"HORSESHOE" SECANT COMPRESSION SHORING SYSTEM FOR TUNNEL REPAIR

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ABSTRACT

A storage and drainage tunnel advancing below I-75 in Detroit, Michigan experienced sudden subsidence. The Tunnel Boring Machine (TBM) was damaged to the extent that its shield, cutting head and extensive interior components needed to be extracted and replaced along with several completed tunnel segments. The tunnel was 16 feet (4.9m) in diameter with crown over 79 feet (24.1m) deep at the time.

The tunneling contractor immediately engaged their designers and specialty subcontractors in order to develop a scheme to access the machine and repair the tunnel. They required a shaft 99 feet (30.2m) deep, with unobstructed plan dimension of 50 feet (15.2m) to accommodate the large components that needed to be removed and replaced. This precluded the application of an internally braced excavation and instead earth support solutions focused on use of a compression ring. Since the completed tunnel section behind the TBM obstructed closure of the compression ring below its invert, this paper describes the innovative access shaft solution employed.

A conventional compression ring was constructed using 5 feet diameter drilled shafts down to the tunnel crown. In front of, and to the sides of the tunnel heading, the secant shafts were extended to over 150 feet (45.7m) depth, creating a horseshoe of support extending 50 feet (15.2m) below the planned excavation invert. Larger diameter "King Pile" shafts were drilled immediately to either side of the tunnel, overlapped into each end of the secant "horseshoe". The king pile shafts, together with a heavily reinforced ring beam above the crown elevation, acted as a door frame to transfer hoop loads from the incomplete secant arc into reaction supports above and below the tunnel. These oversize king pile shafts were extended and socketed into rock over 70 feet (21.3m) below tunnel invert.

Very tight installation tolerances were necessary to maintain secant shaft alignment to depths exceeding 150 feet (45.7m). The project operational, geotechnical and quality data was managed and visualized using a custom GIS interface. This paper will present the design approach employed and review the construction and quality program selected to repair the tunnel.

Keywords: Cased Drilled Shafts, Secant Pile Wall, Compression Ring, Support of Excavation, FEM, Tunnel, TBM, Infrastructure

INTRODUTION

The overall I-75 Modernization project consists of the design and reconstruction of approximately 18 miles (29 km) of the freeway, north of Detroit, Michigan. This stretch of freeway has been divided into three segments for reconstruction. As part of the I-75 reconstruction, a proposed drainage/storage tunnel from north of 8 Mile Road to north of 12 Mile Road is planned to be constructed within Segment 3. The current drainage system is almost 50 years old and in need of improvements. The proposed 14.5-foot (4.4 m) diameter drainage tunnel will provide storage and conveyance to help avoid future flooding in the depressed portion of the I-75 freeway. The proposed tunnel is approximately 22,370 feet (6820 m) long and is generally located along the northbound I-75 service drive, 100 feet (30.5m) below ground.

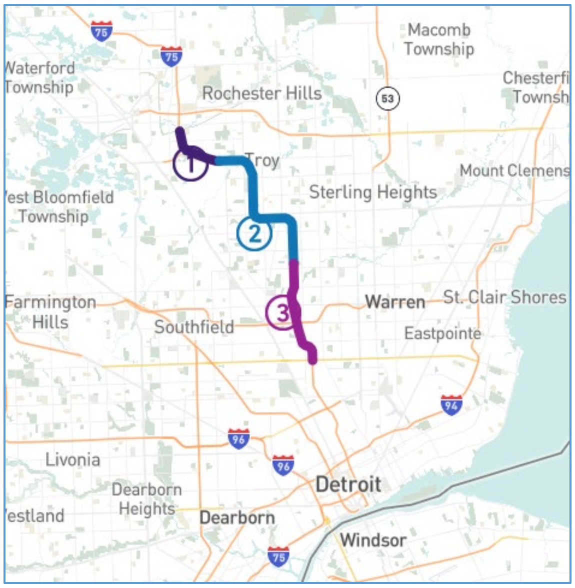


Figure 1 - I-75 Modernization Project Map With Segment ID's

On July 30, 2021 the tunnel excavation experienced mine subsidence resulting in earth sinking and shifting, casing settling, cracking and disarrangement of the constructed tunnel lining. The Tunnel Boring Machine (TBM) was damaged to the extent that required its shield, cutting head and extensive interior components to be extracted and replaced. The tunnel was 16 feet (4.9m) in diameter with the crown over 79 feet (24m) below ground surface at the time.

The tunneling contractor immediately engaged their designers and specialty subcontractors in order to develop a scheme to access and repair the machine and tunnel liner. To accommodate the large components that needed to be replaced, a 50 foot (15.2m) unobstructed excavation was required. The invert of the tunnel was 96 feet (29.2m) below surface, so the excavation would need to be supported beyond 100 feet (30.5m). Damage to the tunnel lining meant that the excavation support would have to encapsulate the machine, without the ability to construct below it, so an innovative solution was required.

SUBSURFACE CONDITIONS

Based on the completed borings for the additional phase of Geotechnical Exploration, subsurface conditions were encountered as follows: Surficial pavements, bedding, and predominantly cohesionless fill were encountered to depths of approximately 3 to 5 feet (0.9 to 1.5m). The fill materials were underlain by native gray silty clays. Clay consistency was hard to stiff immediately below the surficial fills, then transitioned to become to medium to stiff with increasing depth to 108 feet (32.9m) below the ground surface, as measured at the closest boring to the shaft location. Granular soils, consisting of saturated dense silts and sands were encountered beneath the silty clay, alternating with layers of hard gray silty clay to the explored depths of the borings, or to bedrock in those borings in which bedrock was encountered. Highly to completely weathered shale, in combination with sand and gravel, was encountered within the upper 3 to 10 feet (0.9 to 3m) of the bedrock unit.

It should be noted that, due to the mine subsidence experienced in the tunnel, construction dewatering was on-going and drew groundwater table below tunnel invert during the performance of the supplemental geotechnical exploration and the shaft construction. Prior to the start of this construction dewatering effort, the groundwater piezometric level ranged between approximately Elevation 603 and Elevation 615, or approximately 21 to 33 feet (6.4 to 10m) below the ground surface. See Figure 2 below for a geologic profile of the tunnel alignment.

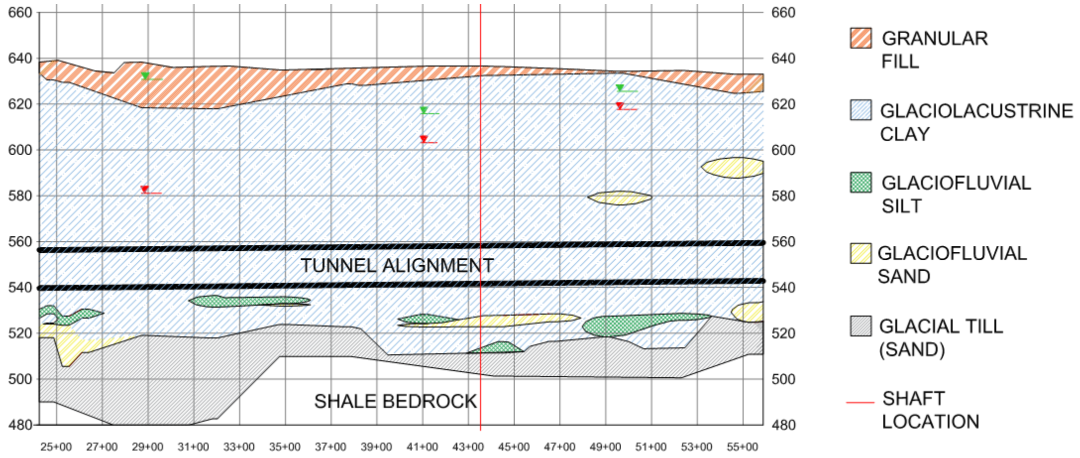


Figure 2 - Subsurface Profile

SITE CONDITIONS

The TBM experienced the damage at approximately ST 43+50 of the tunnel alignment. This placed the TBM directly beneath N Stephenson Highway, which is a local access road running parallel, and just to the east of I-75. The centerline of the tunnel alignment is roughly 75 feet (22.9m) from the edge of I-75, which has two lanes in each direction at this location. There was a 15 feet tall brick sound barrier wall just to the west of N Stephenson Highway, and a 40 foot (12.2m) wide grass shoulder between the wall and I-75.

To further facilitate construction, a portion of the sound barrier wall was removed, and K-rail was placed at the edge of the I-75 shoulder. Despite the project gaining so much valuable work extents, the project would still be considered congested on the best of days. Staging casing, building and storing cages, a BG-50, and sundry support equipment all take up real estate very quickly.

DESIGN

Soon after the incident, the tunnel contractor started working with their rescue team members to develop the most expedient and efficient solution to the challenging problem. The AECOM Structural team developed preliminary designs. The tunnel contractor and Malcolm would provide operational constraints and constructability inputs, and AECOM would revise designs accordingly. The coordination between the three companies rapidly converged on the unique solution that created the required access to the stranded TBM.

Given that the TBM and tunnel final liner damage occurred in a densely populated area, the impacts on engineered structures and other urban edifices was a major risk for the design of a repair shaft. The ground subsidence above the TBM caused a depression which extended to the interstate and prompted a temporary closure of the north bound traffic. In addition, the proximal apartment building, was also within the impacted zone and effected one of the entrances to the apartment complex and the associated parking lot. To limit damage to surrounding existing buildings and infrastructures, a robust approach to both geo-structural analyses of the soil structure interaction and to structural elements reciprocal interaction was undertaken.

Description of the Shaft Structural System

The selected support of excavation system comprised a circular shaft with internal diameter of 55 feet. (16.76m). A ring beam with dimensions of 60 inches X 60 inches (1.5m X 1.5m) was introduced at 67.2 feet below grade (20.5m), 4 feet (1.2m) above the TBM and the existing precast concrete tunnel liner system (PCTL). The circular shaft wall consists of interlocking primary and secondary secant drilled shafts. The shafts extend close to bedrock or are terminated above the tunnel where layout conflicted with the existing PCTL segments. Primary secant piles are unreinforced and are drilled first. Secondary secant piles are reinforced with circular steel cage and are installed keyed into two previously-installed primary piles. The secant piles have a minimum outside diameter of 59 inches (1.5m) and are installed at 41 inch (1.1m), center-to-center intervals, resulting in an overlap of 18 inches (0.46m). On either side of the PCTL, composite cast-in-place oversized secant piles (King piles) embedded in bedrock are required. King piles have a minimum outside diameter of 79 inches (2m) and are reinforced with steel circular reinforcing steel cages and a steel HP 14X117 beam (metric HP360X174). After excavation to shaft subgrade, a 20-inch thick cast-in-place structural concrete slab is required to provide support and bracing while mining through the soft-eye. Figure 3 below shows plan and isometric views of the shaft design.

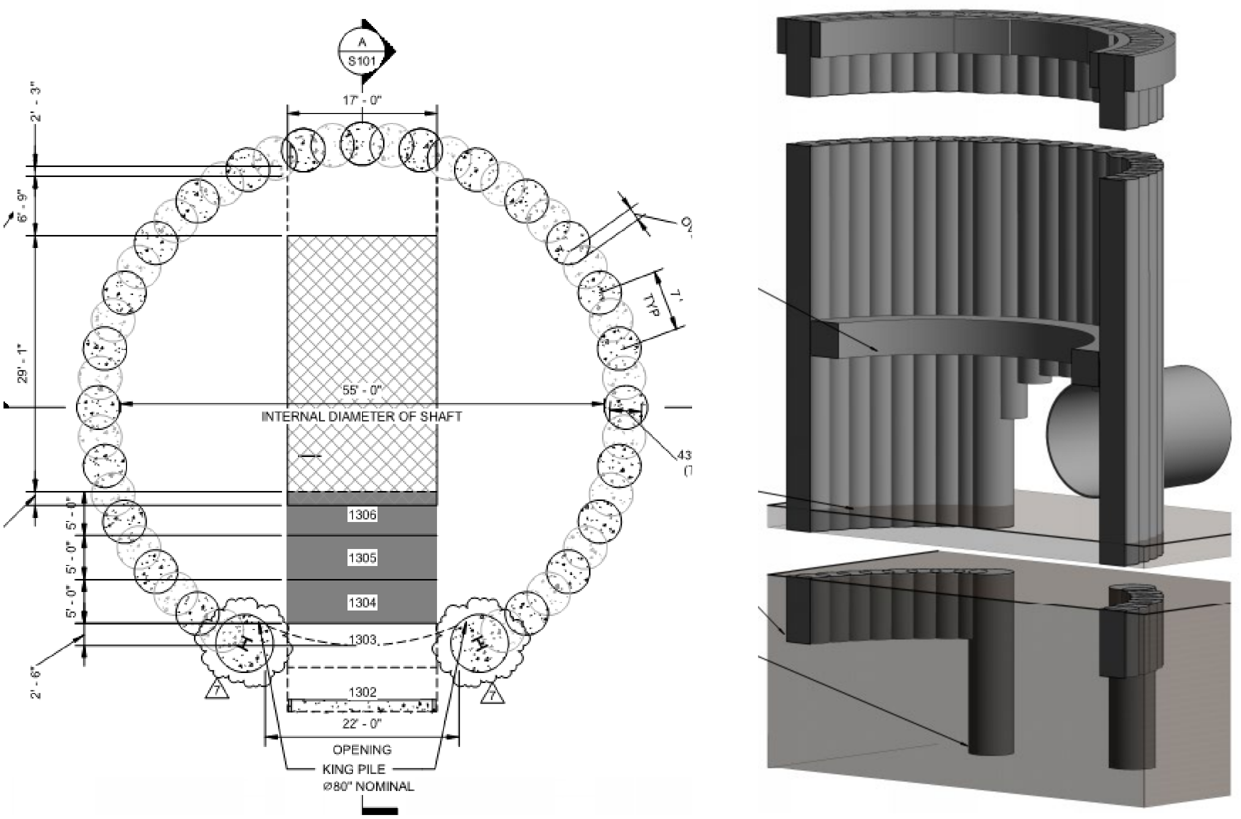


Figure 3 - Shaft Plan and Isometric Views

Three main analysis regimes were instituted to design the complex shaft. Through coordination across geotechnical and structural teams in AECOM, it was agreed to develop an approach that could utilize the soil-structure numerical modeling results provided by PLAXIS while allowing full structural detailing of the various members via a rational load distribution and load combinations in a SAP2000 structural model. Both numerical models are based on the finite element method and the geometry of the structural elements was studied to be fully consistent. Finally, the design of structural members was performed using S-Concrete software and was based on outputs from the SAP2000 model.

Applied lateral earth pressure values were based on the output of the PLAXIS numerical model created by the AECOM Geotechnical and tunnel teams. Lateral soil sub-grade springs were introduced to the shaft with horizontal subgrade modulus values based on empirical equations and soil properties provided by the AECOM Geotechnical team. The PLAXIS model does not consider the ability of shell structural elements to distribute horizontal moments across the unreinforced primary piles after the tensile concrete stresses have been exceeded, but it properly describes the soil/structure interaction and addresses the load transfer from the ground into the structural elements for a variety of construction phases. PLAXIS readily provides net force output which is used for design of the shaft members. However, it does not perform a design check to determine the resulting net stresses on the inside and outside faces of the wall section. Stress output is critical in determining the performance of the primary piles. The limitation of PLAXIS to model the complexity of redistribution of stresses among multiple structural elements, such as between the walls and the ring beam, is addressed with the SAP2000 structural model. See Figure 4 below for selected outputs from PLAXIS and a 3D model view from SAP2000 which will be discussed in subsequent paragraphs.

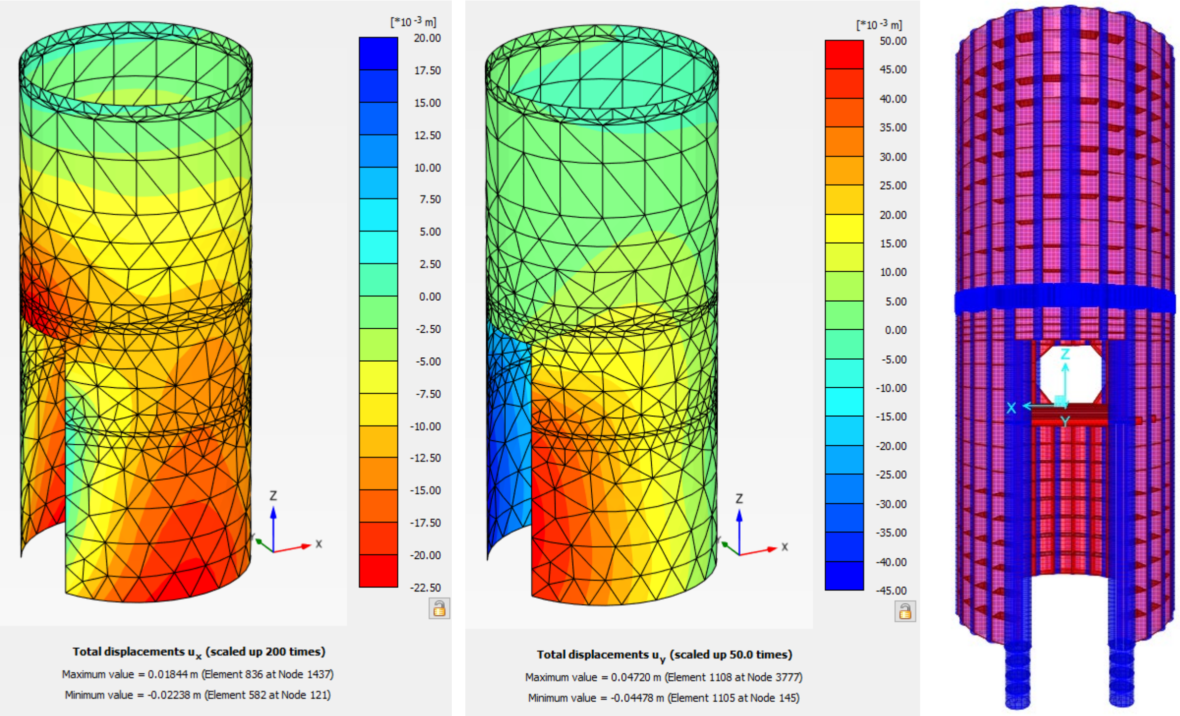


Figure 4 – (a)(b) PLAXIS 3D Model Output (c) SAP2000 Model Frame

Analysis of the structural system was carried out by creating a non-linear elastic frame analysis using SAP2000 software with rational load distribution between structural framing members. Staged construction steps were created in the model. Proposed structural member sizes for the secant piles, ring beam, king piles, and structural slab, as well as their properties, were introduced into the SAP2000 model. King piles and secondary secant piles are introduced as frame elements. The ring beam consists of continuous frame elements and is located 67.2 feet (20.5m) below ground surface. Shell elements simulating the unreinforced primary secant piles were considered to be 42.5 inch (1.08m) thick concrete walls with a compressive strength of 3600 psi (25MPa), and were set up to distribute the soil lateral pressure onto the secondary secant piles in one-way action. A reinforced structural slab at the bottom of the excavation was modeled as a shell element with a thickness of 20 inches (0.51m).

The reinforcing steel design for the king pile, ring beam, secondary secant piles, and structural slab is derived from the force envelope diagrams from the SAP200 and PLAXIS models. In most cases, SAP2000 results were equal to or higher than the results from the PLAXIS model. The reinforcing for structural elements was designed using the reaction forces from SAP2000. For King piles, shear results from the PLAXIS model were used for design of structural reinforcing between El 480 and El. 467 because the shear forces were greater than predicted by SAP2000. Figure 4.c above contains a 3D view from SAP2000 of the shaft structural system, including the secant piles, king piles, ring beam, and structural slab. The reader will note that the soft eye is modeled as an octagonal opening, rather than circular.

Structural Design Using S-Concrete

The structural resistance of the Structural Concrete members was calculated in accordance with ACI-318-14 with a load factor of 1.6 applied to the Lateral Earth Pressure (H) and 1.2 for Dead Load (DL) according to ASCE-7-16. Ring beam, secant piles, and king piles are subjected to combined moment, shear, and axial loads. The structural slab-on-grade, which provides lateral support to the shaft at invert level, is subjected to only axial load. Verification of the adequacy of the concrete compressive strength against hoop stress at the location of interlock between primary and secondary secant piles was completed. Finally, S-Concrete was used to verify the stability of the secant piles above the opening, and check to ensure the concrete in the rock sockets would not be compromised.

CONSTRUCTION

Working Platform

The I-75 access shaft requires 4.90 feet (1.5m) secants and 6.56 feet (2.0m) king piles to extend over 150 feet depth (46m). The Bauer BG50 drilling rig is uniquely capable of handling the size and weight of drill tooling necessary to construct these elements. However, the size and weight of this equipment required careful evaluation to ensure the drill working platform was suitable and stable to manage the imposed operational loading. Further, it was important to verify that any ground disturbance or voiding that could undermine the working platform had been repaired prior to mobilization. Malcolm performed a series of 21 each Cone Penetration Tests (CPT) at the site in order to verify the consistency of subgrade materials and probe for potential soft spots which could have remained after the subsidence event and subsequent remedial grouting. This testing did not identify any data of concern, but since ground investigation is only performed at discrete points, work still needed to proceed with caution.

The ground surface above the TBM subsided in a "crater" fashion as much as 5.5 feet (1.7m). The work platform was constructed by backfilling this area with 9 inch (14cm) thick, compacted lifts of crushed concrete and MDOT 21AA stone, to bring grade to one foot (30.5cm) below top of pile EL. The working platform was then capped with hardwood crane mats for load spread, and a thin layer of compacted sand to provide a clean wear surface. This system was evaluated and determined to have sufficient bearing support for the expected operating pressures imposed by the drilling and concreting operations. See Figure 5 below for depictions of the working pad was constructed.

Figure 5 - Working Platform Construction

Verticality Control

The innovative access shaft design relied on maintaining drilled secant shaft verticality tolerances of less than 0.5% at depths exceeding 150 feet (46m). Secant shafts must be drilled straight and true from ground surface and cannot be steered down-hole during the advance. While secant piling methods have been regularly employed for support of excavations reaching 60 to 80 feet (18 to 24m) depth, it is unusual for this technique to be employed for elements with the depth required at I-75.

All of the secant shafts were to be advanced with temporary sectional casing. The stiffness and rigidity of the casing maintains drilling alignment during advance, and the casing cores into the primary shafts to create required overlap as the secondary shafts are installed. The drilling contractor was engaged to provide guidance during the interactive design process. Based on Malcolm's experience, 59 inch (1.5m) diameter secant piles were selected as the optimum size to minimize the number of elements and construction joints in the secant ring. The size and weight of this casing size helps to maintain alignment during advance, but due to the weight and diameter of the full casing string, a Bauer BG50 drilling rig, the largest production rig currently operating in North America, was required for the operation.

The initial step in verticality control was construction of a reinforced concrete guide wall. As the working pad was constructed, a leveling mat was poured and formwork was braced into inner and outer circles. Slightly oversized Sonotubes were used to form each pile location. The forms were cut, fitted together, surveyed to ensure accuracy and then fixed in place. Reinforcing steel was placed between the Sonotubes and the formwork and then the trench backfilled with structural concrete. The guide trench enables secant shafts to be located within 1 inch (2.5cm) of design location at ground surface. Figure 6 below shows Guidewall construction.

Figure 6 - Guidewall Construction Details

The key to successful secant installation is to ensure the shaft is started straight, since the rigid steel casing effectively maintains its direction. The rig mast can be plumbed using built in inclinometers, however the most critical measure is actual casing alignment. The digital level is the tool of choice for field control of casing alignment. The operators ensured that casing was within 0.1 degrees of vertical in all directions at start of advance. The casing alignment was repeatedly checked and adjusted at grade using the drill rotary attachment during advance. After casing was advanced to between 60 and 80 feet (18 to 24m), a downhole verticality measurement using sonic caliper or SHAPE tool was performed to verify verticality was within tolerance, and once confirmed, casing advance was continued to designed depth. The as-built alignment was surveyed after completion of drilling using a sonic-caliper to confirm construction met tolerance requirements. Figure 7 below shows a Sonic Caliper report from a 6.6 foot (2m) king pile, confirming that verticality of less than half a percent is achievable.

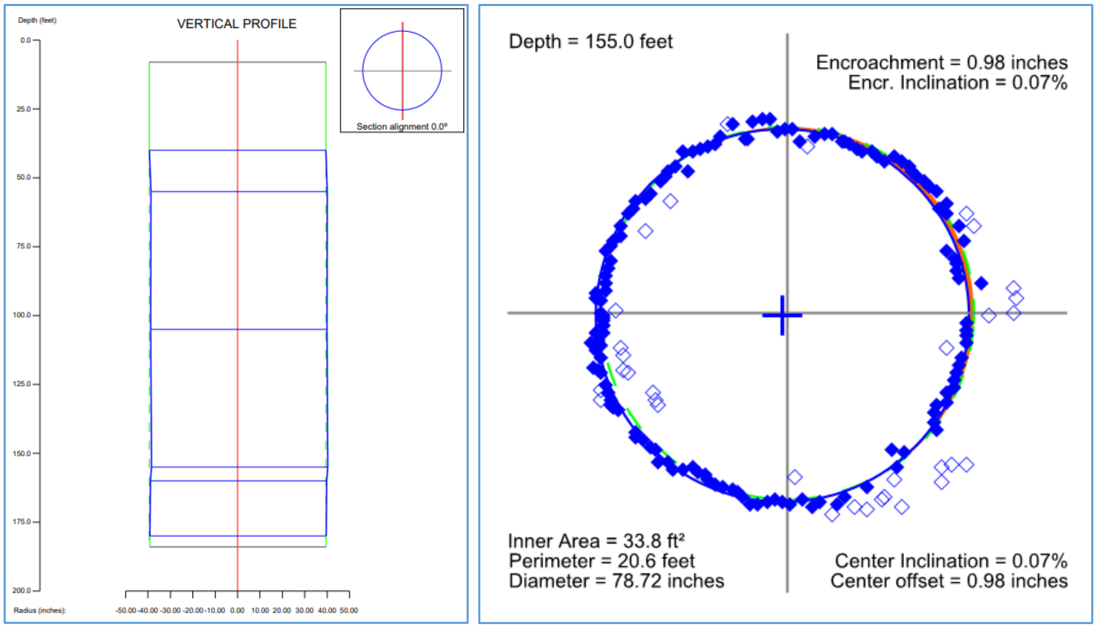


Figure 7 - King Pile Sonic Caliper Verticality Report

Concrete Strength Control

The primary shafts are constructed in native ground which generally has uniform radial characteristics. In contrast, the secondary piles cut into and overlap the previously placed primary elements. It is more challenging to maintain verticality in the secondary elements since there is a non-uniform drilling condition with concrete on two opposite sides of the shaft and softer soil on the remaining perimeter. The secant operations were planned to ensure that secondary piles were cut into two adjacent elements with similar strengths in order to avoid the casing being pushed preferentially in one direction by harder concrete. Specific to this project, the King Piles required construction cutting into concrete on only one side of the shaft. Exceptional care was required to ensure these shafts could be constructed without excessive deviation due to the unbalanced drilling condition.

In order to assist with secant construction, Malcolm aimed to limit early strength gain in the concrete and sequence work such that secondary shafts could be constructed within the period of 3-5 days after the adjacent primary elements were placed. A series of trial batches were performed with variable additive doses in order to limit strength gain during this target construction window. Figure 8 below shows typical strength curves for the tremie concrete mixes used for primary and secondary shafts.

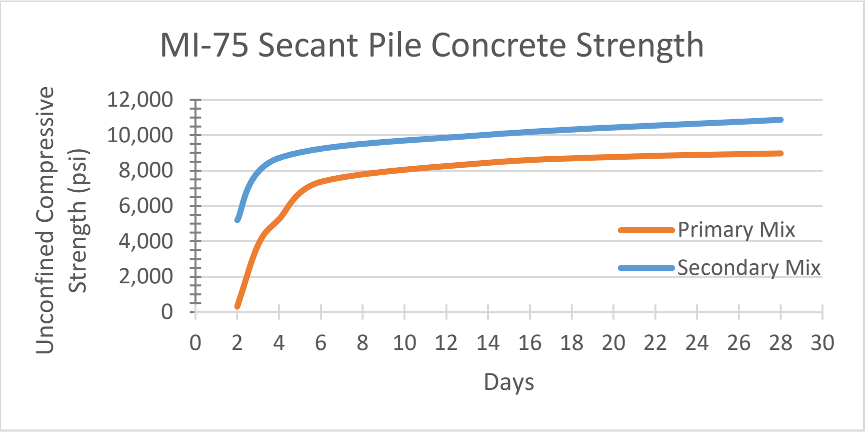


Figure 8 - Typical Secant Concrete Strength Curves

Excavation, Reinforcing Cages, and Concrete Placement

The secant shafts were fully cased to mitigate concerns associated with verticality, potential voids, and damage to surrounding structures. Casing was advanced with the rotary head of the BG-50, and overburden was removed with various augers and buckets. For the two king piles, bedrock sockets were completed using progressive rock augers and roller bits. See Figure 9 below for a picture of a drilling method used on site.

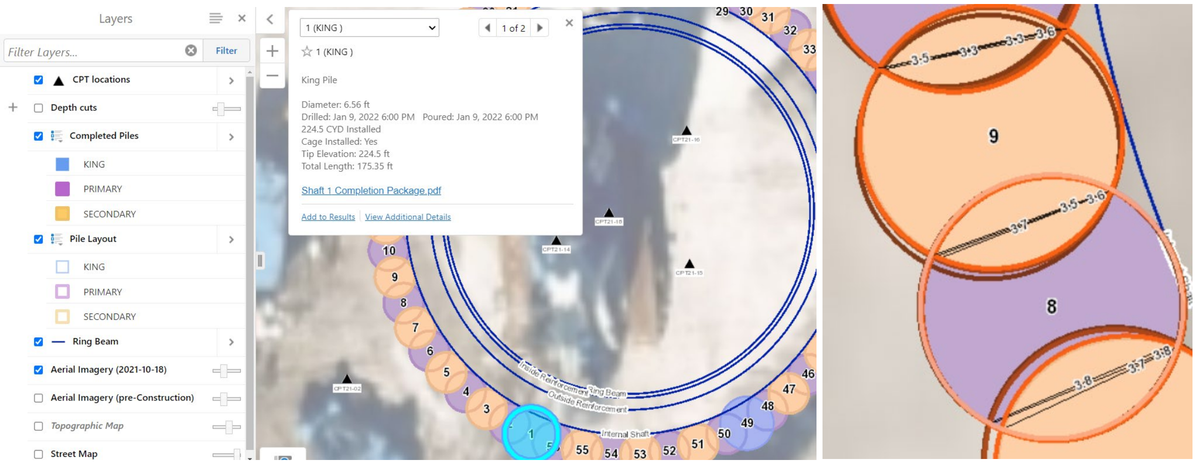
The size, complexity, and variability of the cage designs required careful attention. Large shear forces required heavy lateral reinforcement which went through multiple iterations of design to meet the loading demand, while ensuring that there were large enough windows to allow free flow of the tremie concrete. Splicing cages over the hole was chosen as the method to place cages with lengths of over 100 feet (30.5m). In order to allow the TBM to exit the shaft after completion of repairs, composite cages were constructed with fiberglass reinforcement for partial lengths across the soft eye. See Figure 9 below for an examples of a composite cage being lifted on site.

The most critical operation in the construction of a drilled shaft is the placement of concrete. During concreting on a cased drilled shaft, many moving parts that need to be coordinated with precision to ensure a smooth operation. Pulling casing, monitoring fluid and concrete levels, hanging cages, breaking lines and more need to be synchronized. On this project, Malcolm elected to utilize a boom truck to deliver fluid concrete to the tremie and to extract casing with Leffer Oscillators. Figure 9 below shows a picture of the concreting operation on site.

Figure 9 - Excavation, Composite Cage Placement, and Concreting

GIS Database

There were numerous data streams that were relevant to the project teams. With this in mind, Malcolm teamed with Geosyntec to create an interactive project map. All relevant pile production information, pile quality control information, preproduction CPT data, and more was built into a real-time project map. Using the information from the verticality surveys, a minimum pile overlap tool was developed to instantly devise if two proximal piles had met the verticality and minimum overlap requirements. Screenshots of the map and tool can be seen in Figure 10 on the following page.



1 (KING)

King Pile

Diameter: 6.56 ft
Drilled: Jan 9, 2022 6:00 PM   Poured: Jan 9, 2022 6:00 PM
224.5 CYD Installed
Cage Installed: Yes
Tip Elevation: 224.5 ft
Total Length: 175.35 ft

Shaft 1 Completion Package.pdf

Add to Results | View Additional Details

Figure 10 - GIS Screenshots

INSTRUMENTATION AND PERFORMANCE

There were very real concerns that movements of the shaft structure could lead to unacceptable external impacts. Various instrumentation methodologies were employed to monitor the shaft and surrounding structures. The most compelling data on the performance of the shaft design and construction is the proximal inclinometer data which showed a maximum lateral deflection of just under one quarter inch (6.3mm), at the top of the shaft after being fully excavated.

CONCLUSION

At the time of writing, the once stranded TBM has been fully exhumed and replaced with a new unit set to finish the tunnel. The timely execution of planning, design, construction and commission speaks to the effective collaboration of the tunnel contractor, designer, and drilling subcontractor. The efficient accomplishment of this novel challenge could only have been achieved through inclusion of the full project team throughout the planning, design and execution. From the moment it was stranded to the day the final element was installed in the shaft system, the TBM had an escape route in less than six months.