Geotechnical Considerations of Deep Mine Shaft, Sinking by Combined VSM and Drill & Blast Construction Methodology

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ABSTRACT
The vertical shaft sinking machine (VSM) is an innovative method of mechanized shaft excavation and liner construction technology developed in the context of rapid mechanical shaft sinking. This paper highlights geotechnical design considerations of VSM use for the upper section of a shaft prior to proceeding with conventional drill and blast methodology below the VSM section, in the perspective of deep mine shaft construction. Segmental liner stability and hydro-sealing concerns including liner basal stability, the detrimental effect of slurry on liner watertightness, liner deviation, and settlement are identified as important factors. Considerations of ground improvement prior to shaft sinking are also discussed. A good understanding of the geotechnical, geological, and hydrogeological characteristics of the ground are key to the optimization of the VSM liner depth.

RÉSUMÉ
L'utilisation de la machine de fonçage vertical de puits (VSM) est une méthode d'excavation ou technologie d'installation de revêtement mécanisée relativement nouvelle dans le contexte du fonçage de puits profonds. Cet article mettra en lumière des éléments importants à considérer lors de conception géotechnique de fonçage de puit. Il traitera entre autres de la stabilité du revêtement (segments) et des préoccupations d'étanchéité pour la construction de puit profonds, particulièrement de la stabilité du revêtement de fond, de l'effet néfaste de la boue de forage sur l'étanchéité du revêtement, de conséquence relevant de la déviation du revêtement et de tassements différentiels. Les considérations relatives à l'amélioration du sous-sol avant le fonçage du puits seront également abordées. Une bonne compréhension des caractéristiques géotechniques, géologiques et hydrogéologiques du sous-sol est essentielle à l'optimisation de la profondeur du revêtement VSM.

1 INTRODUCTION

Vertical Shaft Sinking machine (VSM) is an innovative technology that uses a unique mechanized shaft sinking method for efficient and reliable construction of vertical shaft.
This mechanized method is commonly employed for shallow infrastructure applications such as launch and reception shafts for tunnelling operations, access and ventilation shafts for traffic tunnels or service and access points for all kinds of underground structures and buildings.

VSM has also been used for construction of the upper section of mine shafts. It is used to excavate the overburden soil and/or weak to strong strength rock (less than 200 MPa) before conventional shaft sinking methods using drill and blast (D & B) excavation commences. VSM methodology replaces several excavation, mucking, and support installation cycles pertinent to conventional shaft sinking methodology. Typically, retaining structures (secant pile walls or diaphragm walls), or ground freezing techniques would be needed to support the weak soils/rock if VSM was not used. VSM technology is mostly applied under submerged conditions and using high specific gravity bentonite slurry as temporary excavation support and prefabricated concrete segments as permanent liner.

The main objective of this paper is to highlight geotechnical design considerations of VSM use for the upper section of a shaft prior to proceeding with conventional drill and blast methodology below the VSM section. Considerations such as segmental liner stability, temporary plug stability, post-grout effectiveness, liner deviation, detrimental effect of slurry on liner hydro-sealing, water proofing impact and foundation settlement are discussed. Considerations of ground improvement prior to shaft sinking are also discussed.

This paper primarily focuses on the geotechnical consideration in the perspective of deep mine shaft construction at depths of greater than 100 m. The implications of using D&B below a VSM shaft liner is also discussed. The project names where VSM was used for deep excavation will not be disclosed for confidentially purposes.

2 OVERVIEW OF VSM

The VSM machine consists of two main components: shaft boring machine and the lowering units. The shaft boring machine is lowered and attached to the base of the shaft liner structure using three machine arms. A rotating cutting drum with chisel tool is used to excavate and break soil/rock at the base of the shaft. The excavation occurs while the entire shaft is flooded with slurry water. The excavated material is then hydraulically removed through a submersible pump to a separation plant at surface. (Herrenknecht, 2022).

Simultaneously with shaft excavation, the liner is assembled on the ground surface by attaching segments of prefabricated concrete to form concrete rings which are then attached to the top of the existing liner. It is also possible to employ the cast-in-situ methodology for the construction of the concrete rings. Three to four lowering units with hydraulic cylinders are then used to lower the entire shaft structure as the excavation advances. The lowering units lie on a ring-shaped concrete foundation around the shaft at ground surface. Steel cables extending from the lowering units are attached to the base of the shaft edge to lower the shaft structure in a controllable manner. The bottom edge of the lowest ring, also known as the cutting edge, is beveled to help cut through soil. In addition, bentonite lubrication in the annular gap between the liner and perimeter of the excavated ground is used to reduce the frictional resistance between the concrete wall and soil/rock during sinking. Once the shaft structure is lowered to the desired depth, the machine is recovered. The shaft bottom is sealed by an underwater concrete plug and the bentonite in the annular gap is displaced with grout to lock the shaft liner in place. Finally, the water slurry from within the shaft is pumped out and the shaft is ready to use. (Herrenknecht, 2022). Figure 1 illustrates the components of a VSM arrangement which are described individually in Table 1.

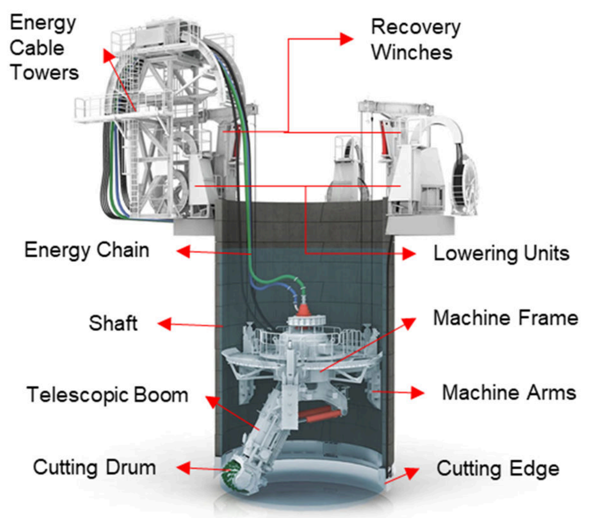

Figure 1. Illustration of a Vertical Shaft Sinking Machine (from Herrenknecht, 2022)

Table 1. Description of VSM components (Herrenchknect, 2022)

VSM Component	Component Functionality
Energy Cable Towers	Guide the cables and hoses of the energy chain into the shaft-synchronized with lowering of the shaft structure
Energy Chain	Consist of all the supply lines between the boring machine and the ground surface

Table 1 cont'd. Description of VSM components

Shaft	Overall shaft liner made of reinforced concrete segments or in-situ concrete
Telescopic Boom	Due to hydraulic movability and telescopic adjustment, the entire cross-section of the shaft can be reached
Cutting Edge	Cuts into soft soils when lowering the shaft structure into ground – thus, eliminating the need for an overcut
Machine Arms	Secure the shaft boring machine to the bottom segments of the shaft structure
Machine Frame	Supports the rotary drive of the telescopic boom and the supply units for the machine
Lowering Units	Lower the entire shaft structure on steel cables attached to the shaft cutting edge
Recovery Winches	The machine is recovered if necessary using steel cables and recovery winches

VSM technology can be used for various geological conditions including soft ground, heterogenous ground and low to medium strength rocks up to 140 Mpa. Although, most documented cases were in sedimentary rocks such as sandstones, shale and limestone, VSM has preven to cut through boulders of compressive strength up to 200 Mpa in the St-Petersburg Sewage Project Its main strength is highlighted by its application for subsurface excavation below the effects of ground water. Depending on the ground conditions and excavation diameter, VSM technology allows for a high advance rate of up to 5m per day. Furthermore, one VSM can be adjusted for different shaft diameters in a project. The shaft's external diameter can range from 4.5-18m.

Primary benefits over a conventional shaft sinking method are summarized below:

- Flexible arrangement of the machine equipment allows for operation under tight space constraints;
- Cutting drum type and liner type (cast in place, in-situ, or reinforced) can be changed accordingly to accommodate for various ground conditions;
- There is no requirement to lower water table during excavation, resulting in less subsidence/settlement, less seepage issues and lower environmental risks;
- Fast installation due to simultaneous excavation and ring building (shaft liner installed during the VSM excavation is the final liner);
- Safe operation process since excavation is controlled and monitored from surface (no personnel inside shaft);
- High performance due to high planning reliability, permanent control of excavation and sinking process, high accuracy of shaft construction, watertight liner, and high advance rate;
- No excessive overcut (compared to blasting), good overbreak control;
- The extent of excavation damage zone is smaller with no potential for crack propagation compared to blasting;
- No detrimental effect on the adjacent utilities (no vibrations, no seismic accelerations).

Primary limitations including risks associated with deep excavation on VSM application are summarized below:

- Initial capital investment in the equipment;
- Submerged excavation means no access inside the shaft until dewatered;
- VSM technology and methodology needs to be revised for deeper excavation application (+200m);
  - Liner deviation;
  - Risk of liner getting stuck;
  - Larger liner weight to be supported ;
  - Liner gaskets can only support 18 bar of pressure;
  - Ground support required in weak rocks.

Regardless of these limitations, VSM technology is becoming more prevalent in medium strength rock units due to its various advantages over the conventional method of manual excavation and liner installation. However, it is only cost effective to implement for depth greater than 15-25m, depending on the geological conditions, and number of shafts (Schmäh, 2007). Also, its application for excavation deeper than 100m is questionable. The operation depth using VSM has to be optimized based on the associated risks and limitations listed above.

Since its first deployment in 2006, at least 75 VSM projects have been successfully executed for vertical shaft construction with a total accumulated depth of 3.8km (Frey, 2020). One of the notable projects include the Woodsmith mine in the U.K., which holds the world record for the deepest shaft constructed using VSM at a depth of 115.2m (GeoDrilling, 2019). Another notable project is the Grand Paris Express, where VSM was used to build four ventilation and rescue shafts for approximately 200 Km of new metro tunnels. The use of VSM in a highly populated area with limited accessibility to site is particularly highlighted in this project (Herrenknecht, 2022).

In the case of one project, conceptual study has shown that use of VSM for the upper 120m of shaft in weak rock was found to be a better alternative than using D&B with foreshaft secant pile wall (SPW). With VSM, no cover grouting and probe drilling for excavation at shaft base is required. Furthermore, there is no need of injecting grout behind the SPW. It was also found that VSM provides better quality improvement of the shaft liner as it can be sunk with high precision of approximately 2mm of deviation per metre of depth excavated. Furthermore, the watertight liner reduces the operational cost of pumping and treating water. Less personnel and machinery onsite are also required to operate due to the mechanized shaft sinking, making the project safe and cost effective. Altogether, using VSM as an alternative to D&B was found to reduce the cost of project by €2 million and accelerate the shaft sinking schedule by up to two months. In essence, if VSM can be properly implemented along with good understanding of subsoil conditions, it can be a cost and time effective solution, all while reducing environmental impact and minimizing risk.

3 DISCUSSION

The application of VSM in shaft excavation of some projects have been studied and reviewed. The following sections describe the geotechnical challenges associated with the use of the VSM for deep excavation in various rock types and more specifically in weak and fractured rocks.

3.1 VSM Geotechnical Challenges in all Rock Types

3.1.1 Lowering Units Foundation

In VSM construction, the weight of the concrete structure and VSM machine is supported by steel cables, which transfer the load to the lowering unit, then to the surface ring foundation and finally to the foundation soil. For greater excavation depths, a larger dead weight of the concrete shaft structure is required to be supported. This means that the steel cables and lowering units must be designed accordingly. Additional lowering units and thicker steel cables must be considered for deeper excavation. Most importantly, the foundation must be competent enough to withstand the large load and sustain tolerable settlement. One solution is to increase the circular width of the lowering units' foundation. However, this reduces the effectiveness of VSM usage in tight spaces. Pile foundations around the shaft can also be implemented to support the additional capacity. Another solution is to use a lighter concrete mix for the liner to reduce the load acting on the surface foundation.

To highlight the impact of concrete liner load on the foundation, consider a hypothetical situation of foundation design for a shaft depth of 120m. Furthermore, assume a concrete unit weight of 24kN/m^3, outer shaft diameter of 15m and shaft liner thickness of 0.4m. This results in a force of 60MN exerted on the foundation.

To further illustrate this issue, RS2, a finite element analysis software (Rocscience©), was used to perform an elastic settlement analysis of native soil and the concrete ring slab foundation. For this scenario, a dense sand overburden of 30m thickness overlying a competent elastic bedrock was modelled. The geometry of the axisymmetric model is shown in Figure 2. The dense sand was modelled as an elastic, perfectly plastic material, with an elastic modulus of 50 000 kPa and friction angle of 35°. The bedrock was modelled to behave as a rigid material. The concrete ring slab foundation was modelled as a liner element in RS2, with a circumferential width of 4m and thickness of 2.5m. The uniform distributed load was calculated assuming four lowering units equally sharing the load of the 60MN liner. This results in a uniform distributed load of 243 kPa acting on the foundation. Lastly, it is assumed that the impact of the shaft liner on settlement is negligible. Therefore, the shaft liner was modelled as a boundary condition with restraint on the horizontal/radial displacements. The free movement in the vertical direction suggests that no friction is considered between the soil/rock and liner.

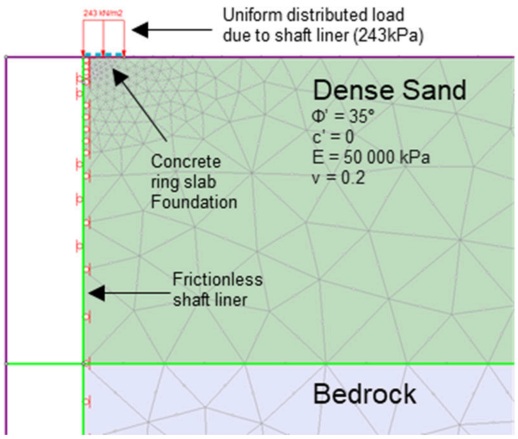

Figure 2. Axisymmetric model of a hypothetical scenario to evaluate foundation settlement

From the analysis, the average settlement of the slab foundation was calculated to be approximately 47mm, as shown in Figure 3 (left). Although the settlement is somewhat uniform, it is questionable whether this limit is acceptable for VSM operation. The main concern involves differential settlement of the foundation that may lead to shaft deviation. Lastly, bearing failure of the dense sand is noticed by looking at the maximum plastic shear strain results. This is illustrated by the triangular wedges in Figure 3 (right).

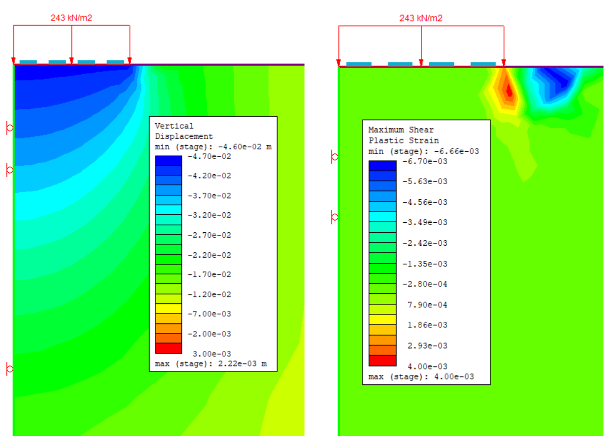

Figure 3. Vertical displacement (left) and maximum plastic shear strain (right) of dense sand due to loading of liner structure.

As seen, considering a likely extreme scenario for a 120m depth VSM excavation can be challenging. For example, if soft clay is encountered, the settlement can be larger by one order of magnitude due to lower elastic modulus and consolidation settlement. Furthermore, loads such as the boring machine, liner brackets, gaskets and other nearby operational structures should be accounted for in this scenario. Lastly, the load is assumed to be uniformly distributed. This is not always the case since some lowering units may carry more load than others during the sinking process depending on the uniformity of the skin resistance around the circumference of the shaft structure.

Considering the same scenario for a 200m deep VSM shaft excavation, the average settlement of foundation was calculated to be approximately 80 mm, an increase of 70%. Also, a similar bearing capacity failure mechanism as shown in Figure 3 (right) is observed. When the circumferential width of the foundation is increased to 6m and the thickness to 4m, the average settlement was decreased to 63mm. It can be proposed that the settlement be further decreased by increasing the foundation circumferential width. However, this may not be a feasible option because the lowering units must now account for higher bending moment since it will be further away from the sinking shaft (load source). Furthermore, an angular distortion of 1/500 is observed at the shallow foundation. This value may not be tolerable for VSM operation as it may lead to excessive deviation of the shaft.

From this conservative analysis, one conclusion is definite: strengthening of the surface foundation (e.g. piles, ground improvement) is almost a must for deep shaft excavation using VSM.

3.1.2 Segmental Liner Stability

At greater depths, high in situ stress (especially high horizontal stresses) can affect the stability and integrity of the concrete liner structure. The understanding of stress redistribution for a circular excavation is vital for designing the liner. In general, a concentration of compression forces is induced in the direction of σH_{min} and tensile forces in the direction of σH_{max}. Both cases should be considered when designing the liner. To accommodate for the excess compression force, the thickness or strength of the concrete liner can be increased. To withstand tensile stress, reinforced concrete is required. If the liner cannot be stabilised, then ground improvement methods such as pre-grouting or tie-back bolts are required. This can be a time consuming and an expensive operation. If frequent or extensive ground improvement methods are required, then it may not be cost effective or time-efficient to use VSM for excavation.

The base of the segmental liner is the critical section of the liner structure since it experiences the most stress during sinking. Due to the open advancing face, it is possible for excess stress to be induced from inside the shaft during potential upward seepage into the shaft. The convergence and heaving of the rock can also impair the cutting edge and possibly cause liner deviation. This can be detrimental to the integrity of the structural liner. In essence, this basal liner requires extra attention when designing for deeper excavation.

3.1.3 Long-term Effect of Bentonite Slurry on Liner Watertightness

Upon completion of the shaft sinking, grouting is used to displace the bentonite slurry and lock the shaft structure in place. Effectiveness of post-grouting would be hampered by bentonite sealing off the joints and fractures in rocks. Bentonite would fill in rock discontinuities and prevent the spread of very fine cementitious grout. Despite this temporary obstruction of the fractures, the clay particles in bentonite will be washed out gradually, leading to building up of permeable zones through time. Also, it is very likely that clay would detrimentally affect the cement hardening process. This could require costly remedial works that could have detrimental effect on operational cost and time of the project. The watertightness of bentonite slurry is only a temporary solution.

3.1.4 Skin Friction Between Permanent Liner and Rock

If the conventional D & B method is required below the VSM liner, a temporary plug at the shaft base is required. The temporary plug provides stability to the liner by providing end-bearing resistance and preventing it from displacing vertically. It is very likely that the shear resistance of the post-grouted interface between the liner segments and the rock wall will be impaired by bentonite and will not suffice. Therefore, the temporary slab-plug will be designed to support the full weight of the liner. Any movement and deformation of the slab-plug will propagate into the rings of the liner structure and potentially impair the structural integrity and water tightness of the segmental liner. In addition, vibration from drill and blast can significantly weaken and disturb the interface resistance and bottom rings if not conducted with extreme care. This can also induce vertical movement of the shaft structure and displace the joints of the concrete rings. To accommodate any friction loss in the post-grouted interface, a larger shaft diameter can be used. However, additional cost and time are required for the latter.

The design of the temporary plug should also accommodate for the possibility of friction loss and high in situ stress conditions. The bearing capacity of the rock due to loading from Galloway (conventional shaft sinking working platform) and other equipment lying on the shaft base for D&B operation should also be considered. In the event where the base of the VSM terminates in water-bearing rock then special precautions must be taken when grouting the temporary plug such that no seepage occurs from the base. To ensure stability of the concrete structure, reinforcing the foundation through fully grouted rock bolts is recommended.

During VSM sinking operation, it is recommended to use high bentonite content slurry to reduce the friction resistance between the outer shaft wall and rock to minimize structural damage. At greater depth, the risk of liner getting stuck is much higher. It is important that the right mix of bentonite is used such that it fulfills its task as supporting liquid and lubricating film instead of flowing into the ground without taking effect. This depends on the type of bentonite, bentonite concentration, mixing time, mixing tools, swelling time and other substance content such as polymers. Although polymers can improve the property of slurry for suspension (act like a gel), it can be very expensive and hard to acquire. In essence, getting the right mix of bentonite slurry for various geology type is difficult to achieve. This makes the bentonite slurry very sensitive to movement. Therefore, fully depending on bentonite slurry to smoothen shaft sinking is not ideal. Controlled over-excavation is recommended to prevent the liner from getting stuck. (DMT, Thyssen Schachtbau, 2021)

3.2 VSM Geotechnical Challenges in Weak Rocks

3.2.1 Shaft Dewatering

During VSM construction, the shaft will be fully submerged and thus the internal pressure will temporarily stabilize segments and counteract the action of the in-situ ground water. Furthermore, the water pressure helps destressing the concrete liner from rock stress relief. Upon completion of the shaft, dewatering the slurry will result in the worst-case loading scenario on the shaft structure. When dewatered, the internal pressure is dropped leading to an increase of the external pressure on segments and activation of internal hydraulic gradients within the surrounding rock mass. In weak, permeable, open-fracture rocks, consolidation settlement occurs. The resulting settlement can affect the integrity of the concrete structure by separating segment joints and/or re-distributing stress around the concrete ring.

When the shaft is submerged, the hydrogeology and rock joint properties cannot be understood to its full effect since rocks joints filled with water can stabilize flow through rock and create a static condition. As such, a quality site investigation is recommended, especially for weak, heavily jointed rocks. Understanding the joint networks and local and regional hydrogeology can help predict new flow patterns that arise from disturbed rock upon excavation. However, extensive site investigation can be costly for certain projects. It may be pertinent to incorporate the uncertainty in design of the concrete liner. Regardless, the liner must be watertight and competent enough to withstand stress re-distribution due to new flow conditions. Furthermore, the segmental liner joints must be secured tightly to withstand consolidation settlement.

3.2.2 Liner Deviation

One of the greater limitations of VSM for deep excavation is liner deviation. With increased depth, the shaft has a higher possibility of deviating from its verticality. Even though the exact alignment of the shaft axis is monitored with high accuracy and real time and can be controlled by differential lowering of the liner, deviations up to 30mm have been observed in certain projects for depths of 50-70m.

One of the reasons for liner deviation is due to the difference in competence and stiffness between rock layers during shaft sinking. Furthermore, excessive, or uncontrolled over-excavation can cause unbalanced slurry pressure in the advancing head. Both actions can induce an unbalanced normal force against the advancing ring structure, resulting in liner deviation and consequently separation of liner joints.

To prevent deviation, continuous monitoring of the built-in system in the VSM is required. This includes the horizontality of the cutting drum and the verticality of the shaft liner using inclinometers. It is possible for a VSM operator to correct the misalignment of the shaft by executing an overcut or by differential lowering of the liner.

For greater excavation depths, the monitoring should be more frequent since the deviation potential is much higher.

3.2.3 Waterproofing of Segmental Liner

Waterproofing is essential for highly jointed rocks and/or water bearing rocks. In VSM, water leakage can occur through the circumferential and radial joint segments and cracks in the concrete structure. It is better to consider the use of waterproofing membranes than relying on the quality of the gasket design and installation, curing of concrete and design tolerances. In addition, there is no access to the shaft for remediation work until it is dewatered. The consequence of water leakage once the shaft has been grouted is far worse compared to the initial investment of time in water proofing to accommodate for geological uncertainty.

3.2.4 Potential Piezometric Layer

Complex hydrogeological conditions with multiple confined aquifers with artesian water pressure conditions can be detrimental for the use of VSM.

There have been cases of over-pressurized aquifer where the piezometric surface is many metres above ground surface. This translates to potential excess pressures of hundreds of kPa that must be supported. The maximum pressure that can be exerted by the static water at the shaft base is dependent on the depth of the submerged water (pressure = unit weight of water * depth). If the piezometric surface is above ground surface, then upward seepage in the shaft occurs and results in overflow. To prevent this, a denser liquid can be used to counteract the excess water pressure. Furthermore, the high-water pressure can induce excess pressure against the structure and compromise its integrity. The segmental liners must accommodate for the additional stress and its joints must be tightly secured to prevent water leakage.

For confined units that are constantly being recharged, a pump with adequate capacity is required inside the shaft to pump out excess water flow. In weak rocks, understanding the hydrogeology is crucial for the sinking of VSM. By understanding the in-situ properties, appropriate measures can be taken when choosing the type of pump and cutting drum for the construction.

3.2.5 Effectiveness of Post-Grouting

Once the shaft is dewatered, post-grouting is the last step performed prior to the use of the structure. It locks the shaft in place by providing adequate shear resistance by filling the annulus between the liner and ground. In weak rocks, it is much more difficult to achieve the required shear resistance because the bentonite slurry can be washed away easily when there are many joints and fractures present in the rock mass.

To identify the impact of post-grouting, RS2 was used to study the relationship between post-grout shear stiffness and liner settlement. The consequence of an unstable temporary plug was also considered. For this analysis, a model similar to Figure 2 was developed. In the model, a very stiff clay was considered as overburden material. The rock was assumed to be weak with an elastic modulus of 50000 kPa. The grout was modelled as a joint interface between the liner and rock/soil. It is important to note that no slip criterion of the grout was considered, indicating it will behave elastically. Only the weakness of post-grouting was considered by changing joint shear stiffness values. The temporary plug was modelled as a boundary condition with restraint in x and y directions. To simulate partial destruction of the plug during D&B operation, the restraints were removed at the node of the liner-plug interface. This methodology may not be fully representative of the plug failure mechanism but for this hypothetical model it is considered adequate. The shear stiffness of the grout was determined by dividing the shear modulus of grout by annulus thickness (Rocscience, 2022). The shear modulus of cement grout was assumed to be approximately 5 MPa. The thickness of the annulus was assumed to be 0.2m. This results in a grout shear stiffness of 25000 kPa/m. To simulate the impairment of bentonite in post-grouting, there scenarios were considered: 100% effective stiffness, 50% effective stiffness and no effective stiffness. The geometry model used for this analysis is shown in Figure 4.

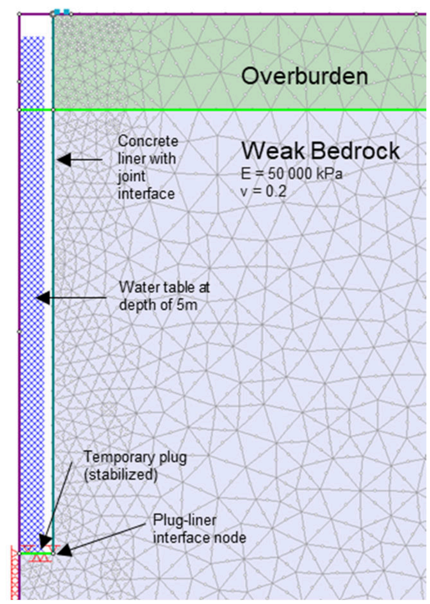

Figure 4. Axisymmetric model of liner to evaluate post-grout effectiveness

Table 2 summarizes the results from the analysis. It is evident that the stability of the temporary plug is more influential than the stiffness of the grout to prevent the liner from settling. Regardless, it is noticed that 100% and 50% grout shear stiffness have similar results. Both contribute to a liner settlement of approximately 12 mm with plug and 18mm without plug. When the grout is fully impaired (0 shear stuffiness), a liner settlement of 17 mm with plug and 62mm without plug is observed.

Table 2. Liner settlement results for various post-grout effectiveness cases

Joint Shear Stiffness (kPa/m)	Liner Location	Displacement with Plug (mm)	Displacement without Plug (mm)
25 000 (100% effective)	Top	12	17
	Bottom	0	9
12 500 (50% effective)	Top	12	18
	Bottom	0	10
0 (No effectiveness)	Top	17	62
	Bottom	0	45

For the case above, the rock is treated a continuum and porous material. The behaviour of weak rock was assumed to be captured by an elastic material. Furthermore, the post-grout strength criteria were not modelled. If the grout was modelled more accurately with a slip criterion, then larger displacement will be observed. This conservative analysis highlights the importance of the effectiveness of post-grout in weak rocks. In very weak rocks, pre-grouting is recommended to achieve the full effectiveness of post-grouting. Depending on the geologic condition, pre-grouting should be performed until a certain distance away from the shaft diameter. Pre-grouting can fill in the joints and fractures of weak rock, allowing for post-grout to maximize friction around the shaft diameter. This methodology can impact the schedule heavily since boreholes of great depths needs to be drilled beside the shaft to access the weak rock layers for pre-grouting. This may even defeat the purpose of using VSM, since it is more efficient to perform post-grouting when D&B methods are used. Another solution is to consider grouting pressure in the liner segment design load combination.

4 CONCLUSION

As the demand for underground infrastructure arises around the world, the importance of VSM is being recognized where conditions allow. The emergence of VSM for shallow shafts in softer rock applications is beginning to challenge conventional shaft construction methodology due to the various advantages VSM provides cost and time efficiency, safe operation, and lower environmental risk. However, this technology is limitated for application for deeper shafts and excavations in hard rock.

This paper highlights many geotechnical considerations involving deep shaft excavation (+150m depth) using VSM. A competent foundation is required to support the weight of the entire concrete structure. The liner and the base plug must be designed to withstand convergence and heaving of rock due to high in situ stress. Also, one must be careful with the use of bentonite slurry to reduce shaft friction during sinking and be aware of the possibility of the liner structure becoming stuck. Bentonite is only a temporary solution for the watertightness of liner. In the long-term, the clay particles will be washed away and impair the shear resistance of post-grouted interface.

Extra precaution is required for weak or fractured rocks with high water pressure. When entering a weak or fractured layer from a hard layer, the difference in stiffness and competence of the rock can result in liner deviation. Furthermore, the joint properties of the rock cannot be fully understood when the shaft is submerged. It is only when dewatered, new loading conditions and joint properties of the disturbed rock take effect This results in increase of external pressure on the segmental liners and activation of internal hydraulic gradients in the rock mass. Consequently, consolidation settlement will occur and affect the structural integrity of the liner. Therefore, a good site investigation is vital in predicting new flow patterns arising from disturbed rock. Most of the time, site conditions only become evident during inspection during shaft excavation. The site investigation data, if available, will be supplemented by site inspection but any access to shaft base for remediation effort requires dewatering of the shaft. Good planning and water sealing prior to shaft sinking is highly recommended if these conditions are encountered.
In heavily jointed rock, ground improvement methods such as pre-grouting is recommended prior to post-grouting. Although this can be a time-consuming operation, it is vital for the stability of the liner.

5 ACKNOWLEDGEMENTS

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