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SHAFT CONSTRUCTION METHODS COMPARISON

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ABSTRACT:

Shafts are the bottleneck of tunnelling logistics when it comes to moving spoil, products and equipment in and out the tunnel. The choice of a shaft's temporary ground support method can have a significant impact on a tunneling project's cost and program. This paper will address the key differences between the most prominent temporary ground support methods adopted within the industry and explore how they can be assessed against each other to ensure efficient, viable and economical selection decisions are made.

1. INTRODUCTION

As tunneling construction becomes increasingly popular within the Greater Toronto Area (GTA) as a low impact method across a growing range of industry sectors; the pursuit for safer, cheaper, quicker and more flexible temporary ground support systems has intensified. Fundamental to shaft design and construction is the method of temporary ground support. Prominent methods of temporary ground support in the Greater Toronto Area includes secant piling, sheet piling, diaphragm walls, jet grouting, slurry walls, ground freezing, and/ or shotcrete. The selection of the method across a wide range of criteria in the early stages of a project is critical to the overall project success.

This paper will present a quick reference guide which can be applied to the selection of temporary ground support methods within the Greater Toronto Area. The reference guide will include the available market technologies within the area, and refined selection criteria applicable to tunnelling projects including safety, cost, program, local experience and social impacts as the main components. The quick reference guide will center on a qualitative evaluation procedure that can be used to quickly and efficiently lock in the temporary ground support method. The output of the quick reference guide will include a summary of the advantages and disadvantages of each of the methods and a unit cost rate for each method that can generally be used by asset owners and design engineers to plan projects.

2. SHAFT CONSTRUCTION METHOD SELECTION CRITERIA

Not only does each tunneling project have its own unique characteristics, but each proposed shaft within a project will have its own individual characteristics and conditions. This unique set of characteristics and conditions will dictate the selection process of the temporary ground support method. At present, it is common industry practice for clients to transfer the design responsibility and risk of temporary ground support structures onto the Contractor. This is typically carried out due to the temporary nature of the structure and the absence of stringent client functional requirements.
Contractors will typically transfer the design responsibility and risk of temporary ground support structures to a specialized design consultancy firm who will complete the required calculations, drawings, specifications and design reports. However, in practice, the selection process to lock in the temporary ground support method is typically a highly consultative and combined effort between the Contractor and the Designer, which is highly scrutinized by the Clients Representative. This selection process will typically be based on a set of factors including, but not limited to the following:

- Functional requirements / purpose
- Required shaft depth
- Shape and geometry of the shaft
- Subsurface geotechnical/ hydrogeological/ and environmental conditions
- Available shaft compound and working areas
- Adjacent third party assets (surrounding structures, underground utilities, overhead utilities)
- Adjacent and direct surcharge loadings (traffic & jacking thrust forces)
- Allocated budgets
- Timeline and schedule requirements
- Local Contractors / Designers experience and capability
- Local bylaws
- Client & stakeholder requirements

All of the above factors are critical in selecting a temporary ground support method. Subsequently, the greater the understanding into each of these factors, the more optimal the solution will be for each of the relevant stakeholders. Each of the above factors will be discussed further in the following sections.

Shaft Function:

Temporary ground support shafts are required for a wide range of engineering applications. Specification of the functional requirements of the shaft will dictate specific requirements for the shaft's geometry, depth, and space proofing, and subsequently the shaft's temporary ground support method. In respect to tunneling projects, temporary ground shafts may be required for the launch and servicing of a TBM, intermediate TBM maintenance, or for TBM retrieval.

A TBM launch shaft will typically require a relatively larger shaft area to cater for the thrust frame, surveying equipment, ventilation plant, spoil handling equipment, services and extra safety equipment. In addition, a TBM's launch procedure may also require space for a thrust (or push) frame, cutterhead access, front stationary and trailing shields, a launch eye seal to hold back groundwater/slurry and trailing gantries. Typically, the larger the shaft the more significant structural capacity required. In addition, the temporary ground support will need to be able to resist the anticipated thrust loads sufficiently to avoid unsustainable deflection.

TBM maintenance shafts will require significantly less space to allow quick and cheap access to the TBM cutterhead for the purpose of cutter inspections, maintenance and replacements; and TBM retrieval shafts are typically space proofed based on the absolute minimum area required to detach, connect and safely lift the

TBM. Smaller diameter circular or ovular shafts will require less structural capacity to be provided by the temporary ground support.

Where applicable, the proposed permanent application will influence the choice of the temporary ground support. For stormwater and wastewater projects, temporary ground support shafts are typically coupled with permanent access manholes, valve and inspection chambers and pump stations. For transportation projects, temporary ground shafts are typically coupled with underground stations or vent stack structures.

The specification of permanent structures can have a significant impact on both the depth and space proofing associated with temporary ground support shafts. This notion is complicated by the fact that commonly these structures are designed by the client's own design engineers creating significant interface and design assumption issues.

Shaft Depth:

The depth of the proposed shaft is a critical determinant in the feasibility of a temporary ground support method. For the range of piled ground support options, the allowable maximum depth will be dictated by the limitations of the available plant and machinery. For the range of soil support shaft options, the deeper the shaft gets the greater the degree of external loading which is required to be suspected. For significantly deep soil support shafts, the ground support methods such as shotcrete, timbers and lagging will not likely to have the required level of structural capacity.

Shaft Shape and Geometry:

Typically shaft shapes include circular, ovular and a range of rectangular shapes. Circular shapes are typically adopted in soil support shafts in order to efficiently transfer the ground loading onto the shaft support into axial compression of the shaft lining. Typically these shafts require less lateral bracing and reinforcement. Oval shapes are typically adopted for deep shafts in order to save excavation time, spoil disposal costs and backfill costs. Rectangular shafts are typically adopted when the length to width ratio makes the option of circular or ovular unfeasible or uneconomical.

Geotechnical and Hydrogeological Conditions:

The anticipated geotechnical and hydrogeological conditions are the most significantly influential factors on the selection of the temporary ground support method. Whether the shaft is in soil or rock, is dry or wet, is stiff or loose, is massif or highly fractured, will directly influence the degree of structural capacity required, the degree of accessibility for excavators and personnel and the capacity of the plant and equipment required.

For this reason, the geotechnical and hydrogeological conditions and associated interpreted parameters need to be adequately investigated in order to be able to plan, design and construct the temporary ground support shaft with an acceptable level of confidence.

Key hydrogeological characteristics such as the level of the groundwater and the degree of permeability are critical. For undrained shafts, the prevention of instability due to buoyancy and structural capacity is paramount. For drained shafts, the prevention of excessive or unmanageable groundwater infiltration or shaft instability due to piping is paramount. All of these issues must be addressed when specifying the temporary ground support method and the specific design elements.

Project Schedule:

The allowable degree of time available for a shafts construction will influence the selection of the temporary ground support method. For soil support shafts, the installation of sheet piles is significantly quicker than the lengthy installation of hard and soft secant piles. For rock support shafts, the installation of timbers and lagging is relatively swifter than the installation of rockbolts and shotcrete.

Cost:

Cost is generally a critical factor in the decision making process of the shaft construction method. The method of ground support is usually designed to act as a temporary structure with significantly shorter design life (durability) requirements than that for permanent structures. Therefore, Contractors will always seek cost effective design solutions when selecting between the feasible methods of shaft support. Once the temporary ground support method options are shortlisted, the labor, equipment and material costs for each method will be assessed in order to produce a direct comparison and determine the most cost effective option. For projects which require a significant number of similar shafts, there is potential for significant economies of scale.

Local Contractor's Experience:

The local construction industries plant, capability and experience have a significant impact on the construction selection methods. Local Contractors who have been constructing shafts in the region for a significant period of time will have acute knowledge of how the geotechnical conditions will perform under different construction processes and will therefore be more comfortable with certain shaft construction methods over others. This factor also feeds into the cost element as Contractors who are highly experienced in a certain method will deliver that method more cost effectively than adopting a new method regardless of any subtle feasibility issues. In addition, the ability of a Contractor to access equipment and specialized personnel will significantly dictate their decisions.

Clients' Requirements

Each shaft location will operate within a unique set of conditions and constraints, including local municipality bylaws; third party surface, subsurface and overhead asset restrictions and natural feature limitations, etc. These factors are typically assessed by the client's engineer as part of the permanent works, however where there is no obvious solution it is often left to the Contractor to navigate through. The course of navigation is typically guided by the contract documents and specifications.

For example, where shafts are required to be constructed in the middle of a highly urban location, high vibratory equipment is typically not allowed in order to minimize construction noise and vibrations. This restriction will eliminate the use of temporary support methods which rely on vibratory elements such as sheet piles etc.

Similarly, where a shaft is required to be constructed in an area that uses a well based water supply system, active dewatering is typically not allowed as it may impact the groundwater supply volume and quality. In such cases watertight (tanked) ground support methods are typically specified.

3. SHAFT CONSTRUCTION METHODS

Each shaft construction method has a series of advantages and disadvantages when evaluated against the full spectrum of selection criteria. This next section provides a discussion on the temporary shaft ground support methods commonly adopted for tunnelling projects and presents an example where each method was used temporary.

Secant Piling

Secant piled shafts incorporate a series of overlapping circular alternating reinforced and unreinforced concrete columns which combine to provide a watertight and structurally robust shoring support for medium depth excavations. The construction of secant piles involves the use of a Continuous Flight Auger (CFA) drilling rig to excavate the pile opening and simultaneously pour concrete. The reinforcement is then pushed down through the concrete immediately after placement in the form of a rebar cage or a steel beam.

This method is limited in regard to the maximum depth that can achieved due to the verticality tolerances associated with pile installation and the subsequent ability to maintain water tightness. Typically, the maximum depth for secant piling is between 20 and 25 meters. Secant piling is expensive due to the nature of the specialist drilling rig, however it can provide a heavily robust structurally solution and a reliable watertight barrier which can easily accommodate a wide range of different shaft shapes and sizes. Secant piling can be used in combination with other methods to combat mixed ground shafts. Commonly, secant piles are used to toe into a lower rock material prior to continuing with a cheaper and quicker rock support method.

The secant piling temporary ground support method is often used in the GTA area for tunneling shafts. On the York Region’s southeast collector trunk sewer project located in Ontario, Canada, the majority of the temporary shafts were constructed using this method. The key advantages of this method includes it's feasibility in most ground conditions; it’s relatively rapid installation time in comparison to other methods and relatively small working area requirement. Figure 1 below presents an example of a temporary shaft (Shaft No. 6) where secant piling was used in combination with shotcrete.

Figure 1 Southeast Collector Trunk Sewer Shaft No. 6

Two adjacent circular temporary shafts No. 6 and No. 7 were used as launch and retrieval shafts respectively on the south east collector project. Shaft No. 6 was ~13 m in diameter and 33 m deep with the upper 20 m in non-plastic (sandy silt to silty sand) till and the lower portion in plastic (clayey silt to silty clay) till. Shaft No. 7 was 8 m in diameter with a depth of ~18 m within the non-plastic till layer. Groundwater was 1.5 m below the surface level. The shafts typical cross section within the geological profile is shown in Figure 2.

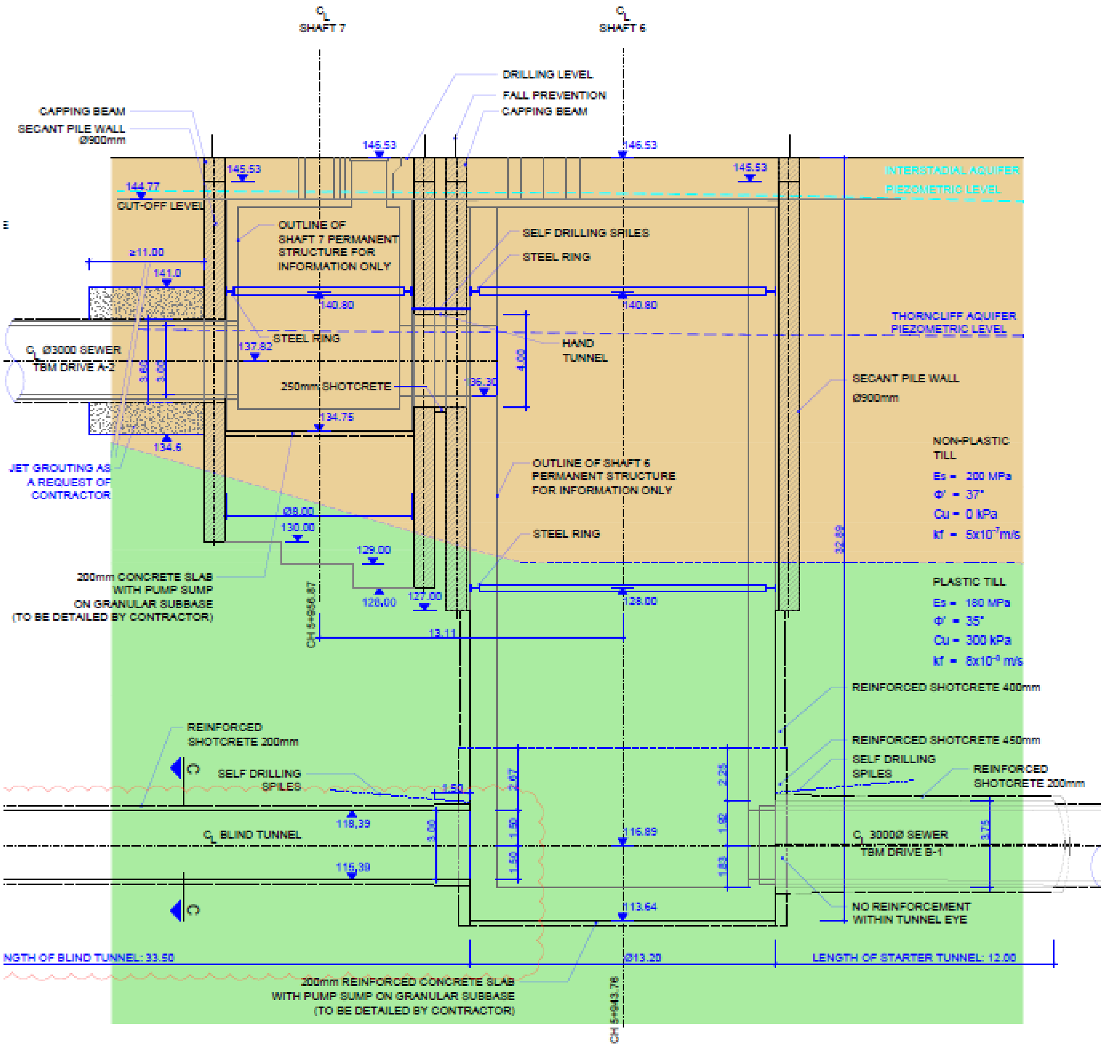

Figure 2 Southeast Collector Shafts No. 6/No. 7 Secant Pile Shaft Design

For Shaft No. 6, secant piling was used for the upper non-plastic till layer, and shotcrete was used for the lower portion. For Shaft No. 7, secant piling was used for the full depth. This method was suitable for these two shafts due to the following conditions:

- Limited working space as the site was crowded with different construction activities.
- Active dewatering was prohibited in order to limit the impact on the groundwater level. Secant piling provided a watertight solution.
- A tight project schedule. The secant piling program was shorter and with less risk compared to the other feasible methods.

Sheet Piles

Sheet piling is a common shaft shoring method in the GTA. Sheet piles are interlocking steel sheets driven or vibrated into the ground via a drilling rig. The sheet piles are interlocked in order to form watertight joints as well as a means to distribute the ground loading. Internal waler ring beams or with tie backs can be used to brace the sheet piles at intermediate locations along the depth of the shaft. In some cases, predrilling will be required to break through anticipated hard or stiff conditions in the path of the sheet piles.

Sheet piles can be used to achieve a variety of shaft shapes and sizes; however with a limited angle of rotation sheet piles are not able to achieve small diameter circles.

The main disadvantage of this method of temporary ground support is the significant noise and vibration impacts on the surrounding environment. Figure 3 below presents an example of a sheet piled shaft used as a retrieval shaft on the Woolloongabba Trunk Sewer Upgrade project in Brisbane, Australia.

Figure 3 Woolloongabba Trunk Sewer Upgrade Retrieval Shaft

The following challenges were faced as part of the shafts design and construction planning:

- A split level permanent structure to be built inside the shaft
- Existing sewer pipes through the shaft had to be kept fully operational until cut over
- External groundwater
- Overhead power lines
- Soft alluvium silty clay & gravel bands
- Immediately adjacent roads required to be kept operational

Sheet piles were selected with an internal steel frame bracing as shown in figure 4 due to the following reasons:

- High capacity to resist the soft soil, groundwater and traffic surcharge loadings
- Selected piles able to be held up over the top of existing sewer pipe
- Quick installation
- Efficient for a square footprint
- Piles installed via a specialized low cover rig to avoid the power lines
- A relatively cheap price due to access to recycled piles which were reused afterwards
- No jacking forces required to be resisted

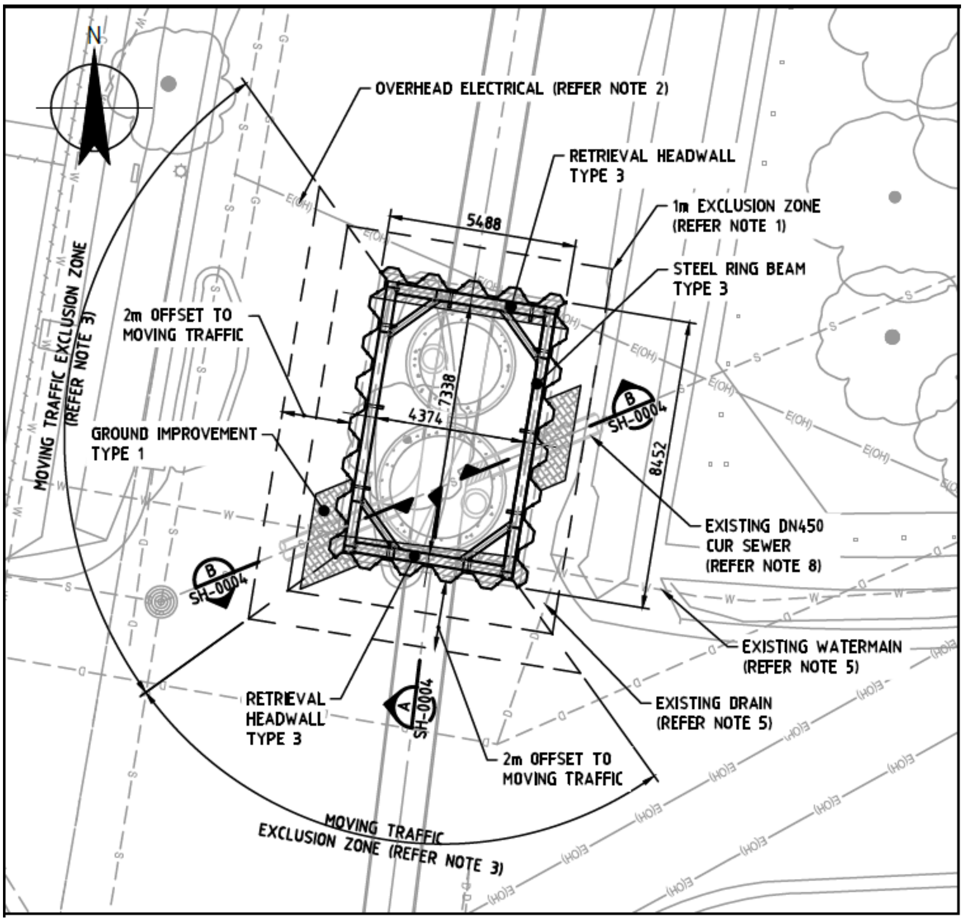

Figure 4 Woolloongabba Trunk Sewer Upgrade Sheet Pile Shaft General Arrangement

The performance of the sheet piles included a relatively rapid installation program, the void around the existing sewer was made water tight via ground improvement and leakage through the void reduced to a very manageable level, the convergence movements were insignificant and time and costs were avoided due to avoiding the need to relocate the powerlines.

Diaphragm Walls

Diaphragm wall installation commences with the construction of a concrete guide wall which spans both sides of the proposed wall alignment.. The purpose of the guide walls is to provide an accurate reference point for the excavation, the maintenance of verticality and the provision of a stable platform for a range of temporary construction activities. After the guide walls are installed, a clamshell grab or hydromill would typically be used to excavate the rectangular panels which are continuously stabilized by the application of a bentonite slurry mixture. After the slurry panel is fully excavated and filled with slurry, a reinforcement cage would be installed and concrete is then poured in to replace the slurry mix using tremie pipes. Multiple primary and secondary panels are constructed to form the interlocking watertight perimeter of the shaft. Similar to the process of secant piling, verticality must be maintained in order to achieve the structural capacity requirements. Figure 5 below shows the excavation of a diaphragm wall using a clamshell grab on the south east collector project.

Figure 5 Diaphragm Wall Construction on the Southeast Collector

Diaphragm walls were used on the Southeast Collector Project as the temporary ground support method for Shaft No. 4W, which was a retrieval shaft for the TBM drive from Shaft No. 1. The shaft was designed as a polygonal shape with a depth of approximately 40 m. The soil conditions ranged from low to medium plasticity silty clay till to non-plastic sand silt till. The diaphragm walls were embedded into the bedrock to provide a watertight barrier against the flow of groundwater. Figure 6 below shows the layout plan of the diaphragm wall shaft. One of the key challenges encountered included the intersection of significantly sized rock boulders (or floaters) during the excavation. The removal of the boulders resulted in localized zones of over excavation and the subsequent ballooning of excess concrete in the walls. This excess concrete on the inside face was required to be removed during the excavation of the shaft. In addition, the shaft construction experienced significant environmental control issues due to the frequent spillage of slurry around the working areas surface.

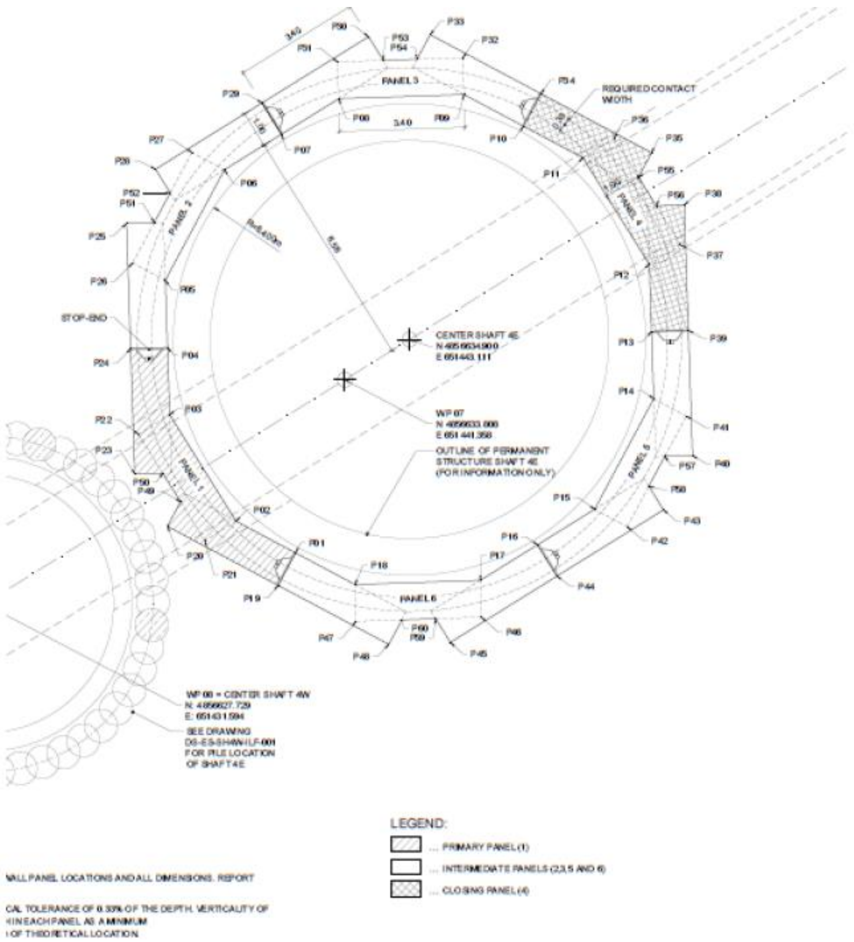

Figure 6 Southeast Collector Shaft No. 4 General Arrangement

Ground Freezing

Ground freezing is a temporary ground method which relies on the formation of a frozen soil wall around the perimeter of the shaft. The frozen wall acts as an impervious block to prevent water inflow and has sufficient structural strength to retain the ground and hydrostatic pressures. The freezing of the soil is achieved by the installation of a series of pipes drilled around the excavation perimeter which circulate brine in order to remove the heat energy from the ground material.

Different soil characteristics will inherently interact differently during ground freezing processes. Granular materials typically achieve sufficient strength at 20 degrees Fahrenheit whereas plastic clay materials can requires below zero temperatures and thicker wall thicknesses to achieve comparable strength characteristics. Ground freezing is an effective solution in challenging situations. On the Southeast Collector Project, Shaft No. 11 was 4.65m in diameter and approximately42 m deep within very hard soils ranging from plastic till to non-plastic till and was exposed to three aquifers. Active dewatering was not allowed for this particular shaft in order to avoid any impacts on the groundwater which serviced some of the neighboring groundwater wells.

The proposed temporary shaft ground support method for Shaft No. 11 included a preliminary slurry wall around the outer perimeter of the shaft down to the base of the shaft. The shaft was then to be excavated with routine shotcrete layerings. However, due to the significantly hard soils and the presence of a large number of boulders, the late decision was made to terminate the slurry wall construction at a depth of 20 m and opt to an alternative more flexible method. Subsequently, this late change forced the construction of this shaft to be the critical path on the project schedule.

Ground freezing was selected as the replacement method on the basis that it would provide the required level of groundwater control and structural support without the need for active dewatering. It was also assessed as a relatively rapid method which would assist the tight program constraints. The ground freezing subcontractor worked very closely with the general project Contractor to assess the loading conditions and prepare the ground freezing wall design. Equipment mobilization, commissioning, testing and installation of freeze pipes took approximately 8 weeks. Figure 7 below shows the freezing equipment and pipes installed around the shaft.

In summary, the key challenges faced during the planning of the shafts design and construction included harder than expected soils, tight restrictions on active dewatering and very significant time constraints.

Figure 7 Southeast Collector Shaft 11 Ground Freezing Setup

The performance of the ground freezing was very positive. The excavation and shotcreting of the shaft down to a depth of 28 m was able to commence as soon as the freezing pipes were installed and did not need to wait for the wall to freeze. This was because the soil in this zone was sealed by the preliminary slurry walls. Excavation beyond the 28 m depth required the formation of the frozen wall where the characteristics were verified with the use of temperature cells and piezometers. One of the key issues identified during the construction of the shaft was that the shotcrete ring positioned in the top 28 m was subjected to unexpected levels of squeezing pressure from the frozen wall formation. This pressure resulted in significant cracking issues in the shotcrete ring which was resolved by increasing the temperature of the frozen wall in order to limit the exerted pressure.

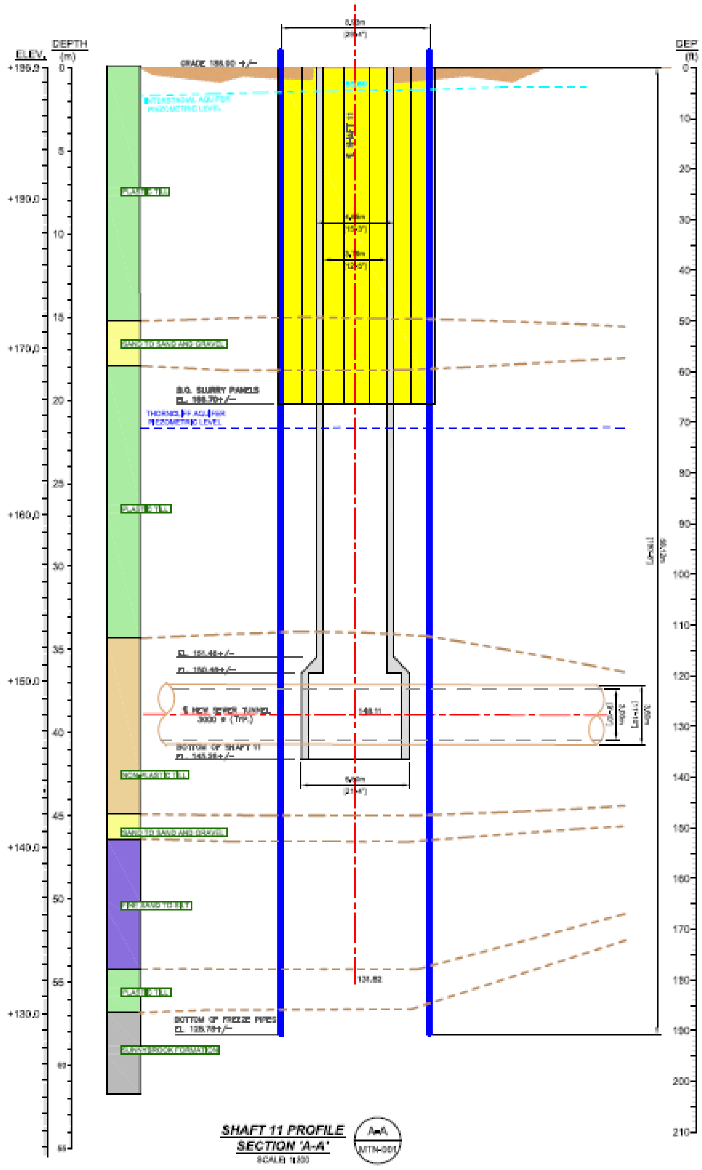

Figure 8 Southeast Collector Shaft No. 11 Ground Freezing Design

On the same project, Maintenance Shaft No.1 was located within an existing hydro corridor. The existing hydro lines had a designated exclusion zone which could not be encroached on by any plant or machinery. Subsequently, the use of large equipment such as drill rigs was not able to be employed. Ground freezing was therefore again selected and provided a successful solution to the constraints.

For tunneling shafts, the key advantage associated with ground freezing is that it is very successful at forming a sealed TBM entry block where groundwater flow is controlled. Ground freezing is also considered an environmentally friendly method as it is not associated with any level of ground contamination.

4. Temporary Ground Support Methods Comparison

The following summary table has been prepared as a quick reference guide to be used to compare the four prominent shaft construction methods discussed in the previous sections against the key design criteria identified.

	Secant Piling	Sheet Piling	Diaphragm Walls	Ground Freezing
Depth	An approximate depth of 25 m can be achieved by this method.	An approximate depth of 21 m can be achieved by this method.	An approximate depth of 60 m can be achieved by this method.	An approximate depth of 600 m can be achieved by this method.
Shape and Geometry	Offers significant flexibility in the shape adopted. Circular shapes are typically more economical as less bracing is required.	Well suited for rectangular shaped shafts due to the restrictions associated with the connection arrangement. Only large diameter circular shafts are achievable.	Any shape which can be made up of a series of straight section panels. Diaphragm walls have been used as permanent structural elements.	More suitable for circular shapes to avoid significant bending action and the formation of tensile forces.
Geotechnical / Hydrogeological Conditions	Suitable for most ground types. Provides effective water tightness. Depth of pile below the shaft base to be designed to avoid instability and groundwater piping.	Most suitable for alluvial materials. Pre-drilling may be required where large cobbles and boulders exist. The interlocking joints provide water tightness.	Excavation is challenging in very hard clay and very dense sands. Water tightness is achieved through the interlocking end joints of the individual wall panels.	Suitable for any type of soil. Groundwater must be present in order for the method to work as the bond between the soil particles forms the binding agent.
Cost	> $1400/m^2	> $500/m^2	> $2000/m^2	Most expensive method. Around 50% to 100% higher cost than other methods.

Duration	Low program risk due to robust nature of the technology.	Relatively rapid installation, however reliant on suitable soils and no unexpected obstructions.	A relatively time consuming process due to the need to first install a guide wall, the nature of the excavation and the need to dismantle the guide wall prior to installing the capping beam.	Will vary depending on the shaft area. Smaller areas will take 6 - 8 weeks while larger shafts will take up to 12 weeks (plus mobilization and installation of the freezing pipes.
Limitations	Verticality of piles hard to maintain as the depth increases.	Significant vibrations which need to be considered in the planning process. Risk of intercepting underground obstacles must be carefully assessed.	Requires a relatively large area for equipment setup. Environmental measures critical to controlling slurry spillage.	High costs. Contractors are typically not experienced with ground freezing methods and that tends to create issues in the launch and retrieval of TBMs.

5. Summary

A broad and thorough understanding of each project and site's specific characteristics and conditions is crucial to the successful decision making process when selecting a temporary shaft ground support method. Specifically, a detailed understanding into the shaft's depth requirements, geotechnical and hydrogeological conditions, shape and size restrictions, available budget and duration, is required.

The shaft's function discussed in section 2 will determine the required depth, shape, and geometry of the shaft. The geotechnical and hydrogeological conditions will be investigated through borehole drilling, in-situ and lab testing and studied based on available geotechnical investigations reports. Project's specific conditions and restrictions will be assessed and considered in the decision making process. After that, the contractor will carry out a detailed cost estimate considering available resources and project program to select the suitable temporary support method.

As shown in section 4 of this paper, a variety of watertight shaft support methods is available within the Greater Toronto Area. A comparison table is presented in section 4 showing each method's limitations against each of the criteria discussed in section 2. This table can be used as a quick reference guide for determining the suitable shaft temporary support method.