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Spiling in unstable tunnel sections – a benchmark and case study review

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ABSTRACT

In unstable ground, the tunnel can be pre-supported by driving spiles and forepoles into the crown and walls ahead of the excavation face with a small inclination angle upward. In Sweden, the nomenclature for this type of pre-support is "spiling". Spiling, which is a temporary support, is frequently used in Swedish tunnels. However, there is a lack of guidelines and international standardization for the design of spiling. This paper explores the design of spiling in unstable ground with focus on tunnels excavated in the Nordic countries with generally hard rock masses. Based on a benchmark, case and literature study review, example of guidelines and starting points in the design of spiling have been compiled. Cases, with different types of designed and installed spiling, are presented in the paper, followed by a discussion of when, and for what rock conditions, to use rebar spiles, pipe spiles, or self-drilling spiles to achieve a safe excavation progress. Analytical design methodologies used in Swedish cases are presented, including beam models for spiling sections between supporting arches or the face. Cases where numerical modelling have been used in the design of spiling are also described. The findings presented in this paper shows a lack of guidelines on how to design spiling. Future research work linked to model uncertainty, local arching effect and quality assessment is suggested, which will be beneficial for tunnel engineers in designing spiling in the future.

KEYWORDS

Spile, forepole, design, analytical, numerical

1. INTRODUCTION

In unstable ground, the tunnel can be pre-supported by driving spiles and forepoles into the crown and walls ahead of the excavation face with a small inclination angle upward. When the bearing capacity of the rock is insufficient due to weak rock, extensive weak zones, etc. an adapted and extensive reinforcement solution with spiling (longer bolts, pipes or braces) can be designed to secure the excavation, the working environment, and the surroundings (ground surface). Today, there is no clear compiled advice, recommended calculation methods or instructions for dimensioning of spiling (e.g., Oke et al., 2016; Strømsvik et al., 2016) even though excavating through complex passages involves a large cost. Based on previously completed and ongoing projects where spiling was used, examples of design and experience of temporary reinforcement with spiling have been compiled. The definition of spiling in this article is longer spiles (bolts or pipes) that are installed in the crown above the face, to create bearing capacity in the longitudinal direction of the tunnel (see Figure 1).

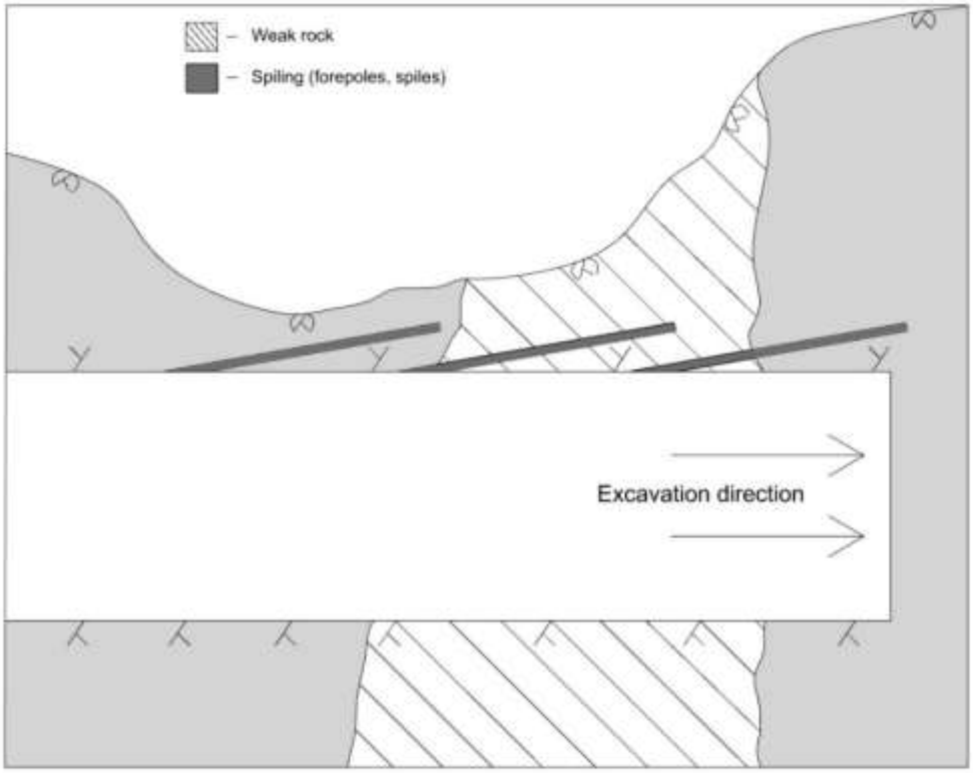


Figure 1. Example of a longitudinal section for a tunnel with spiling in weak rock and low rock cover.

The study does not address assessed risks and the actual risk management process associated with complex passages. The compilation does not deal with questions regarding durability, water and frost protection, form of contract and form of compensation. The compilation does not describe in detail other temporary reinforcement of the rock (e.g., fiberglass bolts) or changing its character (e.g., freezing, drainage, jet grouting) or other type of extraction (e.g., pilot tunnel, split fronts) when excavating through complex passages.

2. NOMENCLATURE

The concept of spiling, without further specification, is unclear. Within the concept of spiling, in our Swedish tunnel projects different terminology is used. Generally, spiling in Sweden means support added in the vicinity of the crown above the face; however, it does not specify the type of support nor its application or interaction with the rock mass. Typical used types of spiling (including the Swedish word in brackets), are rebar spiles (kamjärnsbultar), pipe spiles (rör), self-drilling spiles (självborrande stag, e.g., MAI, IBO, Ischebeck). Rebar spiles (bolts) are usually longer rebars that are cast into pre-drilled boreholes in hard rock where there is a risk of block failure or hammered into weaker, more earth-like material to provide a stabilizing effect. Pipes can be steel pipes, with a great diameter and larger thickness, which are installed in boreholes and where the pipe and the gap between the pipe and the rock is filled with concrete. The steel pipes are used and drilled into mainly heavily jointed rock or hammered into softer more earth-like material (Li, 2017). A certain risk with pre-drilled holes is that the holes collapse before steel pipes have time to be installed. Self-drilled spiles, to put it simply, are pipes that are left in the rock after drilling. Self-drilling spiles are often used for very weak rock to soil-like conditions.

Examples of terminology used in literature, when it comes to support in the crown above the face, are all from pipe roofing, pipe roof support, sub-horizontal jet grouting, steel pile canopy etc. Oke et.al. (2014a) presented a standardization proposal on the international nomenclature associated with support in the crown above the face to make everyone use the same words. The general term of the support in the crown have been suggested to be “umbrella arch”. In Oke et al., 2014a, "spiles" are defined as reinforcing elements whose length is shorter than the height of the rock tunnel. "Spiles" are installed closely (<30 cm distance) and at an angle of 5–40° from the axis of the tunnel. "Forepoles" are installed when longer stretches of weak rock are expected, which means that these are often thicker than "spiles" and longer (longer than the height of the rock tunnel).

3. DESIGN STRATEGY

Based on this study there is a lack of guidelines for calculation and analysis when designing spiling as well as lack of flowcharts in decision-making which considers if, what type, where and when spiling should be installed. A basic flowchart and some general principles that are suggested to be used in the design of spiling are proposed according to Figure 2. As part of the design strategy and during the entire work from identifying potential failure mechanisms to verifying the technical solution with calculations, a risk assessment is performed in parallel. Risks are identified, analyzed, and evaluated to decide how they should be treated and to discuss the possibilities to have back-up plans for unexpected occasions.

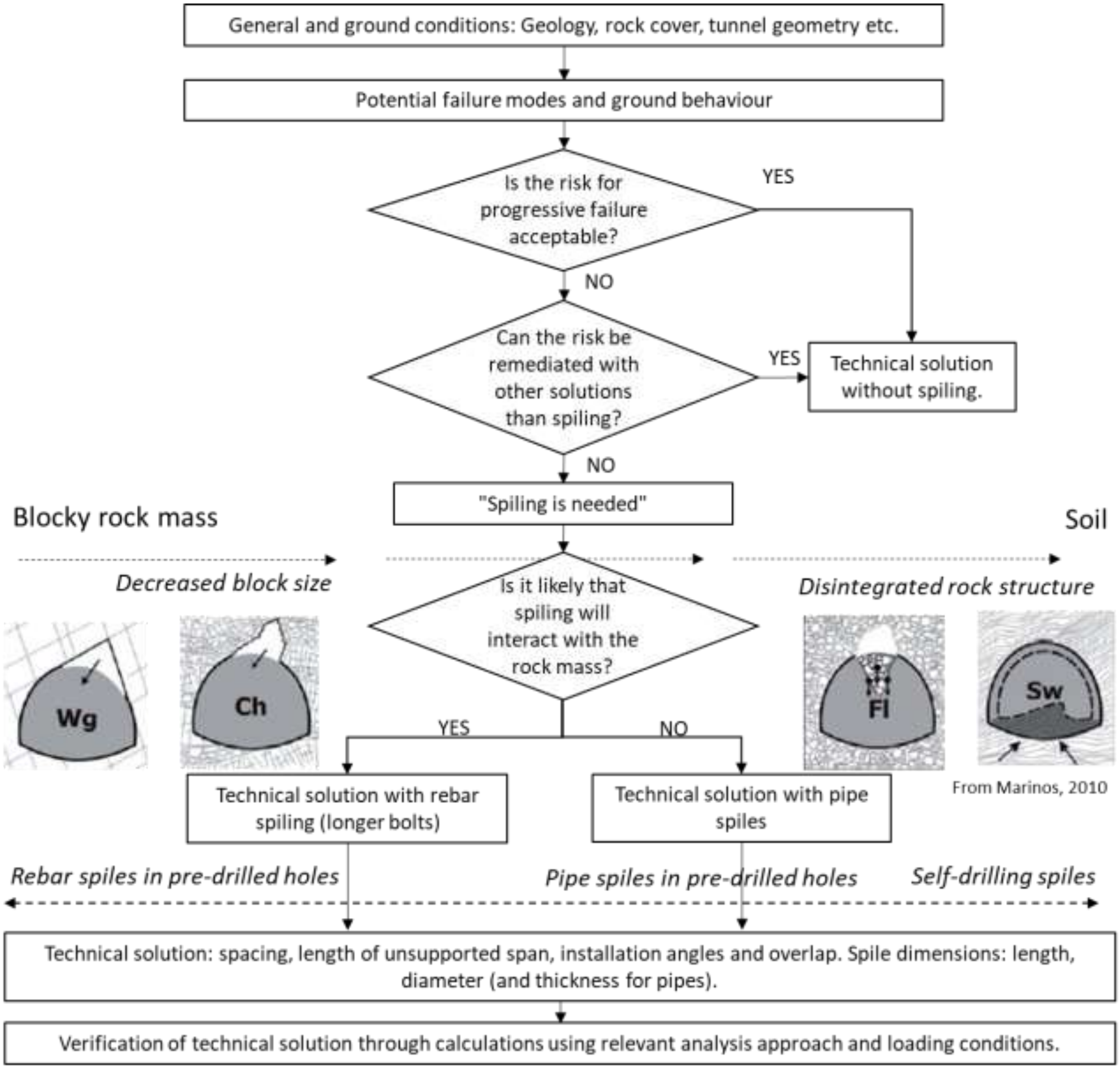


Figure 2. Proposed overall design strategy for temporary support using spiling.

All rock mechanical design requires an understanding of what ground behavior the rock mass can be expected to exhibit when excavating the tunnel. This behavior is due to a combination of rock mass composition, rock mass conditions and tunnel geometries etc. (Stille & Palmström, 2008). Ground conditions that must be considered include e.g., geology (lithology, structure, weathering), structures, groundwater conditions, rock cover, stress conditions and orientation of fracture groups in relation to the orientation of the tunnel. Decisions, whether spiling is needed, should be suggested based on the expected behavior of the rock mass, potential failure mechanisms, the accepted risk for raveling ground and if other temporary support measures (such as freezing, jetgrouting etc.) would be more applicable.

In Strømsvik et al. (2016) an attempt was made to study any correlation between rock mass quality (*Q*-value) and design of umbrella arches. According to Strømsvik et al. (2016), it was not possible to concretize any relationship between *Q*-value and choice of diameter of spiling pipes, distance between pipes nor the overlap over the pipe shields. A poor rock, say Q < 1, could represent all from a very blocky rock with intermediate water and clay problems to a sandy/soil like material. These two types of rock masses have different behaviour, potential failure modes and thereby different need for temporary support. For the Hallandsås tunnel in Sweden, eight scenarios were set up for *Q*-values < 1, based on expected geology (Sturk & Brantmark, 1998). For each scenario, geological risks were identified linked to potential failure mechanisms (e.g., loosening of the rock mass (raveling ground, running ground, swelling ground, etc.)) as well as how excavation and temporary reinforcement was expected to take place. Based on the above issues, and how to address the issue of low-quality rock masses, a thorough risk assessment is of importance. The risk assessment should include defined potential scenarios based on expected geology.

Once it has been decided that some type of spiling is required, the next decision is what type of spiling to use. The completed literature study shows that there are two fundamentally different reinforcement principles to choose from. The first principle is to use cast-in spiling rebar (bolts) that interact with the rock mass according to the same principle as for a reinforced concrete beam. An interaction between bolt and the rock mass can be expected for a blocky rock mass. The second principle is based on that the spiling carries through its ability to absorb moment. This principle is primarily used in rock masses of very poor (soil and/or sand) quality, to achieve the required load-bearing capacity. For this purpose, it is common to use thicker pipes.

When a suitable spiling solution has been chosen, a proposal for a technical solution can be produced, which is then verified through calculations. The verification of the technical solution through calculations requires that both load conditions and bearing capacity are considered through a suitable model, which is discussed in more detail in section 4. During the construction phase (not shown in Figure 2 above), the design conditions are continuously checked using e.g. geological mapping; and a final verification of the technical solution is obtained through monitoring of the rock mass and support behaviour.

4. TUNNELS WITH SPILING

There are several published cases of tunnels in rock masses with consistently weak rock and/or soil-like material (on the right in Figure 2) close to the surface where spiling has been used. In most of these cases, the focus has been on the evaluation of spiling as an effect to counteract settlements in an urban environment. It is also for these cases that most numerical analyzes have been performed. However, there are fewer examples of cases with a similar geology to hard Fennoscandian rock masses with passages through zones of weaker rock.

Examples of cases in Sweden where spiling pipes have been installed in tunnels are presented in Table 1. In all these cases, the rock mass structure has been disintegrated having a potential of raveling ground or chimney type failure. One of the most difficult technical challenges for the Stockholm Bypass project was the passage under the Lake Mälaren and the regional fault zone in the Fiskar fjord. The uncertainties and risks associated with this fault zone in the Fiskar fjord originated from limited information about the rock cover, the rock quality in the fault zone, possible large water leakages and existing in-situ stresses together with the relatively large width of the tunnels. To secure the excavation of the tunnels, a pipe umbrella with a length of 15 m, an overlap of 5 m and drilled at c/c 500 mm spacing was used. The steel pipes have a diameter of 140 mm and a thickness of 10 mm. In addition, to avoid stability problems at the tunnel face during excavation through the fault zone, self-drilling rock bolts installed at c/c 1.5 m were considered necessary (Stille et al., 2019). During the excavation of the rock tunnels in the Northern link project a critical part with soil within the profile of the rock tunnel was challenging. The excavation was completed with a temporary support using injection anchors above the crown (as spiling), lattice girders and sprayed fiber concrete together with short excavation steps (Andersson et al., 2011).

Examples of spiling bolts in intersections and tunnels with large span can be found, among others, from Västlänken (Eriksson & Fransson, 2022), New subway in Stockholm (Söder & Åkerlind, 2022), Götatunneln (Stille & von Matérn, 2003) and Hallandsås (Sturk & Brantmark, 1998). For the cases where bolts have been installed, the rock mass structure is very blocky to blocky. The compilation from the case study review shows that the design strategy and the design of spiling differ, and that different calculation methods, elementary cases and load cases have been chosen for the same expected behavior of the rock mass.

Table 1. Some examples of cases and projects in Sweden where spiling pipes have been applied.

Case (Project)	Quality of ground	Length of pipe [m]	Angle of application [°]	Overlap/Round length [m]	Spacing [m]
Yxhugget (Northern Link, Stockholm) *	Soil and rock	15 m (9-25 m)	8	-/3	0.4 (soil), 0.8 (rock)
Södra randzonen (Hallandsås tunnel) **		16 m (ø 140 mm)	5-10	-	0.4
Sätra-Kungshatt (Stockholm Bypass) ***	RMR_{base} 29 – 40	16 m (ø 140 mm)	7	5/2	0.5
Södermalmstunneln (Citybanan, Stockholm) ****	Soil	15 m (ø 139 mm)	7	5/1 pilot top heading	0.3 0.45
Kungsgatan (West link, Gothenburg) *****		18 m			

* Andersson et al., 2011, ** Sturk et al., 2005, *** Stille et al., 2019 **** Eriksson et al., 2016; Hjälmbacken & Söderberg, 2011, ***** Eriksson & Fransson, 2022

5. CALCULATION METHODS

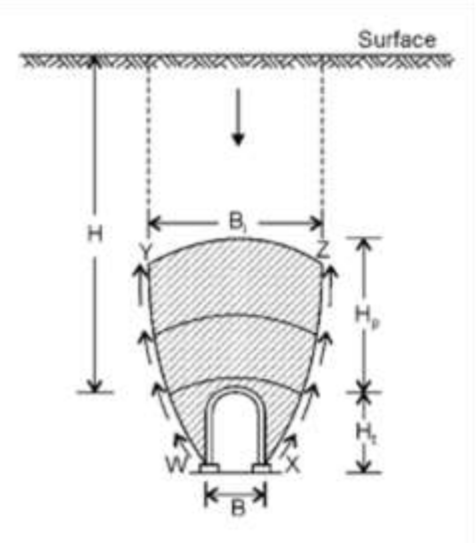
5.1. Load cases in analytical calculation

To assess the size of the load on the spiling during excavation, there are several different examples of assumptions that can be made. Most ways to calculate the load have been compiled in, among others, Lukic & Zlatanovic (2019) and Moses & Malik (2019). Spiling bolts installed in tunnels with “good rock” and where the purpose is to hold a large span, or a crossing, must generally be capable of carrying loads from a block. The weight of the load can be derived from e.g., arrow height, interpretation of block size, etc. When calculating the loads on shallow tunnels, it is suggested (Franzén, 2003) that the strength of the surrounding soil/rock is not used, and the load is calculated in these cases as the overlay pressure (and water pressure). How large this pressure from above is assumed to be, should be based on the nature of the rock or soil. Furthermore, the pressure from above depends on the ability to receive an arching effect above the tunnel caused by the horizontal stresses. From the examples in the case study review, for loose rock masses, the pressure from above has been estimated based on, for example, numerical analysis, Terzaghi's methodology (Terzaghi, 1946) or rock cover height.

The well-known empirical method for assessing load from soil and rock is Terzaghi's compilation from 1946 where calculation of load (Figure 3) has its basis in the nature of the rock divided into nine rock classes. In this work, rock classes V-IX are in focus. There are several calculation examples for spiling where the Terzaghi theory is used as a basis for assessing the load. The height of the zone with loose soil or rock mass, H_p is a function of the tunnel's width, B, and height, H_t, according to Figure 3. The material above this zone is assumed not to load the tunnel roof. The shear strength is assumed to counteract the weight of the loose rock. Terzaghi's theory is applicable for tunnels with a width of up to 6 meters.

For tunnels in rock and soil located above the water table, the actual loads are significantly lower (50%) than those calculated according to Terzaghi's method (Franzén, 2003; Singh & Goel, 2011). The reason is believed to be that a quickly installed support and good contact with the soil/rock causes only a small deformation and the pressure arch in the soil/rock can then be formed quickly (Franzén, 2003). For a fictitious example, the uniform distributed vertical (non-sustaining) load, q, is as a function of rock material density, ρ, gravity acceleration, g, and overburden height, H_p, according to equation (1).

$$q = \rho \cdot g \cdot H_p \tag{1}$$



Rock class	Rock condition	H_p	Remarks
V	Very blocky and seamy	(0.35 to 1.10) $(B + H_t)$	Little or no side pressure.
VI	Completely crished, but chemically intact	1.10 $(B + H_t)$	Considerable side pressure. Softening effects of seepage toward bottom of tunnel. Requires either continuous support for lower ends of ribs or circular ribs.
VII	Squeezing rock, moderate depth	(1.10 to 2.10) $(B + H_t)$	Heavy side pressure. Invert struts reqired. Circular ribs are recommended.
VIII	Squeezing rock, great depth	(2.10 to 4.50) $(B + H_t)$	
IX	Swelling rock	Up to 80 m	Circular ribs are required. In extreme cases, use of yielding support recommended.

B = tunnel span in meters, H_t = height of the opening in meters,
H_p = height of the loosened rock mass above tunnel crown developing load

Figure 3. Left: Load from loose material above a tunnel (after Terzaghi, 1946). Right: Height of the loose rock mass based on rock classes (after Sing & Goel, 2011).

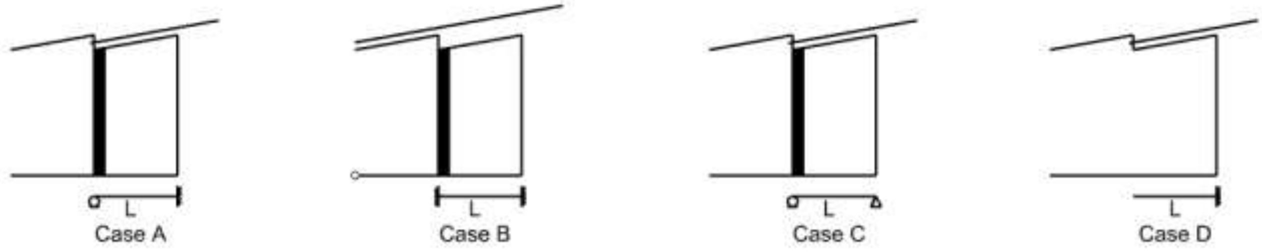
5.2. Analytical beam calculation

Analytical calculations for the bearing capacity are mainly based on the beam theory. When using beam theory, the rock mass is divided into strips where each strip consists of a spiling bolt/pipe and has a width corresponding to the c/c distance to the next bolt/pipe, alternatively calculated per meter in width. The assumption is considered conservative as the bending moments and loads are determined for the worst possible geometry (Stille & von Matérn, 2003).

Based on the bending moments to which the spiling is subjected, it can be assumed that it is a beam that is loaded according to four load cases, A to D according to Figure 4. The proposed load cases depend on excavation step and support or non-support at the near-end of the beam. The uniformly distributed load per spile, $q \cdot s$, is a product of the loose rock/ground pressure, q (as in equation 1), and the spacing between spiles, s. Analytical calculations using load case A and B for the different excavation steps (see example in Figure 5) and by assuming near-end support have been applied for, among others, the New Subway in Stockholm and the West Link in Gothenburg, Sweden.

Another way of looking at bearing capacity is that it is a simply supported beam (hereafter named case C) where the support of the beam consists of the reinforced rock vault (excavated tunnel) and the rock mass in the unexcavated tunnel. A fourth way used in the design is a cantilever beam (hereafter named case D,) which could represent the spiling before installing the first supporting arch. In case D, the spiling is only supported by the rock ahead of the front. Spiling is in such case installed at the bottom of the beam to sustain bending moments and the calculation method has been used for example for the Göta tunnel in Gothenburg, Sweden (Stille & von Matérn, 2003). The different load cases that may be relevant in analytical beam calculation, are described according to classical beam theory as four elementary cases:

A. Beam fixed at one end and simple support at the other, with uniform distributed load.
B. Beam fixed at both ends, with uniform distributed load.
C. Beam simple support at both ends, with uniform distributed load.
D. Cantilever beam, that is fixed at one and free at the other, with uniform distributed load.



Case A	Case B	Case C	Case D
$M_{max} = M_B = \frac{q \cdot s \cdot L^2}{8}$	$M_{max} = M_A = M_B = \frac{q \cdot s \cdot L^2}{12}$	$M_{max} = M_{mid} = \frac{q \cdot s \cdot L^2}{8}$	$M_{max} = M_A = \frac{q \cdot s \cdot L^2}{2}$
$V_{max} = V_B = \frac{5 \cdot q \cdot s \cdot L}{8}$	$V_{max} = V_A = V_B = \frac{q \cdot s \cdot L}{2}$	$V_{max} = V_A = V_B = \frac{q \cdot s \cdot L}{2}$	$V_{max} = V_A = q \cdot s \cdot L$

Figure 4. The four different elementary cases for spiling and equations for the maximum bending moment and shear force.

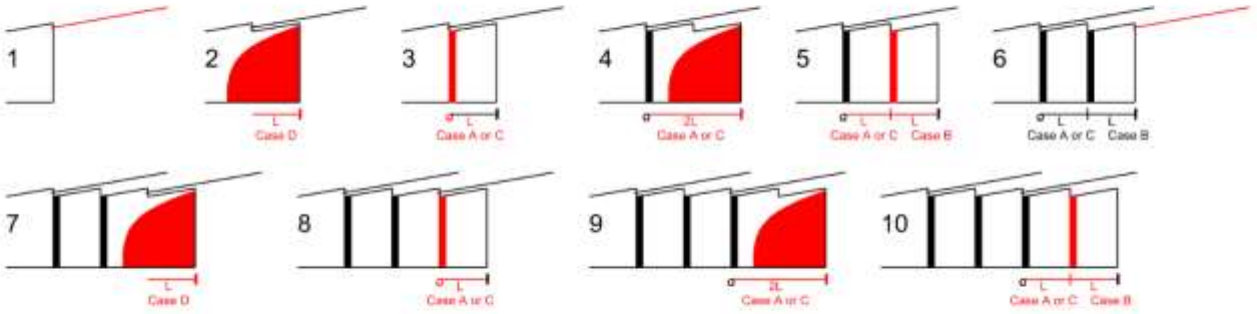


Figure 5. Excavation and installation sequence for spiling together with example of applicable elementary cases. L is the distance between ribs.

To assess the load-bearing capacity of the spiling, one (or more) of the following criteria has been used in the different case studies: moment (2), shear force (3) or normal and shear force (4):

$$M_{Ed} \leq M_{Rd} \tag{2}$$

$$V_{Ed} \leq V_{Rd} \tag{3}$$

$$\left(\frac{N_{Ed}}{N_{Rd}}\right)^2 + \left(\frac{V_{Ed}}{V_{Rd}}\right)^2 \leq 1 \tag{4}$$

where*:*
M = moment, V = shear force, N = normal force (tensile or compressive force), $_{Ed}$= design load effect and $_{Rd}$ =design load resistance. To determine the diameter and length of the spile, the moment, shear force and/or normal force to which the spiling will be exposed to, is compared with its capacity.

5.3. Numerical calculations

Internationally, spiling and its effect on ground movements been studied, using numerical modelling, mainly for near-surface tunnels in consistently weak rock or soil in e.g., Klotoé & Bourgeois, 2019. In Sweden, spiling in tunnels has been studied and designed through both 2D and 3D numerical calculation models. The evaluation of the results from numerical modeling is often done using moment-normal force interaction diagrams. Since the spiling is installed in front of the face, it is exposed, compared to permanent reinforcement installed in the tunnel, to all deformations caused by the rock excavation. The compilation has shown that numerical modeling in 2D does not capture the arching between spiling elements, the change of rock stress along the spiling element, and the response of the rock element in the longitudinal direction (e.g., Volkmann & Schubert, 2007; Peila, 2013; Oke et al, 2014b). The change in stress and response is especially important to consider in 3D if the tunnel is excavated in steps and partial face with heading-and-bench (which is common in complex passages) is used. However, it is recommended to use 2D modeling to design distances between spiles. This local arching effect has been studied in 2D models for properties corresponding to soil and sand (e.g., Doi et al., 2009) but there is nothing in the literature showing similar results for a fractured and blocky rock mass.

6. DISCUSSION

The literature and case study review have shown that there is a need for clarity regarding nomenclature and definition of what we refer to as spiling. When choosing spiling as a technical solution, the following should be described (i) function and mode of action, (ii) type and dimension, (iii) casting of the spile, (iv) interaction with other reinforcement and (v) installation (angles, single arch or double arch with spiles etc.).

The compilation focused on Swedish cases. For other Nordic countries, there may be other proposals for design strategies and more ways to design and calculate that are not publicly published. In general, the overall principles for design of spiling are well described in the literature, the main difficulties lie in: (i) being able to determine when spiling is needed, (ii) choosing the correct technical solution that works for the prevailing ground conditions, and (iii) being able to estimate design load and (iv) set up an acceptable bearing capacity model and calculation method. However, the model uncertainty of the bearing capacity model and its impact on the dimensioning in combination with other uncertainties linked to the rock mass mean that the probability of failure is difficult to determine, which also means that it is difficult to assess whether the dimensioning is associated with an unacceptable risk.

The compilation from literature and the case study review shows that the design of spiling differs, and that different calculation methods, beam models and load cases have been chosen for the same expected behavior of the rock mass. Material parameters in general, both regarding relevant material parameters for loose rock masses and surrounding rock but also parameters that describe the spiling interaction with the rock are difficult to assess. According to Andersson et al. (2011), the calculation method itself when calculating spiling and its accuracy is not decisive for the result. What is decisive is the interpretation and assumptions of the strength parameters of the rock and the soil along the tunnel and whether the material behaves as a friction material or is cohesive. To capture the variation of strength parameters, they proposed sensitivity analysis.

In the design stage, it is important to consider how the proposed technical solution can affect the construction stage, but also relative to other technical disciplines. When designing spiling, the following aspects should be considered:

- Grouting
  How is the developed grouting solution affected, considering location, length, direction, angle of spiling?
- Work environment when installing long spiling bolts.
- In terms of work environment, it is heavy and tiring, and thereby nonacceptable from a health and safety perspective to install 32 mm bolts. It is rarely or never that there are machines to install these bolts. Long bolts with ø 32 mm are not suggested to be designed if they are to be installed manually. Furthermore, there is a risk that long bolts will start sway, which partly makes it difficult to hit the hole, but which also risks creating motion sickness for those working from a sky lift.
- Investment cost and time required for special machines.
- Installation of pipes requires special machines. Investment cost for special machines constitutes a noticeable cost. Furthermore, installation of pipes gives extra time compared to simpler reinforcement installations.

7. CONCLUSION AND RECOMMENDATION FOR FUTURE WORK

The main conclusions of the literature and case study review are:

- The literature and case study review has shown that there is a need for clarity regarding nomenclature and definition of what we refer to as spiling.
- When describing spiling as a technical solution, the following should be described: (i) function and mode of action, (ii) type and dimension, (iii) grouting and spiling, (iv) interaction with other type of rock support and (v) installation (single or double arch for a pipe umbrella arch).
- There is a need for advisory documents for dimensioning spiling and flow charts for decision-making about: if, where and when spiling should be installed. The principle flow chart shown in this article can be used as a basis in future advisory documents. In the design of spiling, it is important to consider, among other things, the following aspects compared to other disciplines and in the construction phase: grouting, working environment, investment cost and time consumption.
- To address the issue of low-quality rock masses, a thorough risk assessment is recommended. The risk assessment should include defined potential scenarios based on expected geology.
- The preliminary study shows that the design of spiling differs, and that different calculation methods, beam models and load cases have been chosen for the same expected behavior of the rock mass.
- Material parameters in general, both regarding relevant material parameters for loose rock masses and surrounding rock, and parameters that describe the spiling interaction with the rock, are difficult to assess.
- According to the compilation, modeling of how spiling is loaded regarding excavation method and split front should be studied with a numerical 3D model. Numerical 2D modeling should only be used to study the arch effect to dimension pipe spacing.

The recommendation for future work includes:

- Linked to model uncertainty, it is suggested that one or more practice cases be studied regarding approach, calculation methodology, variation in parameter values through sensitivity analysis and reliability-based design.
- A similar compilation of how to dimension, and how to follow up, the developed technical solution in the construction phase should be made for the support arch themselves, such as shotcrete and lattice arches.
- This local arching action should be studied for jointed rock in 2D models to study block size and its connection to the arching action and thus the need for either bolt or pipe and the distance between them.
- Since classification systems, such as the Q system, are applied in tunnel construction, different probable scenarios for Q values below 1 should be described, which can be linked to the relevant choice of temporary reinforcement solution.

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