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UNDERPINNING HISTORIC MUSEUM FOR U-505 SUBMARINE RELOCATION

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UNDERPINNING HISTORIC MUSEUM FOR U-505 SUBMARINE RELOCATION

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The Museum of Science and Industry U-505 Submarine Relocation project in Chicago, IL consisted of building an underground reinforced concrete vault (37' deep) for the Museum's new U-505 exhibit. This WWII submarine was captured in 1944, had been located outdoors at the Museum since 1954 and was lowered into its new exhibit area in 2004. A unique combination of earth retention, water cutoff and underpinning systems allowed a forty-two foot (42') deep excavation underneath this historic museum. The museum - originally built in 1893 for the Chicago World's Fair - was closely monitored for building movements throughout construction. The underpinning systems, construction activities and monitoring results are presented herein.

Introduction

The historic U-505 German submarine at the Museum of Science & Industry was restored, moved approximately 1,000' and then lowered into its new indoor home (Figures 1, 2 and 3). The new underground exhibit opened this year celebrating the 61st anniversary of the German submarine's capture on June 4, 1944. On this historic day, Captain Daniel V. Gallery, a Chicago native, led the Navy in the siege of this submarine near the coast of Africa. This U-boat was the only German sub captured by the United States Navy in WWII and the Enigma machines, codebooks and publications recovered from the sub helped the war effort.

Figure 1: U-505 Submarine Ready for Launch

Historic Structure

The Museum of Science & Industry's East Pavilion was built in 1893 for the Chicago World's Fair. It was originally called the Palace of Fine Arts and was built as a temporary structure for a cost of $542,000. Due to its masonry construction, the East Pavilion is the only building that has survived since the World Exposition. Reconstruction began in 1929 and the Museum of Science & Industry opened in 1933. The East Pavilion consisted of masonry load bearing walls on top of a concrete footing. The architectural limestone facade was attached to the existing masonry walls. The East Pavilion footing was founded on the natural sand at Elevation +2 CCD (Chicago City Datum).

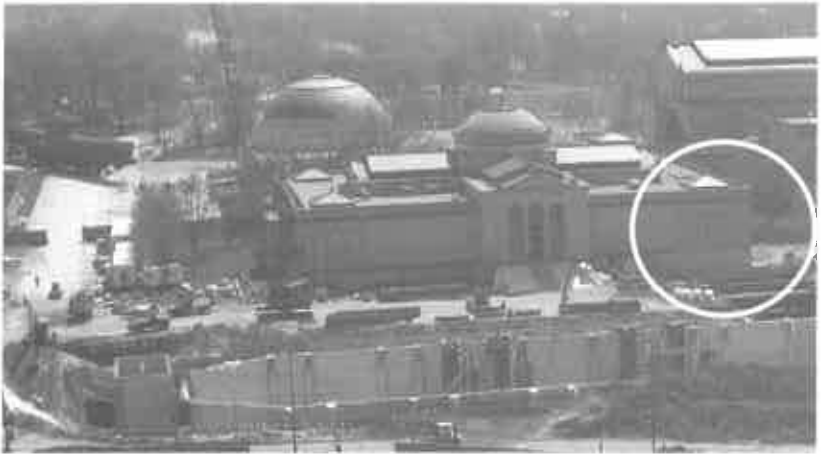

Figure 2: U-505 New Underground Exhibit and East Pavilion Underpinning Area (circled above)

Subsurface Conditions

One of the greatest challenges of this project was the difficult soil conditions with the watertable approximately 6 feet below grade and the close proximity of Lake Michigan. Existing ground surface was El. +6 CCD. Borings encountered four soil strata: fill, sand, stiff silty clay and hard silty clay.

Figure 3: U-505 Submarine - New Exhibit Area

Fill consisted of silty sand with gravel. The fill extended 3 to 5 feet below grade and was underlain by a fine to medium sand containing varying amounts of silt. The sand extended 17 feet below grade to El. -11 CCD. Average N-value in the sand layer was 16 blows per foot.

Below the sand was a stiff, gray silty clay layer that extended to El. -27 CCD. For this layer, the average water content was 22%, N-value was 14 and undrained shear strength was 1,500 psf.

Below the stiff clay was a hard, gray clay layer (hardpan). For this layer, the average water content was 16%, N-value was 44 and undrained shear strength was greater than 4,500 psf. The new exhibit and link structure shown in Figure 4 below would be supported by large spread footings founded on the hardpan.

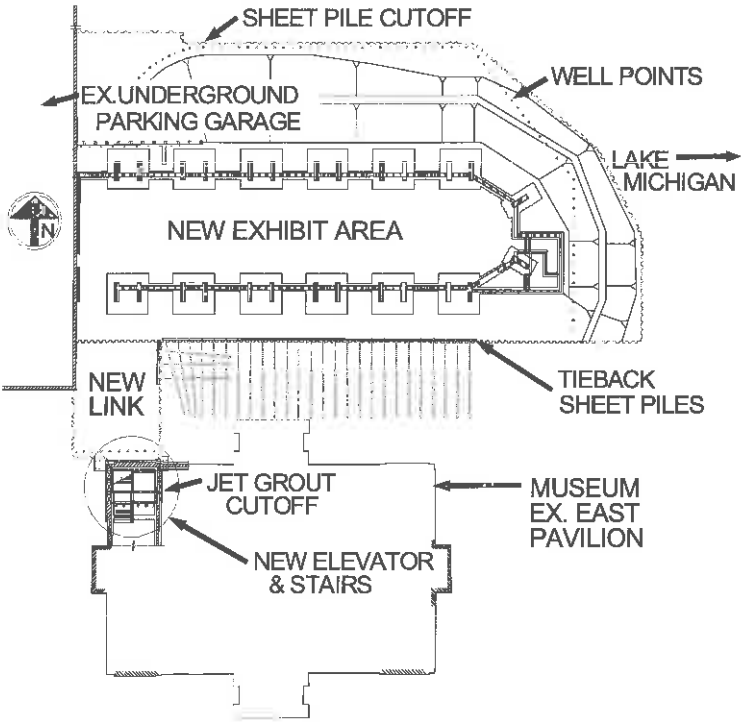

Figure 4: Overall Project Site Plan

Contract Requirements

For the new elevator and stairwell area, the contract documents showed a schematic jet grout and soil nailed wall. Schnabel Foundation Company and STS Consultants redesigned the earth retention system shown on the contract documents to utilize underpinning piers, micropiles and tiebacks. The overall project goal was to minimize movements and the contract limit was 0.75" settlement for the East Pavilion. Special care was taken during all phases of construction to ensure that there was no damage to the historic structure. For the new link and exhibit areas shown in Figure 4, braced and tieback sheet piling was designed for the dual purpose of excavation support and water cutoff.

Design

Vertical Support of the Existing Structure

East and west walls of the East Pavilion were supported by a combination of hand-dug concrete underpinning piers and micropiles (Figure 5). Existing north wall of the East Pavilion was supported by a post-tensioned transfer beam designed by the project Structural Engineers - Halvorson & Kaye. The post-tensioned transfer beam was doweled into the existing wall and supported on each end with four 150-kip micropiles (Figure 5).

Dead and live loads for the existing structure were provided by Halvorson & Kaye. The underpinning system was designed for vertical loads of 25 and 14 kips per linear foot for the west and east walls, respectively.

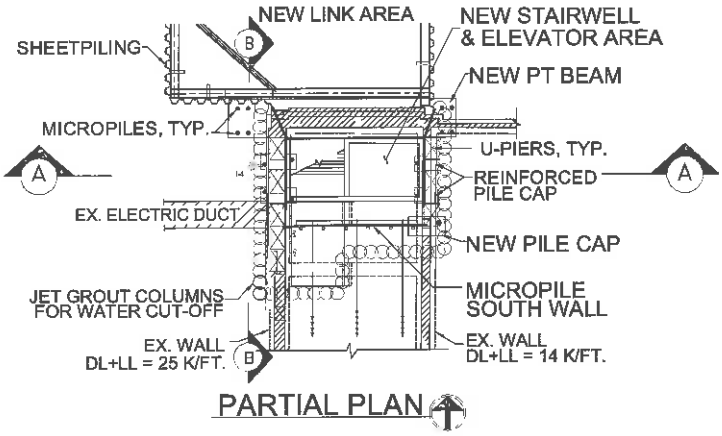

Figure 5: East Pavilion - Partial Plan

Initially, east and west walls of the existing East Pavilion building were designed to be supported only by the hand-dug concrete pit-type underpinning piers. The owner and design team were concerned about the critical nature of the existing structure and micropiles were added to provide additional vertical support.

Hand-dug concrete piers (Figures 6 and 8) were designed for combined axial and bending stresses. Allowable bearing pressure for the hand-dug concrete piers was 8 ksf, as stated in the geotechnical report prepared by Ground Engineering Consultants, Inc. Underpinning piers extended from the bottom of the existing footings (El. +2 CCD) to below the bottom of the new elevator mat foundation.

Figure 6: Underpinning Pier Construction

Each micropile had a 150-kip design load. Micropiles were designed in accordance with the Chicago Building Code. This code limits the structural capacity of steel bar and casing to an allowable stress of 18 ksi and the grout to an allowable stress of 25% of the compressive strength of the (unconfined) grout. A factor of safety was applied to the grout-ground bond stress to determine the bond length in the hardpan. Micropiles consisted of a 9-5/8" diameter by 0.545-inch thick casing extending into the stiff clay and a #20 bar extending the full length into the hardpan.

Lateral Support for New Construction

East, west and south walls of the excavation for the new elevator and stairway under the East Pavilion were supported using tieback walls (Figures 7 and 8). The hand-dug concrete underpinning piers acted as the vertical elements for the east and west walls. Permanent tiebacks were installed through the concrete underpinning piers (Figure 8).

Figure 7: East Pavilion - Excavating to final tieback tier in new elevator & stairwell area.

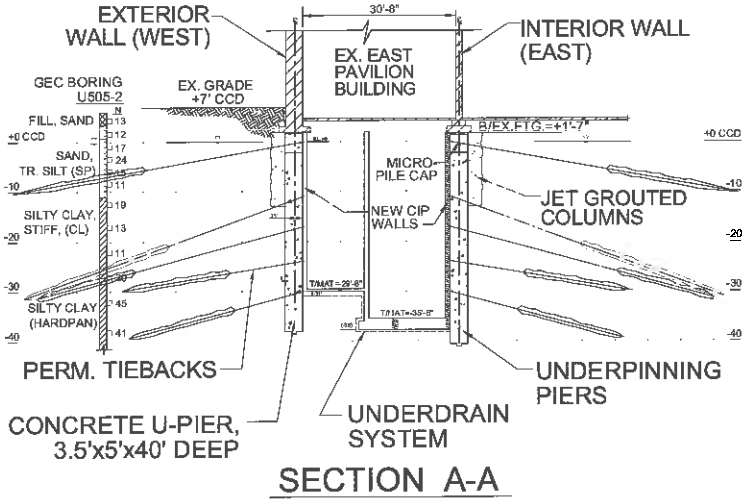

Figure 8: East Pavilion Section (from Figure 5 - Partial Plan)

To accommodate overhead restrictions inside the structure, micropiles were designed as the vertical element for the south tieback wall. Steel walers were designed to transfer tieback loads to the micropiles. Shotcrete was utilized as the temporary construction facing spanning between the vertical elements. Geocomposite drains were placed behind the shotcrete to collect seepage and carry it to the bottom of the excavation. The micropile south wall was designed using Terzaghi & Peck's apparent earth pressure diagram for stiff clays.

The permanent earth retention system for the new elevator and stairway was designed for a ground water table at El. +3.5 CCD. Tiebacks and concrete underpinning piers were designed using an earth pressure diagram with an upper trapezoidal shape and lower triangular shape. The upper trapezoidal portion was based on apparent earth pressure diagrams by Terzaghi & Peck. The lower triangular portion was based on active earth pressures using drained soil parameters. Water and surcharge loads were added to develop the total pressure diagram. The east and west walls were designed for heights of 42.5 and 38 feet, respectively.

The final design consisted of 3 feet by 5 feet deep concrete underpinning piers with five levels of tiebacks. The top tier tiebacks were designed to be anchored in the upper sand layer. Tieback loads in the upper sand layer were 80 kips. All other tieback levels were designed to be anchored in the hardpan and tieback loads varied from 107 to 200 kips. Tieback inclinations varied from 10° to 20° from horizontal.

Construction

As described above, the construction of the link between the Museum's East Pavilion and the new underground exhibit required extensive underpinning to facilitate con-

struction of a new elevator and stairwell. Prior to underpinning, steel sheet piles and jet grouted columns were installed to cutoff the water. A water cutoff wall was needed to hold the groundwater back in the sand layer so that construction could proceed in dewatered conditions without lowering the groundwater outside the excavation. Due to the difficult access inside the structure, a jet grout wall was selected to provide the water cutoff. The jet-grout wall extended from existing grade to 2 feet into the stiff clay layer. The jet grouting subcontractor, Spartan Specialties, installed numerous columns inside (east & south walls) and outside (west wall) of the East Pavilion footings to cutoff the water. These columns overlapped with the steel sheet pile cofferdam completing the water cutoff wall.

For the east and west walls, micropiles were drilled-in at a slight batter underneath the existing Museum footing and were founded in the Chicago hardpan. One micropile was successfully load tested to 300 kips. After the area was dewatered using closely spaced well points, micropile caps and hand-dug underpinning piers were constructed one at a time underneath the existing Museum footing to support the vertical building load for future construction (Figure 9). The new permanent CIP walls would be poured against the underpinning piers.

New Exhibit & Link Area - Retention Systems

Extending north from the East Pavilion underpinning area, braced and tieback sheet pile walls were designed and constructed for excavation of the link and new U-505 exhibit area (Figures 4 and 10).

Figure 9: East Pavilion Building - Looking up at under-pinning pier, micropile and south wall work

Due to a conflict with the permanent tiebacks supporting the existing underground parking garage, the sheet pile on each side of the new link was internally braced. Sheet pile along the south side of the new exhibit area - shown in Figure 10 - was installed as part of a separate contract for Lake Shore Drive improvements. Since the sheet pile sections were only driven a short distance into the hard-pan, this south wall had to be laterally supported by tiebacks and designed for excavation below the tip elevation.

Figure 10: Sheet pile south wall - New Exhibit Area

Construction Sequencing Summary

Below is the construction sequence for Link and East Pavilion underpinning work:

- Steel sheet pile installation in Link Area.
- Jet grouting inside and outside of East Pavilion building (Along west, south and east existing footings).
- Micropiles drilled inside and outside the existing structure (Figure 11).

Figure 11: Installing Micropiles for PT Beam

- Excavation for and construction of concrete post-tensioned transfer beam to support East Pavilion north wall in the final design condition (Figures 12 & 13).
- Reinforced concrete micropile caps (Figure. 9).

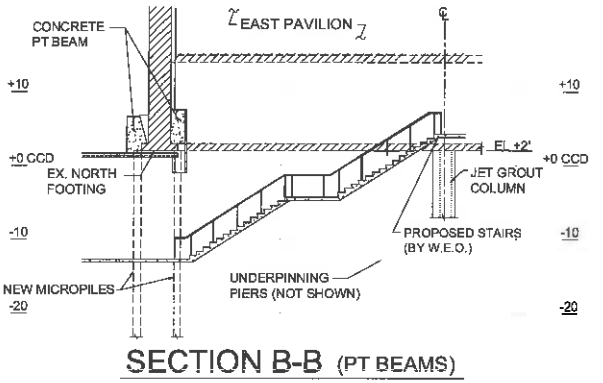

Figure 12: East Pavilion - PT Beam Section (from Figure 5)

Figure 13: North Wall footing exposed (Left) and PT beam reinforcement (Right)

- Dewater utilizing well points in close proximity to north wall footing.
- Hand-dug underpinning piers (Figure 6).
- Walers and cross-lot braces in Link Area.
- Link and East Pavilion excavation and shotcreting in lifts inside building.
- Tiebacks, wales and braces installed during excavation in lifts (Figure 14).

Figure 14: New Link and East Pavilion Area Excavation, Braces and Tieback Construction

Jet Grouting

Prior to the start of the work, a jet grout test section was completed, partially exhumed and examined to evaluate the performance (Figure 15). The double tube jet grout system was chosen based on the test section performance of sequential interlocking columns. A total of six (6) test columns provided the data required to verify the correct jet nozzle, rotation and withdrawal rate, column diameter, column overlap and water-cement ratio. The column diameter was 3.5 feet with depths as much as 21 feet.

Figure 15: Jet grout test section - Link Area

The low headroom conditions inside the East Pavilion building and close proximity of an electrical room which contained high voltage switchgear and transformers (Museum's primary power) made this work extremely difficult. Since there was only two (2) feet of space between the existing electric transformer and east foundation wall, the jet grout drilling equipment had to be dismantled and setup on the floor above. Casing and pipe sleeves were utilized to isolate the drilling operation between the floors and to prevent spoils from migrating into the live electric room. The drilling spoils were collected and pumped for disposal approximately 200 feet from the operation. The jet grout equipment used was electric powered to minimize harmful fumes and noise since Museum visitors and exhibits were close by.

For closure in two corners, the jet grout columns had to cross an existing five (5) foot wide footing. To ensure water cutoff in this area, additional battered columns were installed and the column size was increased. During construction, an existing 6.5 foot wide electrical duct extending west from the East Pavilion to the main Museum building was uncovered. Two additional lines of angled jet grouted columns were installed on both sides of the electric duct. Due to the close proximity to the high voltage lines, this work was done during planned nightly shutdowns and required a coordinated effort with the Museum, owners design team, W.E. O'Neil and all subcontractors working on this project.

Upon completion of the jet grouted water cutoff wall, it was estimated that less than 2 gallons per minute of water migrated into the excavation. Some of this measured water seepage was from an old drainage pipe running perpendicular to the jet grout wall that was uncovered later during underpinning work.

Instrumentation/Monitoring Program

The City of Chicago and owner required that the contractor provide inclinometers, lateral and vertical monitoring points, and crackmeters on the adjacent structures and retention systems during excavation and construction of the U-505 structure.

Prior to the start of construction, numerous vertical and lateral points were scribed on the north and west exterior walls of the East Pavilion building (Figure 16). Several settlement points were setup inside the building on the walls and concrete floors. Two (2) inclinometers were installed in close proximity to the west wall (one inclinometer was located inside an underpinning pier) to measure lateral movement during all phases of construction (Figure 16 shows inclinometer locations). Several crackmeters were installed on existing building walls to monitor existing crack widths.

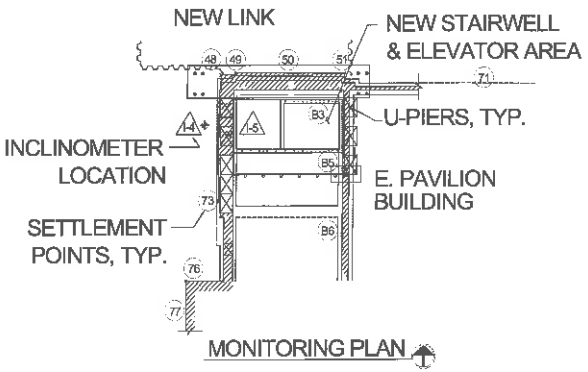

Figure 16: Monitoring Point Locations

As required by the City, monitoring points and inclinometers were read weekly during construction. If unexpected movement was recorded, the monitoring readings were taken at more frequent intervals until no further movements were detected. During the underpinning operations, an automatic level was setup daily inside the building to monitor vertical movements.

Overall Performance

The monitoring results are summarized by Figures 17 and 18 for the lateral and vertical movements. The maximum inclinometer lateral movement was 0.33" and vertical movement was 1" upon completion of project. The maximum vertical movements of the north exterior and east interior walls were 0.875" and 0.75", respectively. As noted earlier, the contract settlement limit was 0.75".

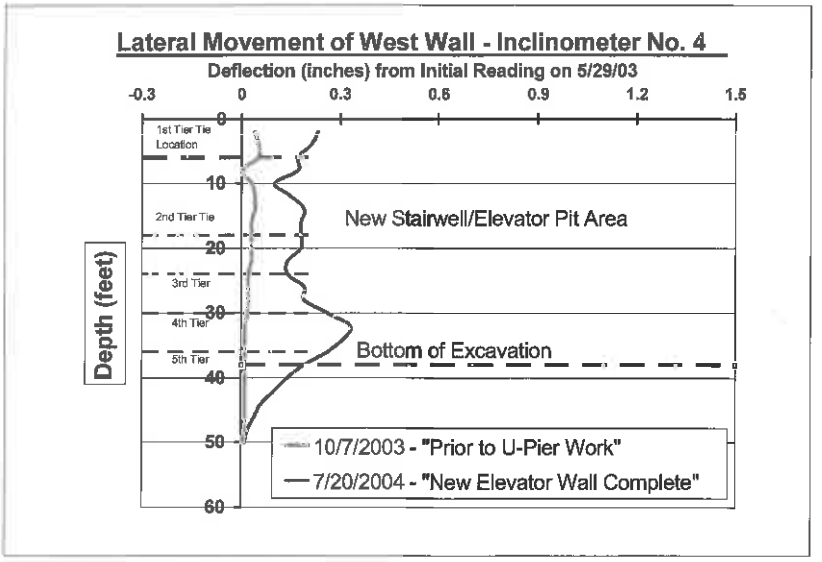

Figure 17: Lateral Movement of East Pavilion

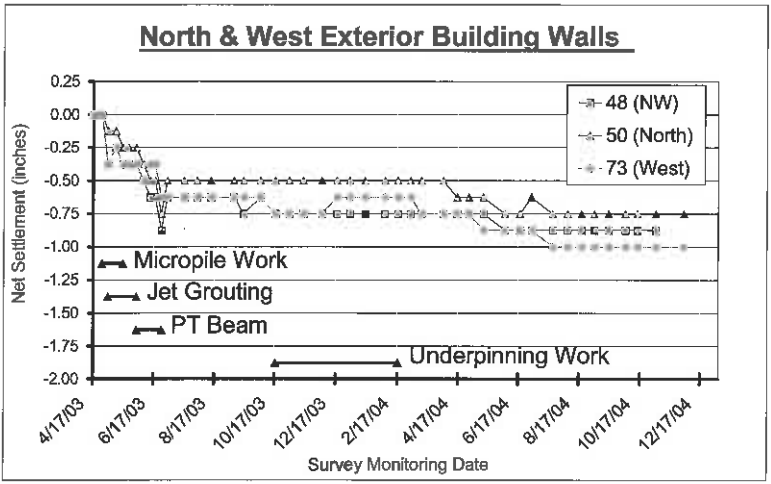

Figure 18: Settlement of East Pavilion Building

From review of the building settlement and construction activities, it was estimated that the initial 0.375" settlement occurred during the jet grouting and micropile work. The additional 0.375" vertical movement occurred during excavation and post-tensioned beam construction. It appears that the additional building movement was the direct response to removal of soil from outside of the north wall footing shown in Figure 13. The excavation for the PT beam work reduced the existing footing confining pressures and lowered the estimated soil bearing capacity by a factor of two (2).

Work Stopped - Settlement Exceeded

On June 24, 2003, work was stopped because movement exceeded the contract limit of 0.75". This settlement occurred prior to the start of underpinning work as shown on Figure 18.

There were several onsite meetings in the Museum's "War Room" to discuss the potential causes of settlement and procedures to continue with the work. There was no agreement as to why these large settlements occurred but the possible causes were discussed:

- Excavation for micropiles and jet grouting work.
- Micropile Installation.
- Jet grouting work.
- Excavation for PT beam.
- PT beam construction.
- Dewatering in New Exhibit area.

Schnabel and STS Consultants focused on future construction sequencing and design procedures. The revised procedures consisted of modifying the underpinning pier and micropile cap sequencing, erecting interior scaffolding, daily performance monitoring and underpinning pier jacking pockets. These procedures were accepted by the owner's design team and the modified underpinning work began.

The revised construction procedures resulted in additional vertical movement of 0.25" (from June 24, 2003 until project completion). The East Pavilion west wall vertical movement was 0.75" prior to underpinning work and 1" upon project completion (Figures 19 and 20). The north and east wall settlement was slightly less than the west side. Due to the gradual nature of the settlement shown by the monitoring data, there was no widening of existing cracks or building distress observed.

Conclusions/Observations

The unique combination of water cutoff, underpinning and excavation support systems minimized movement and prevented damage to the East Pavilion building. The design-build construction approach played a significant

role in the successful performance of this project because it allowed field changes to be made immediately when unexpected conditions were encountered.

Figure 19: New Elevator & Stair CIP Walls Complete

Figure 20: New Exhibit Area backfilled and Link roof water-proofing test underway

Acknowledgements

The author would like to personally thank Bill Walton - STS Consultants - for all of the hard work, dedication, attentiveness, extra effort and time spent on this project. Thanks for revising and reviewing the drawings and design calculations numerous times - outside of normal working hours - to satisfy critical project requirements.

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Architect: Lohan, Caprile, Goettsch Architects
Structural Engineer: Halvorson Kaye Structural Engineers
Geotechnical Engineer: Ground Engineering Consultants
General Contractor: W.E. O'Neil Construction Co.
Underpinning & Retention System Subcontractor: Schnabel Foundation Company

Subcontractor's Design: STS Consultants
Sheet pile Installation: Herlihy Midcontinent, Inc.
Jet Grouting: Spartan Specialties, Ltd.
Inclinometer Monitoring: CTI, Inc.
Vertical and Lateral Survey Monitoring: James Schaeffer & Schimming, Inc.
Crack & Vibration Monitoring: Vibra-Tech
Excavation Subcontractor: T.W. Edmier
Dewatering Subcontractor: Midwest Dewatering

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