ASCE 1994 ANNUAL
CONVENTION & EXPOSITION

*"Civil Engineers—
Champions for the Global Environment"*

October 9-13, 1994 Atlanta, Georgia

TEMPORARY SHORING SUPPORT SYSTEMS IN AN URBAN ENVIRONMENT

by

Thomas C. Anderson
John E. Reinfurt
Paul Reitz
Tony Licari

MEETING REPRINT

TEMPORARY SHORING SUPPORT SYSTEMS IN AN URBAN ENVIRONMENT

by

John E. Reinfurt, P.E.[1]
Thomas C. Anderson, P.E.[2]
Paul Reitz, P.E.[3]
Tony Lican[4]

ABSTRACT

This paper describes the design, construction, and monitoring of a temporary shoring support system, which permitted the construction of two urban stations for the Metro Link St. Louis Light Rail System. The retention systems allowed 9.2m (30-ft.)-deep excavations adjacent to historic structures, Fortune 500 Corporate headquarters, and a large shopping mall.

[1] Manager, Geotechnical Section & Resident Engineer, Sverdrup Corporation
[2] Vice President, Schnabel Foundation Company
[3] Principal, Reitz & Jens, Inc.
[4] Project Manager, McCarthy Brothers Company

INTRODUCTION

The Metro Link St. Louis rail system is a 30km (18 mile)-long ($340 million) light rail transit system extending from East St. Louis, Illinois to the St. Louis International Airport in St. Louis County, Missouri. A segment of this alignment utilizes the existing unused Eighth Street tunnel to a portal near Busch Memorial Stadium. The twin horseshoe-shaped tunnel was constructed during the 1870's and was last used in 1974 for freight trains. Four new stations have been constructed along the Eighth Street tunnel alignment: at Laclede's Landing, St. Louis Centre Shopping Mall, Eighth and Pine Streets, and adjacent to Busch Memorial Stadium.

This paper focuses on the temporary support systems required for the construction of the St. Louis Centre and the Eighth and Pine Stations. The excavations are approximately 20m by 67m (65 ft. by 220 ft.) in plan area and 9.2m (30 ft.) deep. Adjacent to the stations were historic structures, Fortune 500 Corporate headquarters, and a large, four-story urban shopping mall. The loads from these structures would have to be transferred to an elevation below the subgrade of the excavation prior to construction of the stations or supported by the earth retention system itself. This would require a combination of drilled-in soldier beams, tiebacks, and hand-dug underpinning piers designed specifically to control the settlement of each structure. The construction of the two stations would require the installation of 105, 750mm (30 in.)-wide drilled-in soldier piles and 198, 140mm (5.5 in.)-diameter soil tiebacks. A plan depicting the alignment and the station locations is presented as Figure 1.

The design consultant specified an open specification for the design and installation of the shoring system, thus leaving the responsibility for the design with the contractor. This method of contracting allowed a firm lump-sum price and allowed the contractors to evaluate alternative methods of performing the work while maintaining the most economical approach.

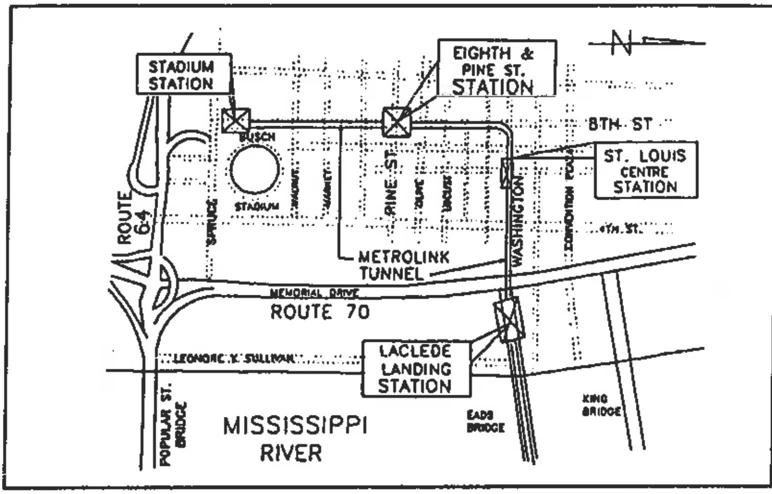

Figure 1. Plan of Alignment

PROJECT DESCRIPTION

St. Louis Centre Station

The St. Louis Centre Station is located beneath Washington Avenue at Sixth Street. There will be access to the station at Dillard's Department Store, St. Louis Centre Shopping Mall, and adjacent to the 555 Washington and Edison Brothers buildings. The station is approximately 16.8m by 62.5m (55 ft. by 205 ft.) in plan area and is founded on a flexible structural mat approximately 9.2m (30 ft.) below grade (El. 133.5m or 438 ft.). Figure 2 shows a plan of the station.

St. Louis Centre is a four-story, steel-framed structure connected to the Dillard's Building by a pedestrian bridge. The foundation for the bridge is H-piles driven to refusal on bedrock. Old building basements and foundations were backfilled to grade for the main structure. The portion of the structure closest to the excavation is supported on shallow spread footings.

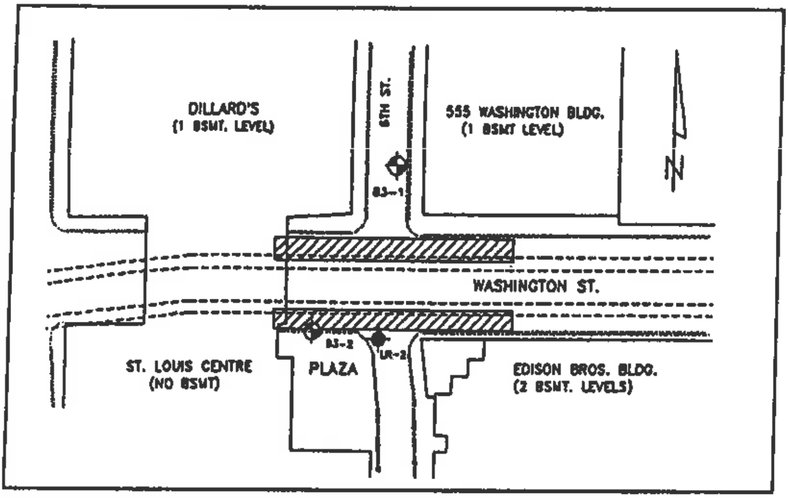

Figure 2. St. Louis Centre Station Plan

The Dillard's Building was built in stages between 1905 through 1948. The portion of the building closest to the excavation is a ten-story, steel-framed structure founded on stepped cast-in-place concrete (unreinforced) foundations. It is estimated the foundation pressures range from 190kPa to 290kPa (4ksf to 6ksf).

The 555 Washington Building was placed on the Register of National Historic Landmarks in 1983. None of the original drawings were available during design; but, from observations during rehabilitation in 1985 indicated that the five-story building is a steel and cast-iron framed structure with an Italian Renaissance facade. It is founded on stone spread footings just below basement level and the external foundation wall is a stacked limestone block wall.

The Edison Brothers headquarters is a steel-framed, masonry clad, 13-story structure constructed in 1983, and is founded on H-piles driven to bedrock. This building contains a two-story, below-grade garage which extends to within 1.8m (6 ft.) of the bottom of the station excavation.

Eighth and Pine Station

The Eighth and Pine Station is located beneath Eighth Street between Pine and Chestnut Streets. The adjacent structures affected by construction of the station are the Laclede Gas Building, the Wright Building, the Wainwright State Office Complex, and the Southwestern Bell Data Center. This station is approximately 16.8m by 62.5m (55 ft. by 205 ft.) in plan area with an annex between the Laclede Gas Building and the Wainwright Building. This station is also founded on a flexible structural mat bearing approximately 9.2m (30 ft.) below grade (El. 132.0m or 433 ft.). Figure 3 presents a plan of the station and surrounding structures.

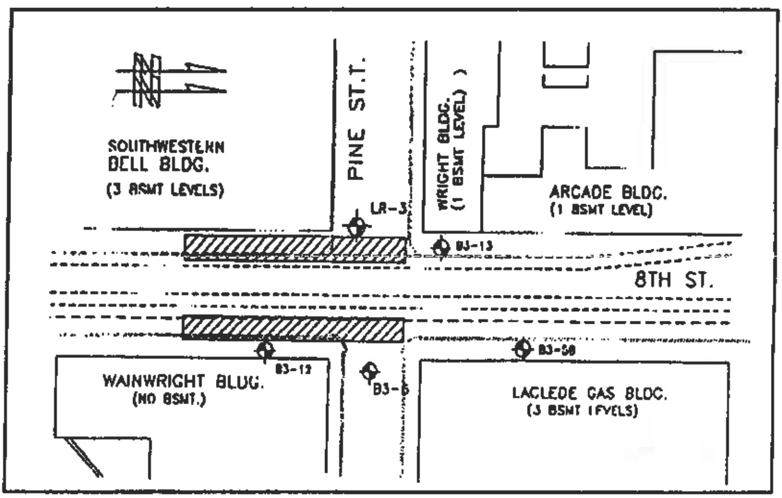

Figure 3. Plan of Eighth and Pine Station

The Laclede Gas Building is a L-shaped, steel-framed building which extends along the eastern side of Eighth Street between Olive and Pine Streets. The northern half of the building consists of a 34-story structure, while the southern half consists of a 15.5m (51 ft.)-high, two-story structure. The southern half has three underground parking garage levels. The two-story structure is supported on a 910mm (36 in.)-thick mat foundation bearing at

Elevation 132.6m or 435 ft. The foundation construction of this structure is documented by Jackson, et al. (1973).

The Wright Building is an 18-story office building with a single level basement constructed at the turn of the century. The building is supported on stepped, reinforced concrete spread footing foundations bearing approximately at Elevation 134.0m or 439.8 ft. The basement extends below the sidewalk and abuts the Eighth Street tunnel wall. The building is unoccupied.

The Wainwright State Office Complex comprised the old Wainwright Building, a nine-story structure on the corner of Seventh and Chestnut Streets, built around 1890 and the three-story, steel-framed and brick veneer Wainwright Building Annex built in 1981. The three-story structure is founded on shallow spread footings approximately 1.5m (5 ft.) below surface grade and immediately abuts the excavation.

The Southwestern Bell Data System was under construction while this station was being shored and excavated. The building is a nine-story, steel-framed, marble-clad structure. The building is founded on H-piles driven to bedrock. A station entry was constructed by the building owners within their building. The station will abut the below grade foundation walls.

REGIONAL AND SITE GEOLOGY

The geology of the Metro Link St. Louis Rail System alignment through downtown St. Louis is characterized by sections of fill material, eolian deposits, glacial deposits and Mississippian Age Limestone.

The fill materials are the result of backfill operations performed during construction of the Eighth Street tunnel, installation of utilities and the backfilling of adjacent building basements. Eolian deposits were identified immediately underlying the fill material that consisted of loessial silts that become clay-rich with depth.

The glacial deposits were found to immediately overlie the bedrock and generally consisted of a thick sequence of glaciofluvial/alluvial terrace deposits and glaciolacustrine deposits. These glacial deposits were generally formed by fluvial erosion and deposition of tills to the north of St. Louis.

The entire downtown St. Louis area is underlain by Middle Mississippian-aged St. Louis limestone. The St. Louis formation is finely crystalline, thin to massively bedded limestone containing thin interbeds of shale. A deep depression in the bedrock surface exists with the approximate depth of bedrock at 15m (50 ft.) and 30m (100 ft.) at St. Louis Centre and the Eighth and Pine Station, respectively.

SUBSURFACE CONDITIONS

St. Louis Centre Station

Test borings encountered three strata of soil deposits overlying the bedrock: clayey silt fill, loessial silts, and clayey silt and sand deposits of glacial origin.

The fill material consisted of soft to medium stiff silt with varying amounts of gravel, brick, rubble, and debris. Fill materials extended to approximately 6m (20 ft.) below grade and were underlain by loessial silt deposits of soft to medium stiff silt with little to some clay. These deposits extended to depths of 6.7m (22 ft.) to 11.0m (36 ft.) below street level.

Below the loessial deposits, a layer of glacial clayey silts and sand overlies bedrock. The depositional sequence consisted of an upper layer of bluish-gray, medium-stiff, clayey silt underlain by loose to medium dense fine sands, silty sands, and sandy silts, and a basal layer above bedrock of soft to medium stiff, gray clay or silt containing secondary amounts of fine sand.

Limestone bedrock was encountered at depths of 14.3m (47 ft.) (El. 127.4m or 418 ft.) to 17.7m (58 ft.) (El. 123.1m or 404 ft.) below street level. The rock surface was generally higher to the east and sloped downwards to the west. Ground water was approximately 7.0m (23 ft.) below ground level.

Eighth and Pine Station

Test borings at this location encountered an upper layer of soft, clayey silt fill with varying amounts of debris. Several borings penetrated old building rubble within an abandoned basement vault adjacent to the Laclede Gas Building.

The fill was underlain by eolian and glacial deposits. The medium-stiff eolian deposits consisted of slightly to medium plastic silts containing little clay. The eolian deposits extended to depths of 7.0m (23 ft.) (El. 134.7m or 442 ft.) to 9.5m (31 ft.) (El. 132.0m or 433 ft.) below street level, respectively. The underlying glacial deposits consisted of an upper 2.5m (8 ft.)- to 4.3m (14 ft.)-thick layer of medium to highly plastic clay and clayey silt extending to El. 129.5m or 425 ft.; a 1.5m (5 ft.)-thick layer of soft, sandy silt; dense to very dense fine sand to around El. 123.4m or 405 ft.; soft to medium stiff sandy silt extending to approximately El. 118.9m or 390 ft.; and a lower layer of soft to medium stiff, highly plastic silty clay.

St. Louis Limestone was encountered at depths of 24.4m (80 ft.) (El. 117.2m or 384.5 ft.) to 31.4m (103 ft.) (El. 109.9m or 360.5 ft.).

Two groundwater regimes were identified below the station location. An upper perched water level was encountered at around 6.7m (22 ft.) below ground level, approximately El. 134.4m or 441 ft. A second groundwater regime was encountered within a confined aquifer at El. 129.5m or 425 ft. and was believed to be effected by dewatering during construction of the adjacent Southwestern Bell Data Centre. Prior to construction of the Southwestern Bell project, water levels in observation wells were reported at El. 136.2m or 447 ft. and El. 132.0m or 433 ft. in the upper and lower groundwater regimes, respectively.

OPEN SPECIFICATION

An open specification was used for the earth retention system on this project. The scope, design, and installation of the earth retention systems were left entirely up to the contractor. The responsibility for the design was clearly placed upon the contractor, thus allowing maximum flexibility to choose the most appropriate system. With this type of specification approach, the expertise and experience of the specialty contractors could be used to the fullest to decide on the best means and methods of performing the work and also on the most appropriate earth pressure diagrams based not only on the soil conditions, but also their particular installation method.

On this project, the contractor was completely responsible for the design of the earth support and protection systems for the adjacent structures to ensure visual and structural integrity and safety. In addition, the contractor was required to establish structure displacement limits, which would ensure visual and structural integrity and safety of the adjacent buildings. Further, the specifications required extensive preconstruction surveys of all buildings within the zone of influence of the proposed construction, along with a comprehensive instrumentation program consisting of tiltmeters, inclinometers, crackmeters and survey readings to monitor displacements of the retention systems and affected structures. The required instrumentation system was designed to inform the contractor of movements in the vicinity of the earth support and protective systems, so that the contractor could modify his techniques to control displacements within the predefined limits. Finally, the contractor was responsible for restoration of the adjacent structures to a condition equivalent to that prior to the start of work.

SHORING SUPPORT SYSTEM

Philosophy

At the two station locations, there were several existing buildings supported on shallow footings. Where space permitted, the earth retention system was designed to support the earth pressures along with the surcharge loads from the existing footings. Along the west side of the Wainwright Building, there was insufficient space to construct an earth retention system and the proposed station wall. As a result, a combination underpinning and earth retention system was utilized.

Limiting the settlements and lateral movement of the earth retention systems, and the effects on the adjacent structures, was a major design requirement. Estimates of expected movements were made based on the types of earth retention systems considered and the soil conditions at the stations. The intended function of the earth retention system was to prevent structural damage to the adjacent structures, although some architectural (cosmetic) damage was expected.

Design

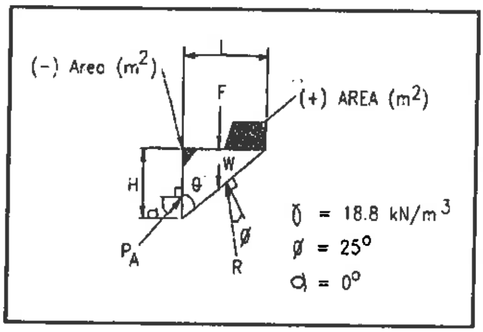

Figure 4. Critical Wedge Analysis

For the retention system design, a limit equilibrium trial wedge analysis was used (see Figure 4) in order to incorporate the effects of the adjacent footing loads [F] along with variation in grades and basement levels [(+) or (-) areas]. The critical Pa value was then divided by the exposed height of cut resulting in a uniform design pressure diagram. For these locations, drilled-in soldier beams consisting of double channel sections at typically 1.5m (5 ft.) to 1.8m (6 ft.) on center were designed. Wood lagging was used to support the earth between the vertical soldier beams. As a result of the marginal soil conditions, two rows of low-capacity tiebacks with design loads of 220kN to 310kN (50 to 70 kips) inclined at 15 to 20 degrees below horizontal were utilized. This also served to increase the stiffness of the earth retention system and thereby aid in controlling deflections.

The use of relatively flat tiebacks minimized the vertical load on the soldier beams, allowing a soldier beam toe embedment of 1.5m (5 ft.) to be used, which easily satisfied the toe lateral capacity requirements. Longer soldier beam toe embedments could have been a real problem, especially at the Eighth and Pine Street Station where water-bearing sands under an excess hydrostatic head were located at roughly 3.0m (10 ft.) below subgrade.

At the west side of the Wainwright Building, a pair of 0.9m (3 ft.) by 1.5m (5 ft.), hand-dug concrete underpinning piers with belled bases were designed to support the main exterior building footings that were roughly 2.0m (6.5 ft.) by 2.0m (6.5 ft.) in plan. Bracket piles were then designed to support the intermediate pedestal footing projections between the main building columns. These underpinning piers and bracket piles were supported by two rows of tiebacks (265kN to 310kN or 60 kips to 70 kips design loads). Wood lagging was used to support the earth between the piers and piles.

Figures 5 through 8 show typical sections at the St. Louis Centre, 555 Washington and Wainwright buildings on which the boring information and design pressure diagrams are plotted.

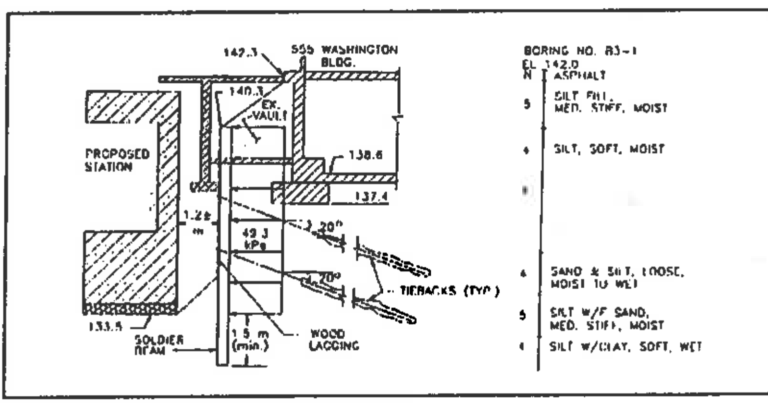

Figure 5. Section at 555 Washington Building

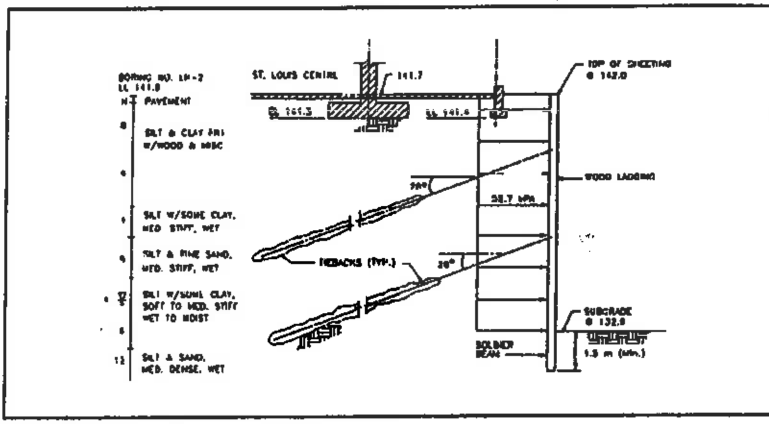

Figure 6. Section at St. Louis Centre

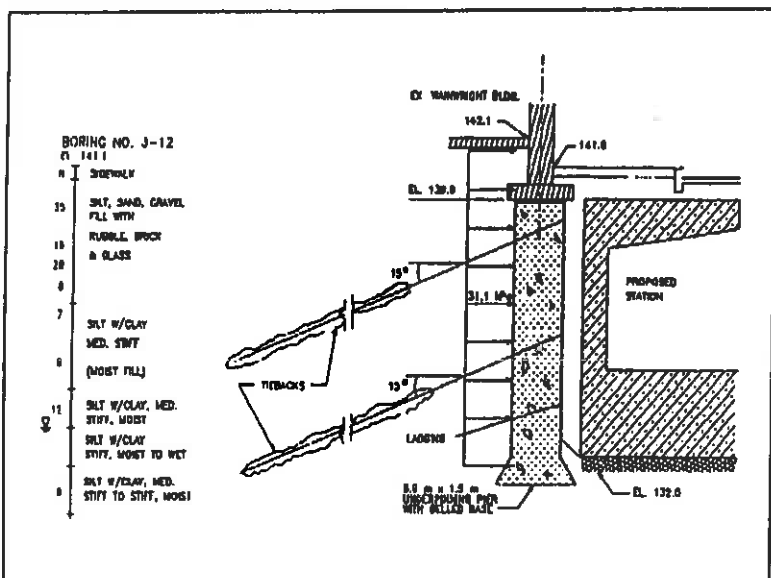

Figure 7. Section at Wainwright Building (west side)

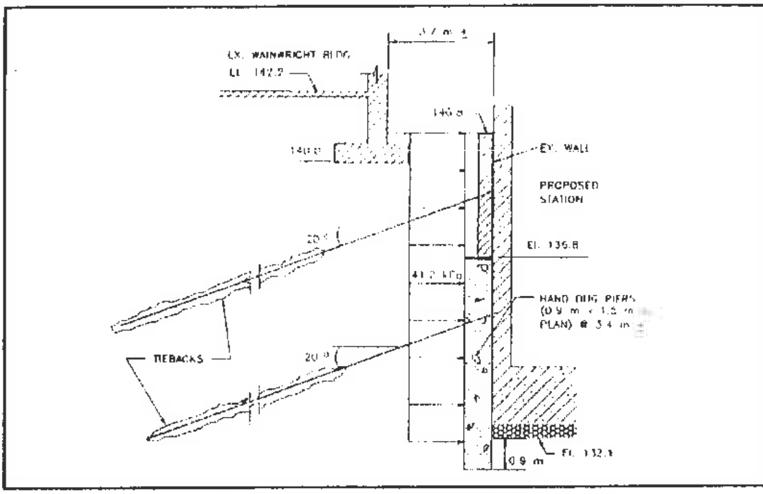

Figure 8. Section at Wainwright (north side)

The evaluation of settlements, resulting from the earth retention work, was based upon an assumed settlement profile of 0.3% to 0.5% of the maximum depth of excavation (Clough and O'Rourke, 1990) at the retention system, decreasing to zero at a distance equal to twice the depth of excavation (see Figure 9). Greater settlements were expected at the St. Louis Centre Station due to the soft to medium stiff consistency in comparison to the Eighth

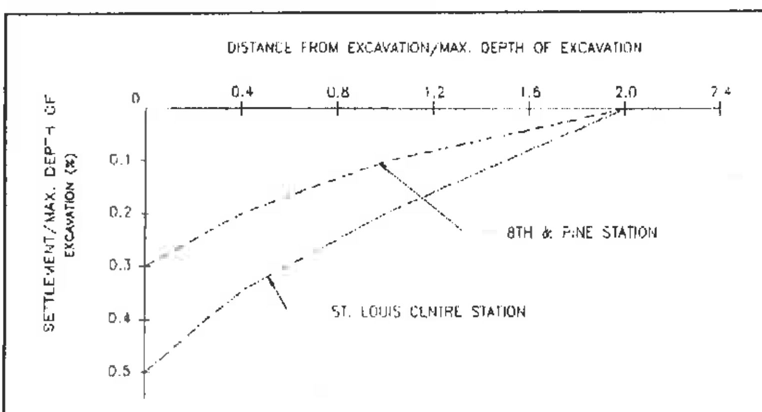

Figure 9. Estimated Settlement Profiles

and Pine Street Station where the soils typically had a consistency of medium stiff to stiff. Lateral displacement of the earth retention systems was expected to be of the same magnitude as the settlements. The anticipated settlements were utilized to copute the anticipated angular distortions between the exterior and first interior rows of columns of the various affected structures (see Table 1).

Table 1. Summary of Expected Values

Building	Settlement Exterior Column Line	Expected Angular Distortion
Wainwright Bldg.	20.0 mm±	0.0015±
St. Louis Centre	25.0 mm±	0.0017±
555 Washington Bldg.	12.5 mm±	0.0019±
Dillard Bldg.	6.5 mm±	0.0008±

Concerning the question of tolerable displacements for the structures adjacent to the station excavations, the consensus of published evidence suggests that the limiting value of angular distortion at the onset of visible damage for steel and concrete infill frame structures is 0.002 (References 3, 4, and 5). The above expected values of angular distortion for the various affected buildings are all below the 0.002 limiting value. However, it should be noted that the anticipated angular distortion values are only for that distortion related to the earth retention systems and do not include any effects of past differential settlements that these structures might have undergone.

Installation

The 750mm (30 in.)-diameter soldier beam holes were drilled with a truck-mounted Hughes LDH-80 rig. This turned out to be a wise decision because numerous uncharted old footings and walls were encountered which had to be cored. Double channel sections (2C12x20.7) were used for the soldier beams, with the sections set in the pre-drilled holes and backfilled with a lean concrete (one sack) mix.

The tiebacks were drilled through the 250mm (10 in.)-space between the double channels, thus eliminating the need for an external waler to connect the tiebacks to the soldier beams. A Krupp hydraulic track rig was utilized to drill and install the tiebacks. A 140mm (5.5 in.) O.D. casing was advanced by rotary percussive means to the required depths. This drilling method eliminated the problem of caving of the drill holes beneath the existing buildings, which could lead to settlements, and also was capable of penetrating the obstructions that were encountered. Once the holes were advanced to the required depths, the holes were tremie grouted and a strand tendon, with a regroutable tube attached, was inserted. The drill casing was then removed. In order to increase the capacity in the marginal soils, the tiebacks were regrouted one to three times on successive days. After the tieback grout had set for roughly five days, all of the tiebacks were either performance or proof tested to 120% to 133% of the design loads.

On the north side of the Wainwright Building, an existing concrete foundation wall was encountered to a depth of 4.0m (13 ft.) along the soldier beam line that was at the curb line. Since the face of this wall also lined up with the back of the proposed station wall, it was decided to leave the existing wall in and redesign the earth retention system. Tiebacks were used to support the existing wall and tiedback underpinning piers were installed from the bottom of the existing wall to below subgrade of the new station wall (Figure 8).

Figures 10 and 11 present photographs depicting the completed shoring installation at the 555 Washington and Wainwright buildings, respectively.

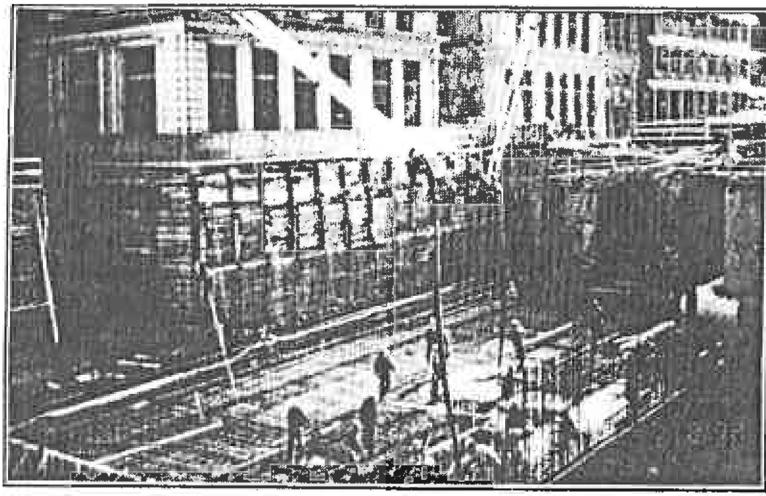

Figure 10.
Photo of St. Louis Centre Station Shoring

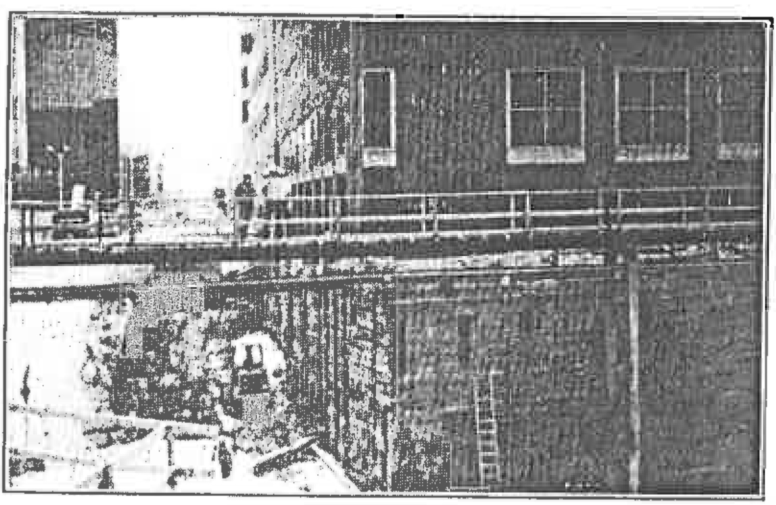

Figure 11.
Photo of Eighth and Pine Streets Station Shoring

INSTRUMENTATION PROGRAM

The construction documents required the contractor to provide geotechnical monitoring of surrounding structures during excavation and construction of the stations. They also required the monitoring system include tiltmeters, inclinometers, crackmeters, and settlement points.

Tiltmeters

The tiltmeter system utilized Applied Geomechanics Inc. (AGI) Model 716 bi-xial, wall-mounted tiltmeters mounted to the structural members of buildings within 30m (100 ft.) of the station excavations. The tiltmeters were connected to an AGI Model 796 recording unit at each station, which were periodically downloaded to an office-based 386 microcomputer.

The data were downloaded, sorted and filtered for reporting. The system polled each tiltmeter once per minute and compared the resultant tilt readings with alarm limits set at approximately 75% of the tilt expected prior to the onset of structural damage. Readings outside the alarm limits enabled a silent alarm via a second connection at the 796 unit to a 24-hour, per day coverage by a security alarm system. Upon receipt of an alarm, the security agency notified appropriate personnel. The 796 unit recorded tiltmeter readings once every ten minutes, which were downloaded to the central computer every four hours.

Inclinometers

The inclinometer system utilized a Geo Group MK-4 inclinometer probe, Geo Group INS 5.2 Inclinometer Datalogger, and Geo Group supplied software for the microcomputer. Inclinometer boreholes were installed at approximately 30m (100 ft.) intervals around the perimeter of the station excavations. The casings were located within 1.5m (5 ft.) of the retention systems, and placed between soldier beams in order to provide maximum information about ground movement. The casings were set to a depth of 15m (50 ft.) where possible, or 0.3m (1 ft.) into bedrock when encountered at less that 15m (50 ft.).

Displacement profiles were developed for each casing comparing the most recent casing profile with the baseline reading.

Settlement Points

A system of settlement points was used to monitor the vertical and lateral displacement of critical structures including the retention system and surrounding buildings. The system utilized standard Missouri State Highway and Transportation Department 75mm (3 in.)-diameter reflectors, permanently affixed to the retention system, and both structural and architectural components of surrounding buildings. The retention system mounting locations included the tops of soldier piles, horizontal bracing members, and underpinning piers. The points were read and recorded using a Lietz Set 2C total surveying station, and was downloaded into the micro computer using supplier provided software. The readings were then imported into Paradox, which compiled the data and reported the historical maximum, minimum, and the average of each point as well as the latest reading for that point.

The points were read daily during excavation and three times a week during construction. If a measurable movement was found, settlement point readings in the area of movement were taken at a more frequent interval until no further movement was detected.

Crackmeters

Crackmeters were purchased for installation on existing structural cracks found in adjacent buildings, or on structural cracks which developed as a result of the excavations. GeoKon Model 4420 vibrating wire crackmeters were specified for installation, and plaster "Bow Tie" crackmeters were approved as alternates. One vibrating wire crackmeter and three sets of bow ties were installed.

The monitoring system was designed to detect the retention system and subsequent building movements prior to the onset of structural damage, and to evaluate the total amount of movement at the surrounding structures.

The accuracies of the monitoring system components dictated that minor movement would first be detected by the tiltmeters and inclinometers, and total movement would be more accurately determined by survey data. The tiltmeters could detect vertical differential settlements as small as 0.050mm (0.0020 ft.) in buildings, depending on the mounting location, while the inclinometers accurately detected lateral ground movements as small as 1.5mm (0.005 ft.). The extreme accuracy of the tiltmeters regularly detected lateral ground movements as small as 1.5mm (0.005 ft.). The extreme accuracy of the tiltmeters was not necessarily a benefit, as the tiltmeters regularly detected movements due to thermal expansion and contraction of the building's structural members that, in some cases, caused unnecessary concern on the part of building owners.

The system was effective in detecting several minor movements in their early stages, allowing the shoring contractor to adjust the system to counteract these movements before structural damage occurred in surrounding buildings. Two specific occurrences are detailed, demonstrating the capabilities and advantages of the comprehensive retention system approach.

Occurrence 1

Excavation of the St. Louis Centre Station had proceeded to the second tier tieback level when tiltmeter 206 detected a movement in the X-axis on January 9, 1992. This tiltmeter was mounted on a tubular steel beam connecting two columns in the atrium of St. Louis Centre. Movements of up to 6.7mm (0.022 ft.) were detected in the January 10th and 12th readings of Inclinometers B5, B6, and B7. Reference is made to Figure 12 which depicts the results for Inclinometer B5. Based on these readings it was decided to place a 1.5m (5 ft.)-high berm in front of the shoring until the second tier tiebacks could be tested and locked off. The first indication of building settlement at this location was detected by a survey between January 10th and 13th. No further movement was detected by inclinometer after January 14th while no substantial movement was detected by tiltmeter 206 after January 16th. Between January 6th and February 6th, a total of 18mm (0.06 ft.) of movement was recorded at settlement point 3411 on the corner of the St. Louis Centre atrium.

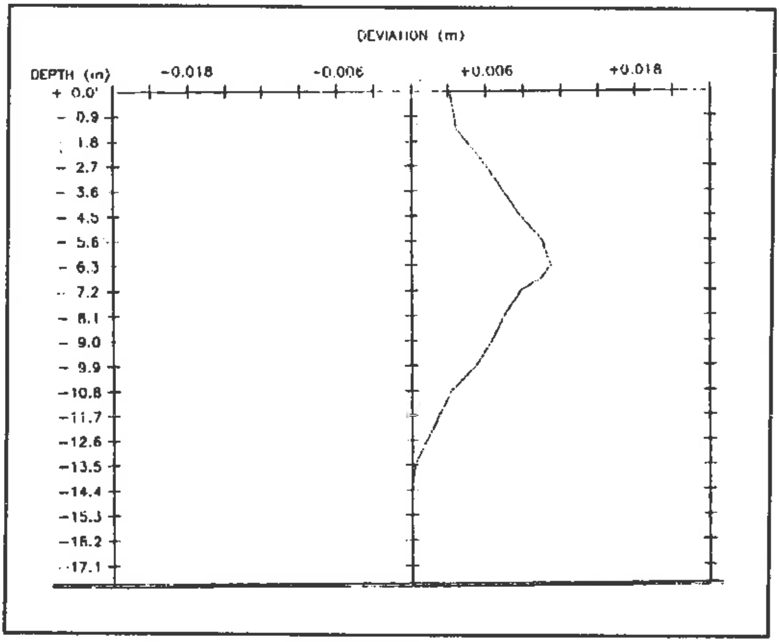

Figure 12.
Inclinometer B-5 Summary at St. Louis Centre

Occurrence 2

The relative consistency of the St. Louis Centre tiltmeter readings simplified detection of the first building movements of the station. A less clear movement was detected at the Eighth and Pine Street Station in the spring of 1992. By May 19th, the majority of excavation had been completed at this station and the contractor was hand excavating an underpinning pier beneath the corner spread footing of the Wright Building. Tiltmeter 310 reading (see Figure 13) detected a sharp drop in the Y-axis of this tiltmeter, which was mounted on the building column supported by the footing. Historically, this tiltmeter had detected widely fluctuating Y-axis movements attributed to ambient temperature changes. While the sudden change in the Y-axis reading was suspected to be settlement and not temperature related, the history of readings at this tiltmeter did not allow a definitive determination of the cause for change in the tiltmeter reading. As a precautionary measure, the shoring contractor revised the underpinning design of the corner column to minimize the amount of excavation beneath the footing that would be open at any given time. The remedial measures proved effective as the movement first detected by the tiltmeter on May 19th had essentially stopped on May 20th. Figure 12 presents a summary of Tiltmeter 310 results during this period. The settlement point at this column detected settlement beginning May 20th with slow minor settlement continuing until June 9th. During this period a total settlement of 9.0mm (0.03 ft.) was detected at this column only.

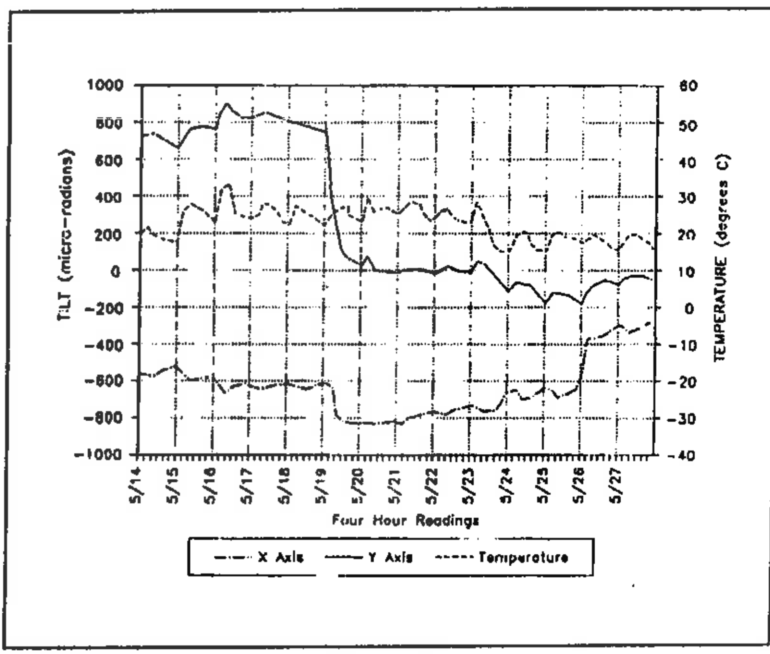

Figure 13.
Tiltmeter 310 Summary at Eighth and Pine Station

CHALLENGES ENCOUNTERED DURING PROJECT

Both the Wainwright State Office Complex and St. Louis Centre were founded on shallow spread footings bearing at roughly 0.9m (3 ft.) to 1.5m (5 ft.) below existing grade. As discovered during construction, both of these relatively new buildings were located on sites formerly occupied by old buildings with basements. Apparently, these old buildings were demolished to street level leaving their basements filled with construction debris; thus, their basement walls and foundations were left in place. For the new structures, the sites were overexcavated to a depth of roughly 1.5m (5 ft.) to 2.1m (7 ft.) and the new foundations placed on a layer of compacted fill.

As a result, the old basement walls and footings presented very serious obstruction problems for the soldier beams, tiebacks and underpinning piers at the Wainwright building and the St. Louis Centre site areas. These conditions necessitated extensive coring of the concrete obstructions for the soldier beam holes, rotary/percussive double tube drilling for the tieback holes, jackhammering, and the use of concrete breakers for the hand-dug underpinning pits. The extra costs associated with penetrating these obstructions were handled as "changed conditions."

Another challenge was the Wright Building. Before start of construction, it was unknown whether this 18-story building was supported on spread footings, a mat foundation, or deep foundations consisting of hand-dug piers or timber piles. During construction, some exploratory test pits were dug once the excavation had reached the level of the Wright Building basement. The pits revealed that this building was indeed supported on stepped cast-in-place concrete foundations bearing at roughly 3.0m (10 ft.) below the basement level slab level, or approximately 2.0m (6.5 ft.) above the station subgrade. These large footings were apparently designed for a bearing pressure in the range of 190kPa to 290kPa (4 ksf to 6 ksf). An underpinning pit system was then designed to support the southwest corner column, which was later modified as a result of the tiltmeter readings.

PERFORMANCE OF THE EARTH RETENTION SYSTEMS

Figures 14 and 15 summarize the results of the monitoring for the observed maximum lateral movements from the inclinometer readings and the observed maximum settlements from the settlement points, respectively, versus the depth of excavation. As indicated in these figures, both the maximum lateral movements and maximum settlements are essentially less than or equal to 0.2% of the depth of the excavation [H], except for the Wainwright building [N], where the tieback installation displaced the inclinometer casing. With the exception of the results for Dillard's, all of these values are less than the predicted values before construction. In comparison, Clough and O'Rourke (1990) reported that the maximum lateral wall movements for all types of retaining walls in stiff clays, residual soils and sand averages around 0.2% [H] to 0.3% [H], and in general are less than 0.5% [H], except for cases where poor conditions, adverse groundwater conditions, etc., occurred.

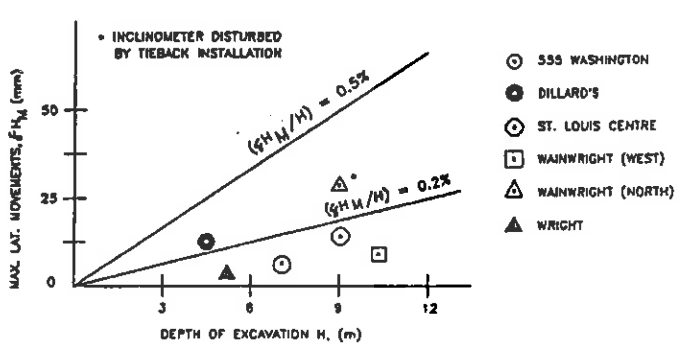

Figure 14. Observed Maximum Lateral Movements

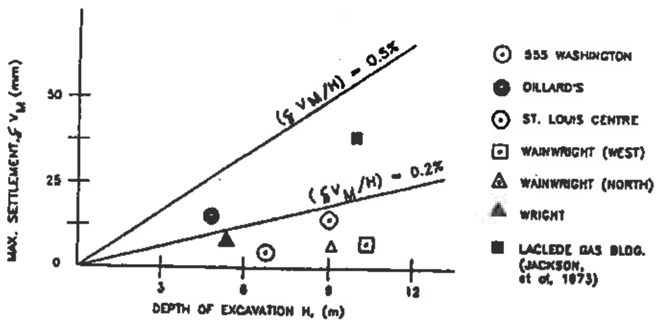

Figure 15. Observed Maximum Settlements of Adjacent Buildings

Also shown in Figure 15 is the measured settlement for a six-story building with one basement located east across the alley during the construction of the Laclede Gas Building at Eighth and Pine Streets (Jackson, et al. 1973). This construction involved a 9.8m (32 ft.)-deep excavation that was supported by steel sheetpiling braced by two levels of prestressed inclined rakers. The maximum settlement of this adjacent building was 34mm (1.32 in.), which represents 0.35% of the depth of excavation.

For Dillard's, the maximum recorded settlement and lateral movements were 12.2mm (0.48 in.) and 11.5mm (0.45 in.), respectively, which is nearly twice the predicted value of 6.5mm (0.25 in.). It is interesting to note that more than half of the recorded displacement occurred when the excavation was at the level of the bottom of the existing building footings for the installation of the single row of tiebacks. It appears that these building movements were the response of the building to removal of the outside confining pressure. Once the tiebacks were locked off, small amounts of additional displacements were recorded during the next several months' period as the excavation was made to subgrade and the station structure constructed and backfilled.

For the Wainwright Building, no measurable settlements were recorded during the underpinning operations. A total settlement of 6.0mm (0.24 in.) was measured during the excavation to subgrade and the next four-month period before the station base mat was cast. Roughly half of this settlement occurred during the excavation process, with the remaining settlement representing time-dependent consolidation of the stiff, clay layer on which the underpinning was supported.

CONCLUSION

The performance of the retention systems at both stations can be classified as excellent, especially considering the soft to medium stiff consistency soils. Furthermore, no distress was observed for the adjacent buildings, except for the slight opening up of an existing stair-step crack in the brick work at St. Louis Centre. The design-build retention system approach utilized on this project played a major part in the successful retention system performance by allowing for rapid adaptation to the soils, obstructions, and unexpected conditions which were identified only after the excavation was well under way.

ACKNOWLEDGEMENTS

The authors would like to acknowledge the following firms involved with this project:

Owner: Bi-State Development Agency
Program Managers and Geotechnical Engineers:
Sverdrup Corporation
General Contractor: McCarthy Brothers Company
Instrumentation Engineer: Reitz & Jens, Inc.
Retention System Shoring Subcontractor:
Schnabel Foundation Company
Design Consultant: Kuhlmann Design Group

REFERENCES

1. Jackson, W.T., Perez, J.Y., and Lacroix, Y. (1973), *Foundation, Construction, and Performance for a 34-story Building in St. Louis*, Geotechnique 24, No. 1, 63-90.
2. Clough, G.W. and O'Rourke, T.D. (1990), *Construction Induced Movements of Insitu Walls*, Proc. Conference on Design and Performance of Earth Retaining Structures, ASCE, Ithaca, NY, 439-470.
3. O'Rourke, T.D., Cording, E. J., Boscardin, M., *The Ground Movements Related to Braced Excavation and Their Influence on Adjacent Buildings*, U.S. DOT Report No. DOT-TST 767-23, August 1976.
4. Geddes, James D., *Large Ground Movements and Structures*, Proceedings of the Conference held at the University of Wales Institute of Science and Technology, Cardift, July, 1977. Papers by M.D. Boscardin and T.D. O'Rourke, p. 162-186; T.D. O'Rourke, E.J. Cording and M. Boscardin, p. 647-671; P.B. Attewell, p. 812-948; and J.D. Graddes, p. 949-976.
5. Goldberg, D.T., Jaworski, W.E., and Gordon, M.D., *Lateral Support Systems and Underpinning*, FHWA Report No. FHWA-RD-75-129, Vol. II, April 1976.
6. Schnabel Jr., H., *Tiebacks in Foundation Engineering and Construction*, McGraw-Hill, Inc., 1982, p. 65-72.