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Optimizing artificial ground freezing design for cross passage construction: Construction and practical considerations

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ABSTRACT: Artificial Ground Freezing (AGF) is a favoured method for temporary ground support in cross passage construction between tunnels in soft soils, noted for its structural stability and water tightness. This paper addresses a notable gap in AGF optimization from a construction perspective, by delineating critical design considerations. The design of AGF's configurations range from dual-sided with standard collars to minimal collar, each influencing pipe length, number, and installation angles. Reducing collar height optimizes these variables, decreasing both material costs and project duration. Lining type selection is crucial, with considerations extending to spatial constraints posed by traditional reinforced concrete segments. Steel linings can be proposed as an alternative, facilitating improved load transfer and minimizing internal temporary support for spaceproofing. The use of nitrogen as a freezing agent, offering substantial reductions in freezing time compared to brine, is evaluated against safety risks and cost. The goal of this paper is to present a comprehensive framework for integrating design considerations for AGF, and discuss their practical implications in a construction context.

1 INTRODUCTION

Artificial Ground Freezing (AGF), a technique pioneered in Germany, has become a versatile solution for ground stabilization in various engineering projects. The core principle of AGF involves extracting heat from the soil, lowering its temperature below the freezing point of interstitial water. As this moisture freezes, it acts as a binding agent, effectively cementing soil particles together and creating a robust structural network within the soil mass.

The AGF process is implemented through a system of freezing pipes strategically installed in the target area and circulate a cryogenic liquid through these pipes. This process creates cylindrical frozen zones around each pipe, which gradually expand and merge to form a continuous, self-supporting, and impermeable frozen body.

While significant research exists on the thermal and structural behaviour of AGF, there is limited guidance on optimizing its design during construction. Existing studies primarily focus on freeze wall development and frozen soil strength. However, the design optimization for pipe arrangements and interdisciplinary collaboration remains underexplored. These gaps can result in conservative and cost-inefficient designs. This paper aims to address the gap in the literature by presenting an integrated design framework for AGF in cross passage construction. The focus is on practical considerations that influence geometry and time optimization, including freezing pipe arrangements and lining design. The objectives are to propose a design framework for AGF that balances safety, cost, and construction time and provide a decision-making framework that integrates multidisciplinary inputs for AGF design optimization.

2 CROSS PASSAGE CONSTRUCTION WITH ARTIFICIAL GROUND FREEZING

AGF plays a crucial role in the construction of cross passages between bored tunnels, particularly in challenging subsurface conditions. Cross passages are essential safety features in modern twin tunnel designs, providing emergency escape routes between tunnels (Murray & Eskesen 1997). There are different methods for cross passage construction. The paper focuses on developing an integrated design framework for a Sprayed Concrete Lining (SCL), also known as shotcrete primary lining with a sheet membrane for waterproofing, followed by cast-in situ reinforced concrete secondary lining.

AGF offers an effective solution by creating a stable, impermeable frozen soil mass between tunnels, enabling safe cross passage excavation. The construction of a cross passage using AGF typically involves five stages (Figure 1 - left).

The soil freezing process for cross passage construction involves placing freezing pipes in a strategic pattern between tunnels. Temperature sensors are installed to monitor the growth of the frozen body. Depending on inter-tunnel distance, pipes may be inserted through the segment lining from one or both tunnels (Figure 1 - right). The freezing process begins with the formation of frozen columns around each pipe, which eventually merge into a continuous freeze wall (Figure 1c - left). This method allows for controlled soil stabilization, enabling safe excavation of the cross passage.

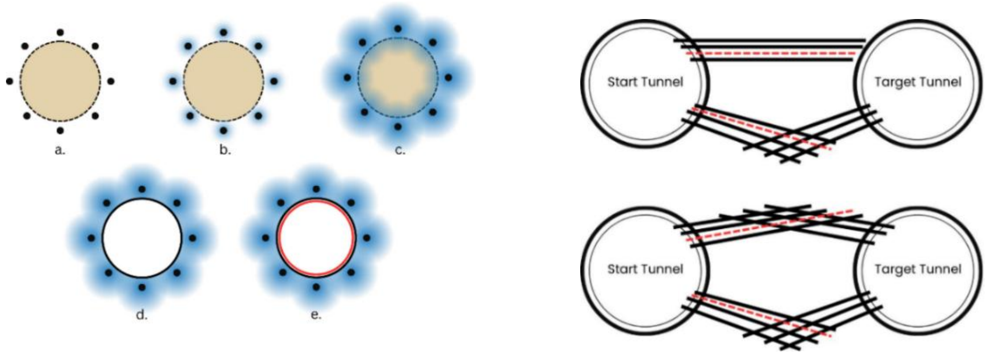

Figure 1. (left) Schematic view of artificial ground freezing stages during cross passage construction. a. Installation of the freeze pipes b. Growing of the columns around the freeze pipes c. Closing of freeze wall d. Excavation of the cross passage and apply primary lining e. Installation of the secondary lining; (right) Possible freeze pipe configurations.

3 SITE ASSESSMENT

A comprehensive site assessment is imperative before implementing AGF in construction projects. This assessment entails a detailed evaluation of the site's geological and hydrological conditions. Accurate characterization of soil and rock, including permeability, thermal conductivity, and moisture content, is crucial for designing the freezing system. Soils with low permeability require extended freezing times, while low thermal conductivity soils demand more intensive freezing efforts. Groundwater flow velocity is critical, as flowing water increases heat transfer, potentially undermining freeze wall integrity.

Lab tests provide essential data on soil behavior under freezing conditions. Tests on thermal conductivity, uniaxial compression, and creep behavior are conducted at temperatures between -10°C and -20°C. Groundwater analysis identifies salinity, chemical composition, and flow rates, as these factors can lower the freezing point and affect freeze wall formation. A list of typical tests for AGF generally include moisture content, dry density and specific gravity, Atterberg limits, grain size analysis, triaxial compression test (CU), uniaxial compression test (frozen), triaxial compression test (frozen), uniaxial creep test (frozen), frost heave, frost pressure and salinity.

4 PROJECT REQUIREMENTS AND CONSTRAINTS

The effective implementation of AGF for cross passage construction requires a thorough understanding of specific project requirements and constraints. These considerations encompass geometric constraints and interfaces, specified tolerances, and clearly defined target properties for the frozen body.

A critical geometric constraint is the diameter of the Tunnel Boring Machine (TBM) tunnel, which determines the available space for installing freezing equipment and influences the design of the freeze wall. Additionally, the timing of the cross passage construction whether it occurs during or after the mainline TBM tunnelling, impacts the sequencing of operations and resource allocation. Space constraints due to operational utilities, such as ventilation ducts, further limit the area available for freezing pipe installation and must be carefully considered.

Specifying tolerances is vital to ensure the accuracy and effectiveness of the freezing process. Freezing pipe drilling tolerances must be strictly adhered to, as deviations can lead to discontinuities in the freeze wall. The effect of tolerances on AGF design will be discussed in details under section 6.3.

Defining target properties for the frozen body is essential to achieve the desired ground stabilization and impermeability. The following are example criteria that needs to be established for the frozen body: i) thickness of the frozen body is ≥ 1.5 m, ii) temperature of the frozen wall boundary is ≤ –2 °C, iii) average temperature within the ring is ≤ –10 °C and iv) temperature at the core of the frozen body is ≤ –15 °C. These parameters ensure that the frozen body provides sufficient structural support and watertightness. A freeze wall thickness of at least 1.5 m is required to maintain stability, measured outward from the excavation line.

5 SEGMENTAL LINING DESIGN AND MATERIAL CONSIDERATIONS

Selecting appropriate segmental lining materials is crucial for both structural performance and construction efficiency. Reinforced concrete segments are commonly used but may not be suitable in certain situations. They often require internal temporary supports during installation, which can cause space constraints within the tunnel. This space proofing issue can interfere with equipment placement and construction activities inside the tunnel.

To address these challenges, steel linings may be considered as an alternative. However, the use of steel segments introduces other considerations. The steel lining details, such as whether an open pan design, post-fixed panels, or concrete-filled configurations are used, can significantly influence the freeze program. For instance, an open pan steel lining may lack sufficient thermal insulation at the interface of the frozen ground and the segmental lining, leading to increased freeze times.

Steel linings with pre-defined drill ports offer advantages in terms of reduced collar thickness and, consequently, reduced freeze time. However, this option has limitations. The drilling pattern must be pre-defined and account for all anticipated tolerances for each cross passage. This requirement demands precise planning and may limit flexibility during construction.

6 GEOMETRY OPTIMIZATION

Geometry optimization for freezing pipe layout is crucial for project scheduling and cost management in cross passage construction using AGF. Optimized freezing pipe layout can result in reduction of freezing pipes and freezing time. Factors influencing geometry include the primary and secondary lining design, and construction tolerances.

6.1 *Primary lining design*

The primary lining must interact effectively with the frozen ground, accommodating loads from the frozen soil and any movements that occur during thawing. Thickness optimization is necessary to balance structural requirements with material costs and installation feasibility. Two scenarios are typically considered for primary lining design. In the first scenario, the freezing system is switched off after the primary lining has been installed but prior to the installation of the waterproofing membrane. This approach requires the primary lining to withstand all loads during thawing, including groundwater pressures, potentially increasing thickness and reinforcement needs. In the second scenario, the freezing system is maintained until after the secondary lining has been installed, allowing the primary lining to be thinner since the secondary lining provides full support. A critical consideration is the interaction of the frozen ground with the primary support. The frozen ground and primary lining must provide temporary support during excavation.

6.1.1 *Excavation line*

To accurately determine the required locations for the start and end points of each freezing pipe in the crown and along the sides of the cross passage collars, a design line is employed. This design line is positioned in relation to the Excavation Line (E-Line)**,** from which the freeze wall must be dimensioned outward to ensure the necessary structural integrity and watertightness.

Given that the targeted freeze wall thickness is 1.5 m, the design line is established at a distance approximately equal to half of this required thickness from the E-Line. This positioning allows for the development of the freeze wall to the full required thickness while accommodating construction tolerances and ensuring that the frozen body fully encompasses the excavation area.

By extending the freezing pipes beyond the design line, the design ensures that any potential deviations or tolerances in drilling and excavation do not compromise the minimum required freeze wall thickness.

6.2 *Secondary lining design*

The secondary lining is integral to the long-term structural integrity and durability of cross passages constructed using AGF. Its design must accommodate the complex interactions between the frozen ground and primary support structures. A critical component of the secondary lining is the collar, whose size and geometry significantly influence the placement of freezing pipes.

6.2.1 *Collar design*

The collar's dimensions control the location of freezing pipes by defining the excavation limits and the necessary freeze wall thickness. Specifically, the targeted freeze wall thickness of 1.5 m is measured from the E-Line of the collar. Therefore, optimizing the collar size is essential not only for structural considerations but also for enhancing the efficiency of the freezing process.

Collaboration between the secondary lining designer and the primary lining designer is essential to achieve an optimal collar design. The secondary lining designer must ensure that the collar provides sufficient structural integrity for the cross passage opening, while the primary lining designer must determine an appropriate shotcrete thickness that offers adequate support during excavation. By jointly refining the collar dimensions and shotcrete thickness, it is possible to reduce the number of freezing pipes required, thereby streamlining construction and reducing costs.

6.2.2 *Freezing pipe pattern*

Optimizing the geometry of freezing pipe arrangements is crucial for efficient cross passage construction. The overall pipe arrangement broadly comprises two components: 1) The configuration of each pipe in relation to the 'start' and 'target' tunnel and 2) the pipe layout around the cross passage. The pipe configuration needs to be considered with respect to the tunnel geometric constraints and construction-related logistical considerations. An example of four different configurations is presented in Table 1, each with distinct characteristics:

Table 1. Freezing pipe configurations

Pattern	Configuration	Collar Design
1	Two-sided from crown and invert	Standard size collar
2	One-sided from crown and invert	Standard size collar
3	Two-sided at tunnel crown and one-sided at invert	No collar or smaller collar
4	One-sided at tunnel crown and two-sided at invert	No collar or smaller collar

The design of the pipe layout and spacing surrounding the cross passage opening is also critical for achieving uniform freezing, with pipes typically installed in a grid pattern and should be considered in conjunction with the pipe configuration. Pipe spacing is determined by the required freezing radius and the ground's thermal conductivity, ensuring the entire area receives adequate cooling to form a continuous frozen mass. Collaboration with the cross passage designer to improve the structural form of the opening set enables placement of freezing pipes as close to the excavation area as possible.

Collar geometry plays a vital role; reducing collar height allows for a lower freezing pipe angle, decreasing both the number and length of pipes needed. Patterns 3 and 4, featuring reduced or no collar, potentially reducing the total number of required pipes, thereby enhancing efficiency and potentially reducing costs and construction time. Operational constraints within the tunnels, such as TBM operation, must be considered when determining the freezing timeline. Precise installation of freezing pipes is essential to avoid gaps or overlaps that could lead to ineffective freezing, underscoring the importance of careful planning and execution in freezing pipe arrangement optimization.

6.3 *Tolerances management*

AGF design needs to integrate all geometric constraints, interfaces, and anticipated construction tolerances to facilitate the formation of a freeze wall meeting the required target properties. Freezing pipe design is influenced by several expected construction tolerances. These tolerances include: i) Freezing pipe drilling tolerances, ii) cross passage excavation and primary lining tolerances and iii) bored tunnel driving tolerances.

6.3.1 *Freezing pipe drilling tolerances*

During the drilling of designed freezing pipe boreholes, deviations along the length of the drilling are expected. The design accounts for a maximum drilling tolerance of the drilling length for the freezing pipes. The drilling tolerance must be defined by the designers or contractors depending on the cross passage length or drilling length.

6.3.2 *Cross passage excavation and primary lining tolerances*

In developing the freeze wall, it is essential to consider that the excavation of the cross passage may overlap with the surrounding frozen ground, leading to a reduction in the available freeze wall thickness. By definition, the interior surface of the primary lining corresponds to the exterior surface of the permanent lining. To determine the distance of the E-Line from the outside of the permanent lining, the cross passage excavation and primary lining tolerances need to be considered. The tolerances that need to be considered are shown in Figure 2.

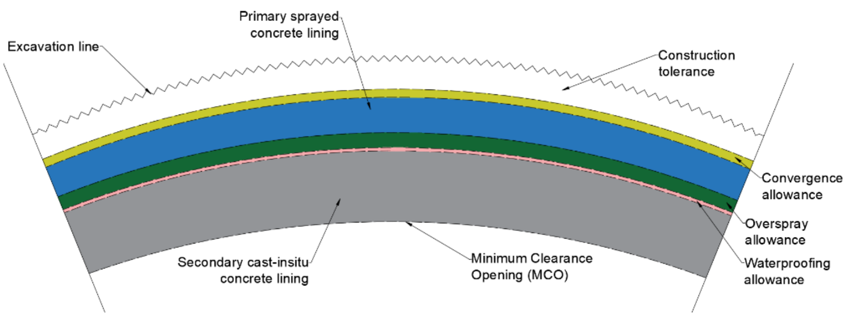

Figure 2. Cross passage excavation and primary lining tolerances

6.3.3 *Bored tunnel driving tolerances*

AGF with a reinforced concrete lining in the bored tunnels is typically unaffected by potential vertical and horizontal shifts, ring roll, and skew of the tunnel from which they are drilled. On the other hand, AGF with steel lining requires consideration of bored tunnel driving tolerances as the freezing pipe drillings are conducted through pre-determined drilling ports located within the steel lining.

For steel linings the following bored tunnel driving tolerances are considered: i) vertical tolerances, ii) horizontal tolerances, iii) ring roll and iv) skew.

These bored tunnel driving tolerances should be integral to the development of the preliminary freezing pipe drilling design. By combining the tolerances of individual cases, various scenarios can be modelled and investigated. For each case, the freezing pipe drilling design should be adjusted to ensure that, regardless of the tolerances encountered, the required freeze wall could be established. This involved applying and combining the maximum tolerances to the relevant elements of the model, checking for potential object collisions, and ensuring minimum required distances between freezing pipes and the tunnel extrados.

7 TIME OPTIMIZATION

Optimizing the freezing duration is pivotal for project scheduling and cost management in cross passage construction using AGF. Factors influencing freezing time include the choice of cooling systems, the impact of lining materials, and the excavation sequence.

7.1 *Cooling system*

AGF employs two main cooling systems: closed brine systems and open liquid nitrogen systems, each with distinct benefits and limitations.

Brine system is a closed-loop system using calcium chloride ($CaCl_2$) brine cooled to approximately -32°C. The brine circulates through freezing pipes, absorbing heat from the surrounding soil before being re-cooled and recirculated. This system is cost-effective for long-term use and safer in enclosed spaces, as it eliminates the risk of gas leakage. However, it has slower freeze times and is less effective in soils with water flow velocities above 2 m/day (Mira-Catto & Roberti 2018). Liquid nitrogen is an open-loop system where liquid nitrogen at -196°C is injected into the pipes. The extreme cold rapidly freezes the soil and creates a more rigid frozen body, effective in high groundwater flow conditions (up to 10 m/day). However, the system is costly due to continuous nitrogen consumption and poses safety risks in confined spaces due to potential oxygen displacement. Each system has distinct characteristics, advantages, and limitations that influence their suitability for different project conditions. Brine systems are preferred for long-term, lower-flow projects, while nitrogen is used for rapid freezing or in high-flow conditions. Balancing cost, efficiency, and safety is critical in AGF system selection.

7.2 *Excavation sequence*

Once the freeze wall has been established and its watertightness verified, construction of the cross passage can proceed. The construction sequence includes the following steps in order: i) door opening in segmental lining, ii) excavation of frozen ground, iii) application of primary lining (shotcrete), iv) placement of waterproof membrane and v) secondary lining (cast-in situ reinforced concrete). Optimizing the excavation sequence is critical for enhancing both the advance rate and overall project efficiency. One of the primary considerations is the behaviour of the frozen ground itself. The properties of the frozen soil, including its strength and ability to support itself (stand-up time), dictate the rate at which excavation can proceed. Generally, a single cross passage can be excavated within two weeks, with an average excavation rate of approximately 1 to 1.6 m/ day. However, this rate is subject to the specific conditions of the frozen ground and must be closely monitored to ensure stability throughout the excavation process.

Another critical factor is the thickness of the shotcrete used for the primary lining. The thickness must be carefully calibrated to provide adequate temporary support during the excavation phase while minimizing the impact on the excavation rate. The design team must balance the need for rapid excavation with the requirements for stability and safety during the transition from the primary to the secondary lining.

Successful excavation sequence optimization requires close collaboration between the ground freezing designer and the primary lining designer. The ground freezing designer must provide accurate and detailed information regarding the properties of the frozen ground. The primary lining designer, in turn, must use this information to determine the excavation advance rate.

8 CONSTRUCTION AND PRACTICAL CONSIDERATIONS

8.1 *Excavation methodology and sequencing*

Excavation of the cross passages proceeds with advance lengths appropriate for the project conditions, with extended lengths in the enlarged collar areas. Excavated material and shotcrete are transported to the cross passage face via dumper and mixer trucks. It is anticipated that the heat generated from the application of shotcrete may cause the frozen body to thaw, leading to a lack of adhesion during spraying operations and resulting in material wastage.

Initially, the excavation face may be sealed in the first few advances, as is common in shotcrete works; however, to enhance stability and reduce heat generation, this requirement might be removed based on site conditions. Shotcrete will be applied in multiple passes to ensure proper adhesion to the frozen ground. In unfavourable ground conditions, the initial application may be restricted to 50 mm in the crown and shoulders, allowing for initial adhesion before topping up to the full design thickness as work advances (Hamad et al. 2024).

8.2 *Tunnel logistics and waterproofing*

Simultaneously with cross passage construction, various activities occur within the Upline and Downline tunnels. These include operations involving MSVs, TBM passenger service vehicles (PSVs), construction of tunnel invert concrete, subcontractor logistics, and tasks such as extending tunnel conveyor belts and cables. AGF design needs to consider the spaceproofing within the mainline tunnel, in which temporary supports should be minimized.

Temperature fluctuations during the freezing and thawing processes can affect gasket materials used in the tunnel lining, potentially leading to leakage paths. Selecting gaskets that can accommodate thermal expansion and contraction is essential for maintaining long-term tunnel integrity.

8.3 *Monitoring and instrumentation practices*

Temperature monitoring is required to assess the freeze wall growth during construction and confirm minimum design requirements are met and maintained. Temperature measurement pipes need to be designed alongside with freezing pipes to target critical areas of freeze wall development as determined during design. Thermocouples are installed at regular intervals internally within the pipes to monitor soil temperatures at varying distances from freezing pipes, enabling precise assessment of freeze wall development. Additional thermocouples need to be strategically installed at the opposite tunnel, where fewer freezing pipes are installed, to ensure sufficient sealing at the target tunnel extrados. Placement of these sensors targets potential weak or critical zones identified by thermal design.

Furthermore, pore water pressure is also required to be monitored inside the frozen body using drainage pipes equipped with valves and pressure gauges. As the freeze wall forms and confines the enclosed water, there is a sharp increase in pore water pressure inside the frozen body, indicating that cut-off of groundwater by the frozen body has been achieved. These measurements provide real-time data to assess freeze wall integrity, with excess water pressure measured at inside the cross passages barrel. This instrumentation strategy ensures robust monitoring, enabling informed decisions during construction. Monitoring is a key element for AGF design and this will be further discussed in future publications.

9 INTEGRATED DESIGN FRAMEWORK

An integrated design framework for AGF in cross passage construction involves a holistic approach that considers feasibility, geometry, time, cost, and safety is presented in Figure 3. This framework is a summary of the design considerations mentioned hereinbefore.

10 CONCLUSIONS

This paper presents an integrated approach to optimizing AGF for cross passage construction in tunnelling projects. By addressing practical design considerations, including freezing pipe arrangements, freezing durations, lining material selection, and tolerance management. The paper bridges the gap in the literature concerning the application of AGF in construction settings. The proposed framework emphasizes the importance of multidisciplinary collaboration, integrating geotechnical, structural, thermal, and construction expertise to develop efficient and safe designs. The consideration of tolerances in drilling, excavation, and tunnel driving is critical to ensuring the integrity of the freeze wall. This comprehensive approach aims to improve the efficacy of AGF in cross passage construction, contributing valuable insights to the field of underground engineering.

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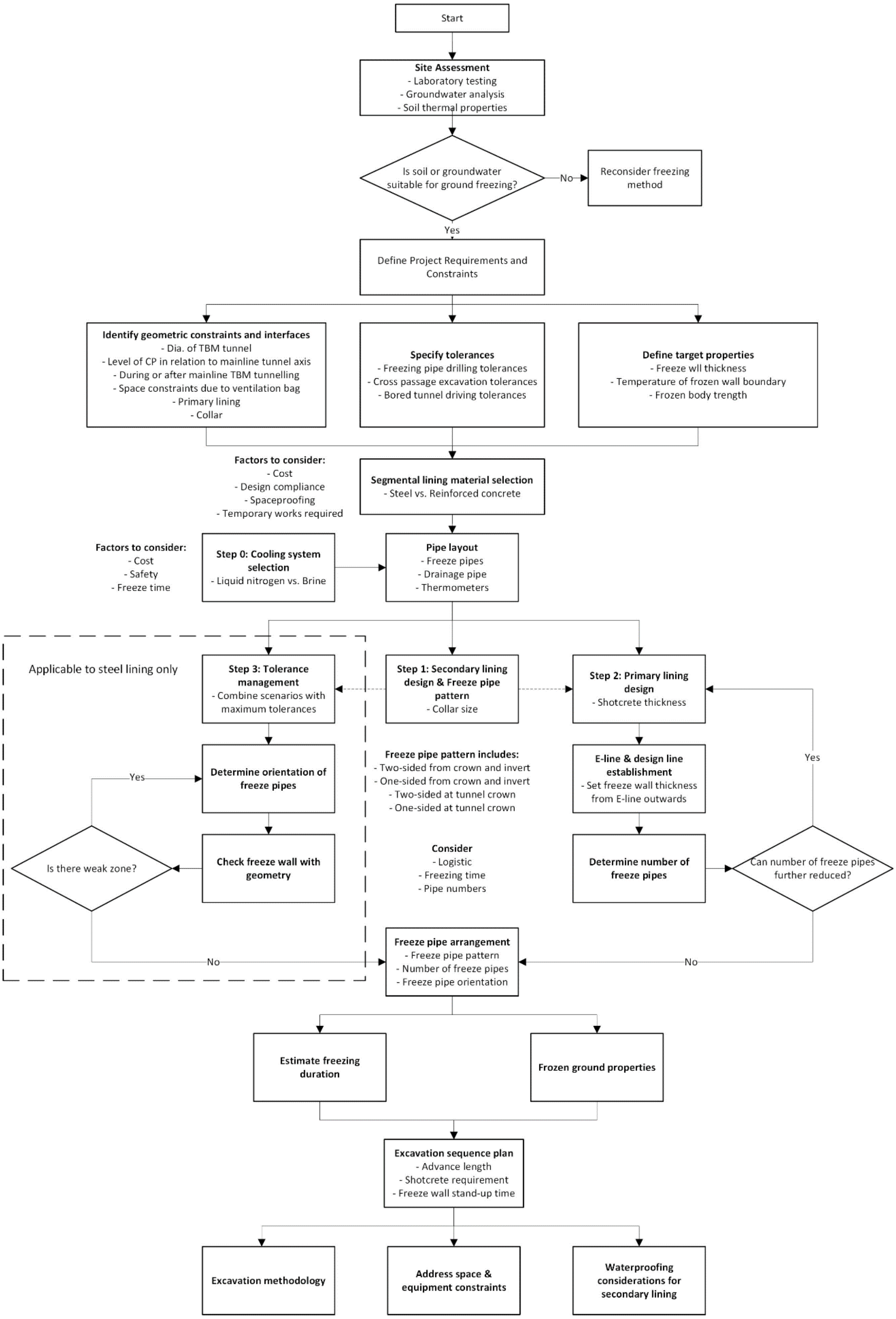

Figure 3. Integrated design framework for AGF in cross passage construction