NATM THROUGH CLEAN SANDS— THE MICHIGAN STREET EXPERIENCE

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INTRODUCTION

A 100 ft long, 20 ft high and 18 ft wide NATM tunnel was excavated through grouted clean sands beneath a busy city street, including a variety of existing utility lines. The new tunnel associated with a hospital expansion will serve as a pedestrian tunnel connecting a parking structure with a new hospital facility.

Tunnel construction started on December 15, 2005 when drilling for the grouting program started and was completed on May 26, 2006 when the tunnel final lining was completed. The tunnel was constructed by Kiewit Construction Company as a tunnel subcontractor to The Christman Company who is constructing the hospital facility for Spectrum Health in Grand Rapids, Michigan. URS was the project designer. Gall Zeidler Consultants, LLC were the contractor's NATM consultant.

PROJECT DESCRIPTION

The Michigan Street Pedestrian Tunnel is a component of the Michigan Street Development located along the north side of Michigan Street NE between Coit Avenue NE and North Division Avenue in the downtown area of the Grand Rapids, Michigan. The Michigan Street Development includes a parking deck and four new towers to be constructed over the proposed parking deck. The tower planned furthest east is being developed by Spectrum Health as the Lemmen-Holton Cancer Pavillion. The purpose of the pedestrian tunnel is to connect the proposed Lemmen-Holton Cancer Pavillion with the future Spectrum building to be located on the south side of Michigan Street NE. The southern end of the tunnel was constructed with a bulkhead until the future Spectrum building is constructed at which time interconnection will be required. The tunnel site plan and profile are shown in Figure 1, Site Plan, and Figure 2, Tunnel Profile.

Several challenges were faced during the design and construction of the Michigan Street Pedestrian Tunnel. These challenges included compressed design and construction schedule, maintenance of traffic and protection of old underground utilities. The tunnel was being constructed as part of the Michigan Street Development and coordination with other concurrent construction activities was required. The tunnel was constructed within a specified window of time to allow other associated construction activities to take place without compromising the overall project schedule. The design started in June 2005 and construction was completed by June 2006.



Figure 1. Site plan



TUNNEL STATION (FT.)

Figure 2. Tunnel profile

The required internal finished dimensions of the tunnel cross section are 12 feet wide by 12 feet high at a length of approximately 100 feet. The tunnel will be equipped with heating, ventilation, and air conditioning (HVAC), lighting, fire suppression, and drainage systems. The tunnel was constructed as a modified horseshoe shape with an outside height of 19.6 feet and a outside width of 18.5 feet using the New Austrian Tunneling Method (NATM) with ground modification consisting of chemical grouting within the tunnel horizon. Tunnel cover is approximately 22 feet. A NATM design scheme was provided and was successfully implemented during construction with no significant modifications. Details of the support system and the construction sequence are provided below.

DESIGN

Project Requirements/Constraints and Challenges

Surface Settlement. Requirements were that the tunnel construction does not cause any roadway surface settlement. Any roadway surface settlement that occurred as a result of the tunnel construction activities had to be kept within reasonable limits so as not to disrupt traffic, endanger users of Michigan Street NE, or adversely affect underground utilities.

Existing Utilities. Several existing utility lines including several electrical and telephone conduits, a 6-inch gas main, a 24-inch water main, a 12-inch water main, an abandoned 12-inch water main, a 15-inch storm drain pipe, and a 15-inch sanitary sewer pipe are located perpendicular to the tunnel alignment along Michigan Street NE. Of particular concern was the presence of the high-pressure, 24-inch water main and the 15-inch sanitary sewer pipe. Refer to Figure 2, Tunnel Profile, for utility locations.

The 24-inch water main was believed to be a high-pressure cast iron pipe over 100 years old and located approximately 17 feet above the tunnel crown. The 15-inch sanitary sewer pipe was believed to be made of clay and located 7 feet above the proposed tunnel crown. The age of the existing 15-inch sanitary sewer pipe was not known.

Waterproofing. The Owner required that the tunnel be waterproofed to offset any groundwater infiltration (resulting from precipitation and/or utility leakage) into the tunnel. Watertight joints were planned between the tunnel and the parking deck permanent structure and the future Spectrum building.

Subsurface Conditions

Three borings were drilled along the tunnel alignment to investigate soil subsurface conditions. In addition, several borings were drilled in the vicinity of the tunnel alignment. The borings revealed that the subsurface soils consist of a Fill layer, varying in thickness between 0 and 8 feet below ground surface, underlain by Glacial Sand extending to 77 feet below ground surface within the tunnel alignment. The Fill and the Glacial Sand layers consist predominantly of poorly graded sand (SP) and well graded sand (SW) based on visual classification. Standard Penetration Test (SPT) blow counts ranged from 6 to over 100 blows per foot (bpf). The high blow counts may be attributed to the presence of cobbles and boulders. The soil medium within the tunnel horizon was generally classified as medium-dense to dense sand. The Glacial Sands overlie the Glacial Till comprising silty clay to silty sandy clay including layers of sand. Figure 3, Geological Profile, presents geological conditions along the tunnel alignment.

Groundwater was not encountered within the tunnel horizon during the subsurface investigation. It was anticipated that the tunnel would be constructed entirely above the groundwater table.



Figure 3. Geological profile

SILT. AND CLAY.

The ground behavior for the Glacial Sand materials within the tunnel envelope, as classified in accordance with the Tunnelman's Ground Classification system (Heuer, 1974), was "slow to fast running."

Tunneling Alternatives Evaluation

Two tunneling construction method alternatives were considered for the tunnel construction: the New Austrian Tunneling Method (NATM) with ground modification and the use of a tunnel excavator shield. The alternative study included tunneling method applicability, pro's, con's, and construction cost estimates for comparison. A recommendation was provided to adopt the New Austrian Tunneling Method (NATM) as the most economically and practically preferred alternative.

Two main issues of concern were identified. These challenges were (1) the presence of boulders or obstructions within the tunnel envelope, and (2) excessive ground surface settlement as a result of tunneling operations.

Boulders and cobbles are commonly encountered within the glacial sand. The difficulty of the removal of these boulders and other obstructions depends on the tunneling method used. Obstructions are more accessible and easier to remove with the NATM. With the excavator shield, the obstruction may need to be broken in place prior to removal due to limited accessibility at the tunnel face. In addition, boulders only partially within the face and extending beyond the limit of shield excavation will cause excess settlement with a shield but not with the NATM. Excessive settlement at utility elevations could lead to undermining utility lines with consequent leakage of

water being catastrophic to tunnel stability. To mitigate the effect of tunneling on existing underground utilities, ground modification applications were employed. Based on the ground conditions provided on the boring logs, jet grouting and chemical grouting were considered options to mitigate for settlement near utilities. The use of an excavator shield without any ground modification could lead to excessive ground surface settlement.

NATM Design

Numerical Analysis. Numerical analysis was performed to study and prepare a design for the tunnel structural support system, stand-up time for native soil and grouted soil within the tunnel horizon, and to investigate the estimated surface and underground movement likely to result from tunneling operations. Data obtained from the numerical analysis was utilized to determine the appropriate measures to protect existing underground utilities. In addition, empirical analysis was performed to validate the numerical analysis results.

The preliminary assessment of ground surface settlement resulting from tunneling operations for the proposed tunnel indicates that surface settlement could be controlled to less than 1 inch, providing that proper design is implemented including ground modification such as grouting and good construction workmanship.

Permeation Grouting. The tunnel crown is approximately 22 feet below the existing ground surface and a preliminary estimate of the required mined tunnel height is 19.6 feet (width is 18.5 feet). Therefore, the ratio of cover to tunnel diameter is close to 1:1. The potential for ground settlement during mining in a loose to very dense Glacial Sand without ground treatment was considered significant.

Permeation grouting creates an in-situ cemented soil matrix that increases strength and reduces permeability of the original soils and thereby increases tunnel stability during construction. This method is suitable for granular soils, sand, and gravel with less than 15% of fines that have sufficient void space to be permeated with fluid cement or chemical grout to produce the cemented matrix. Permeation grouting can be performed from vertical or horizontal pipe arrangements. Due to the limited access available on Michigan Street, horizontal grouting pipe arrangement was selected. The suggested design pipe arrangement is presented in Figure 4, Grouting Scheme (Design Phase).

Permeation grouts are injected into the soil void spaces through tube-a-manchette (TAM) pipes. A stabilizer added to the grout controls gel time. The grout bonds with the soil particles, producing a composite soil mass with a higher shear and compressive strength than the un-grouted formation. Permeation grouting also reduces the soil permeability by filling the voids. This grouting technique does not use mechanical means to restructure the soil in the process, and therefore the soil structure remains relatively undisturbed. The operation creates minimal ground disturbances and reduces adverse deformation and damage to the ground formation.

NATM Excavation. The NATM design included excavation sequencing and support system details and installation. The excavation sequence was selected based on the modified ground condition, tunnel cross section size, and settlement requirements. The numerical analysis assisted in selecting the NATM excavation sequence. The excavation sequence consisted of top heading and bench with a 5 ft round length. Details of the excavation sequence are presented in Figure 5. The NATM design was implemented during construction without any significant modifications to round length, top heading dimensions or pre-support philosophy.

Primary and Final Support System. The primary support system consisted of a 7-inch steel fiber reinforced shotcrete initial layer applied directly onto the excavated



2" DIA TUBE-A-MANCHETTE STEEL PIPES
1.5" DIA TUBE-A-MANCHETTE PVC PIPES







grouted soil mass. A PVC waterproofing membrane with welded joints was installed and a final 6-inch steel fiber reinforced shotcrete layer was installed followed by a smoothing 1-inch un-reinforced shotcrete layer. Isolation joints were provided at both ends of the tunnel to structurally isolate the tunnel from the garage parking deck and proposed future Spectrum building. The isolation joints were designed as watertight joints to prevent groundwater infiltration into the tunnel at the joint locations.

Geotechnical Instrumentation. A ground surface movement monitoring program was implemented before, during, and after tunnel construction. The monitoring program included surface settlement monitoring points, multiple point borehole extensometers (MPBXs), and in-tunnel instrumentation including convergence meters and crown settlement markers. Additional instrumentation was needed during construction including inclinometers to monitor the headwall during tunnel breakout and construction. Additionally, an alternative in-tunnel monitoring system consisting of optical targets was implemented during construction.

Contractor Selection

Due to the compressed schedule, three tunneling contractors were invited to bid on the project as the contract documents were being developed. Only two contractors provided bids on the project. The lowest bid was 43% above the engineer's estimate. This was attributed to the constraints to the work area, the schedule as well as the unexpectedly increase in cost for raw materials and in particular the rising cost for permeation grouting. Value engineering proposals were requested from both bidders in an attempt to lower the price. Figure 6, Grouting Scheme shows a modified grouting pipe arrangement proposed by Kiewit that was accepted by the Owner's team. The modified grouting pipe arrangement reduced the lowest bid price by 15%.

PERMEATION GROUTING

Drilling

The grouting sub contractor utilized a crawler rig in combination with a specialized system to advance a 4" casing using down the hole hammer. Weaknesses would occur in the casing after multiple uses causing the casing to shear at the thread to straight casing intersection. This problem was overcome by using a thicker and higher grade casing.

Following the drilling of each hole the TAM pipe was inserted and the annular space between the pipe and the drill hole tremied with a cement bentonite grout, while retracting the casing. Using this system a high degree of drilling accuracy could be achieved since the casing did not rotate. The soil loss is also minimized due to drilling since the spoils are flushed back through the casing using compressed air.

A total of 21 steel TAM grout pipes, 2" diameter, were installed above the crown, and 20 PVC 1.5" TAM pipes were installed throughout the profile as seen on Figure 6. The total drilling length of 4,000' was completed in 18 working days on two 12-hour shifts per day. No obstructions such as cobbles or boulders were encountered during the drilling. However, it was a challenge drilling the pipes between soldier piles, tie back anchors and the MPBXs previously installed from the road surface above the tunnel.

Grouting

The chemical grout mix consisted of 50 percent liquid sodium silicate, five percent reactant and 45 percent water. Prior to grouting laboratory testing was conducted by injecting the mix into medium dense sand samples and curing them to study the



Figure 6. Grouting scheme (proposed and constructed by Kiewit)

unconfined compressive strength performance at seven and 28 days. The 28 day strength requirement was 150 psi. Grouting volume was based on a 30 percent void ratio of the Sands with a void filling factor of nearly 100 percent resulting in a target volume of 188,100 Gallons. Grouting started on February 6, 2006 and was completed in 29 workdays on March 13, 2006. The actual injected volume was 212,000 Gallons. The actual strength of the grouted soil ranged upwards of 500 psi to an estimated 1000 psi causing the tunnel excavation tool described below to almost reach its limit. The maximum distance between the pipes was five to six feet, which was at the limit for obtaining required soil mass permeation.

Verification and Testing

To verify the compressive strength, and the extent of the grouted sand zone, standard penetration tests (SPT) were performed prior to and following grouting. The blow counts typically increased to 50/4" or refusal from pre-grouting values of around 25/6", in the grouted zone. Other tests during construction included gel times of grout sampled every 60 minutes or 1,000 gallons of grout, which ever came first. Gel time requirements ranged from five to fifty minutes.

Hand-written grouting reports were prepared by the technician at the manifold. The report contained information regarding target and actual volumes and pressures for each sleeve, date and time of injection and flow/pressure measurements every 15 minutes.

TUNNEL CONSTRUCTION

Safety

The Michigan Street tunnel was constructed without any Recordable, Reportable or First Aid cases.

This success, for a job with rapidly changing operation that does not allow time for learning curves, can be contributed to a few main factors.

First, Kiewit's safety program, that does not allow an operation to start unless it has an approved Job Hazard Analysis combined with a work plan, reviewed and signed off by the Crew.

Second the entire crew, except for a few, all had experience with working on projects for Kiewit, either locally in Grand Rapids or on other tunnel projects. Third, without jeopardizing the safety of the crew the field supervision was able to direct the work when the ground conditions were challenging.

Excavation Method

The selection criteria for the tunnel excavator were as follows:

- Must be able to efficiently excavate the required profile.
- Have enough power and weight to excavate the chemically grouted sands, while still being able to fit within the tunnel.
- Be readily available.
- Be reliable.
- Be cost effective.

After performing three dimensional simulations to check working range, a new excavator with a modified stick attachment was selected together with a new grinding head attachment to cut a smooth profile in the grouted sands, which behaved like a weak sand stone. The excavation time for a five foot top heading round would be two hours excavating the bulk 80% followed two hours of trimming to the desired profile. Three times during the excavation the excavator would back out of the tunnel to allow for muck to be removed.

The excavation profile together with girder installation was set-out, checked and as-built in real time using a tunnel specific software package onboard a total station. Excavation started on March 18, 2006 and was completed on May 6, 2006. Progress was stopped for a number of days during the period in order to perform additional localized grouting from within the tunnel, and due to finalizing portions of the parking structures work in front of the portal, resulting in 24 actual tunneling days working an average of 10.5 hour shifts.

Shotcrete was supplied by a local readymix supplier and pumped from a lane closure on Michigan Street down to the tunnel where it was applied by a certified nozzleman.

Waterproofing

A tanked, closed perimeter PVC waterproofing system was designed for the tunnel consisting of a layer of fleece followed by a 3mm PVC continuous welded membrane. To facilitate the final lining shotcrete application, applied onto the membrane, BA-Anchors were used to secure a 4×4 W4.0×W4.0 Welded Wire Fabric (WWF) tightly against the membrane for the shotcrete to adhere to.

The WWF was held at a specific distance from the membrane using PVC spacers that also prevent the risk of punctuating the membrane.

The waterproofing system was purchased through a supplier who also supplied required submittals and an experienced superintendent to oversee the installation, which was performed by Kiewit on seven 10 hour shifts, including WWF installation.

INSTRUMENTATION AND MONITORING

System

The instrumentation and monitoring system for the Michigan Street Tunnel was laid out according to typical monitoring requirements and principles for a shallow NATM tunnel driven in soft ground conditions in an urban setting.

The instruments included four arrays of Surface Monitoring Points (SMPs) arranged in lines perpendicular to the tunnel axis with the most distant instrument located about 40 feet from the tunnel centerline, four Multiple Point Borehole Extensometers (MPBXs) located outside the excavation profile, Inclinometers at the soldier pile and lagging wall and four monitoring cross sections within the tunnel with each having five prisms for the optical monitoring of in-tunnel deformations. The instruments were monitored on a three-times-per shift basis during active tunneling and every 24 hours when no mining was on going. Data were evaluated by plotting monitoring values vs. time and vs. tunnel progress to show ground deformation behavior as a function of the tunneling process. Monitoring data were compared to a two-level observation system consisting of threshold and limiting values for each instrument. Monitoring results were graphed by the contractor's NATM consultant on a daily basis. The contract stipulated the implementation of contingency measures upon reaching of threshold values, which was 12.5 mm for convergence points and 6.25 mm for surface settlement.

Representative Observations

The deformation values for the SMPs in Array #3, located 60 feet from the portal, vs. time for a time frame between late April 2006 and mid May of 2006 illustrate a number of observations made during tunneling. Close to tunnel centerline the increase in settlement was on the order of some 1–3 millimeters as the heading passed the array. Comparing the graphs for the individual SMPs in Array #3 the settlement values decrease clearly with increasing distance from the tunnel centerline. The maxim cumulative surface settlement trough was some 15 millimeters. The cumulative graphs included surface settlement data measured prior to the tunneling operation before mid March 2006 that were caused by movements of the support of excavation wall at the tunnel portal.

An evaluation of the tunnel convergence values showed that the deformation of individual prisms was generally below a 5 millimeter-value although at occasion values close to 10 millimeters were recorded.

Instrumentation Summary

In summary, the instrumentation and monitoring system installed allowed for a detailed evaluation of the deformation regime within the ground affected by the tunneling operation. The deformation values measured are viewed as typical for shallow soft ground tunneling considering size of the tunnel, soil conditions and ground improvement measures implemented.

The MPBXs installed prior to the parking structure excavation reaching full depth turned out to provide valuable information regarding soil movement prior to start of tunnel excavation.