholes prohibited access to the footings. At Union Trust, all drilling and grouting operations were performed from street level. Otherwise, after excavating to the top of each footing, 3-inch (75-mm) diameter holes were drilled through and adjacent to the building footings to a minimum of 10 feet (3 m) except 15 feet (4.5 m) at the W. R. Grace Building, below the bottoms of the footings. The holes were spaced 4 to 5 feet (1.2 to 1.5 m) apart along the lengths of the buildings adjacent to the Station, except at the Union Trust Bank where the grouting effort was more concentrated at the individual footings. Also at Union Trust, grouting was performed to a depth of 40 feet (12 m) below the footings at the southwest corner of the building where soldier piles and slurry wall could not be installed due to utility obstructions. The grout holes were generally inclined under the buildings to obtain the desired shape of the grout zone. Sodium silicate (Geloc-3) grout was injected through sleeved ports in 1.5-inch (38-mm) diameter PVC pipe under a pressure of 35 psi (240 kPa) at 1.5-to 2.0-foot (0.45- to 0.6-m) vertical intervals. Primary and secondary phases of grouting were effected through the use of a packer to close off every second sleeved port, thereby alternating grout intervals, beginning at the bottom of the hole. At completion of the grouting, the footings were cut off as necessary and the excavated soil above the footings was backfilled to street level so that the cast-in-place concrete slurry trench wall could be installed from street level.

Grout takes were estimated based on approximately 25 percent of the soil volume being groutable voids. The total grout take for the five buildings was approximately 79,000 gallons (300 kl), or about 78 percent of the estimated volume of 101,000 gallons (383 kl). Expressed as a percentage of the estimated takes, the actual pumped volumes ranged from 72 percent (B&O Railroad Building) to 109 percent (Union Trust Bank).

INSTRUMENTATION

An extensive program of contractor-installed instrumentation was specified by the contract documents to monitor movements of the support of excavation system, the adjacent building structures, and the affected soil mass, as well as to measure the stress in the pipe struts. The locations of the instrumentation are shown in Figure 5.

Lateral deflections of the support system were monitored by inclinometer casings affixed to soldier piles. Each slotted PVC casing was set and grouted inside a steel outer casing which had been welded to a soldier pile before the pile was placed in the slurry trench. In some cases, the PVC casings were advanced below the pile tips to an estimated 5 feet (1.5 m) above the top or rock by predrilling from inside the outer casing. Twenty-two inclinometer casings were installed to typical depths of 20 to 30 feet (6 to 9 m) below the bottom of the excavation, concentrated at the locations of the major buildings.

The compressive loads on the steel pipe struts supporting the walls of the excavation were measured at 13 vertical sections using vibrating wire strain gauges. A total of 40 struts were monitored by installing the gauges on the top, bottom, and each side of the pipe at locations a minimum of 6 pipe diameters from the end of the pipe.

The buildings adjacent to the Station excavation were monitored for settlement by survey measurement of points installed on the exterior walls at 25-foot (7.6-m) intervals and on interior columns located within 75 feet (23 m) of the subway structure. Surface settlement points were also installed on the sidewalk and street pavements at distances of as much as 150 feet (46 m) from the Station. Four subsurface settlement gauges were installed to monitor settlement of the soil adjacent to the excavation at a depth of about 45 feet (14 m) below street level.

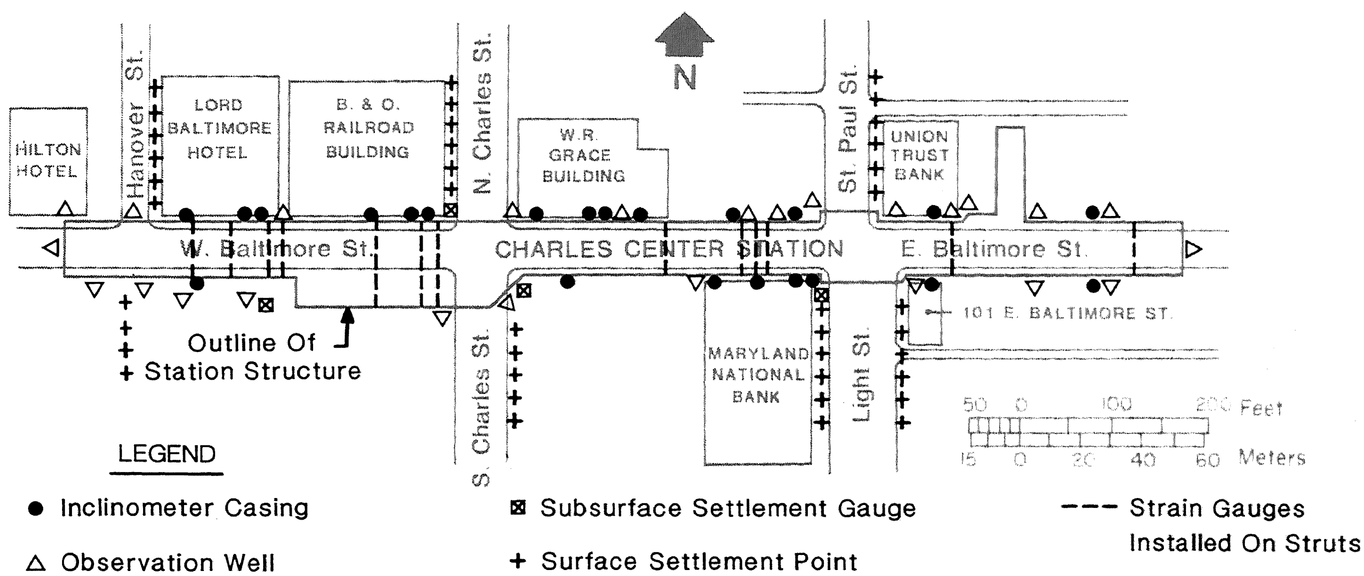

Figure 5. Charles Center Station Site Plan showing locations of instrumentation.

A total of 25 observation wells were included to monitor changes in groundwater levels adjacent to the excavation.

The contract documents specified the installation of 14 heave gauges to monitor the vertical deflection of the bottom of the excavation. However, the Contractor's difficulties in installing and maintaining these instruments in good working order resulted in an unsuccessful monitoring effort, suggesting that the installation of heave gauges under these excavation conditions was impractical.

Detailed visual observation of existing minor cracks on the exterior and interior walls of the major buildings was performed on a regular basis. It was believed that settlement-induced stresses would first be reflected in the lengthening or widening of existing cracks and development of new cracks at points of suspected structural weakness.

All monitoring of the instrumentaiton, analysis of the data, and visual observations were performed by construction management personnel from firms retained by the Mass Transit Administration.

INSTRUMENTATION RESULTS

At the time of the deletion of the underpinning piles and redesign of the support of excavation, it was estimated that building settlements after completion of underpinning and construction of the Station would have been on the order of 1/2 inch (13 mm). If reinforced slurry trench walls were to be an effective substitute for jacked pile underpinning, building settlements should likewise have been limited to approximately the same settlement. The performance of the modified support system is recorded by the results of instrumenting and monitoring the support components as well as the buildings and ground surface adjacent to the excavation. Data obtained from the instrumentation monitoring are presented to indicate the horizontal movements which occurred in the concrete slurry trench wall support of excavation, the building settlements which occurred and the strut loads which developed. Results of visual observations made to detect evidence of structural or architectural damage are also presented.

Horizontal Movements

Since all inclinometer casings were installed inside a steel casing which had been welded to the soldier piles which were used as reinforcement in the concrete slurry trench wall, the horizontal deflection data obtained pertain only to movement of the concrete support of excavation system. The only exception to this statement is at the east end of the Metro Station where two inclinometer casings were attached to soldier piles in an area where the support of excavation consisted of soldier piles and timber lagging. All horizontal movement data reported herein are for movements in a direction perpendicular to the walls of the excavation.

Figure 6 presents results of the monitoring of an inclinometer casing located near the northeast corner of the Maryland National Bank. At this location the total depth of the excavation for the Metro Station was approximately 66 feet (20 m) measured from the street surface, and the bottoms of the footings for the Maryland National Bank are at a depth of approximately 33 feet (10 m).

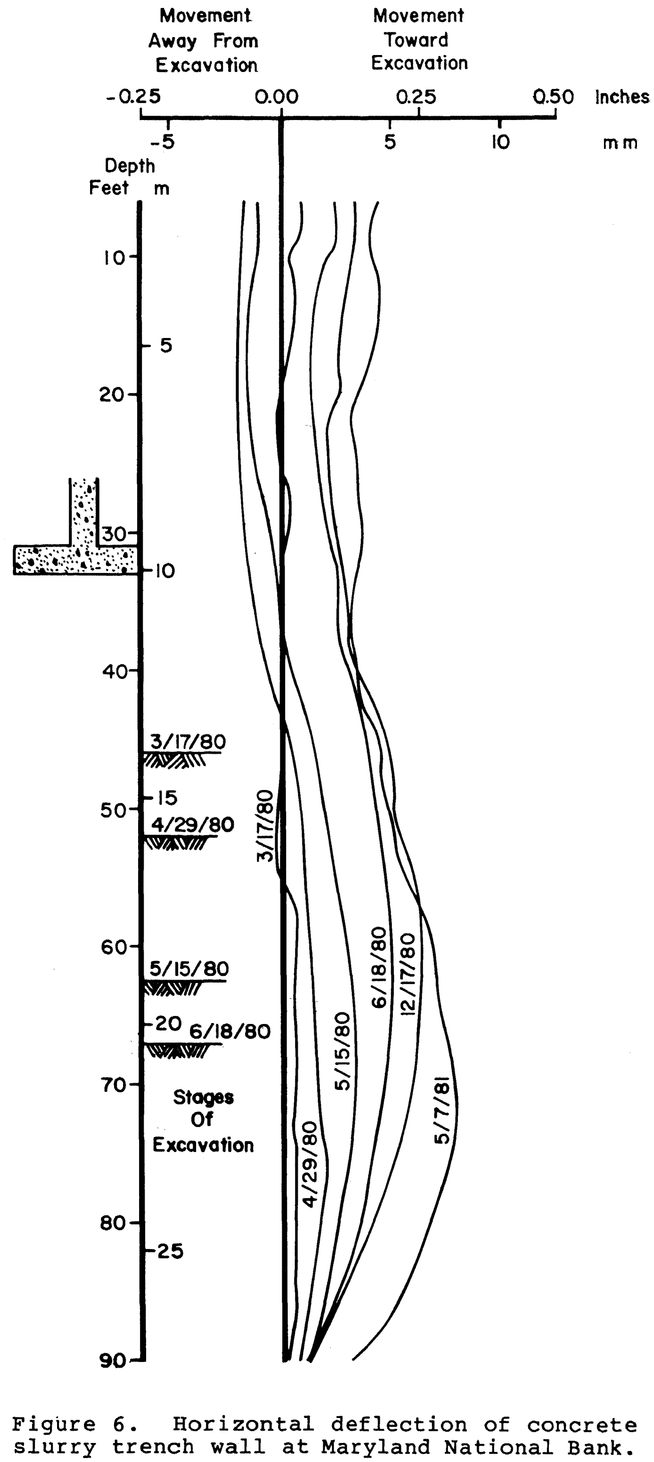

Figure 6. Horizontal deflection of concrete slurry trench wall at Maryland National Bank.

Reference to the figure indicates that deflection of the support of excavation system was negligible until the excavation was approximately 50 feet (15 m) deep at which time there was a slight outward movement of the top 40 feet (12 m) of the support of excavation. This slight outward movement of less than 0.1 inch (2.5 mm) is attributed to the presence of the backfill which had been placed in the excavation previously made to the top of the bank building footings to enable the footings to be cut off and the chemical grout to be placed. Below 40 feet (12 m) depth, the slurry trench wall had moved into the excavation less than 0.1 inch (2.5 mm), but the depth of movement was at least 26 feet (8 m) below the bottom of the excavation at that time.

As the excavation was deepened to its full depth of 66 feet (20 m), a general movement of the support of excavation into the excavation was recorded, with the maximum horizontal deflection being approximately at or slightly below the bottom of the excavation. However, the maximum horizontal deflection at this location was only slightly over 0.25 inch (6 mm). The settlement of the adjacent spread footing foundation was measured to be slightly over 0.4 inch (10 mm). The horizontal deflection of the support of excavation at this location and measured building settlement were typical of the deflections and settlements recorded elsewhere on the project except at the B&O Railroad Building.

Figure 7 presents the results of the monitoring of an inclinometer casing located near the southeast corner of the B&O Railroad Building. The data shown in this figure were selected to show the typical maximum horizontal deflections which occurred in the concrete slurry trench wall. At this location, the building settlement of 0.80 inches (20 mm) which occurred was greater than for any other of the major buildings whose spread footing foundations were supported by soil confined by the redesigned support of excavation system.

Excavation for the Metro Station began at the location of the B&O Railroad Building in August, 1980 and was completed on November 4, 1980. The dates of installation of the various struts are shown on Figure 7 so that the horizontal deflection of the support of excavation at various times can be related to the depth of excavation as indicated by the installation of struts at various levels. At the approximate time that the bottom of the excavation was reached (November 4, 1980), the maximum inward deflection of the support of excavation was 0.4 inches (10 mm) at a depth approximately 10 feet (3 m) above the bottom of the excavation, as indicated by the monitoring of November 3, 1980. Inward deflection of the support of excavation continued, however, and approximately six weeks later on December 16, 1980 the maximum inward deflection had increased to 0.6 inches (15 mm). Horizontal deflections after this date which were associated with removal of the struts and construction of the Metro Station were minimal. Similar to the deflections indicated by the inclinometer casing at the Maryland National Bank, there was appreciable

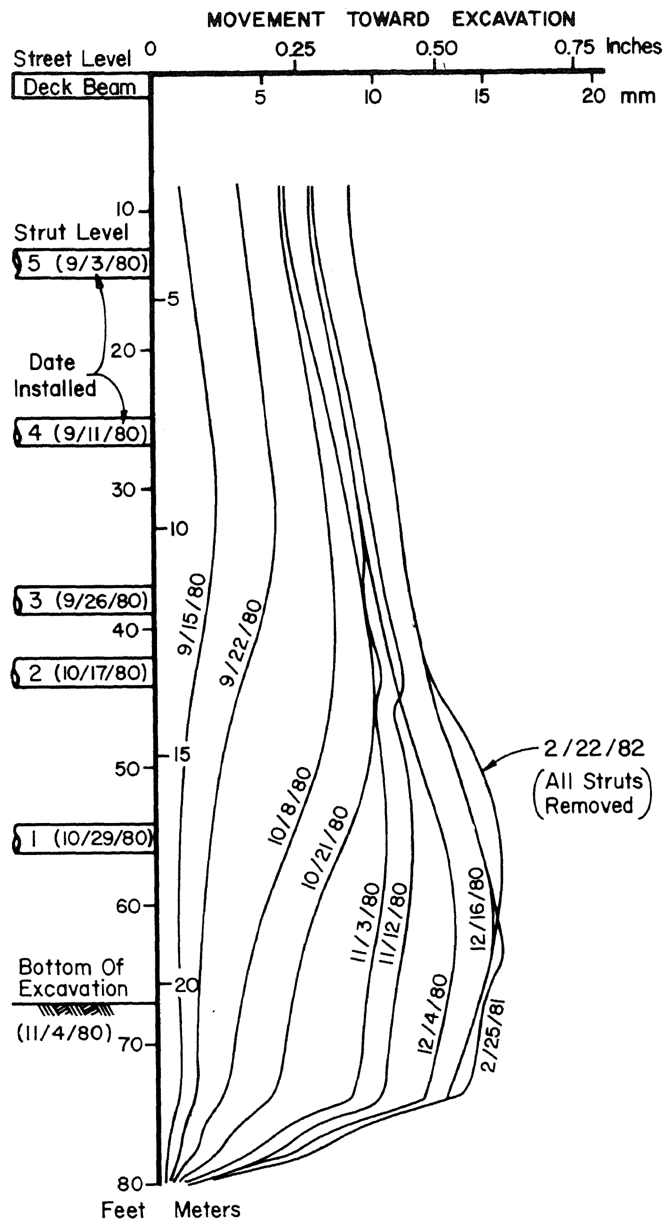

Figure 7. Horizontal deflection of concrete slurry trench wall at B&O Railroad Building.

deflection of the support of excavation system to the bottom of the inclinometer casing at approximately 13 feet (4 m) below the bottom of the excavation. As has been indicated previously, the building settlement which occurred at the approximate location of this inclinometer casing was 0.80 inches (20 mm).

Strut Loads

Vibrating wire strain gauges were installed on selected struts to measure strut loads during and following Station excavation. To obtain a complete loading history for certain vertical sections the strain gauges were intended to be installed on the pipe struts prior to their installation in the support of excavation system. However, gauges were occasionally installed on additional struts, as supplements to those gauges originally installed, and only changes in loading on those struts could be monitored.

Of the total of 40 struts monitored during the course of excavation and construction, 26 were instrumented prior to installation, enabling the determination of the preload stress jacked into the strut during erection. Preload stresses were measured to range from 16 to 60 percent of the design load, averaging 33 percent. This value should be compared with a specified preload of 50 perent of design load. The results of strain gauge monitoring of struts at the B&O Railroad Building are shown in Figure 8 and are fairly typical for this project. Following preloading, the general pattern of load development on the struts was an initial decrease in loading due to preloading of adjacent struts and relaxation of steel bracing members, followed by a fairly constant increase in load with increasing depth of the excavation. Loads generally continued to increase by approximately 25 percent over a period of about 6 weeks after excavation was complete. Maximum loads measured on the struts ranged from only 24 to 150 percent of the design load, averaging 69 percent.

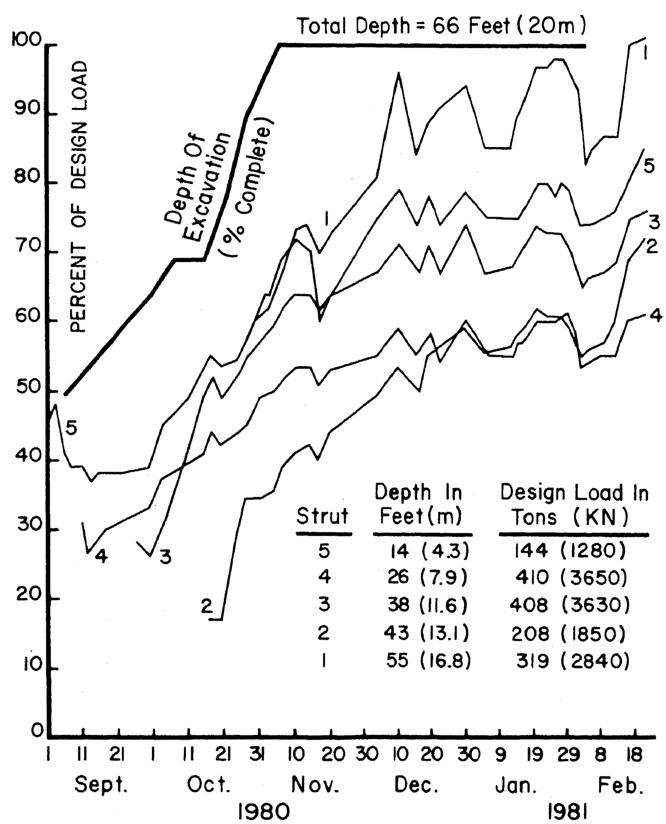

Figure 8. Development of strut loads at the B&O Railroad Building.

The lateral pressures to be used in the design of temporary earth retaining structures were provided in the contract drawings. These pressures were based on a rectangular distribution of 100 percent of full-depth active earth pressure combined with a triangular distribution of groundwater hydrostatic pressure. The total lateral pressure at invert level of the excavation was estimated to be as much as 4000 pounds per square foot (200 kPa). The average measured value of only 69 percent of the design loads in the monitored struts indicated that, assuming development of full hydrostatic load, only 57 percent of the design earth pressures were developed. This average value of 57 percent can also be derived by computing the average maximum loads (as a percentage of design load) in struts above groundwater level. This determination of lateral loads correlates well with a factor of 65 percent of full depth active earth pressure suggested by Terzaghi and Peck (1967).

The elastic compression of the monitored pipe struts between the time when the struts were preloaded and when the maximum load had developed resulted in shortening averaging about 0.1 inch (2.5 mm). Specifying and obtaining a higher percentage of preloading, say 65 percent, would have virtually eliminated this source of lateral deflection and resultant building settlement.

Settlement

The satisfactory performance of the redesigned reinforced concrete slurry trench wall substituting for structure underpinning is best indicated by the results of settlement monitoring. Total settlements for portions of the major buildings adjacent to the Station excavation are shown in Table I. It can be seen that total settlement was consistently less than 0.75 inch (19 mm) except along the south wall of the B&O Railroad Building and at the southeast corner of the Hilton Hotel. Settlement of approximately 1 inch (25 mm) at the Hilton Hotel occurred where underpinning piles were installed to a specified tip elevation above the top of bedrock.

Settlement of the 34-story Maryland National Bank was of primary concern, considering its height, the high percentage of footing area removed by construction of the slurry trench wall, and its prominence as a Baltimore landmark. In the opinion of Maryland National Bank structural consultants, settlements greater than 0.5 inch (13 mm) would probably cause structural damage to the building. Figure 9 shows settlement of three portions of the Maryland National Bank related to time and construction activities for the adjacent Station. Settlement in response to cutting the footings by as much as 24.9 percent was fairly instantaneous. Installation of soldier piles and slurry trench wall and excavation for the Station did not result in any measurable settlement. Settlement of approximately 0.12 inches (3 mm) at the northeast corner of the building, while no settlement was measured at other monitoring locations, was monitored over a period of about 4 months after completion of excavation for the Station structure.

TABLE I Total Settlement of Major Buildings

Building	Total Settlement in Inches (mm)
Hilton Hotel	
Interior Wall	0.30 (7.6)
Southeast Corner	1.01 (25.7)
East Wall	0.49 (12.4)
Lord Baltimore Hotel	
Southwest Corner	0.55 (14.0)
South Wall (West Tower)	0.43 (10.9)
South Wall (East Tower)	0.70 (17.8)
Southeast Corner	0.55 (14.0)
B&O Railroad Building	
South Wall	0.80 (20.3)
East Wall	0.49 (12.4)
W. R. Grace Building	
South Wall	0.53 (13.5)
Southeast Corner	0.29 (7.4)
Maryland National Bank	
Northwest Corner	0.29 (7.4)
North Wall	0.35 (8.9)
Northeast Corner	0.42 (10.7)
East Wall	0.32 (8.1)
Union Trust Bank	
Southwest Corner	0.52 (13.2)
South Wall	0.64 (16.3)
101 E. Baltimore Street	Not Measurable

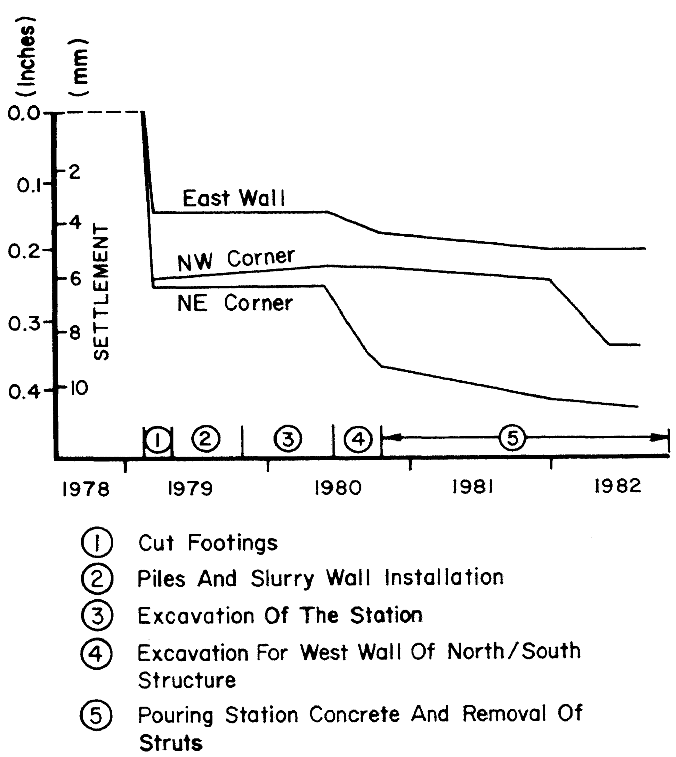

Figure 9. Settlements of portions of Maryland National Bank as related to time and construction activities.

This settlement was determined to be due to excavation for the concrete walls constructed below the Station proper for support of the future North/South Metro alignment at the intersection of Baltimore and Light Streets. These walls were excavated to bedrock which was encountered at a depth of approximately 42 feet (13 m) below the bottom of the Station excavation at the southern end of the west wall, adjacent to the bank building. Settlement, while pouring Station concrete and removing struts, was limited to 0.1 inch (2.5 mm), with maximum total settlement measured to be less than 0.5 inch (13 mm). The average settlement for the portion of the Maryland National Bank adjacent to the Station was 0.35 inches (8.9 mm), well within the value of 0.5 inches (13 mm) which, it was stated, would cause structural damage.

The pattern of settlement of the B&O Railroad Building related to construction activities is shown in Figure 10, which indicates the average settlement of the south side of the building (adjacent to the excavation) with respect to time and construction activity. As was observed at the Maryland National Bank, settlement in response to cutting off portions of certain spread footings was fairly

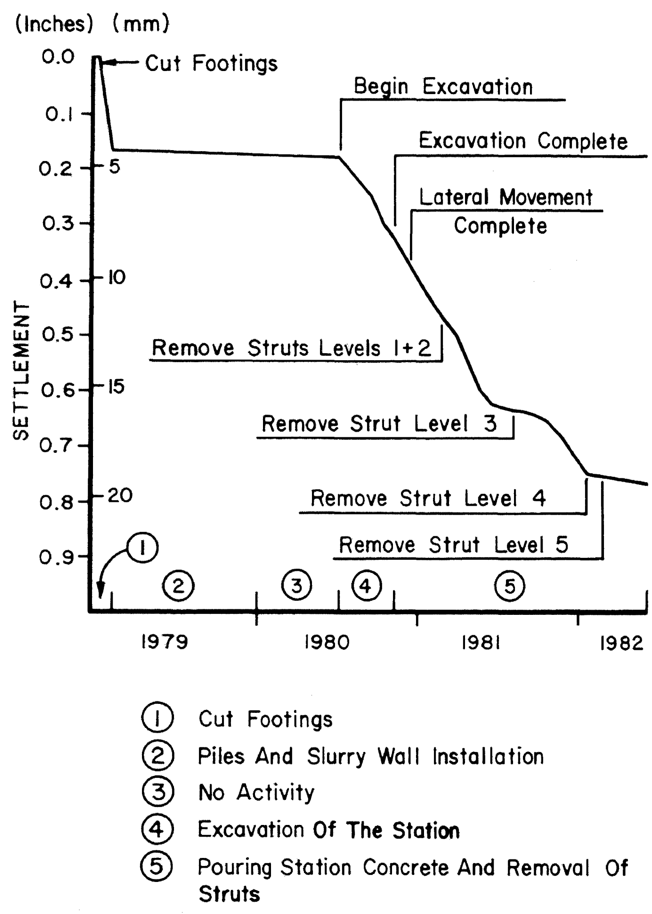

Figure 10. Average settlement on the south side of the B&O Railroad Building as related to time and construction activities.

instantaneous, with negligible settlement during soldier pile and slurry wall installation. Settlement increased rapidly in response to the initiation of excavation, and continued at a fairly constant rate well beyond when excavation was complete, at which time only 40 percent of the total settlement had occurred. Settlement increased by approximately 0.4 inch (10 mm), or 50 percent of the total, while pouring the Station concrete and removing struts. This settlement is apparently a delayed response to lateral deflections measured over a three-month period that extended six weeks beyond the completion of excavation. At the completion of the Station structure, settlement continued at a reduced rate until the backfill over the Station was placed and the street restored.

Visual Observations

During the entire period that construction of the Charles Center Metro Station was in progress, detailed visual observations were made of the interiors and exteriors of the buildings adjacent to the project for the purpose of detecting evidence of architectural or structural distress. Special attention was given to the seven major structures for which the contract documents required underpinning of the footings adjacent to the excavation.

Based on the detailed visual observations, it can be stated that no distress of any kind occurred for six of the seven buildings scheduled for underpinning. For the seventh building, the B&O Railroad Building, several barely noticeable "hairline" cracks occurred in the stone facing near sidewalk level on the east side of the building. The longest of these cracks was approximately 15 inches (0.38 m). Interior plaster walls of the B&O Railroad Building were in very poor condition prior to construction of the Metro Station, with many pre-existing cracks noticeable. Observation of these plaster walls indicated extension of several of the pre-existing cracks.

It is significant that no claims were filed by property owners as a result of damage caused by ground movement or settlement of buildings located adjacent to the project.

CONCLUSIONS

Based on the experience gained during construction of the Charles Center Metro Station in the central business district of Baltimore, Maryland, the following conclusions can be stated:

1. For the favorable subsurface conditions at the project site, underpinning of major high-rise buildings was not required. Settlement of spread footing foundations was successfully controlled to within acceptable limits through the use of a stiff support of excavation system which successfully confined the soil beneath the footings.

2. Horizontal deflection of the support of excavation and loads on the internal bracing continued to increase for as long as six weeks after completion of excavation, even in the predominantly granular soils.

3. Horizontal deflection was measurable to a total depth of 26 feet (8 m), or 40 percent of the total excavated depth, below the bottom of the Station excavation. This phenomenon suggests the need for extending inclinometer casings below the bottoms of deep excavations in soils to at least one-half of the depth excavated.

4. Preload stress levels in struts were measured to average only 33 percent, ranging from 16 to 60 percent, of the design load compared to a specified preload of 50 percent. Better control of applied preload stresses and the specifying of preload values of 65 percent of design load would result in reduction of horizontal deflections of the support of excavation.

5. Major high-rise structures with steel frames and masonry exteriors, such as the B&O Railroad Building, can sustain settlement of as much as 0.8 inch (20 mm) without incurring structural or significant architectural damage.

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