NORWEGIAN
TUNNELLING SOCIETY

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Norwegian Rock Bolting

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Preface

The Norwegian Tunnelling Society (NFF) is an open society for people and enterprises associated with or interested in Norwegian rock technology. A key aspect of the society's work concerns development projects for the benefit of the industry. This takes place in close cooperation with relevant actors, and the results achieved are disseminated through NFF's publications, handbooks and technical reports.

This publication has a relatively long history. In 1973, *Kontor for Fjellsprengningsteknikk KFF* published a practical handbook on rock bolting (*Praktisk håndbok i fjellbolting*). This became a starting point for the Norwegian Public Roads Administration's Publication No. 72 Rock bolting from the road laboratory (*Fjellbolting from veglaboratoriet*), which was published in 1994, and the Norwegian Public Roads Administration’s handbook V224 Rock bolting (*Fjellbolting),* published in 2000 (previously handbook 215). A relatively extensive revision was carried out by the Directorate of Public Roads, before the entire process was handed over to NFF in 2017. NFF’s development committee subsequently set up a group which has ensured that it has now been updated to reflect current practice and products.

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Norwegian Tunnelling Society
International Committee
April 2023

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1. Introduction

This publication is primarily aimed at tunnelling operatives, foremen, supervisors and quality control engineers, although engineering geologists and other professionals will also find the handbook useful in their work. The handbook should ideally be actively used by contractors, consultants, construction clients and others in the professional community.

One of the purposes of this handbook is to provide descriptions concerning bolting. The handbook is intended as a contribution towards ensuring the quality of bolting. The handbook covers bolts for rock reinforcement. It is worth noting that there are also assembly bolts. There are bolts which do not in themselves stabilise rock. These bolts require greater accuracy as regards their positioning and are used to assemble concrete elements, membranes, fabrics and technical installations, etc. These bolts will not be discussed further in this handbook and have only been mentioned because they are used in permanent stabilisation, but they are not used in the construction of tunnels.

Bolts are the most widely used method of stabilisation under most rock conditions. A wide variety of different bolt types are available. The bolts have different designs and behaviours, which are utilised to stabilise rock masses of very different character. Bolts can be end-anchored and pretensioned, or they can be embedded in and act as reinforcement of the rock.

Bolts can be used with other stabilisation methods such as bands, reinforcement meshes and sprayed concrete. Bolts are generally easy to install and they can take up relatively high loads. Bolts can also be used in underground caverns of almost any geometry.

There may be substantial stresses present in the rock, which causes load stresses on any stabilisation measures. As far as possible, the rock should therefore support itself, and bolts and other stabilisation measures should help the rock to become self-supporting.

Water in bolt holes can cause problems and affect the service life of bolts. The presence of water in bolt holes causes problems with grouting and the anchoring of bolts, and can contribute to a corrosive environment.

Norwegian rock stabilisation practice has been, and remains, largely based on making assessments and decisions as the rock is uncovered ("design as you go"). Bolts that act instantaneously, such as end-anchored bolts, are used to provide stabilisation while work is in progress. Bolts used in this way are then included as part of the permanent measures for rock installation, and it must be possible to grout the bolts using cement grout after they have been inserted.

The use of bolts is therefore largely based around choosing bolts that satisfy requirements for a long service life, and such bolts are grouted where there are no rock pressure problems.

The background material for this handbook was taken from more recent experiences and investigations, along with previously published books on bolting /1/, /2/, /3/.

2. Use of bolts

2.1 Stabilisation practice in tunnels and rock cuttings

Protection is installed while work is in progress in order to ensure safe and stable working conditions during the construction of tunnels, cuts/cuttings and rock cuttings. Permanent stabilisation is installed in order to provide long-term stability, thereby ensuring the safety of users over time.

Rock stabilisation is dimensioned on the basis of engineering geological conditions. Assessments made in connection with stabilisation involve observations of rock conditions, including engineering geological mapping and rock mass classification, calculations as and when appropriate, and the selection of stabilisation methods. The assessments that are carried out are then used to determine bolt types, lengths, quantity and placement.

The various bolt types are presented in Chapter 3. This chapter presents a brief description of the use of the most common types of bolts.

For instant stabilisation and protection while work is in progress, two types of bolts are primarily used: either combination bolts with expansion sleeves or end-anchored bolt with polyester cartridges. These bolts are used to provide protection while work is in progress because they are fast-acting. The bolts can be pretensioned and provide an active pressure in the rock mass. Fractures are pressed together, causing the friction and thus the strength and stability of the rock mass to increase.

For permanent stabilisation, fully embedded bolts, either pretensioned combination bolts or unpretensioned bolts, are used based on lifetime considerations. Glued end-anchored bolts can be used to provide permanent protection in the case of high rock stresses. Bolts which are not pretensioned become effective as the rock is deformed.

The various bolting methods used in rock installations can be divided into the following categories:

- Spot bolting
- Systematic bolting
- Spiling
- Bolting in front of the tunnel face

2.1.1 Spot bolting

In the case of spot bolting, each bolt is inserted to stabilise the presumed unstable block or collection of blocks, without the bolts being arranged in a particular pattern (see Figure 2.1). Spot bolting is often used in coarse-blocked to moderately fractured rock, stabilising a delineated, clearly defined block or collection of blocks. Where loose blocks are to be stabilised, bolts are used to provide fast anchoring and pretensioning. The use of dowels is a form of spot bolting, with fully embedded rebar bolts, which primarily act obliquely.

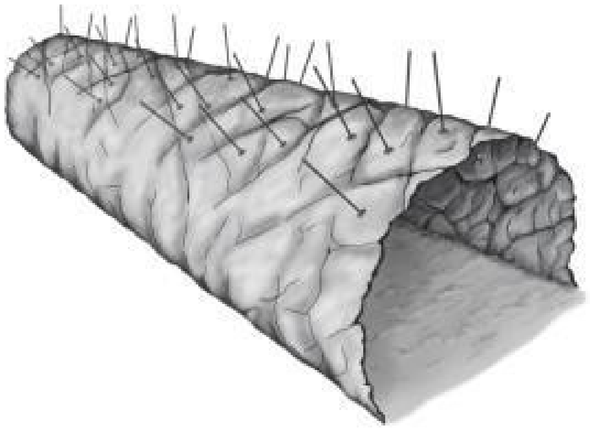


Figure 2.1 Example of spot bolting

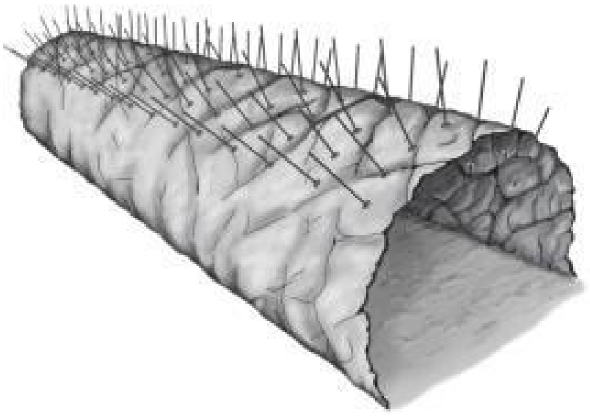


Figure 2.2 Example of systematic bolting

2.1.2 Systematic bolting

In the case of systematic bolting, the bolts are inserted into the rock in specific patterns. It is common to use the same spacing between the bolts and bolt rows, c/c 1.0–2.5 metres (see Figure 2.2). Systematic bolting is normally used in difficult rock conditions and/or heavily to moderately fractured rock.

Where each bolt is placed following a more detailed assessment, without the bolts forming a specific pattern, but with a small bolt spacing (e.g. less than 2.5 metres), it is common to refer to the method as 'systematic bolting'.

Systematic bolting is most often used in combination with sprayed concrete. Wherever possible, systematic bolting is carried out after the sprayed concrete has been applied.

2.1.3 Spiling

Spilling in tunnels is used in particularly poor rock (weakness zones) and where the rock overburden is thin. This bolting method is also commonly used in connection with tunnel entrances/exits. (See Figures 2.3 and 2.4).

The purpose of spiling is to preserve the profile after blasting and avoid collapse of the roof and tunnel faces by creating a "bridge" for the unstable masses which rest against the spiling bolts. The spiling bolts should hold the profile until further stabilisation, such as reinforced sprayed concrete arches, sprayed concrete and radial bolts, is established.

The spiling bolts are inserted in front of the tunnel face and fanned out from the tunnel axis at an angle of 10–15°. It is common to use fully embedded rebar bolts ø32 mm, with a length of 6-8 metres (length ≃ 1½-2 times the blast round length). The bolt ends are permanently anchored/locked by a reinforced spray concrete arch, possibly with temporary bands secured using radial bolts and sprayed over. Bolt spacing can be as little as 0.2-0.3 metres.

Screens with rebar bolts ø32 mm or self-drilling anchors, combined with short blast rounds, can be used in the case of particularly poor rock masses where the holes collapse.

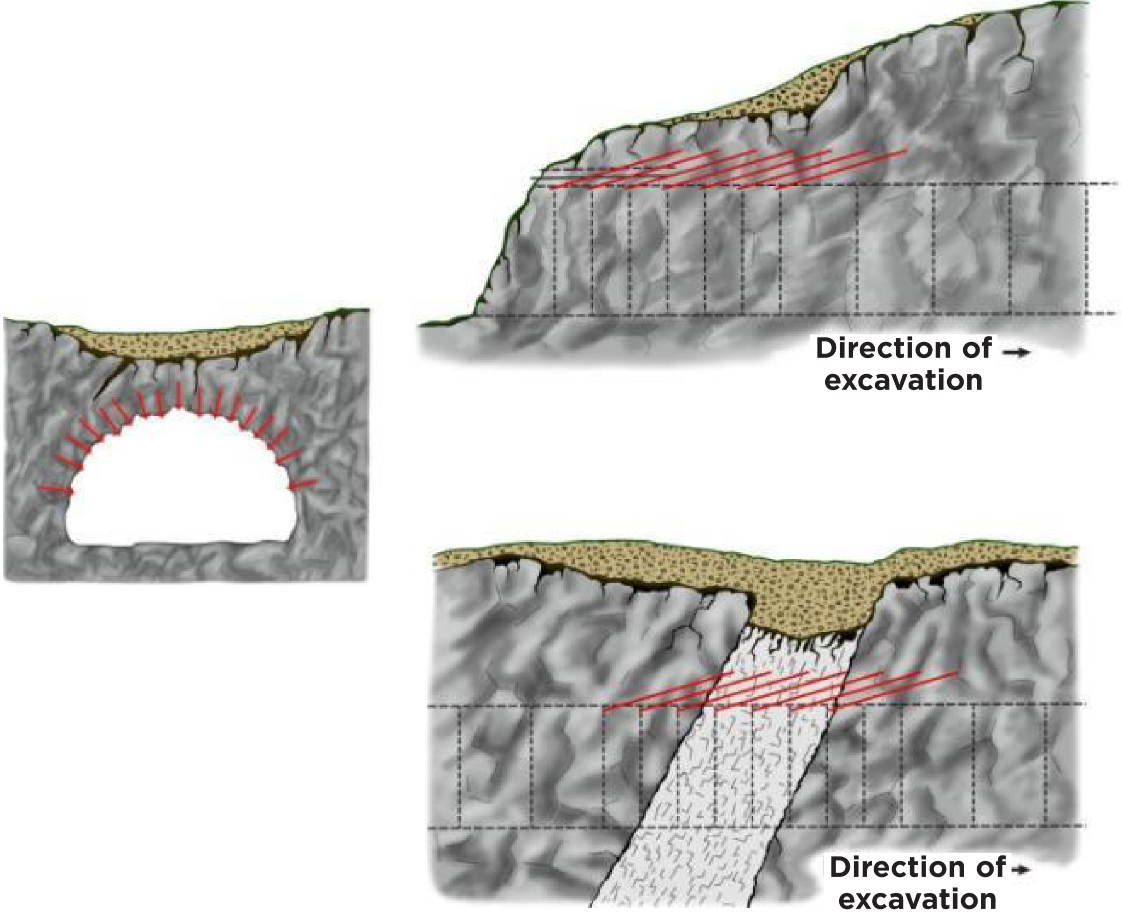


Figure 2.3 Examples of spiling in tunnels

Spiling in rock cuttings is carried out following an assessment of the overall stability, in order to prevent blocks at the top of the cutting from falling in connection with blasting or cutting. The spacing between the spiling bolts, bolt dimensions and bolt orientation is normally assessed based on the rock mass, fracture geometry, block size and cutting height. In particular, the use of spiling should be considered in connection with the blasting or cutting of cuttings close to piles or other structures, and to preserve the contours.

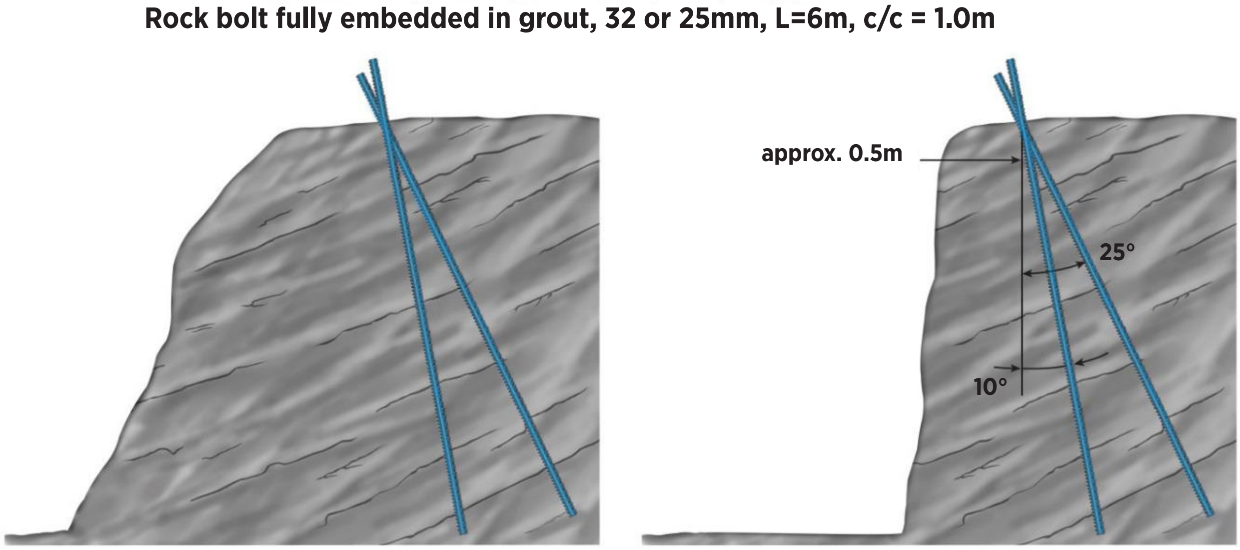


Figure 2.4 Example of spiling in a cutting or tunnel entrance/exit face prior to blasting (left) and after blasting (right)

2.1.4 Bolting in front of the tunnel face

Bolting in front of the tunnel face inside a tunnel is used to preserve the profile where the geology, structural geology and fracture orientation mean that there is a risk of blocks dropping out of the tunnel profile in connection with blasting (see Figure 2.5). The bolts are suspended or supported at the rear. This is done using radial bolts and bands which are fixed to the rock, or by supporting the rock with a sprayed concrete arch. The centre-to-centre spacing between the bolts can be 0.4-0.7 metres. The angle of the bolts is adapted to the fracture geometry.

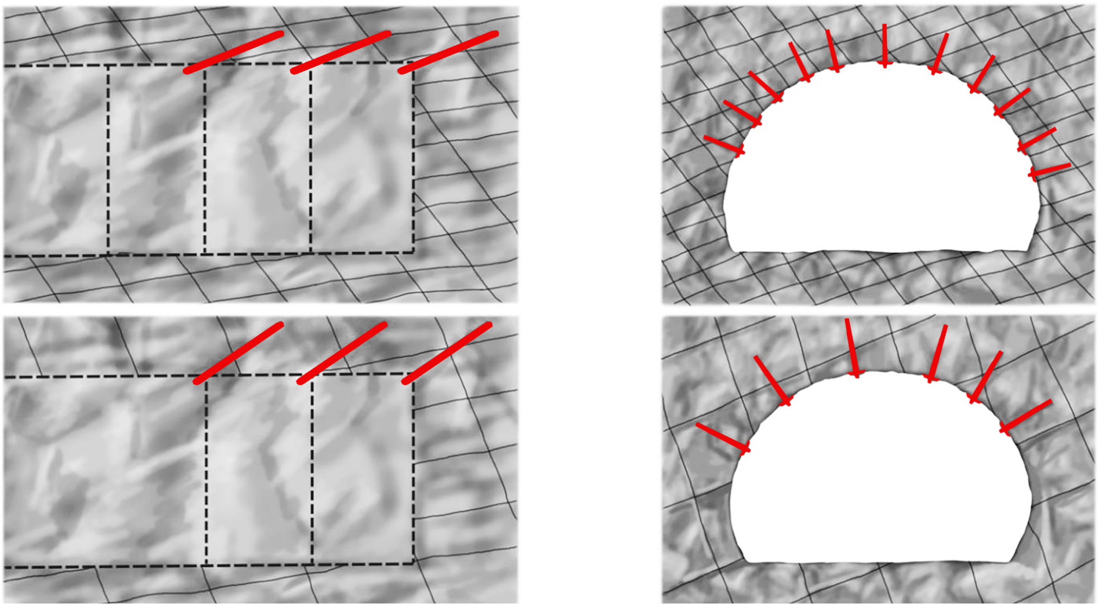


Figure 2.5 Examples of bolting in front of the tunnel face

2.2 Rock conditions and bolt types

2.2.1 Rock conditions and stability

In principle, there are four main factors which are decisive in connection with a stability problem:

1. Stress conditions: stresses to which the rock is being subjected at any given time as a result of gravity, movements in the Earth's crust (tectonics), solidification stresses, structural geology, and the blasting of underground caverns.

2. Material properties: the properties of the rock mass in the broadest sense, such as grain size, grain binding, compressive and tensile strength, elasticity, mechanical anisotropy, etc. Material properties also includes frequency, roughness, weathering rate and fracture filling for fractures and other discontinuities, as well as the properties of gouges and crush zones.

3. Structural geology and geometric conditions: directional factors which impact on stability. Directional factors include the mutual orientation of fractures, gouges and weakness zones and their direction relative to the tunnel/underground cavern or cutting, and the orientation of the principal stress (especially important in the case of rock pressure problems). Other factors included in geometric conditions are the tunnel/underground cavern span and overburden, the rock cutting height and length, and the terrain behind the cutting.

4. Water conditions: water in fractures, fracture water pressure, pore water pressure in the rock, groundwater level, gradients in the water due to blasting, wetting and drying of the rock, major water ingress, flushing of gouge material, etc. Water conditions also includes ice formation. Water in the rock causes reduced stability in the tunnel/underground cavern or cutting.

2.2.2 Rock conditions and stabilisation method

An indicative, simplified classification of rock conditions and stabilisation methods is shown in Table 2.1.

Table 2.1. Main groups of rock conditions where bolts are used for stabilisation (see /4/ for Q values)

	Structures, rock conditions	Examples of stabilisation methods in tunnels	Examples of stabilisation methods in cuttings
Sparsely fractured rock (Q = 100-10)	Mean fracture spacing > 1 m	- spot bolting - sprayed concrete to avoid future scaling	- spot bolting (of locking blocks)
Moderately fractured rock (Q = 10-4)	Mean fracture spacing 0.3–1 m	- systematic bolting - sprayed concrete	- spot bolting - possibly bands and rockfall netting
Heavily fractured rock (Q = 4-1)	Mean fracture spacing < 0.3 m	- systematic bolting - sprayed concrete	- spot or systematic bolting - bands and rockfall netting or sprayed concrete (in high cuttings)
Layered/schistose rock (Q = 4-1)	One dominant fracture system	- systematic bolting - sprayed concrete	- spot or systematic bolting - bands and rockfall netting or sprayed concrete (in high cuttings) - self-drilling anchors
High rock stresses	High rock stresses Rock pressure problems	- systematic bolting with end-anchored bolts - sprayed concrete	- spot or systematic bolting - possibly sprayed concrete - self-drilling anchors
Gouges and weakness zones	Crushed rock with/without swelling clay	- systematically embedded bolts - spiling and radial bolts combined with sprayed concrete - reinforced sprayed concrete arches or grouting	- embedded bolts - sprayed concrete - bands - possible grouting - self-drilling anchors

Stability problems are often combinations of several of the six main groups in Table 2.1. In the following, comments on stabilisation are linked to the various stability problems referred to in the table. Dimensioning in connection with bolting is shown in Chapter 5.

Sparsely fractured rock

The mean fracture spacing is greater than 1 metre and any fill material in the fractures does not exceed 20–30 mm.

Bolting in sparsely fractured rock is normally carried out using spot bolting (Figure 2.6). Amongst other things, this involves bolting key blocks (the locking of key blocks prevents blocks above or behind them from collapsing).

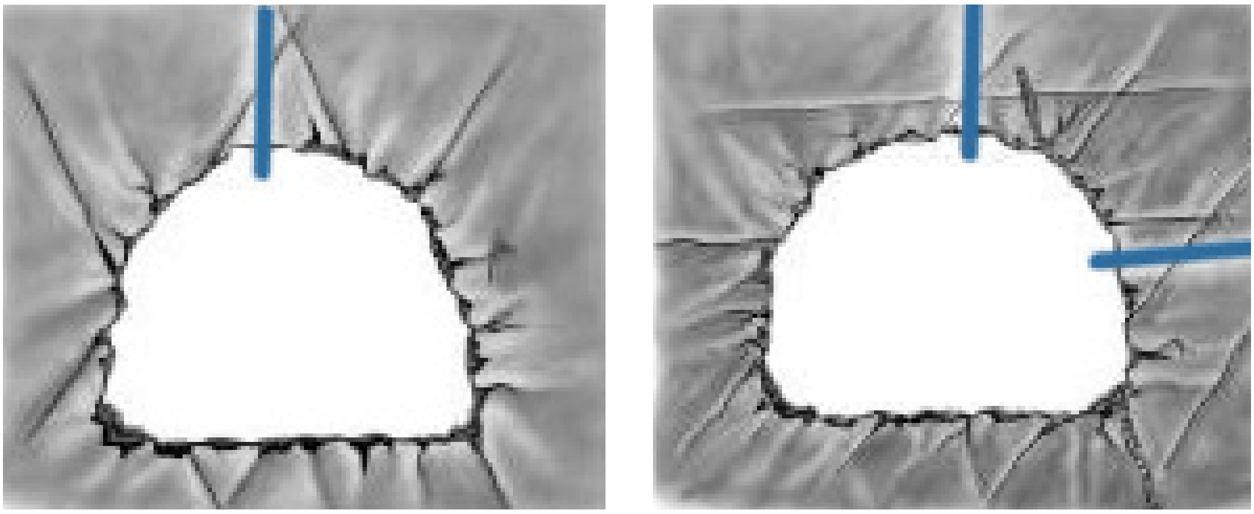


Figure 2.6 Examples of bolting in front of coarse-blocked rock

Moderately fractured rock

The mean fracture spacing is 0.3 – 1 m and there are at least two fracture sets.

Bolting in moderately fractured rock can be carried out using different bolt types and methods (Figure 2.7). Depending on the rock conditions otherwise, the intended use of the rock installation and requirements regarding stabilisation, both spot and systematic bolting can be used, possibly in combination with bands, reinforcement meshes or sprayed concrete.

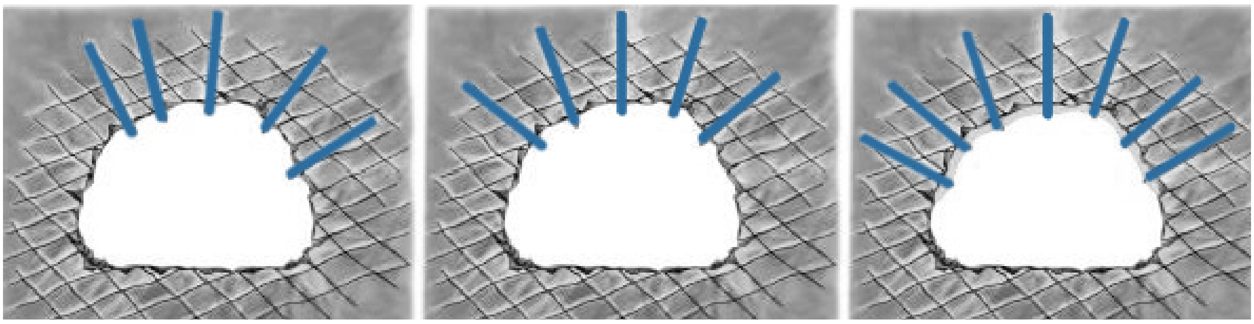


Figure 2.7 Examples of bolting in moderately fractured rock

Heavily fractured rock

The mean fracture spacing is less than 0.3 m and there are at least two fracture sets.

Sprayed concrete in combination with bolts is often used as a tunnel stabilisation measure in heavily fractured rock (Figure 2.8). In rock cuttings, rockfall netting is often used in combination with bolts.

In many cases, weak rock types can be stabilised using sprayed concrete and systematic bolting, in the same way as for heavily fractured rock. The thickness of sprayed concrete and bolt spacing are adapted to the local rock conditions.

Self-drilling anchors can be used in rock cuttings.

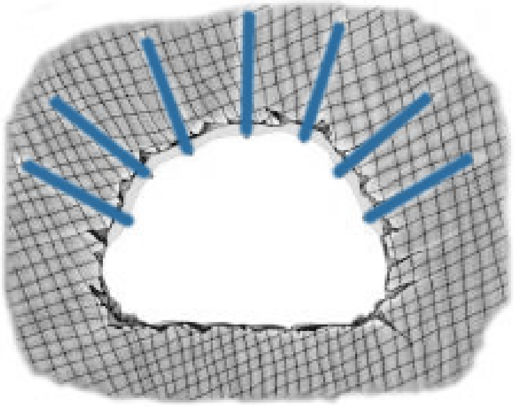


Figure 2.8 Example of the use of bolts and sprayed concrete in heavily fractured rock

Layered/schistose rock

A single dominant fracture system which can form detachment surfaces. Rock masses with only one fully penetrating fracture set can also be included in this group. Rock types which can be classified as layered/schistose include phyllites and mica shales.

The use of spot bolting or bolts in combination with other stabilisation methods may be appropriate. In some cases, the underground cavern may also be left unstabilised. The dominant fracture direction in relation to the orientation of the underground cavern is decisive as regards the choice and placement of stabilisation means (Figure 2.9).

a) b) c)

Figure 2.9 Examples of bolting in layered/schistose rock, a) horizontal, b) oblique and c) vertical

High rock stresses

High and/or anisotropic stresses can lead to rock spalling, peeling or in the worst case scenario rock bursting. In such cases, end-anchored bolts with a high ultimate elongation and large triangular plates are used. The bolts are often supplemented with reinforcement meshes, bands and/or sprayed concrete. Rock stress problems are a surface phenomenon (layered fracturing/peeling), and short bolts are used, usually 3 metres in length (Figure 2.10). The bolts are not pretensioned, but the nut is tightened carefully. The bolts become tensioned as the rock mass becomes deformed. The plates must be secured to the rock surface and not be loose.

Self-drilling anchors can be used in rock cuttings.

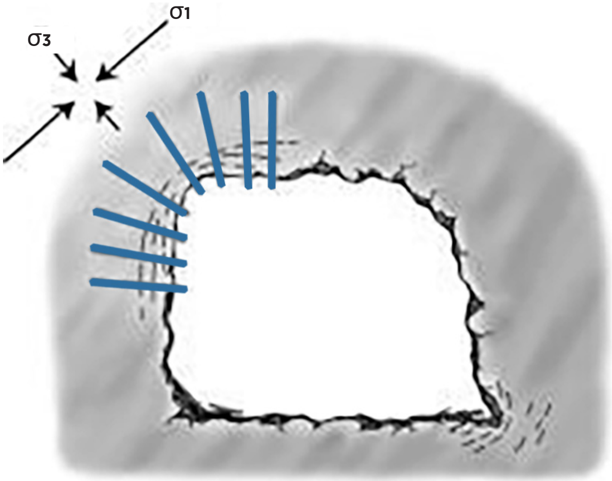


Figure 2.10 Example of bolting in rock spalling

Squeezing rock is a type of rock pressure problem which can result in extensive deformation. Squeezing rock can occur in rocks and weakness zones with low compressive strength and E-module in relation to rock stresses. Squeezing rock often requires substantial stabilisation, such as reinforced sprayed concrete arches supplemented with radial bolts or reinforced cement grouting around the entire tunnel profile.

Gouges and weakness zones
Fully penetrating gouges with fill material of ≥ 20–30 mm, and weakness zones.

The gouges are considered to be virtually frictionless, and stabilisation using embedded bolts is carried out in order to lock the gouges and thereby prevent movement (Figure 2.11).

In some cases, minor weakness zones (< 1 m) containing swelling clay have been stabilised using bolts, bands and fibre-reinforced sprayed concrete, as shown in Figure 2.12.

Self-drilling anchors are often used in rock cuttings.

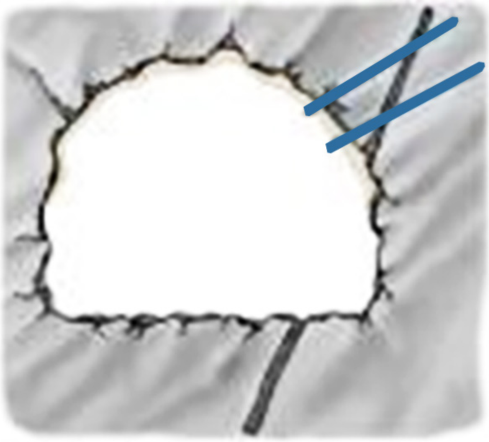


Figure 2.11 Stabilising the gouge in the upper right-hand corner

Consideration may be given to placing deformable material (such as PE foam) up against the zone containing swelling clay. The purpose of the deformable material is to allow some swelling to occur in order to reduce the pressure on the stabilisation means. The most common approach is to stabilise such zones using reinforced sprayed concrete arches. The number of arches must be assessed based on the thickness and direction of the zone in order to lock/prevent movement in the gouge. In case of substantial water leakage, it is important to drill drainage holes, especially in cuttings, which are then covered with sprayed concrete. This is shown in Figure 2.12.

In the case of particularly active swelling clay or where major crush zones need to be stablished, reinforced spray concrete arches with a small spacing or cement grouting are used.

2.2.3. Choice of bolt types in different rock conditions

Requirements regarding permanent stabilisation in connection with different underground installations vary depending on area of use and stabilisation levels for the underground installations. Bolts end-anchored using expansion sleeves, for example, were considered adequate for use as permanent bolts in supply tunnels to hydroelectric power plants /5/, but they are not permitted for use as permanent stabilisation in road tunnels. Bolts end-anchored using an embedding compound (normally polyester cartridges) may be used in areas with rock bursting, as embedded bolts are not appropriate in such rock conditions /6/. In exceptional circumstances, end-anchored bolts are used to provide permanent stabilisation in rock cuttings for roads.

In Table 2.2, the process of selecting a bolt type based on rock conditions is divided into three categories: recommended, may be used or not recommended, based on Norwegian experience and assessments.

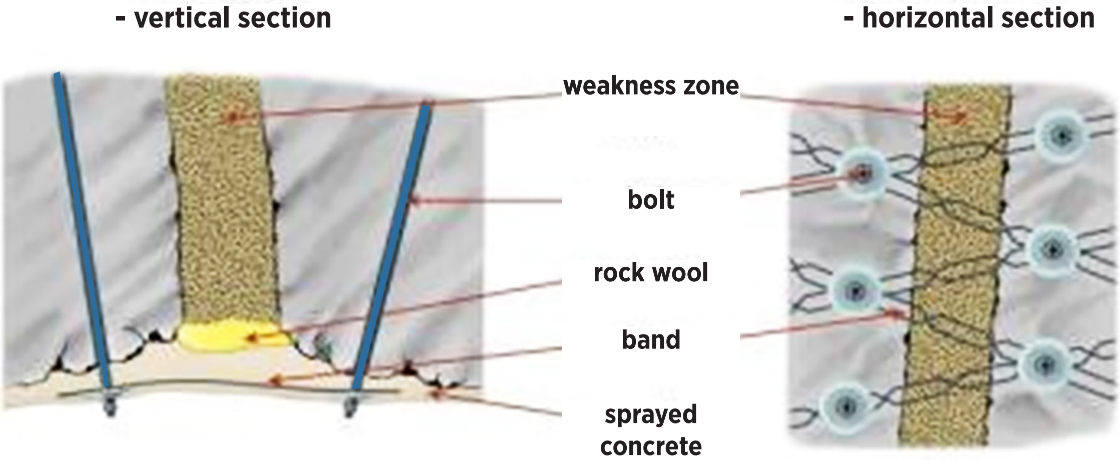


Figure 2.12 Examples of bolting in gouges and weakness zones

Table 2.2 Choice of bolt types in different rock conditions (see /4 / for Q values)

	Bolt end-anchored with expansion sleeve	Bolt end-anchored with polyester	Fully embedded bolt (unpretensioned) 1),2)	Combination bolt (pretensioned and embedded band) 3)
Sparsely fractured rock (Q = 100-10)	recommended	recommended	recommended	recommended
Moderately fractured rock (Q = 10-4)	recommended	recommended	recommended	recommended
Heavily fractured rock (Q = 4-1)	not recommended	may be used	recommended	recommended
Layered/ schistose rock (Q = 4-1)	may be used	recommended	recommended	recommended
High rock stresses	may be used	recommended	not recommended	not recommended
Gouges and weakness zones	not recommended	may be used	recommended3)	may be used3)

1) Cement-based mortar has a relatively long curing time.
2) Cement-based grout can be washed out by continuously flowing water in the bolt hole.
3) May be too stiff for use in zones rich in swelling clay.

Explanatory remarks concerning Table 2.2 are presented below. In addition, some comments are presented concerning friction bolts, little practical experience of which has been gained in Norway.

(a) Bolts end-anchored with an expansion sleeve are not recommended:

- in the case of weak rock masses where the rock type or fracture fill material could affect anchoring capacity, or in heavily fractured rock
- in very hard rocks where no checks are performed on the anchoring capacity
- close to blasting operations where the pretensioning could be lost/loosen unless the bolts behind the tunnel face are retightened
- to resist shearing movements in the rock without the bolt being post-grouted. However, the angle of the bolts relative to the fracture plane and a high level of pretensioning can compensate for an inability to withstand shear movements.

(b) Bolts end-anchored with polyester are not recommended:

- in this case, in heavily fractured rock, a greater anchoring length and checks on anchoring capacity will be required

- in boreholes with loose or sharp particles unless the polyester cartridge is protected with additional reinforcement meshes. The alternative is to use two cartridges or drill a new hole.
- to resist shearing movements in the rock without the bolt being post-grouted. However, the angle of the bolts relative to the fracture plane and a high level of pretensioning can compensate for an inability to withstand shear movements.

(c) Fully embedded, unpretensioned bolts are not recommended:

- in boreholes with continuously flowing water
- for instantaneous protection (using cement-based grout)
- in the case of substantial deformation in the rock (the bolt may be too rigid).

(d) Combination bolts are not recommended:

- in boreholes with continuously flowing water, unless seals are fitted.
- in the case of substantial deformation in the rock (the bolt may be too rigid).

Friction bolt type Swellex is not recommended:

- as permanent stabilisation without special corrosion protection
- to resist shear movements in the rock (can increase shear capacity by "inflating" the bolt with an injection compound during installation)
- in areas where substantial deformation can be expected in the rock.

A Split Set type friction bolt is not recommended:

- as permanent stabilisation
- to resist shear movements in the rock when a rigid bolt is preferred, e.g. in connection with block bolting in a rock cutting (the bolt has a good ability to absorb shear deformation, but a low shear capacity)
- where it is difficult to control the hole diameter.

2.3 Bolts in combination with other stabilisation methods

Bolts alone are used in older road tunnels and in mines and hydroelectric tunnels in coarse-blocked to moderately fractured rock, to some extent in layered, schistose rock and in the case of rock spalling. In rock cuttings, bolts alone are normally used in coarse-blocked to moderately fractured rock, and otherwise in combination with concrete, reinforcement meshes, bands and anchors. Other stabilisation methods include bands, reinforcement meshes, sprayed concrete, reinforced sprayed concrete arches and cement grouting.

The choice of stabilisation method and quantities is primarily based on the local rock conditions, and is often production-adapted. The choice also varies with the type of underground installation and the level of stabilisation required for the installation.

2.3.1 Bolts, bands and reinforcement meshes

In connection with dimensioning, the bolts ensure overall stability, while reinforcement meshes and bands are intended to prevent the dropout of small blocks between the bolts. The spacing between the mesh bolts should not be too great, in order to avoid pockets in the reinforcement meshes. Fibre-reinforced sprayed concrete is primarily used in tunnels and underground caverns. Previously, reinforcement mesh (50 x 50 x 3 mm) has been used. The mesh is less rigid and thus easier to handle than rockfall netting, but is not recommended. The advantage of rockfall netting is that it will not unravel even if the netting breaks. It is available in dimensions of 80x100x2.7/3.7mm (2.7mm has no plastic coating, 3.7mm has a plastic coating).

Rockfall netting is often used in cuttings in heavily to moderately fractured rock. The netting can be supplemented with rock bolts and, if necessary, reinforced using bands. Rockfall netting provides good drainage. Bolts in combination with bands are often used to "sew" together larger and smaller blocks of rock in rock cuttings.

2.3.2 Bolts and sprayed concrete

Fibre-reinforced sprayed concrete is used in combination with bolts to stabilise and reinforce the rock mass. Sprayed concrete is a flexible material that can be used for various stabilisation methods in most rock conditions. The sprayed concrete should penetrate into open fractures and smooth out surface irregularities. Sprayed concrete also prevents water from washing out fine-grained material and pebbles, and can be used to seal small clay zones. A layer of sprayed concrete will have a wedging effect, and also provide binding and adhesion to the rock mass. In the case of thick layers, such as in sprayed concrete arches, the sprayed concrete can have a vault effect.

The use of sprayed concrete and the choice of thickness of the sprayed concrete layer will partly depend on the stabilisation level of the rock installation. End-anchored bolts are often used in combination with fibre-reinforced sprayed concrete in the case of rock pressure problems. Where a sparsely fractured rock mass has marked (fully penetrating) fractures/gouges, bolts should be installed before the sprayed concrete is applied. When checking permanent stabilisation, the sprayed concrete layer should be checked for fracturing and loose sections, and consideration given to possible supplementary bolting or spraying.

2.4 Stabilisation under special conditions

In addition to potential stability problems in connection with different rock conditions (2.2.1), other factors may also affect the choice of stabilisation arrangements:

- timing of the stabilisation
- purpose of the underground cavern and requirements regarding safety in connection with use
- temporary or permanent stabilisation
- practical considerations
- contractual relationships
- production considerations
- access to equipment and bolt types
- cost and availability
- proximity to existing underground caverns
- previous experience
- construction method (full profile boring or conventional construction)
- scaling
- drilling
- blasting

Many of these factors will interact. The significance of some civil engineering conditions in connection with bolting is commented on below.

2.4.1 Drilling and blasting

Accurate drilling is important in order to produce a smooth contour. Inaccurate drilling and careless charging will often result in back-blasting, collapses and the formation of "cavities" and "protruding rocks", which will impact on the scope of the final stabilisation.

Blasting operations can impact on the scope of the stabilisation. Careful blasting with reduced charges in the contour holes and the second outermost row, possibly with line drilling, are important factors which can prevent the formation of blasting fissures and fractures. Careful blasting can reduce the scope of bolting required /7/, /8/.

2.4.2 Scaling

Scaling is an important part of the stabilisation process. Good scaling results in better safety during the bolting operation and reduces the possibility of falling blocks and the need for physical stabilisation. In the case of rock pressure problems, scaling should be omitted, and bolts and other stabilisation methods used directly.

Manual scaling using a crowbar gives an opportunity to become "acquainted" with the rock. High-pressure scaling will uncover the rock and makes it easier to assess the scope of stabilisation needed. Scaling is also carried out mechanically using, for example, an excavator fitted with a hydraulic breaker, rock grinder, etc. Mechanical scaling can lead to a risk of new fissures and fractures forming.

In general, all mechanical scaling should be checked with manual scaling using a crowbar.

3. Bolt types

The following sections cover a selection of different bolt types. The bolts are presented with diagrams, technical data, area of use, installation, advantages and disadvantages. It is nevertheless important to familiarise yourself with the technical data and areas of use described in the product data sheet for the individual bolt concerned. Designations and names of different bolts vary between suppliers. We have included a selection from different suppliers. Reference is made to the full product overviews from individual suppliers, which are generally available in catalogues on the suppliers' websites.

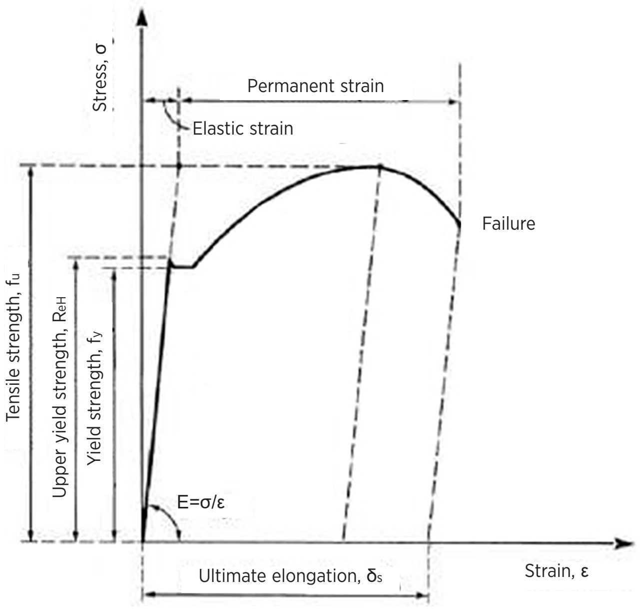


Figure 3.1 Stress-strain diagram for steel, in accordance with NS-EN 10088 /9/

For the $\sigma\ \varepsilon$ curve in Figure 3.1, the following applies:
f_y = yield strength
f_u = fracture stress
$f_{0.2}$ = stress which results in 0.2% permanent strain
δ_5 = ultimate elongation
A_g = total elongation percentage at maximum force /9/

Figure 3.1 shows the stress-strain curve during the tensile testing of a bolt made from ductile carbon steel. This has been included in this book, as the properties of steel generally represent important knowledge in understanding the use of different bolts for different purposes.

3.1 End-anchored bolts

End-anchored bolts are used where there is a need for rapid stabilisation (e.g. on tunnel faces) and to increase tensioning of the rock. Pretensioning of the bolts leads to greater friction on fracture surfaces and increases the strength of the rock. End-anchored, pretensioned bolts are referred to as 'active bolts'. The bolts are anchored using an expansion sleeve, polyester or grout at the bottom of a bolt hole. The pretensioning takes place when a nut is tightened against the plate, which in turn is pressed against the rock surface. This results in tension in the bolt.

At high rock pressures, which can cause rock spalling and substantial deformation, end-anchored bolts are used for yielding stabilisation. In these cases, the nut is tightened against the plate, but the bolts are not pretensioned. They become tensioned as the rock deforms. If the bolts are nevertheless tensioned, the load at high rock pressures, for example, can be so great that they fail.

The steel used for bolts is normally round bar steel or rebar. Where the ribs are removed through milling, the cross-section of the threaded section is smaller than that of the bolt shank. One consequence of this is that overloading results in flow and failure in the threaded section before the bolt shank has been fully activated.

Main types of end-anchored bolts:

- Bolt anchored with expansion sleeve (3.1.1)
- Polyester-anchored bolt (3.1.2, 3.1.3)
- Bolt end-anchored using grout (3.1.4)

3.1.1 Bolts anchored with an expansion sleeve anchor

Area of use
Can be used in medium to hard rock where immediate stabilisation is needed and for tensioning of the rock. Not used in heavily fractured rock. Widely used in water tunnels. The bolt is activated by being tensioned.

Installation
The bolt end with the expansion sleeve is pushed into the bolt hole. The bolt is tightened by tightening the nut towards the plate. See also section 4.3.

Advantages
Fast to install. Provides instant stabilisation after installation. Rapid tensioning. High load capacity in good rock. The bolt can be tightened again if it becomes loose.

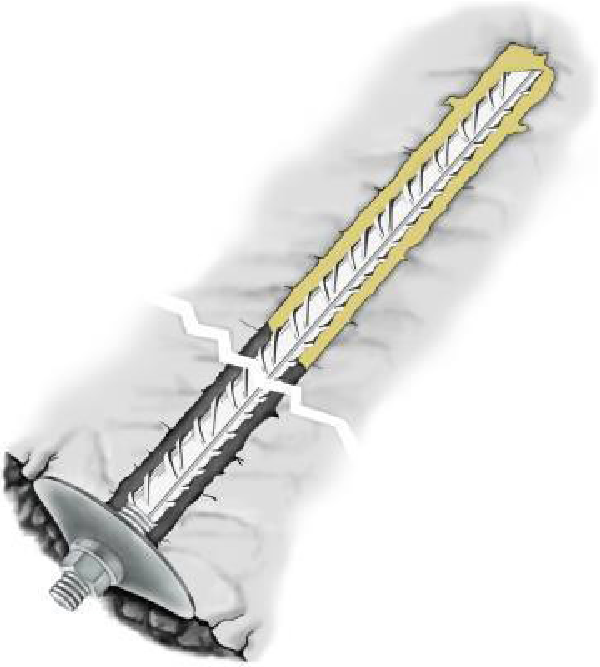
Disadvantages
Provides poor anchoring in weak rocks, heavily fractured rock and weakness zones. Can provide poor anchoring in very hard rocks. The anchoring should then be checked in such cases. Can lose tensioning due to vibrations from blasting and peeling beneath the plate. The bolt should then be retensioned.

Material	Rebar
Designation	B500NC etc.
Hole diameter [mm]	33-52
Diameter [mm]	16-20
Yield strength [MPa]	500
Flow load [kN]	79-123
Failure load [kN]	94-147
Elongation at maximum force [A_{gt}]	8%
Weight [kg/m]	1.6-2.5

Material	Round bar steel
Designation	St 37/S235
Hole diameter [mm]	33-52
Diameter [mm]	16-20
Yield strength [MPa]	225
Flow load [kN]	45-71
Failure load [kN]	72-113
Elongation at maximum force	26%
Weight [kg/m]	1.6-2.5

Length [m]	1.5 - 6
Corrosion protection Hot-dip galvanized Hot-dip galvanized and powder-coated (epoxy)	
Anchoring Expansion sleeve, plate, hemisphere and nut	

3.1.2 Polyester-anchored bolts - bolt holes Ø25-Ø32 mm



Material	Rebar
Designation	B500NC etc.
Hole diameter [mm]	25-32
Diameter [mm]	20
Yield strength [MPa]	500
Flow load [kN]	157
Failure load [kN]	189
Elongation at maximum force [A_{gt}]	8%
Weight [kg/m]	2.5
Length [m]	1.5 - 8

Corrosion protection
Hot-dip galvanized
Hot-dip galvanized and powder-coated (epoxy)

Anchoring
Polyester cartridge, plate, hemispherical cone and nut

Area of use

Used in both hard and weak rock types. Can allow some fractured rock, but polyester can provide poor adhesion in heavily fractured rock or weak/loose rocks. Used where rapid stabilisation or tensioning of the rock is needed. Well-suited for use in connection with rock spalling. The bolt becomes active upon pretensioning.

Installation

The polyester cartridge is pushed to the bottom of the hole using the bolt itself or a stemming rod. The bolt is rotated and slowly fed through the polyester cartridge. The bolt is tensioned (in the case of rock spalling, the nut is tightened against the plate, but the bolt should not be tensioned). See also section 4.4.

Advantages

Provides rapid stabilisation after installation, possibility of tensioning after 4-5 minutes in the case of the fastest-curing polyester types.

Disadvantages

There are various ways in which these bolts can be installed incorrectly: depends on the correctly adapted dimensions of the bolt, polyester cartridge and borehole, as well as the correct rotation time and speed (see also installation, section 4.4).

The correct length of the borehole is important. The pretensioning can be reduced due to peeling beneath the plate. The bolt should then be retightened. Installation personnel must remain under unstabilised tunnel roofs during rotation and reversal (approx. one minute). Uncured polyester has a limited storage time.

3.1.3 Polyester-anchored bolt - bolt holes Ø43-Ø48 mm

Material	Rebar
Designation	B500NC etc.
Hole diameter [mm]	43-48
Diameter [mm]	20
Yield strength [MPa]	500
Flow load [kN]	123
Failure load [kN]	147
Elongation at maximum force [A_{gt}]	8%
Weight [kg/m]	2.5
Length [m]	1.5 - 8

Corrosion protection Hot-dip galvanized Hot-dip galvanized and powder-coated (epoxy)
Anchoring Polyester cartridge, plate, hemispherical cone and nut

Area of use

Can be used in both hard and weak rock types. Polyester cartridges can cause poor adhesion in heavily fractured rock or weak/loose rock. Used where rapid stabilisation or tensioning of the rock is needed. Well-suited for use in connection with rock spalling. Extensively used in road tunnels. The bolt becomes active upon pretensioning. The bolt is not approved as permanent rock bolt in Norwegian road tunnels.

Installation

The polyester cartridge is pushed to the base of the hole using the bolt. The bolt and plate, hemispherical cone and nut are rotated and fed through the polyester cartridge. The bolt is tensioned by tightening the nut against the plate. (In the case of rock spalling, the nut is tightened, but the bolt should not be tensioned). See also section 4.4.

Advantages

The bolts and the polyester cartridges are designed so the same drilling equipment can be used for both holes for the blasting and holes for the bolts. The mixing mechanisms (propeller) cause the polyester and hardener to mix in boreholes with a large diameter relative to the bolt diameter. Provides rapid stabilisation after installation, possibility of pretensioning after 4-5 minutes in the case of the fastest-curing polyester types. Can be used on tunnel faces (does not become detached as a result of vibrations caused by blasting).

Disadvantages

Various possibilities for incorrect installation: depends on the correctly adapted dimensions of the bolt, polyester cartridge and borehole, as well as the correct rotation time and speed; see also installation, section 4.4. The bolt is not approved as a permanent rock bolt in Norwegian road tunnels. Correct length of the borehole is important in order to make sure that the whole of the polyester cartridge is mixed properly.

The pretensioning can be reduced due to peeling beneath the plate. The bolt should then be retightened. Installation personnel must remain under unstabilised tunnel roofs during rotation and reversal (approx. one minute). Uncured polyester has a limited storage time.

3.1.4 Bolt end-anchored using grout

Material	Rebar
Designation	B500NC etc.
Hole diameter [mm]	30-52
Diameter [mm]	20 and 25
Yield strength [MPa]	500
Flow load [kN]	123 and 177*
Failure load [kN]	147 and 212
Elongation at maximum force [A_{gt}]	8%
Weight [kg/m]	2.5 and 3.9
Length [m]	1.5 - 6

Corrosion protection
Hot-dip galvanized
Hot-dip galvanized and powder-coated (epoxy)
*Capacity threads

Anchoring
Grout cartridge(s)
Perforated sleeve (short sleeve at the bottom of the borehole)
Plate, hemisphere and nut

Area of use

Used for small bolt jobs where embedding with cement grout is desired.

Installation

A water-saturated cement cartridge is inserted into the hole with the bolt. The bolt is pressed through the cement. The nut is screwed against the end plate and the bolt is pretensioned after the cement has cured. (When several cartridges are used, the bolt can be fully embedded; it should then not be pretensioned.)

End anchoring with a perforated sleeve; see section 4.5.

Advantages

Easy to install. Does not require special equipment for installation. The bolt can be pretensioned once the cement has cured.

Disadvantages

Curing time for grout. Anchoring length depends on the correct hole depth and diameter. The bolt is not approved as a permanent rock bolt in Norwegian road tunnels.

3.2 Fully embedded bolts

Fully embedded, untensioned bolts are used in most rock conditions. The bolts are especially used for extra stabilisation and systematic bolting in order to improve the stability of the rock. This bolt type is often used for spiling. The stabilisation system is passive. The bolts only become activated once the rock becomes deformed and causes strain in the bolts.

The bolt is too rigid if the deformation of the rock mass is substantial. This can lead to failure of the bolt in areas where the stress is concentrated.

During installation, the bolt hole is filled with cement grout before the bolt is inserted. Rebar is commonly used as bolt steel. In Norway, cement-based grout is normally used as an embedding agent, but polyester can also be used. Where a plate, hemispherical cone and nut are used, the nut should only be tightened. Fully embedded bolts should not be pretensioned.

Full embedding provides greater corrosion protection. Failure of the grout, leaching of the grout due to flowing water, air pockets and acentric positioning of the bolt in the hole will mean that grout as the only form of corrosion protection will not be sufficient. Correct installation requires correct consistency and composition of the grout.

Various fully embedded bolts are shown with diagrams, technical data, area of use, installation, advantages and disadvantages.

Principal types of fully embedded bolts:

• Grouted rebar bolts	(3.2.1)
• Perfobolts	(3.2.2)
• Polyester-anchored bolts	(3.2.3)

3.2.1 Grouted rebar bolts

Material	Rebar
Designation	B500NC etc.
Hole diameter [mm]	30-52
Diameter [mm]	20 and 25 (25 and 32 in the case of spiling)
Yield strength [MPa]	500
Flow load [kN]	157 and 245
Failure load [kN]	189 and 295
Ultimate elongation	Fully embedded – rigid system
Weight [kg/m]	2.5 and 3.9
Length [m]	0.8-8

Corrosion protection
Hot-dip galvanized
Hot-dip galvanized and powder-coated (epoxy)

Anchoring
Cement grout

Area of use

Can be used in all rock types and degrees of fracturing. Is a rigid bolt type and is therefore unsuitable where the rocks are heavily deformed, e.g. at high rock pressures (rock spalling). Extensively used for systematic bolting behind the tunnel face and spiling. The bolt is well-suited for stabilising rock cuttings.

Installation

Grout is pumped into the bolt hole using a grout pump. The bolt is then pressed into the hole. See also section 4.5.

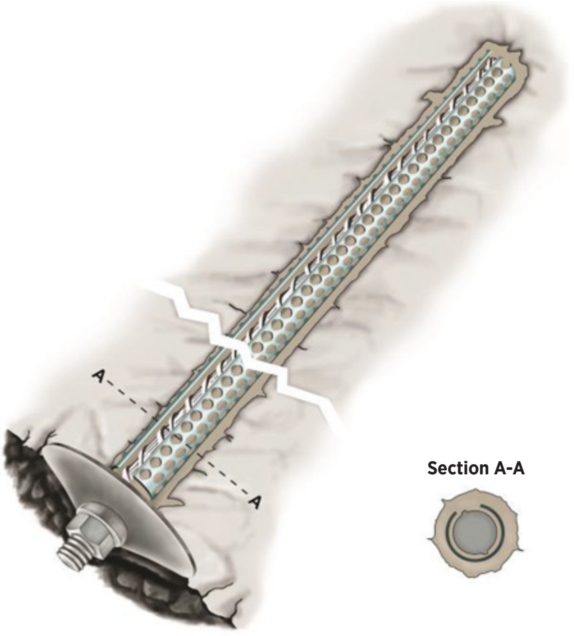
Advantages

Relatively rapid installation behind the tunnel face. Fully embedded bolts provide a high load capacity under a variety of rock conditions. The grout provides increased corrosion protection.

Disadvantages

Does not provide instant stabilisation due to the relatively long curing time of the grout. Unsuitable in the case of continuously flowing water in the borehole. Difficult to check the quality of the grout. Good embedding results depend on correct installation, particularly as regards the use of grout with the correct consistency.

3.2.2 Perfobolts



Material	Rebar
Designation	B500NC etc.
Hole diameter [mm]	33-38
Diameter [mm]	20 and 25
Perforated pipe [mm]	29
Yield strength [MPa]	500
Flow load [kN]	157 and 245
Failure load [kN]	189 and 295
Ultimate elongation	Fully embedded |– rigid system
Weight [kg/m]	2.5 and 3.9
Length [m]	0.8-8

Corrosion protection
Hot-dip galvanized
Hot-dip galvanized and powder-coated (epoxy)

Anchoring
Cement grout

Area of use

Can be used in all rock types and degrees of fracturing (not rock spalling). Perfobolts have been widely used in the past, but are now used to some extent in connection with minor bolting projects. Short perforated lengths can be used to form anchors for end-anchored bolts.

Installation

A perforated tin pipe is filled with grout and inserted into the bolt hole. The bolt is pushed in and the grout is forced out through the openings in the perforated pipe. The space between the pipe and the borehole wall is filled. See also section 4.5.

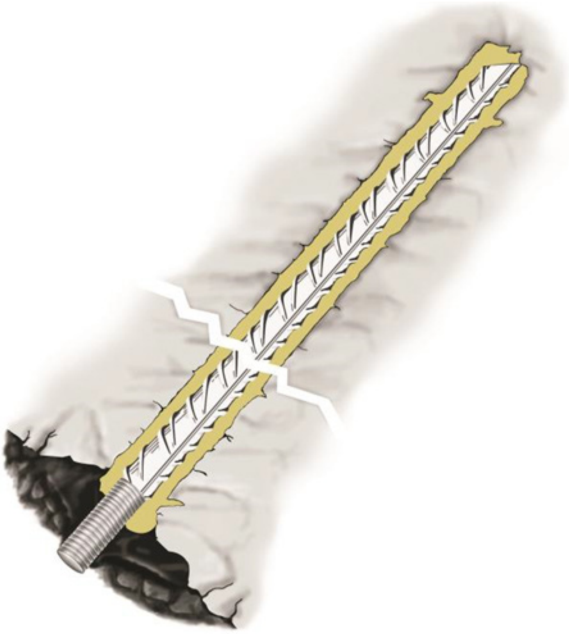
Advantages

Provides good anchoring in all rocks. Easy to use if the dimensions of the bolt and the perforated pipe are correctly matched to the bolt hole. Good control of anchoring. Does not require pumping equipment during installation. Full embedding provides greater corrosion protection.

Disadvantages

Time-consuming and not very efficient installation. Does not provide instant stabilisation due to the relatively long curing time of the grout, and is therefore not suitable for bolting at the tunnel faces or stabilising loose blocks. Unsuitable in the case of continuously flowing water in the borehole. Bolt lengths over 3 metres are difficult to insert into the bolt hole.

3.2.3 Polyester-anchored bolts



Material	Rebar
Designation	B500NC etc.
Hole diameter [mm]	30-45
Diameter [mm]	20 and 25
Yield strength [MPa]	500
Flow load [kN]	157 and 245
Failure load [kN]	189 and 295
Ultimate elongation	Fully embedded – rigid system
Weight [kg/m]	2.5 and 3.9
Length [m]	0.8-6

Corrosion protection
Hot-dip galvanized
Hot-dip galvanized and powder-coated (epoxy)

Anchoring
Injection of polyester compound
Polyester cartridges for bolts up to about approx. 2 metres

Area of use

Can be used in most rock types and degrees of fracturing. The stabilisation system can be activated using fast-curing polyester at the bottom of the borehole and pretensioning. Bolts that are fully embedded with polyester are not used in rock spalling.

Installation

The bolts are injected with polyester compound. For bolt lengths up to 2 metres, polyester cartridges can be pushed into the hole and the bolt then rotated further into the hole. The bolt can be pretensioned using fast-curing polyester at the bottom and slow-curing outermost. Regarding installation, see also section 4.4.

Advantages

The bolt produces a rapid effect after installation if fast-curing polyester is used. The embedding provides greater corrosion protection.

Disadvantages

Special equipment is required to inject the polyester in such a way as to avoid spillages and correct curing around the entire bolt throughout the length of the bolt.

3.3 Combination bolts

Material	Pipe steel
Designation	S355
Hole diameter [mm]	45-48
Diameter [mm]	25
Steel area [mm^2]	314
Yield strength [MPa]	345
Flow load [kN]	108
Failure load [kN]	~148
Ultimate elongation	20% before embedding
Weight [kg/m]	2.5 and 3.9
Length [m]	1.5-6

Corrosion protection
Hot-dip galvanized
Hot-dip galvanized and powder-coated (epoxy)

Anchoring
Expansion sleeve + grout
Plate, hemisphere and nut

A combination bolt is a bolt that is end-anchored and can be post-grouted. The purpose of a combination bolt is to enable the same type of bolt to be used for instant stabilisation (stabilisation while work is in progress) and permanent stabilisation. Combination bolts are ideal when the bolts are pretensioned prior to embedding.

Combination bolts can be used in most rock conditions. The exception is in the case of substantial deformation, such as under high rock pressures (rock spalling). Pretensioning and post-grouting make the bolt very rigid. Thus, in cases where the rocks are severely deformed, the stresses become more concentrated and can cause the bolt to fail.

The grout provides greater corrosion protection, and the bolt type is widely used in highly corrosive environments, such as subsea tunnels. Failure of the grout, leaching of the grout due to flowing water, and the presence of air pockets mean that grout as the only form of corrosion protection will not always be sufficient. The bolts should also be coated with additional corrosion protection.

Installation of combination bolts is carried out in two operations. The bolt is first installed as a normal end-anchored bolt. It is normally post-grouted behind the tunnel face. The grouting is carried out by pumping grout into the bolt hole and forcing air out. Strict requirements apply regarding the consistency of the grout in order to achieve high-quality embedding.

Various combination bolts are shown with diagrams, technical data, area of use, installation, advantages and disadvantages.

Principal types of combination bolts:
- Pipe bolts (3.3.1)
- End-anchored and post-grouted bolts (3.3.2)
- CT bolts (3.3.3)
- NC bolts (3.3.4)
- Fin-bolts (3.3.5)

3.3.1 Pipe bolts

Area of use

Can be used in most rock conditions. Use when both immediate and permanent stabilisation are required. Extensively used in subsea tunnels.

Installation

The bolt is anchored using an expansion sleeve. A grout hose is connected to the bolt end, and grout is pumped up inside the pipe, filling the bolt hole. See also section 4.5. When the bolt is injected before it is post-grouted, additional measures are implemented, e.g. the bolt end can be fitted with a grout hose and a hose in the disc for ventilation.

Advantages

Provides instantaneous stabilisation. Permanent stabilisation after embedding. Embedding provides greater corrosion protection.

Disadvantages

The expansion sleeve can provide poor temporary stabilisation in weak rocks, weakness zones and heavily fractured rock. It is important to monitor the grout constistency closely, to ensure that the grout does not flow out when the grout hose is removed from the bolt. The capacity of the bolt will be reduced in the event of corrosion of the expansion sleeve, and/or corrosion between the bolt threads and the threads on the expansion sleeve. This is due to the fact that the smooth shank does not provide an adequate anchor for the grout compound.

Comments

This type of bolt has previously been used to provide permanent stabilisation in connection with roadworks.

3.3.2 End-anchored and post-grouted bolts

Material	Rebar Round bar steel
Designation	B500NC St37/S235
Hole diameter [mm]	45-52
Diameter [mm] **Steel area** [mm^2]	16 and 20 314
Yield strength [MPa]	500 225
Flow load rebar [kN] **Flow load round steel** [kN]	101 and 157 45 and 71
Failure load rebar [kN] **Failure load round steel** [kN]	121 and 189 72 and 113
Elongation at maximum force [A_{gt}] **Ultimate elongation**	8% 26%
Weight [kg/m]	1.6-2.5
Length [m]	1.5-6

Corrosion protection
Hot-dip galvanized
Hot-dip galvanized and powder-coated (epoxy)

Anchoring
Expansion sleeve and grout
Polyester and grout
Plate, hemisphere and nut

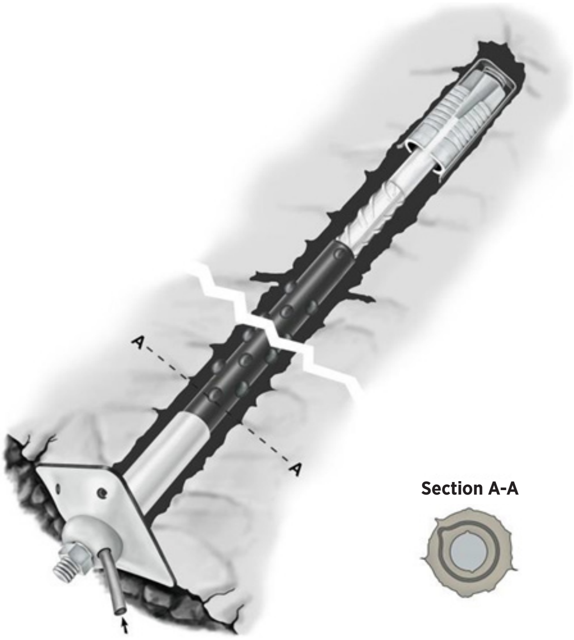
Area of use
Can be used in most rock conditions. Use when both immediate and permanent stabilisation are required. Extensively used in subsea tunnels and elsewhere. The bolts become activated upon pretensioning and result in a rigid system after grouting.

Installation
The bolts are installed as end-anchored bolts and post-grouted. In connection with embedding, polyurethane foam is used between the plate and the rock surface, along with ventilation and grouting hoses. See also section 4.5. Correct length of the holes are important.

Advantages
Provides instantaneous or rapid stabilisation. Embedding provides greater corrosion protection.

Disadvantages
The expansion sleeve can provide poor temporary stabilisation in weak rocks, weakness zones and heavily fractured rock. Temporary stabilisation using polyester cartridges can result in poor adhesion in heavily fractured rock or weak rock. The quality of the polyester anchoring depends on correct installation.

3.3.3 CT-bolts (Different diameters



Material	Rebar
Designation	B500NC
Hole diameter [mm]	43-52 52-63 64-70
Diameter [mm]	20 22 32
Yield strength [MPa]	500
Flow load rebar [kN]	157 237 416
Failure load rebar [kN]	189 296 482
Elongation at maximum force [A_{gt}]	8% (before embedding)
Weight [kg/m]	2.4 4.1 7.3
Length [m]	1.5-8 1.5-8 1.5-12

Corrosion protection
The plastic pipe around the bolt shank
Hot-dip galvanized
Hot-dip galvanized and powder-coated (epoxy)

Anchoring
Expansion sleeve and grout
Alternatively polyester and grout
Plate.
Special hemisphere and nut included

Area of use

Combination bolts which can be used in most rock conditions. Use when both immediate and permanent stabilisation are required. After embedding, the bolt is sealed inside the plastic pipe, which results in excellent corrosion protection and makes the bolt well-suited for use in subsea tunnels. The bolts become activated upon pretensioning and result in a rigid system after grouting.

Installation

The bolt is anchored using an expansion sleeve. With the aid of a grout nozzle connected to the hole in the hemisphere, the grout is pumped up through the plastic pipe to the end of the bolt and then on to the outside of the pipe until the grout emerges around the base disc. Where the bolt is covered with sprayed concrete before being grouted, one grout hose is attached to the hemisphere, while another is connected to the base disc.

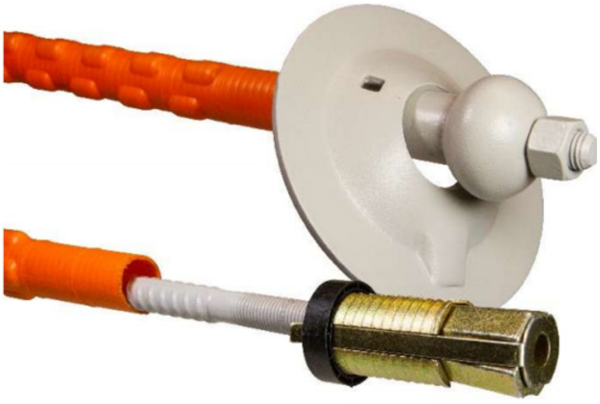
Advantages

Provides instant stabilisation in the case of end anchoring. Permanent stabilisation after embedding. The plastic pipe seals the bolt and provides a long service life due to increased corrosion protection.

Disadvantages

The expansion sleeve can provide poor temporary stabilisation in weak rocks, weakness zones and heavily fractured rock.

3.3.4 NC bolts (different diameters and designations)



Material	Rebar
Designation	HRB500E/600E
Hole diameter [mm]	45-48 64-68
Yield strength [MPa]	500, 600 and 630
Flow load rebar [kN]	123 and 191 347 and 416
Failure load rebar [kN]	147 and 239 416 and 521
Elongation at maximum force [A_{gt}]	8% and 7.5% (before embedding)
Weight [kg/m]	2.47 and 3.0 6.43
Length [m]	5-12

Corrosion protection
The plastic pipe around the bolt shank
Hot-dip galvanized
Hot-dip galvanized and powder-coated (epoxy)

Anchoring
Expansion sleeve and grout
Plate.
Ball screw and nut

Area of use

Combination bolts which can be used in most rock conditions. Use when both immediate and permanent stabilisation are required. After embedding, the bolt is sealed inside the plastic pipe, which results in excellent corrosion protection and makes the bolt well-suited for use in subsea tunnels. The bolts become activated upon pretensioning and result in a rigid system after grouting.

Installation

The bolt is anchored using an expansion sleeve. With the aid of a grout nozzle connected to the hole in the sphere, the grout is pumped up through the plastic pipe to the end of the bolt and then on to the outside of the pipe until the grout emerges around the base disc. Where the bolt is covered with sprayed concrete before being grouted, one grout hose is attached to the hemisphere, while another is connected to the base disc. Correct length of the boreholes are important.

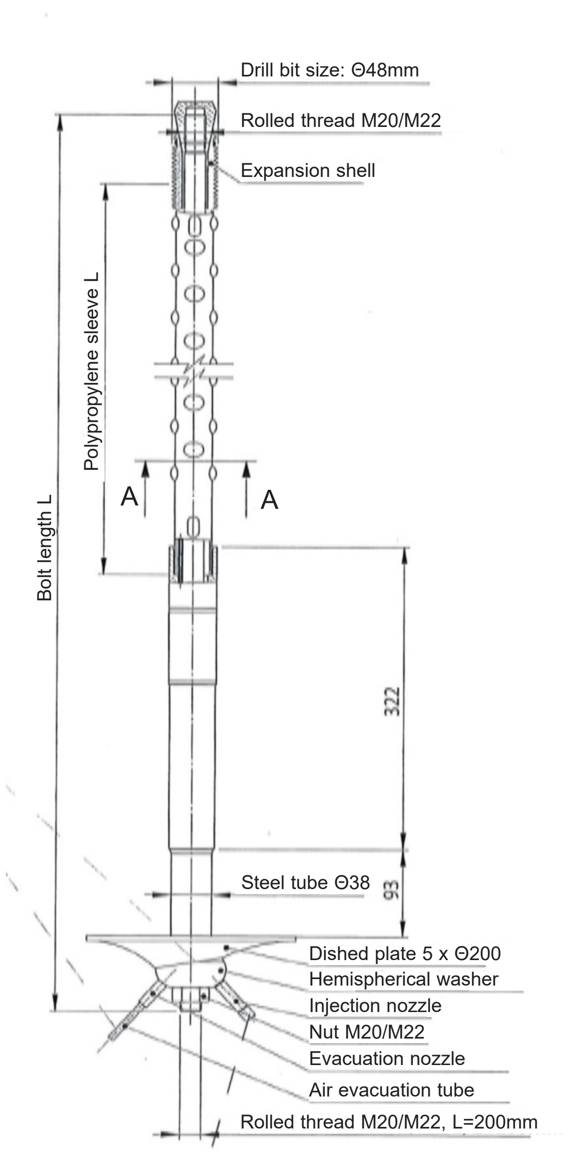
Advantages

Provides instant stabilisation in the case of end anchoring. Permanent stabilisation after embedding. The plastic pipe completely seals the bolt and provides a long service life due to increased corrosion protection.

Disadvantages

The expansion sleeve can provide poor temporary stabilisation in weak rocks, weakness zones and heavily fractured rock.

3.3.5 Fin-bolts



Material	Rebar
Designation	B500NC
Hole diameter [mm]	43-52
Diameter [mm]	20
Yield strength [MPa]	500
Flow load [kN]	157
Failure load rebar [kN]	189
Elongation at maximum force [A_{gt}]	8% (before embedding)
Weight [kg/m]	2.4
Length [m]	1.5-6
Length [m]	0.8-8

Corrosion protection
Hot-dip galvanized
Hot-dip galvanized and powder-coated (epoxy)

Anchoring
Injection of polyester compound
Polyester cartridges for bolts up to about approx. 2 metres

Area of use

Combination bolts specifically designed for bolt holes containing water can be used in most rock conditions. Used where both immediate and permanent stabilisation are required. After embedding, the bolt is sealed inside the plastic pipe, which results in excellent corrosion protection and makes the bolt well-suited for use in subsea tunnels. The bolts become activated upon pretensioning and result in a rigid system after grouting.

Installation

The bolt is anchored using an expansion sleeve. With the aid of a grout nozzle connected to the hole in the hemisphereical washer, the grout is pumped up through the plastic pipe to the end of the bolt and then on to the outside of the pipe until the grout emerges around the evacuation hole.

Advantages

Provides instant stabilisation in the case of end anchoring. Permanent stabilisation after embedding. The plastic pipe seals the bolt and provides a long service life due to increased corrosion protection. Stops leakage in water-bearing bolt holes.

Disadvantages

The expansion sleeve can provide poor temporary stabilisation in weak rocks, weakness zones and heavily fractured rock.

3.4 Other bolt types

This chapter presents various bolt types which do not fall under the other aforementioned bolt groups, or which have not been much used in Norway.

Cables and anchors are presented in section 3.5.

Friction bolts can be used to provide instantaneous stabilisation in most rock types. Friction bolts and fibreglass bolts are not much used in Norway.

A hollow rebar bolt that is end-anchored and post-grouted is available on the international market. This type of combination bolt is rarely used in Norway.

Another type of bolt which has not yet been adopted in Norway is a plug bolt used in the mining industry in the USA. This bolt is anchored in accordance with the same principles as a concrete screw.

Other bolt types are presented with diagrams, technical data, area of use, installation, advantages and disadvantages.

Bolt types placed under this group

• Friction bolts (Split Set, Swellex)	(3.4.1, 3.4.2)
• Fibreglass bolts	(3.4.3)
• D bolts	(3.4.4)
• Drill rod bolt	(not discussed)

3.4.1 Friction bolts - Split Set

Area of use

Material	Steel
Hole diameter [mm]	32-45
Diameter [mm]	33-46
Flow load [kN]	90 (for Ø39 mm bolt)
Failure load [kN]	70-140
Ultimate elongation	16%
Weight [kg/m]	1.8
Length [m]	0.9-3
Length [m]	0.8-8

Corrosion protection
Can be hot-dip galvanized

Anchoring
Friction between steel and rock

Split Set bolts are used for instantaneous stabilisation in most rock conditions. Widely used in mining contexts in the USA. Yielding stabilisation in that the bolt has a considerable capacity to deform without failing.

Installation

The Split Set bolt is knocked into the bolt hole. The diameter of the bolt must be larger than that of the bolt hole.

Advantages

Easy and fast to install. Provides instant stabilisation after installation. Excellent shear deformation capacity (yielding stabilisation).

Disadvantages

The bolt is exposed to corrosion. The borehole diameter is critical: If the bolt hole is too small, it will be difficult or impossible to insert the bolt. If the bolt hole is too large, the friction between the bolt and the rock will be too low and the load capacity will be reduced. Installing long bolts can be difficult. Cannot be pretensioned (although the plate can provide pressure against the rock surface after installation). Can absorb high shear deformation, but has relatively low shear capacity.

3.4.2 Friction bolts - Swellex

Material	Domex 220
Designation	SS 1232-04
Hole diameter [mm]	32-39 43-52
Diameter [mm]	26
Flow load [kN]	130
Failure load [kN]	130
Ultimate elongation	10%
Weight [kg/m]	2
Length [m]	1.5-5

Corrosion protection
Bitumen-based paint or plastic coating

Anchoring
Friction and mechanical resistance

Area of use
In principle, can be used in most rock conditions. Used to some extent in mines in Norway.

Installation
The bolt is pushed into the bolt hole. A water pump is connected to the end of the hollow bolt, high water pressure is applied and the bolt expands in the hole. The steel shapes itself against the borehole wall.

Advantages
Easy and secure installation. Provides instant stabilisation after installation. Withstands vibrations.

Disadvantages
The bolt is exposed to corrosion. Special equipment needed to install this bolt type. Cannot be pretensioned.

3.4.3 Fibreglass bolts

Material	Solid fibreglass bolt (or fibreglass pipe bolt)
Hole diameter [mm]	27-48
Diameter [mm]	22-25
Pipe bolt diameter [mm]	40
Failure load [kN]	85-250
Failure load pipe bolt [kN]	> 62
Expansion value	0.5% for solid bolt 2% for pipe bolt
Weight [kg/m]	0.7-0.9
Length [m]	Can be joined

Anchoring
Grout
Polyester
Epoxy

Area of use

Can be used where stabilised areas will subsequently be used in production, e.g. during the construction of new tunnels in the mining industry. The bolts have an advantage in the vicinity of cutting machines, e.g. in connection with TBM operation. Can be used in corrosive environments, e.g. in aquifers with very acidic water. This bolt type has not been much used in Norway.

Installation

Fibreglass pipe bolts are anchored by grouting through the bolt. Solid fibreglass bolts can be anchored in the same way as steel bolts, e.g. using grout, epoxy or polyester.

Advantages

Easy to cut. Does not corrode. Relatively high tensile strength, high load capacity. Low specific weight.

The bolt is not harmful to crushers like steel bolts, i.e. suitable for (stabilisation while work is in progress) stabilising rock that is to be crushed.

Disadvantages

Relatively rigid bolt with little capacity to deform. Limited shear capacity.

3.4.4 D bolts

Material	Round bar steel
Designation	
Hole diameter [mm]	30-48
Diameter [mm]	20 and 22
Flow load [kN]	141 and 171
Ultimate elongation	15%
Weight [kg/m]	2.5 and 3
Length [m]	1.8-6

Corrosion protection
Hot-dip galvanized
Hot-dip galvanized and powder-coated (epoxy)

Anchoring
Cement grout

Area of use

The bolt is particularly intended for use in severely deformed rocks, but it also has a reinforcing effect that is approximately equal to that of an embedded rebar bolt. The bolt has pointwise anchors which allow the deformation to be distributed over a greater length of the bolt than a rebar bolt which has continuous anchoring.

Installation

Grout is pumped into the bolt hole using a grout pump. The w/c ratio for grout is between 0.3 and 0.4. The bolt is then pressed into the hole. See also section 4.5. The bolt can also be anchored using polyester by pushing in the requisite number of “sausages” to fill the cavity between the bolt and the rock.

Advantages

Relatively rapid installation behind the tunnel face. Fully embedded bolts provide a high load capacity under a variety of rock conditions. The grout provides increased corrosion protection.

Disadvantages

Does not provide instant stabilisation due to the relatively long curing time of the grout. Not suitable in the case of continuously flowing water in the borehole. Good embedding results depend on correct installation, particularly as regards use of the correct grout consistency (see also section 4.5). In the case of severe deformation, corrosion protection can be damaged.

3.5 Cables and anchors

Cables and anchors are not dealt with in detail in this book. Here, cables and anchors are presented as a designation for long bolts (normally over 6 metres) which consist of one or more wires (“laces”) or high-strength steel bar.

The effect and installation principles do not differ from ordinary bolts, but both the dimensioning and installation of cables and steel are normally referred to as “special works”. The installation is carried out by persons with a high level of professional competence and extensive experience of this type of work.

Cables (untensioned cable bolts) are used for stabilising large underground caverns, dams, rock slopes, tall rock cuttings and other situations where long bolts are needed.

Multiple wire anchors (pretensioned cables) can be used to stabilise rock slopes, large underground caverns, dams and excavated pits in rock. The multiple wire anchors have high load capacities and are normally given a high degree of pretensioning.

Threadbars are bolts made from high-strength steel which can be used to stabilise tall rock cuttings, large underground caverns, dams and construction pits in rock. Threadbars normally have high load capacities and require pretensioning to ensure they are fully utilised.

Cables and anchors are presented with diagrams, technical data, area of use, installation, advantages and disadvantages.

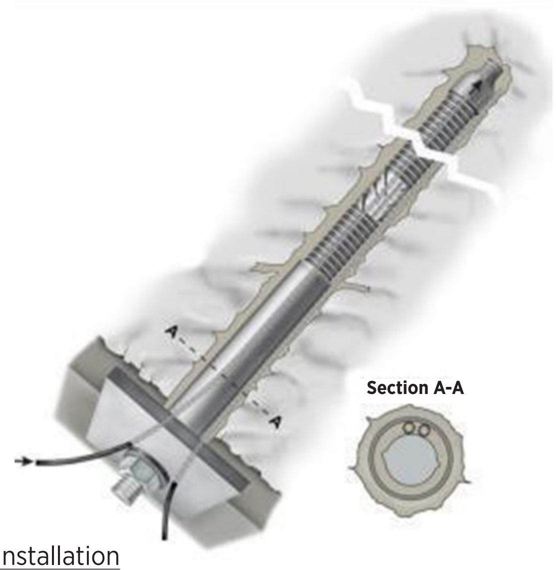
Principal types of cables and anchors:

- Threadbars (3.5.1)
- Self-drilling anchors (3.5.2)
- Multiple wire anchors (prestressed cables) (3.5.3)
- Cables (unpretensioned cable bolts) (3.5.4)

3.5.1 Threadbars

Area of use

Stabilisation of tall rock cuttings, large underground caverns, dams and excavated pits in rock.



Installation

Anchors can be pretensioned and completely embedded in grout, or simply end-anchored in grout or polyester. The principles for installation are the same as for combination bolts. Installation instructions from the supplier.

Advantages

High load capacity, can be pretensioned with considerable force. Grout and any plastic sleeve provide corrosion protection.

Disadvantages

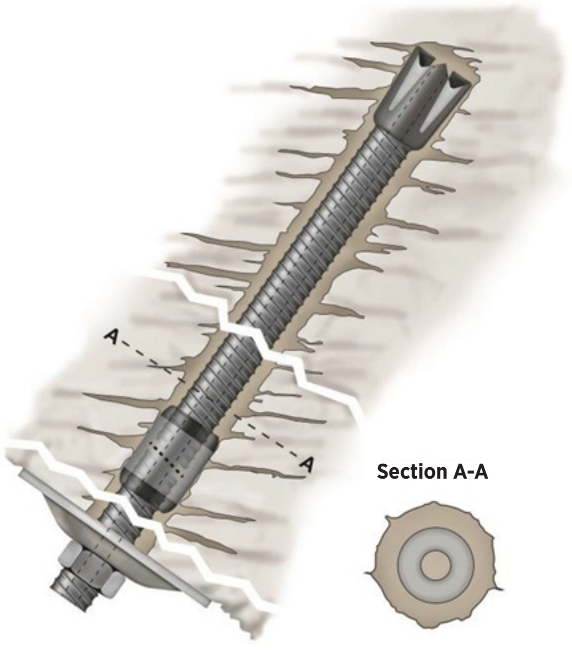
Low shear capacity compared to tensile capacity. The installation process is somewhat more involved than that for ordinary bolts. Threadbars do not provide instantaneous stabilisation due to the relatively long curing time of the grout.

Material	Anchors
Hole diameter [mm]	35-100
Diameter [mm]	15-36
Yield strength [MPa]	835-1230
Flow load [kN]	159-1099
Failure load [kN]	195-1252
Ultimate elongation	0-5%
Weight [kg/m]	1.5-10
Length [m]	Can be joined

Corrosion protection
Grout
Plastic sleeve

Anchoring
Fully embedded in grout
End-anchored in grout
End-anchored in polyester
Carrier plate and nut in the case of end-anchoring.

3.5.2 Self-drilling anchors



Material	Custom-made, fully threaded drill rod bolts.
Hole diameter [mm]	30-70
Diameter [mm]	25-40
Flow load [kN]	130-490
Failure load [kN]	200-660
Ultimate elongation	Fully embedded – rigid system
Weight [kg/m]	2.5-6.9
Length [m]	2-6, provision for splicing

Corrosion protection
Hot-dip galvanized
Hot-dip galvanized and powder-coated (epoxy)
Stainless steel

Anchoring
Cement grout
Polyurethane

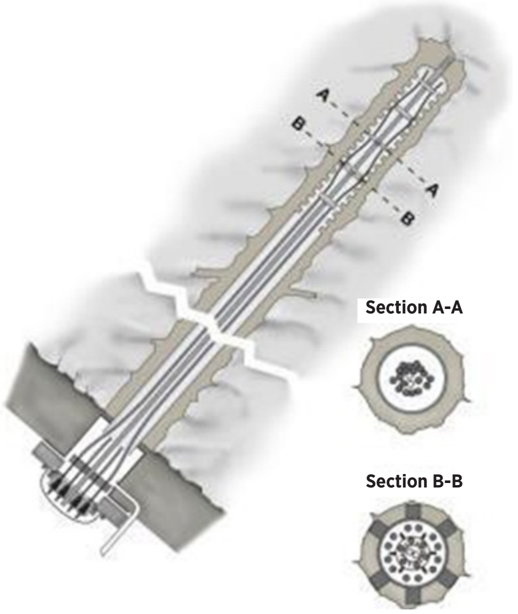
Area of use
The anchor has drill bit and acts like a drill rod during drilling. The bolt can be used for spiling and grouting in densely layered, schistose or heavily fractured and loose rocks, where there is a risk of sections of the borehole collapsing when the drill rod is withdrawn after drilling. On the surface, the bolt can be used in rock with unconsolidated sediment cover, because it is not necessary to remove the sediment when drilling/installing the bolt.

Installation
The drill rod bolt is not withdrawn again after drilling. Grout is injected through the hollow rod.

Advantages
Not necessary to withdraw the drill rod after use. Not necessary to remove the unconsolidated sediment cover before anchoring in the rock. Grouting can take place at the same time as the drill rod bolt is drilling into the rock. Injects an extensive area around the bolt. The grout provides increased corrosion protection.

Disadvantages
Good grouting results depend on correct installation.

3.5.3 Multiple wire anchors (prestressed cables)



Material	Steel wires are joined together to form cables
Hole diameter [mm]	76-200 (for permanent cables)
Diameter [mm]	12.5-15.7 per wire 60-165 per cable
Yield strength [MPa]	1670
Flow load [kN]	1 wire: 167–276 (In practice up to approx. 8,500)
Failure load [kN]	1 wire: 167–307 (In practice up to approx. 9,500)
Ultimate elongation	3.5%
Weight [kg/m]	1 wire: 0.8–1.3 (In practice up to approx. 42)
Length [m]	Desired length

Corrosion protection
Grout and plastic sleeve

Anchoring
End-anchored using grout
Fully embedded in grout

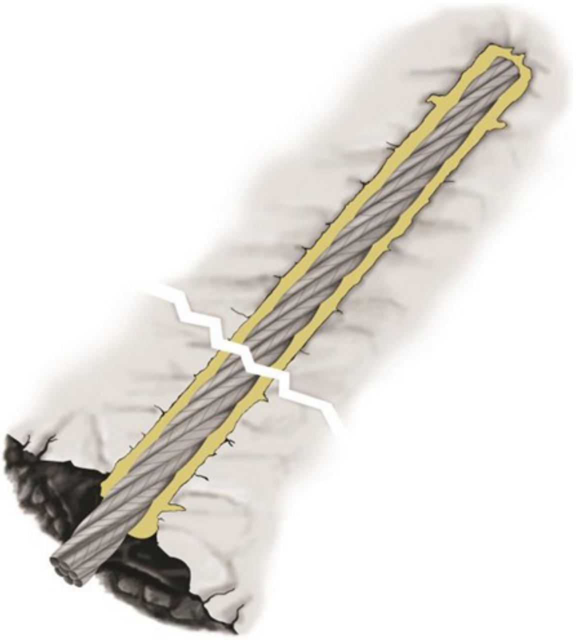
Area of use
Stabilisation of large underground caverns, rock slopes, pile walls, dams and excavated pits in rock.

Installation
There are many different varieties of multiple wire anchors and several different installation methods. The most commonly applied principle is to push them into the hole and grout them from the bottom using a hose. Permanent anchors usually have a protective plastic tube on the outside of the wire anchors and are therefore grouted on both the outside and inside of this. After the grout has cured, the anchor is tested and pretensioned.

Advantages
High load capacity, can be pretensioned with considerable force. The anchoring capacity is verified during pretensioning. The grout and the plastic sleeve provide increased corrosion protection.

Disadvantages
The installation of pretensioned, embedded multiple wire anchors requires specialist expertise. Multiple wire anchors do not provide instantaneous stabilisation due to the relatively long curing time of the grout.

3.5.4 Wire-cables (unpretensioned cable bolts)



Material	Steel wires are joined to form cables
Hole diameter [mm]	35 and upwards
Diameter [mm]	28 and upwards
Yield strength [MPa]	1770
Flow load [kN]	500 and upwards
Failure load [kN]	500 and upwards
Ultimate elongation	3%
Weight [kg/m]	3.1 and upwards
Length [m]	Desired length

Corrosion protection
Grout

Anchoring
Fully embedded using grout
(Can be end-anchored and pretensioned)

Area of use

Used for stabilising underground caverns and cuttings where long bolts (wires) are preferred. This entails the stabilisation of underground caverns, deep rock cuttings, rock slopes, dams. etc.

Installation

The wire and grout hose are fed to the bottom of the bolt hole simultaneously. The pumping of grout into the hole is started. The hose is forced out of the bolt hole by the pump pressure, leaving a fully embedded unpretensioned wire. Multiple wires can be used in the same borehole.
(Wires with expansion sleeves and wire locks can be pretensioned and grouted until full embedding is achieved /10/).

Advantages

Long bolts can be installed, even from small cavities. High load capacity. The grout provides increased corrosion protection.

Disadvantages

It can be difficult to monitor the quality of the grouting. Does not provide instant stabilisation due to the long curing time of the grout. Not normally supplied with corrosion protection.

3.6 Bolt materials and accessories

3.6.1 Plates and hemispheres

Various types of plates are available on the market; see the examples in Figure 3.2. Traditionally, plates with dimensions of 6 x Ø150 mm, 6 x Ø200 mm or 5 x Ø190 mm are mainly used. When stabilising rock spalling using bolts only, it has been common practice to use large triangular plates 5 x 400 x 500 mm, as these provide a large contact surface against the rock.

Semi-hemispherical washers are used to achieve the best possible interaction between the plate, bolt and rock. The washer enable the plate to have a slight angular deviation from the normal on the bolt shank. Hemispheres used in Norway today have a functional range of between 0–20°.

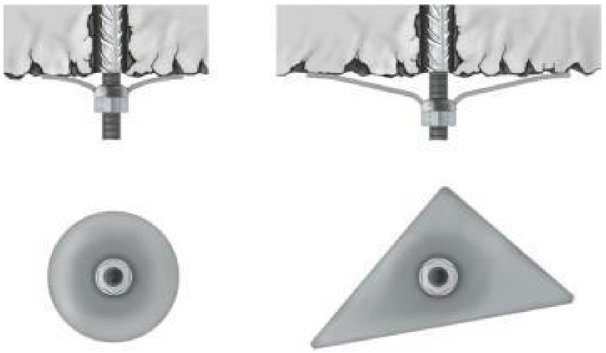


Figure 3.2 Examples of plates

3.6.2 Expansion sleeves

Expansion sleeves are available in several variants. In Norway, the "bail type" is mainly used. This consists of a conical nut and two wedge-shaped, toothed blades. See for example the anchoring in the diagram in section 3.1.1.

3.6.3 Polyester

The supplier's description and/or product description must be followed with regard to storage and installation using polyester. See section 4.4.

The curing time of polyester is temperature-dependent. If the polyester cartridges are stored in a cold environment, they should be brought to room temperature before being used.

3.6.4 Grout

Correct installation requires good consistency and composition of the grout. The grout should have a creamy consistency. The various types and quantities of additives mean that different quantities of water must be added to different grout products in order to achieve the right consistency. This will be specified by the supplier.

The reaction between zinc and cement is discussed in the next section. In connection with the grouting of hot-dip galvanized bolts, suitable bolt grout should be used. Regarding bolt embedding, see also section 4.5.

3.7 Corrosion protection

To achieve the intended service life of bolts and anchors, it is important that they are installed correctly and made from the right materials. All bolts intended for permanent stabilisation and for suspending installations/water and frost protection structures are now protected from corrosion. Corrosion protection usually consists of hot-dip galvanizing and epoxy coating. Fully embedding the bolt improves durability due to the alkaline environment and reduction in contact with water. In the case of suspension bolts, stainless steel is also used.

Multiple wire anchors are protected by embedding in grout, plastic pipes, the use of grease and plastic coatings. Threadbars and self-drilling anchors are normally protected in the same way as ordinary bolts.

3.7.1 Hot-dip galvanization

Hot-dip galvanizing protects the steel in the bolt from corrosion. Zinc acts both as a physical barrier and as a sacrificial anode in connection with the localised exposure of the steel, because zinc is less noble than iron.

The hot-dip galvanizing process involves immersing the steel in a heated zinc bath. The zinc reacts with the steel to form iron-zinc alloys on the surface (metallurgical bond). There will be iron alloyed with zinc throughout the hot-galvanised coating, and the concentration of iron will be greater further into the coating. The coating thickness mainly depends on the thickness of the steel and the silicon content in the steel.

Where local damage in the hot-dip galvanisation occurs or the bolt is cut, the damage/bolt end must be repaired in accordance with the bolt supplier's recommendations.

3.7.2 Hot-dip galvanization + epoxy coating

In the case of epoxy coating, a protective coating is applied to the bolt which acts as a physical barrier

against aggressive substances. Bolts that are hot-dip galvanised and epoxy coated thus have double protection against corrosion.
Following pretreatment, the hot-dip galvanized steel is sprayed with electrostatically charged powder grains which adhere to the surface as a result of electrostatic attraction. The epoxy coated steel is placed in a furnace where the epoxy coating melts, flocks together and hardens. In this process, the steel that is to be epoxy coated is earthed, which causes earthing marks on the epoxy coating. To minimise these earthing marks, the products are suspended with a minimal contact surface. Centring devices are used to centre and lock the bolt in the bolt hole.

3.7.3 Stainless steel

Stainless steel is used in many contexts where special requirements concerning the service life apply and where the environment is very corrosive. For example in subsea tunnels

3.7.4 Fully embedded bolts

Fully embedded bolts tend to have a long service life, and are therefore recommended for use as stabilisation bolts in permanent stabilisation. Bolting grouts are durable grouts which minimise water diffusion and transport, and provide protection against the ingress of aggressive substances. The alkaline environment of cement-based bolting grouts also protects the steel from corrosion by forming a passive protective film on the surface.

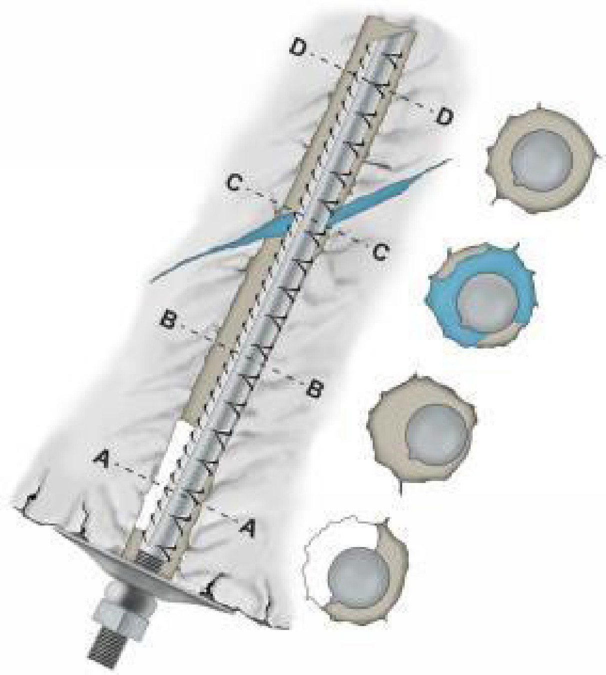


Figure 3.3
Examples of quality deviations on embedded bolts

Full embedding does not always provide the intended corrosion protection /11/, /12/, and bolts which are to be embedded and form part of permanent stabilisation measures must therefore be protected against corrosion in their entirety. See Figure 3.3. See also section 4.5.

Section A: Errors during installation (operator error) can lead to air pockets forming and reduced filling with grout. A common error is to use grout which is too thin.

Section B: Eccentrically positioned bolt – where the bolt is touching the rock in the bolt hole, sections of the bolt may not be fully surrounded by grout. Boreholes with deviations can contribute to contact between rock and bolt. Centring springs or clips should be used.

Section C: Water-bearing holes – can lead to the partial leaching of grout.

Section D: Full coverage. This shows what it should look like when the process is carried out correctly

The pore water in cement-based grouts is highly alkaline, and zinc is unstable in such environments and is broken down by components in the cement. When galvanized steel comes into contact with wet cement, a chemical reaction occurs where crystals are precipitated on the surface, which in turn renders the zinc passive with regard to further corrosion. This reaction is accompanied by the formation of hydrogen gas on the surface between the zinc coating and the grout. The development of hydrogen gas partly depends on the iron concentration in the outer layer of the zinc coating, the chromium content of the cement and the pH /13/, /14/.

When the bolts are hot-dip galvanised, bolting grouts which prevent the reaction between cement and zinc must be used.

4. Equipment and installation

Bolts and other means of stabilisation are intended to protect personnel working in tunnels and underground caverns, and later individual users of the installations. It is therefore essential that the stabilisation process fulfils the requirements regarding the manufacture and installation of the bolts. Personnel who install bolts should have good understanding of the geological conditions, experience of performing rock support or should be given training in the discipline.

Correct execution during installation is crucial to achieving a good final product. The installation of bolts starts with the drilling of the holes for the bolts. Drill dimensions are selected according to the diameter of the bolt and anchoring specified in the bolt supplier's data sheet. Correct fitting and use of bolt drilling equipment improves occupational safety and increases capacity. When inserting and anchoring bolts, it is important that the relevant installation procedures are followed.

4.1 Drilling equipment and bolt hole drilling

In the case of bolting in rock, the diameter, length and direction of the borehole are adapted to the type of bolt concerned (Table 4.1). The drilling rig is positioned so that the boom is at the correct drilling angle in relation to the rock surface at all times. As a rule, the drilling angle is perpendicular to the rock surface. See also Chapter 2.

4.1.1 Handheld drills

Handheld drills are primarily used in cross-sections where it is difficult to gain access with larger equipment. Drilling is carried out either from a basket or working platform, or directly from the invert.

Table 4.1 Drilling equipment for bolt drilling with different tunnel cross-sections

Tunnel cross-section	Equipment for bolt hole drilling	Bolt hole diameter
7 - 15 m^2 (shaft)	Handheld drills	27 - 40 mm
10 - 25 m^2	Handheld drills/Drilling rigs	27 - 40 mm
15 - 40 m^2	Drilling rig or separate bolting rig	38 - 51 mm
40 - 100 m^2	Drilling rig or separate bolting rig	45 - 51 mm
Over 100 m^2 (underground caverns)	Drilling rig or separate bolting rig	45 - 76 mm

4.1.2 Rock bolting rigs

The bolt rig drills the bolt hole, but the bolt is installed manually. The rig normally has a standard rotary boom with a shorter feed length than a standard tunnel rig. This is because the boom needs to be more manoeuvrable and the bolt holes placed at the correct angle. If the boom can be extended telescopically, the reach for each arrangement becomes greater. Where a rig is used for drilling long bolt holes, it should be equipped with a device for automatic drill rod changing. The rig can be equipped with an additional boom with a work basket that can be used when installing the bolt, but bolt installation can also be carried out from a separate work platform.

A fully automated bolting rig (Figure 4.1) can also be used to install bolts, in addition to drilling bolt holes. Both operations are performed from the operator's position on the rig. The rig can be fitted

Figure 4.1 Fully mechanised bolting rig

with equipment for installing various types of bolts, with a magazine for the bolts (8-10 pcs.).

4.1.3 Tunnel boring machines

In the case of tunnel construction, it is common for the tunnel rig to be used to drill holes for the bolts from the preceding blasting round. The bolts are installed manually from the work basket on the rig. For practical reasons, it is common to use Ø48-51 mm for drilling both charging holes and bolt holes when driving tunnels.

Tunnel rigs can be equipped with a split feed bar which makes access easier when bolting in narrow cross-sections. The feed beam consists of two profiles which slide on each other.

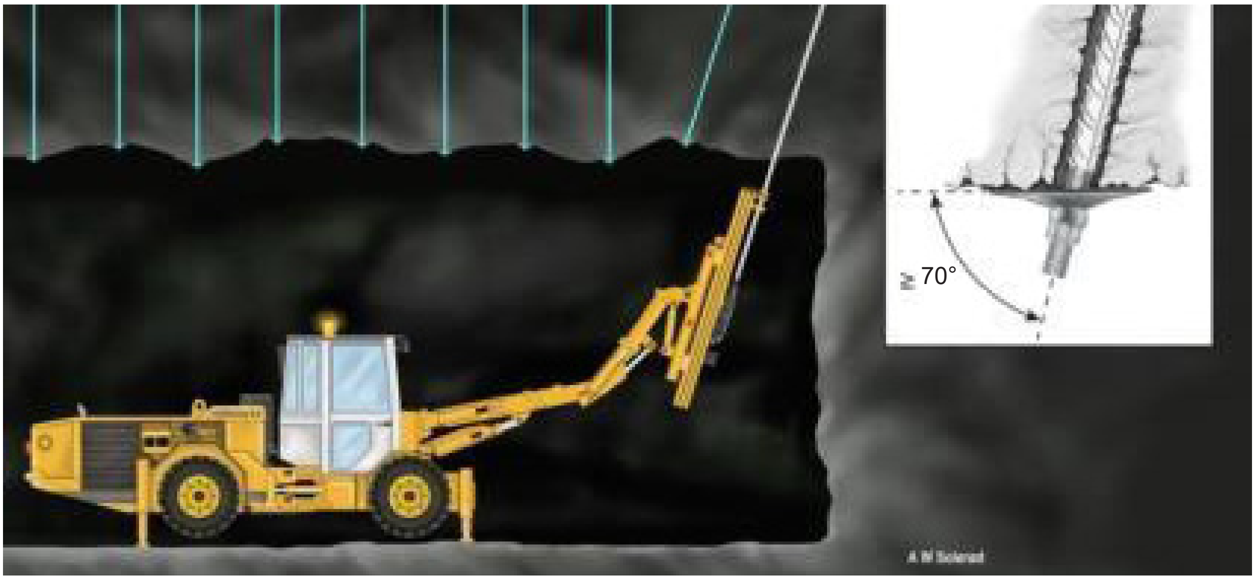


Figure 4.2 Angle between the direction of the borehole and the rock surface

4.1.4 Error sources in connection with the drilling of bolt holes

Errors made in connection with the installation of rock bolts often stem from the drilling process itself. The two most common errors are:

A. Incorrect angle between bolt and rock surface
B. Overly long borehole in the case of the anchoring of bolts using polyester.

A. Incorrect angle between bolt and rock surface
The holes must be drilled as radially around the tunnel axis as possible. A common mistake is for the booms not to be sufficiently far forward during drilling, which causes the bolts to be angled forward in the tunnel. The main reason why this error occurs is either that the feed beam on the rig is too long relative to the height/width of the tunnel, or that the drilling rig is not positioned (moved) correctly in relation to the tunnel face.

Too small an angle between the axis of the borehole and the tunnel axis is unfavourable for end-anchored bolts and other bolts which are to be pretensioned, as the pretensioning force decreases radially as the angle increases. The minimum angle between the axis of the borehole and the rock surface must normally be approximately 70°; see Figure 4.2. This is because the functional range of the hemisphere is between approximately 0-20° deviation. The hemisphere causes the plate to lie flat against the rock and prevents bending stresses in the threaded section of the bolt. The bolt is thus subjected to an axial load as a result of the pretensioning.

B. Excessively long borehole in the case of bolt anchoring using polyester.
Excessively long boreholes must be avoided when using polyester cartridges because the polyester does not mix with the hardener. This results in bolts which have little or no load capacity /12/, /15/.

When drilling for polyester-anchored bolts, it is important that the borehole is 100–150 mm shorter than the bolt (Figure 4.3). This is to take account of the threads that must be outside the bolt hole.

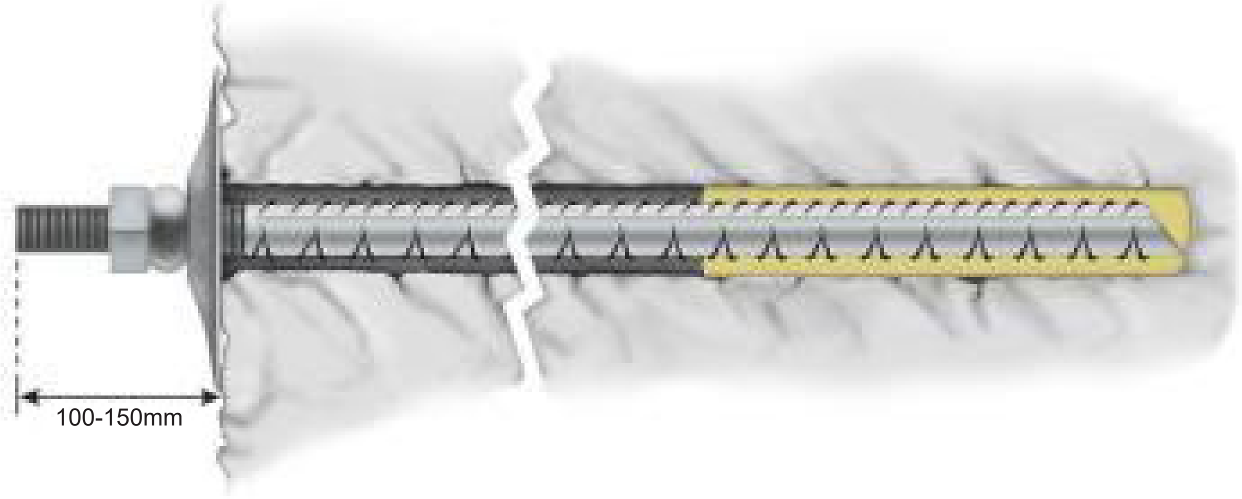


Figure 4.3 Correctly adapted bolt hole length for polyester-anchored bolts

4.2 Bolt installation equipment

4.2.1 Tunnel boring machines, wheel loaders with basket or work platform

In the case of large and medium-sized tunnel cross-sections, tunnel boring machines are normally equipped with a basket, which is used in connection with blasting and bolt installation. In the case of extensive bolting, it may be better to use specific equipment for installation, such as a dedicated bolting rig, an approved wheel loader with a basket (see the illustration in Figure 4.4), or a hydraulic work platform (on a work platform truck).

Figure 4.4 Wheel loader with basket

4.2.2 Pneumatic drills with feed column (feed cylinder)

When installing polyester-anchored bolts, drills with rotational speeds of 300–400 RPM are used. A pneumatic drill fitted with a feed column is normally used (Figure 4.5). The feed column also facilitates the process of feeding the bolt into the hole.

Figure 4.5 Pneumatic drill with feed column

4.2.3 Grout pumps

A grout pump is used to embed bolts. Two types are used: piston pump and progressive cavity pump (Mono pump).

Progressive cavity pumps (Figure 4.6) are normally used when grouting bolts. The advantage of progressive cavity pumps is that they can transport relatively thick grouts, whilst maintaining a consistent supply. This type of pump normally has two chambers, one for mixing and one from which the finished mixed grout is pumped.

Figure 4.6 Grout pump (progressive cavity pump)

4.2.4 Impact wrenches

Impact wrenches are used for tensioning bolts. Impact wrenches are used in combination with a long nut driver for tightening the nut against the plate (Figure 4.7). When an impact wrench is used, the degree of tensioning will always vary slightly. It is important that the impact wrench is calibrated before use because the friction between the thread, nut and hemisphere varies between different bolt types.

Figure 4.7 Impact wrenches

4.2.5 Hydraulic jacks and torque wrenches

The most accurate method of pretensioning bolts is to apply a tensile force using a hydraulic jack, and then tighten the nut to the desired degree of pretensioning (Figure 4.8). This method is relatively time-consuming and is therefore rarely used. Hydraulic jacks are used to check end-anchored bolts; see Chapter 6.

A torque wrench can be used to tighten the nut to a predetermined torque. The torque wrench is fitted with a dial gauge which can be read (there are various patents). The method is laborious and little used in Norway.

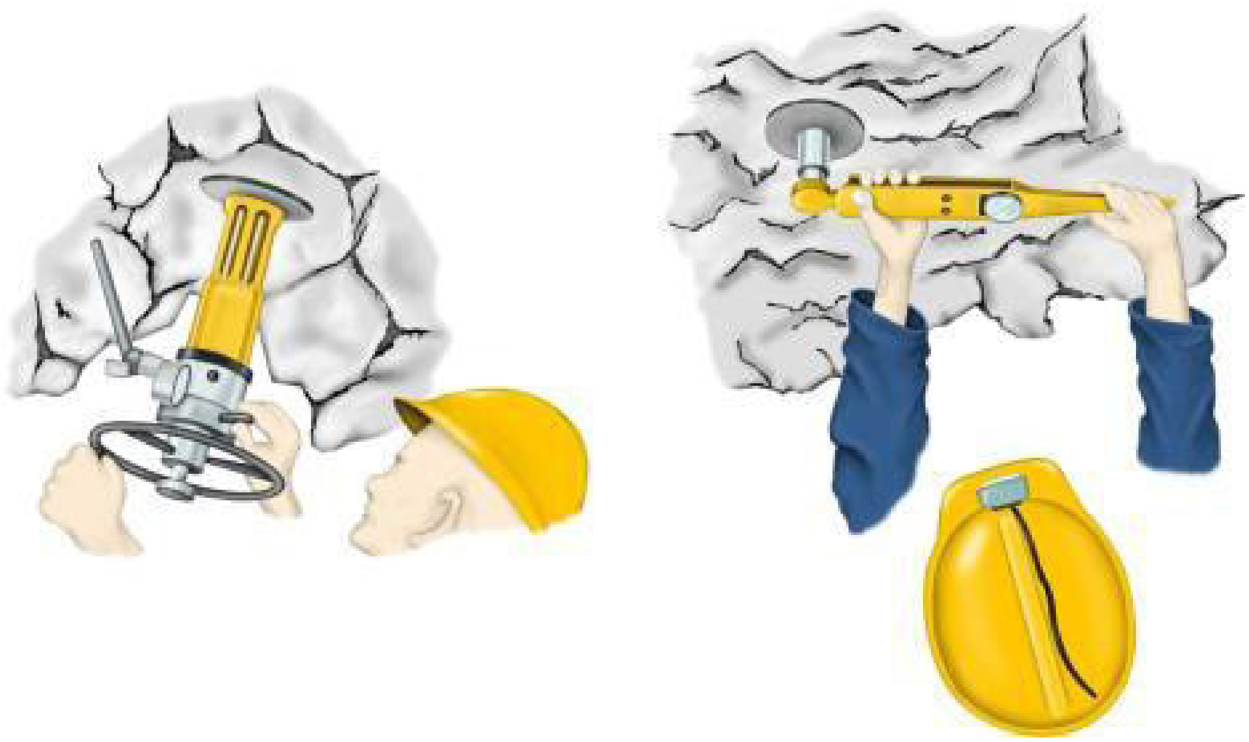


Figure 4.8 Hydraulic jack and torque wrench

4.3 Installation of bolts with an expansion sleeve

An expansion sleeve is a mechanical anchor which is used on a variety of bolt types. The expansion sleeve normally produces good anchoring in medium to good quality rock (Figure 4.9).

The expansion sleeve consists of a conical nut and two wedge-shaped, toothed blades connected by a steel brace. When the bolt is stretched, the nut is wedged between the blades and presses the blades with great force against the hole wall.

Figure 4.9 Installation of bolt using an expansion sleeve (end-anchored bolts).

Table 4.2 Explanation for Figure 4.9

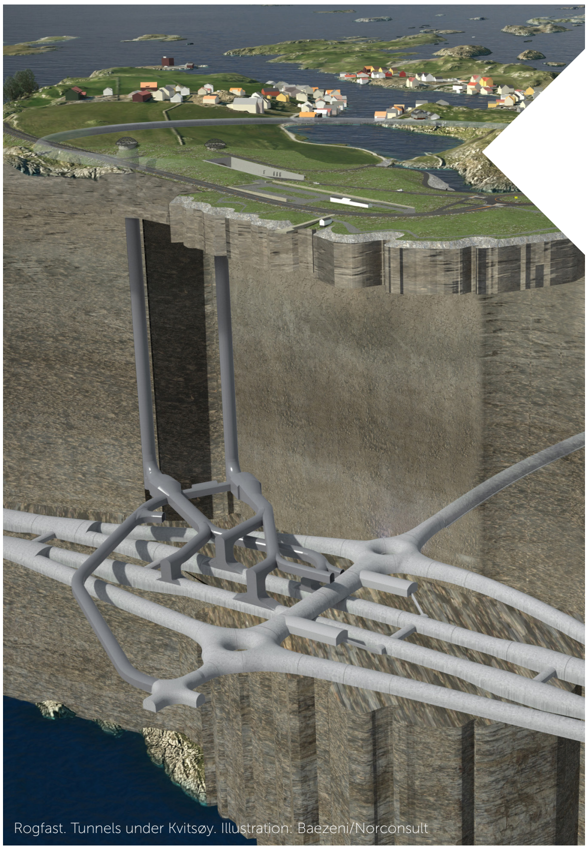
1.	The hole is drilled so that it is at least as long as the bolt.
2.	The expansion sleeve is screwed onto the bolt. If necessary, the clamp can be bent outwards slightly so that the blades touch the wall of the hole when the bolt is pushed into the hole. To prevent the bolt from being pushed in too far, the plate, hemisphere and nut should be fitted to the bolt before it is pushed into the hole.
3.	The bolt is pretensioned by tightening the nut with an impact wrench or a torque wrench.

4.3.1 Error sources in connection with anchoring using expansion sleeves

It is important to note that pretensioned bolts fitted with an expansion sleeve tend to lose their tensioning due to vibrations caused during blasting. Post-tightening should therefore be carried out.

Table 4.3 Error sources in connection with anchoring using expansion sleeves

Error sources	Outcome
Mismatch between borehole diameter and expansion sleeve diameter	Reduced anchoring capacity, substantial stretching
Lack of retrospective tightening/checks on pretensioned bolts behind the tunnel face	Risk of rapid deformation (falling blocks, collapse, etc.)



4.4 Installation of bolts with polyester cartridges

Polyester cartridges are used for anchoring rebar bolts with diameters from Ø16 mm to Ø25 mm. A polyester cartridge consists of polyester and a hardener (catalyst). The hardener is located in a separate plastic sleeve at the outer end of the polyester cartridge. Curing is initiated by mixing the polyester and hardener together when the bolt is rotated through the cartridge.

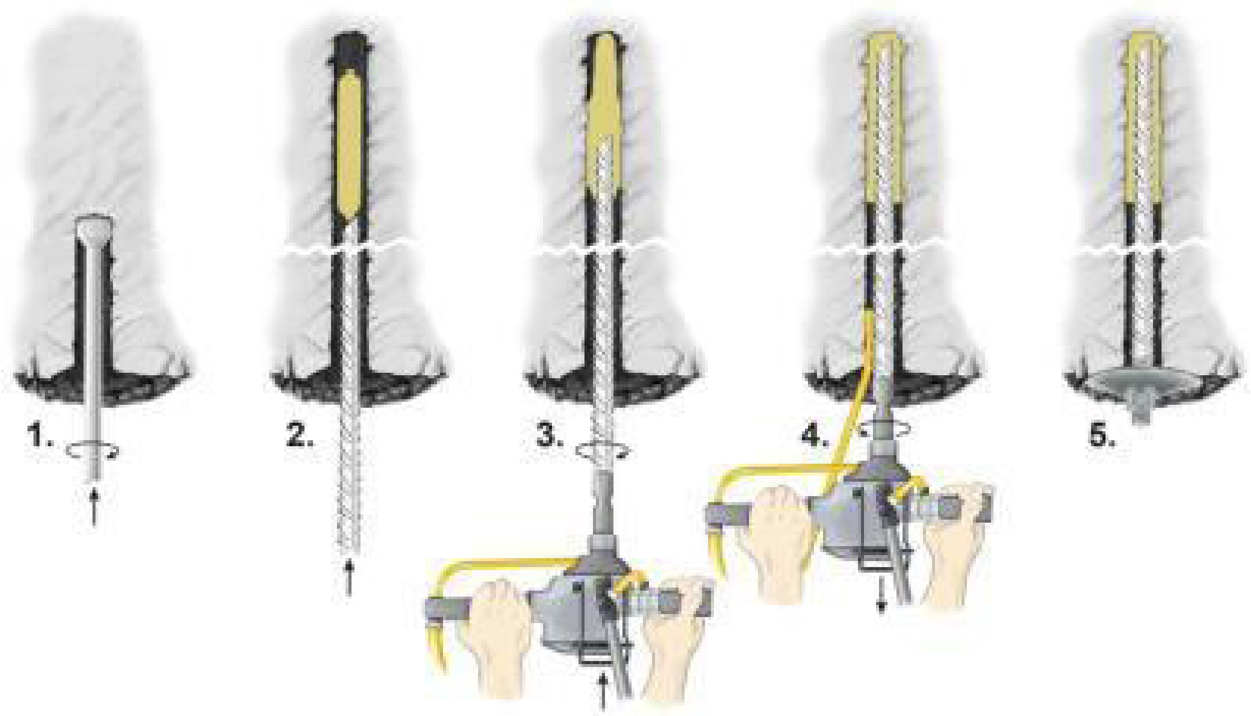


Figure 4.10 Installation of bolt using a polyester sleeve (end-anchored bolts).

Table 4.4 Explanation for Figure 4.10

1.	The drill diameter is adapted to the bolt and polyester cartridge. The hole is drilled 100–150 mm shorter than the bolt and flushed clean with water. (In very weak rocks, such as mica shale, it is important to flush the bolt hole particularly thoroughly in order to flush out drilling mud which adheres to the hole wall and reduces anchoring.)
2.	The cartridge is inserted into the hole using the bolt or a stemming rod until it reaches the end of the borehole. (Additional cartridges may be used in weakly or heavily fractured rocks). Prior to installation, the polyester cartridge should be allowed to reach a temperature of approx. 20 °C. Regarding bolting during the winter, see section C (4.4.1).
3.	The bolt is rotated and fed through the cartridge with the aid of a drill. Rotational speed 300–400 RPM. It is important to feed the cartridge slowly so that the insertion stops at the same time as the rotation. An appropriate insertion time/rotation time is approx. 25–30 seconds for Ø20–Ø25 mm bolts, and approx. 7–10 seconds for Ø16 mm bolts.
4.	The drill must not be reversed by the bolt until the polyester has cured, or alternatively the bolt must be locked using a crow bar, pipe wrench or similar.
5.	The bolt is fitted with a plate, hemisphere and nut, and then pretensioned, e.g. using an impact wrench. At temperatures of ≥ +5°C, the bolt can be pretensioned to 50 kN after five minutes. Premature pretensioning can damage the anchoring.

4.4.1 Quality of polyester anchoring

Polyester bolt anchoring provides good durability if it is executed correctly. Some points that require attention are:

A. Anchoring length
B. Borehole diameter
C. Curing time
D. Storage of the polyester cartridges.

A. Anchoring length
Polyester cartridges are normally supplied in standard lengths which produce an anchoring length and capacity that is sufficient to ensure that failure will occur in the bolt steel before the anchor fails. This applies to hard rock types, such as granite and other similar rock types, where the required anchoring length is approx. 300 mm for Ø20 mm bolts and approx. 500 mm for Ø25 mm. In weaker rocks, such as limestone and phyllite, and in heavily fractured rock, it may be necessary to increase the anchoring length by using two cartridges, for example.

If there is any doubt as regards whether the anchoring length is sufficient, the anchoring should be checked using tensile testing. The theoretical anchoring length for recommended dimensions for borehole, polyester cartridge and bolt is given in Table 4.3.

Table 4.5 Recommended bolt, cartridge and borehole diameters for polyester anchoring

Bolt	Polyester cartridge	Borehole diameter	Anchoring length*
Ø12 mm	Ø14 X 100 mm	Ø16 mm	175 mm
Ø16 mm	Ø19 X 150 mm	Ø21–Ø23 mm	237 mm
Ø20 mm	Ø23 X 400 mm	Ø25–Ø29 mm	480 mm
Ø20 mm	Ø28 X 372 mm	Ø29–Ø32 mm	440 mm
Ø20 mm (with mixing spring, etc.)	Ø38 X 443 mm Ø38 X 570 mm	Ø43–Ø45 mm Ø43–Ø50 mm	384 mm 385 mm
Ø25 mm	Ø28 X 372 mm	Ø32–Ø34 mm	540 mm

* Theoretical anchoring length based on largest borehole diameter.

B. Borehole diameter
The borehole diameter is adapted to the bolt and cartridge dimensions to optimise the mixing of the polyester.

C. Curing time
Temperature has a major impact on the curing time of the polyester. To avoid a long curing time, it is important that polyester cartridges are allowed to reach a temperature of approx. 20°C prior to use. The curing time may vary with the type of polyester concerned and will be specified by the supplier.

The temperature of the bolts also affects the curing time. Bolts should be stored so that they maintain a temperature of in excess of + 5°C. If the bolts are stored below 0°C, they should be allowed to reach an acceptable temperature prior to installation.

At temperatures of ≥ +5°C, bolts anchored using polyester cartridges can be pretensioned to 50 kN after five minutes. Pretensioning before sufficient curing has taken place can damage the anchor.

D. Storage of polyester cartridges
Polyester cartridges have a limited storage time. The shelf-life of polyester cartridges is approx. 9-12 months when stored at 0-20°C. The last month of use must be stamped on the box in which the polyester cartridges are delivered. Storage at higher temperatures (approx. 30°C) significantly reduces the service life of the cartridges. Cartridges should not be stored in steel containers left out in the sun, where the temperature can rapidly reach 40-50°C. Hardener can be damaged at high temperatures.

The necessary precautions must be taken at the facility to avoid improper storage.

4.4.2 Error sources in connection with anchoring using polyester

In connection with anchoring using polyester, experience has shown that the same sources of error recur, and that the error rate is often highest during the start-up phase of an installation. One or more of the error sources can result in reduced anchoring capacity /11/, /12/, /15/. Table 4.6 lists the most common sources of error.

The most common and serious source of error is drilling the borehole too long. See Figure 4.6. In addition to having procedures in place during drilling, the hole depth should be checked using the bolt or a stemming rod. If the anchoring length is too short, the bolt hole must be filled with polyester cartridges to a sufficient anchoring length. If there is any doubt about the anchoring capacity, the bolt should be tested.

It is important to note that holes with uneven sides and steel fibre-reinforced sprayed concrete can tear open the polyester cartridge before it reaches the bottom of the hole. To prevent this, the borehole can be flushed particularly thoroughly, and/or polyester cartridges with reinforcement (plastic grilles) can be used. Protruding steel fibres must be bent in/removed.

Table 4.6 Error sources in connection with anchoring using polyester

Error sources	Outcome
Borehole too long	Reduced anchoring length
Excessive rotation	Falling blocks, separation, destruction. Scale formation in the polyester after it has begun to solidify
Insufficient rotation	Incomplete mixing (weak or no curing)
Bolt is pushed through the polyester cartridge before rotation	Incomplete mixing (weak or no curing)
Cold polyester cartridge	Curing is prolonged and premature pretensioning can reduce the anchor strength
Incorrect storage of polyester cartridges	Damaged hardener in cartridge
Large borehole diameter relative to bolt/ cartridge	Incomplete mixing, reduced anchoring length
Lack of retrospective tightening/checks on pretensioned bolts behind the tunnel face	Excessive deformation (falling blocks, collapse, etc.)
Steel fibre-reinforced sprayed concrete	Tears in polyester cartridge
Incorrect installation direction of polyester cartridge with suspension spring	Incomplete mixing and premature puncturing of the polyester cartridge

4.5 Use of grout for embedding of bolts

It is relatively common to use cement grout for embedding bolts. It is important to be aware that this type of grout should be mixed, processed and used in a certain way to safeguard its properties in the best possible way. See the Norwegian Concrete Association's publication no. 14 *Spennarmeringsarbeider* (Pretensioning reinforcement works) (particularly Chapters 10, 14 and 15)/30/ for detailed information on how this should be done. We have briefly described some tips below. When grouting bolts, it is important that the grout compound is mixed correctly, and that holes and bolts are completely filled (in the case of combination bolts). The grout must be visible and the bolt must be marked as having been grouted.

In retrospect, it can be and often is difficult to check whether the bolt has even been grouted at all (regardless of whether or not it is marked). The bolt may appear to have been grouted, but that will provide little information on the quality of the grout down along the bolt. If, despite this, inadequate grouting is identified, it will not be practicable to rectify the non-conformity without installing a new bolt.

Figure 4.11 Correctly mixed grout in a mixing vessel for a grout pump. Photo Terje Kirkeby

Figure 4.12 Complete filling of hole and combination bolt. Photo Terje Kirkeby

When grouting rebar bolts, the borehole must be filled from the bottom up using a hose, and with enough grout to ensure that it flows out of the hole when the bolt is inserted.

Figure 4.13 Bolt in cutting prior to tightening of the plate. This is done after the grout has cured. Photo Terje Kirkeby

4.5.1 Error sources in connection with the embedding of bolts

When embedding bolts using a cement-based grout, a common error is to make the grout too thin (see Table 4.5). If insufficient water has been added, it will not be possible to pump the grout, and the hose can become blocked. Flushing the hose with water before the grouting process reduces the chance of the hose becoming blocked.

Table 4.7 Error sources in connection with the embedding of bolts

Error sources	Outcome
Excessively thin grout (too much water in the grout)	The grout flows out, resulting in reduced anchoring
The hose is not inserted to the bottom of the borehole	Lack of anchoring at the bottom of the borehole
The hose is pulled out rapidly	Insufficient filling
Poor centring	Lack of corrosion protection
Excessive storage time for grout in mixing vessel	Bolting grout does not expand
Water flow in bolt hole	Water in the borehole has an adverse effect on the grouting of combination bolts and ordinary rebar bolts. Even drips can create water channels along the bolt and be enough to cause the mass to flow back out again before it has had time to cure. If there are drips/drainage within a reasonable period of time, special bolts with seals must be installed (the instructions for use must be followed carefully). It is important not to inject/grout these bolts together with the standard combination bolts in the vicinity, but to wait until the next round of grouting (i.e. to grout the bolts only). Otherwise, there is a risk of forcing the water and the problem over to dry holes.

4.6 Embedding of bolts

Embedded bolts can be divided into two groups: fully embedded, unpretensioned bolts and combination bolts (see Figures 4.11-4.15).

Expanding bolt grouts are used for embedding bolts. In the case of hot-dip galvanized bolts, grouts are used which do not cause a reaction between the grout and zinc. The consistency of the grout is crucial for the outcome, and it is important to adjust the quantity of water in relation to the application in question. Grouting bolts in water-bearing holes can produce poor results and should be avoided wherever possible. Possible measures include drilling a new or relief hole or using bolts with provision for injection.

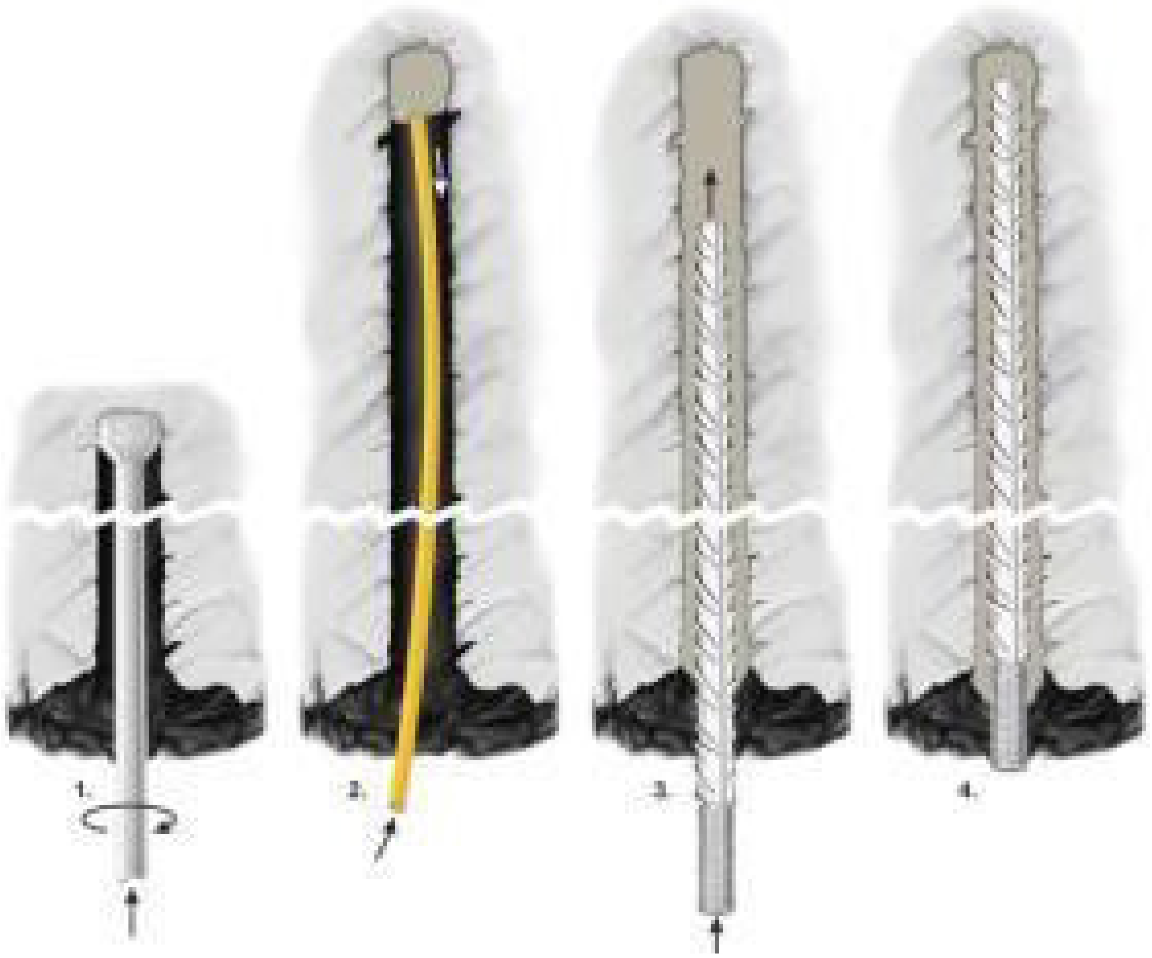


Figure 4.11 Installation of fully embedded rebar bolt. For centring, centring springs are recommended, or alternatively centring clips.

Table 4.8 Explanation for Figure 4.11

1.	The borehole is drilled so that it is at least as long as the bolt. The diameter of the borehole should be at least 10 mm larger than that of the bolt.
2.	The grout hose is inserted all the way to the bottom of the borehole. The hose is slowly pulled/forced out as the grout fills up the borehole.
3.	The bolt is then pushed slowly into the hole. The consistency of the grout should be such that the bolt is suspended. If the bolt sinks at all, it can be secured with a wedge. The bolt must not be bent or broken.
4.	Fully embedded rebar bolts. If a plate, hemisphere and nut are used, the nut must only be tightened after the grout has cured.

Figure 4.12 Installing a perforated bolt

Table 4.9 Explanation for Figure 4.12

1.	The Perfo method is based around the filling of a perforated pipe with grout.
2.	The perforated pipe is pushed in until it reaches the bottom of the borehole.
3.	The rebar bolt is pushed or tapped down through the grout.
4.	The grout is forced out through the hole wall when the bolt is inserted, resulting in full embedding.

Figure 4.13 Installing a pipe bolt

Table 4.10 Explanation for Figure 4.13

1.	The hole is drilled so that it is at least as long as the bolt.
2.	The bolt is initially fitted with an expansion sleeve and pretensioned. The pipe bolt acts like an end-anchored bolt until it has been post-grouted.
3.	In connection with grouting, a grout hose is connected to the bolt end, and the grout is pumped into the pipe and fills up the borehole from the bottom up.
4.	The consistency of the grout must be sufficiently thick to fill the borehole from the bottom up. If the grout is too thin, it will flow out from the inside of the pipe after the filling hose has been removed. In addition, grout can drop down onto the plate and fill the borehole from the bottom up, forming an air pocket at the top.
5.	Fully embedded pipe bolt.

Figure 4.14 Installation of end-anchored and post-grouted bolt

Table 4.11 Explanation for Figure 4.14

1.	The hole is drilled to a depth equivalent to at least the length of the bolt in the case of anchoring using an expansion sleeve, and 100-150 mm shorter than the bolt in the case of polyester anchoring
2.	The bolt is initially fitted with an expansion sleeve or polyester cartridge and pretensioned. A plate with additional holes is used where a vent pipe and injection hose are fitted. Expanding foam (construction foam) is used to lock pipes and hoses, and to ensure a seal. The bolt acts like an end-anchored bolt until it has been post-grouted.
3.	The grout is pumped through the injection hose and fills the borehole from the plate inwards. The air is evacuated through the vent pipe which has been fitted along the full length of the bolt.
4.	End-anchored and post-grouted bolt.

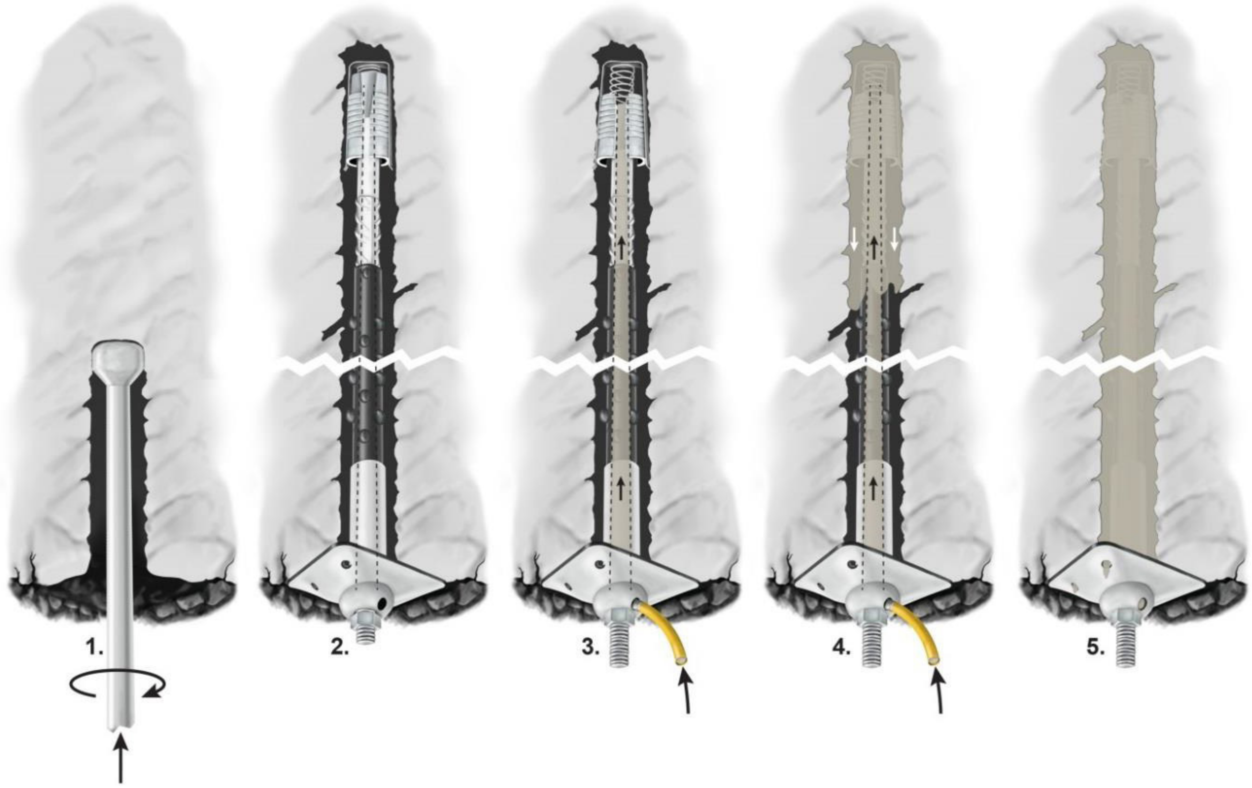


Figure 4.15 Installing a combination bolt

Table 4.12 Explanation for Figure 4.15

1.	The hole is drilled so that it is at least as long as the bolt.
2.	The combination bolt is initially fitted with an expansion sleeve and pretensioned to approx. 200 - 400 Nm. It acts like an end-anchored bolt until it has been post-grouted.
3-4.	The grout nozzle is inserted into the hole in the hemisphere, and the grout is pumped up inside the polyethylene pipe and fills up the borehole from the bottom up until it emerges around the plate. Before removing the grout nozzle, wait until the pressure has decreased in order to avoid splashing. The consistency of the grout should be like a thin porridge or thick soup, v/c number 0.40 – 0.45.
5.	Fully embedded combination bolt

4.7 Pretensioning of bolts

The pretensioning normally varies from 200 – 400 Nm. Impact wrenches are mainly used for pretensioning.

End-anchored bolts are pretensioned to prevent falling blocks or collapse. In the case of rock spalling, the nut is tightened, and little or no pretensioning is carried out. However, the baseplate should not hang loose, but fit snugly against the rock surface.

In addition to taking up the load of individual blocks which are to be stabilised, pretensioned bolts help to stabilise forces by increasing friction along fracture surfaces.

The pretensioning absorbs any unfavourable deformation ("slack") between the bolt, hemisphere and plate. This allows for good interaction between the plate, bolt and rock mass.

Combination bolts should normally be pretensioned prior to embedding. Fully embedded bolts should not be pretensioned.

When using an impact wrench, the pretensioning will always vary, because of variation in the friction in the bolt threads and between the nut and the hemisphere.

The most accurate method of pretensioning bolts is to apply a tensile force using a hydraulic jack, and then tighten the nut to the desired degree of pretensioning. This method is relatively time-consuming and therefore rarely used.

4.8 Water in bolt holes

Suitable bolts should be used for bolt holes which contain water. The presence of water in bolt holes causes problems with grouting and bolt service life. The presence of water is one of several factors that can contribute to a corrosive environment. Bolting in bolt holes with flowing water is problematic and should be avoided.

When the water freezes to form ice, there is an increase in volume. Frost bursting can contribute to unstable conditions in a cutting, tunnel or underground cavern, and must be considered in connection with the stabilisation.

5. Dimensioning

This chapter discusses various dimensioning rules. The dimensioning rules can be an aid when determining the number of bolts, bolt lengths and bolt orientation. It is important to remember that it is the rock conditions and the stress conditions at the site that will form the basis for dimensioning. The chapter also discusses dimensioning in connection with the use of passive and active anchors.

Calculations for dimensioning rock stabilisation are performed using the limit state method. In accordance with EN 1997 Eurocode 7 /16/, partial factors must be used when dimensioning rock stabilisation.

Section 5.2.1 presents equations which make use of both partial factors and safety factors, which were used before Eurocode 7 was introduced.

5.1 Dimensioning of stabilisation

Stabilisation during construction is normally assessed by the work team, often in collaboration with quality control engineers/engineering geologists from the on-site construction management team. The assessments involve choosing appropriate stabilisation methods and quantities. In practice, the dimensioning of bolting in connection with stabilisation while work is in progress will also cover positioning of the bolts. The dimensioning of permanent stabilisation measures must be determined by an experienced engineering geologist or other skilled person.

Stability can be calculated based on static, empirical or numerical models. The stereographic projection of any discontinuities is also an aid that can be used to assess stability, amongst other things. In practice, bolting is largely dimensioned on the basis of empirical systems.
Dimensioning is often based on rules of thumb and static considerations (equilibrium considerations).

The Q method is an empirical model for rock mass classification. The method can be used for indicative dimensioning of stabilisation, and is described in a manual from NGI *Bruk av Q-systemet* (Use of the Q system) /4/. Refer to the literature for other rock mass classification systems and empirical design rules /2/, /17/, /18/.

Numerical models are primarily used to calculate overall stability on tall rock slopes and in large underground caverns, and are not described in more detail here.

Interaction between rock and rock reinforcement can theoretically be described using response curves for the rock and the rock reinforcement. The response curve of the rock is an idealised load/deformation curve, and shows the pressure that rock reinforcement must exert on the rock surface in order to achieve equilibrium and stop further deformation. These considerations will be particularly linked to structurally complex rock that is under stress /2/. Software programs are available which simulate deformations in the tunnel face before and after the installation of bolts and other means of stabilisation.

As a general rule, it is the rock mass itself that is the most important supporting element. For Norwegian conditions, major deformations are particularly associated with rock pressure problems (rock spalling, rock bursting) and weakness zones containing swelling clay.

In a pull test using two separate blocks of cement where the rock bolt is subjected to stretching, it was possible to look at the overall deformation of the rock bolt itself and the anchoring /19/. The equipment can also be used to map the shear deformation for end-anchored and fully embedded bolts (see Figure 5.1).

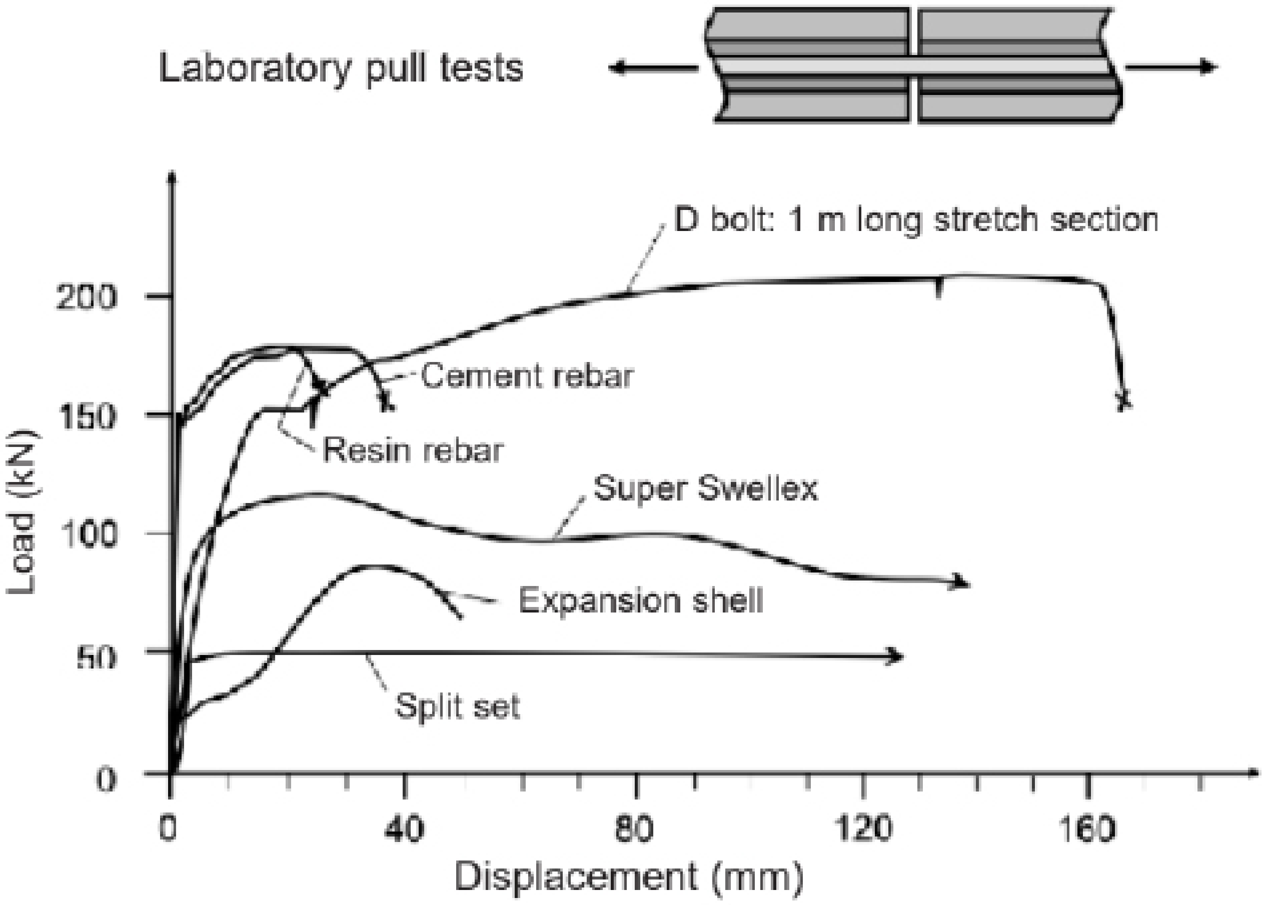


Figure 5.1 Load/deformation curves for various rock bolts during pull tests in blocks with a facture perpendicular to the bolts /19/.

Drilling deviations may cause the bolt to rest against the hole wall on one side, preventing the grout from covering the bolt steel. This weakens the bolt's fastening and compromises corrosion protection.

In rocks with horizontal layering, dimensioning can be performed on the basis of the beam/plate effect. The aim is to bind several "independent" layers together to form a thicker and thus stronger layer; see Figure 5.2. In the case of bolting in horizontally layered rock, it is also relevant to stabilise any unstable layers in an overlying stable layer. To stabilise horizontally layered rocks, a comprehensive design basis has been developed; see /20/.

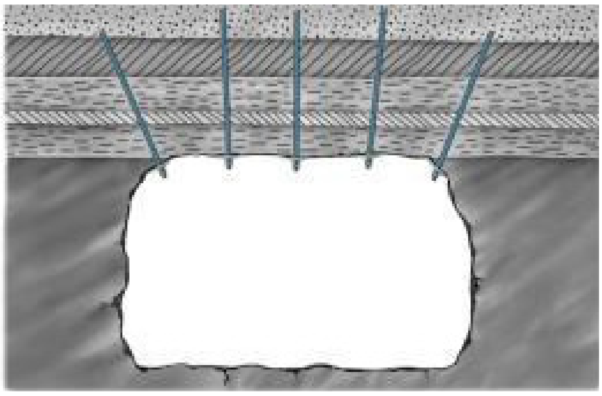


Figure 5.2 Bolting in horizontally layered rock

5.2 Spot bolting

5.2.1 Number of bolts

Dimensioning of a block can be performed by estimating the weight of the block and using the load-bearing capacity of the bolt to determine the number of bolts that are required in order to hold the block in place. Eurocode 7 /16/ is the current standard for the dimensioning of bolts, (1). A safety factor has traditionally been used (2).

Eurocode 7 /16/ is the current standard for the dimensioning of bolts:

(1) $n \bullet Md \geq Fd$

where

n = number of bolts
Md = dimensioning strength of the bolt
Fd = dimensioning load

The dimensioning strength of the bolt (M_d) is the characteristic strength of the bolt (M_k) divided by a material factor (γm).

$$Md = \frac{Mk}{\gamma m}$$

The dimensioning load is the characteristic load (F_k) multiplied by a partial factor for the load (γf).

$$F_d = F_k \bullet \gamma_f$$

Traditional method for dimensioning bolts

(2) n=G*F/B

where

n = number of bolts
G = weight of loose or presumed unstable block or collection of blocks
F = safety factor (e.g. 1.5-3, partly depending on the facility's safety level)
B = load-bearing capacity of the bolt (e.g. flow load of the bolt upon tensioning)

It is common to disregard friction along fractures when dimensioning the stabilisation of individual blocks underground. The friction that is present will provide additional safety in the calculation. By demonstrating that the dimensional strength of the bolts is greater than or equal to the dimensioning load, the partial factor can be used as follows:

Example of a partial factor:
A granite block with a volume of approx. 8 m^3 is to be stabilised using end-anchored bolts in a tunnel roof. The cross-sectional area of the bolt in the threaded section (the weakest part of the bolt) is 245mm^2, and the steel used in the bolt has a yield strength of 500 MPa (0.5 kN/mm^2). The material factor of the steel (γ_m) is 1.25. The partial factor for the load (γ_f), i.e. the level of uncertainty regarding the size of the block and the specific weight of the rock is 1.5. Granite has a specific weight of 27 kN/m^3.

Dimensioning load,
F_d=8 m^3 * 27 kN/m^3 * 1.5= 324 kN

Dimensioning strength of the bolt,
M_d = 245 mm^2 * 0.5 kN/mm^2 / 1.25 = 98 kN

Number of bolts, n ≥ 324 kN/ 98 kN ≥ 3.31

This entails the use of a minimum of four bolts to stabilise the block that is considered to be unstable (illustrated in Figure 5.3).

Example safety factor:
The same calculation can be performed using a safety factor. With a safety factor of 2, the calculation is as follows:

Number of bolts
n = (8 m^3 *27 kN/ m^3 * 2) / (245 mm^2 * 0.5 kN/mm^2) = 3.53

The result is the same when calculating using a safety factor as when calculating using partial factors: four bolts.

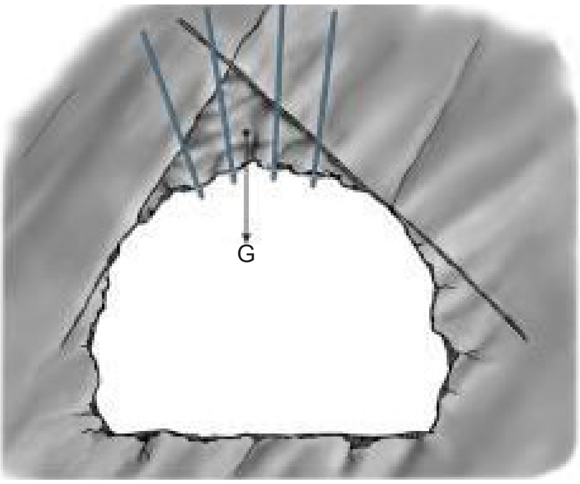


Figure 5.3 Bolting of an individual block

5.2.2 Bolt length

The bolt length (L) is selected so that the bolt is anchored at least 1 metre into solid or stable rock; see Figure 5.4. It is important to take into account the uncertainty relating to the orientation of the triggering fracture plane when determining the bolt length. In the case of injection, bolt lengths must be adapted to the injection curtain in order to prevent puncturing.

(3) $L \geq R + 1.0\,m$

where L = Bolt length
R = Bolt length in unstable part of the block

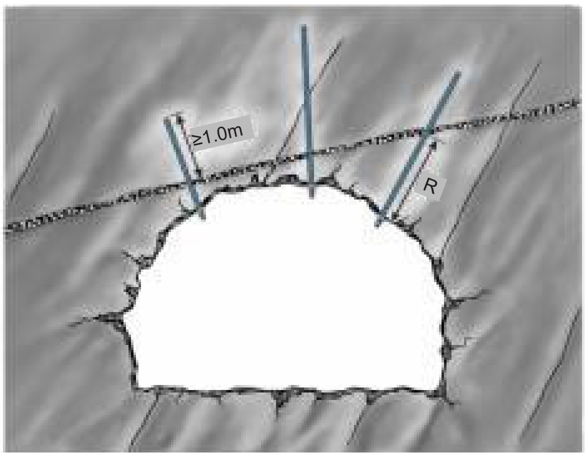


Figure 5.4 Bolt lengths in delimited loose blocks

5.2.3 Bolt orientation

The bolt should be inserted so that its tensile capacity is utilised to the greatest extent possible. End-anchored bolts with polyester should be inserted as perpendicular to the rock surface as possible in order to achieve the best possible interaction between bolt plate and anchoring. The hemisphere will not be able to absorb an angular deviation of more than 20°. This means that the minimum angle between the rock surface and the orientation of the bolt is approx. 70°; see Figure 5.5. Figure 5.6 shows that the deformations for the same load on the bolt can easily double when the angle is increased to 60° /10/. This is unfavourable in terms of stabilisation. The problem is avoided by using fully embedded rebar bolts because this type of bolt is anchored along its full length.

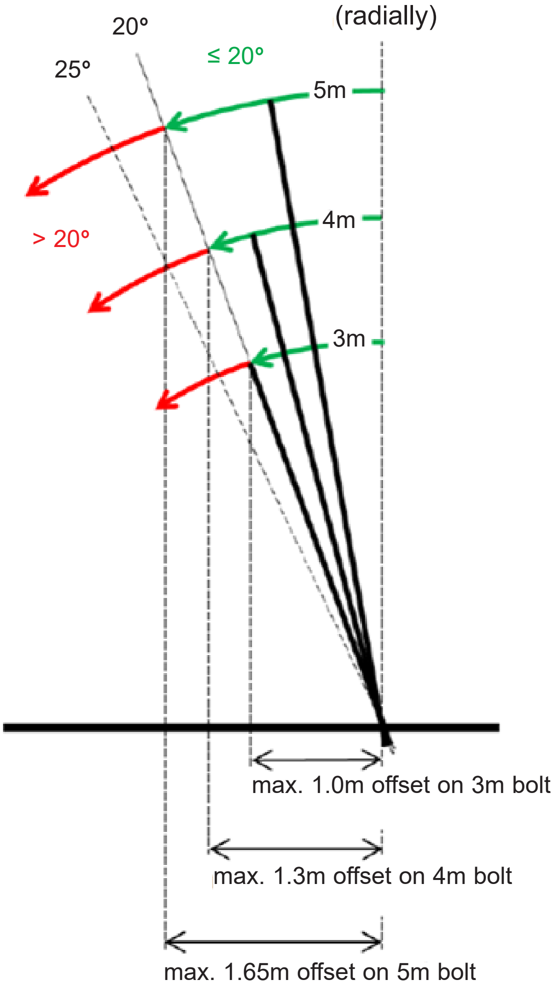


Figure 5.5.
The degree of offset of the bolts will depend on the length of the bolt. It is important to stay below 20° in connection with stitching (Terje Kirkeby, Norwegian Public Roads Administration).

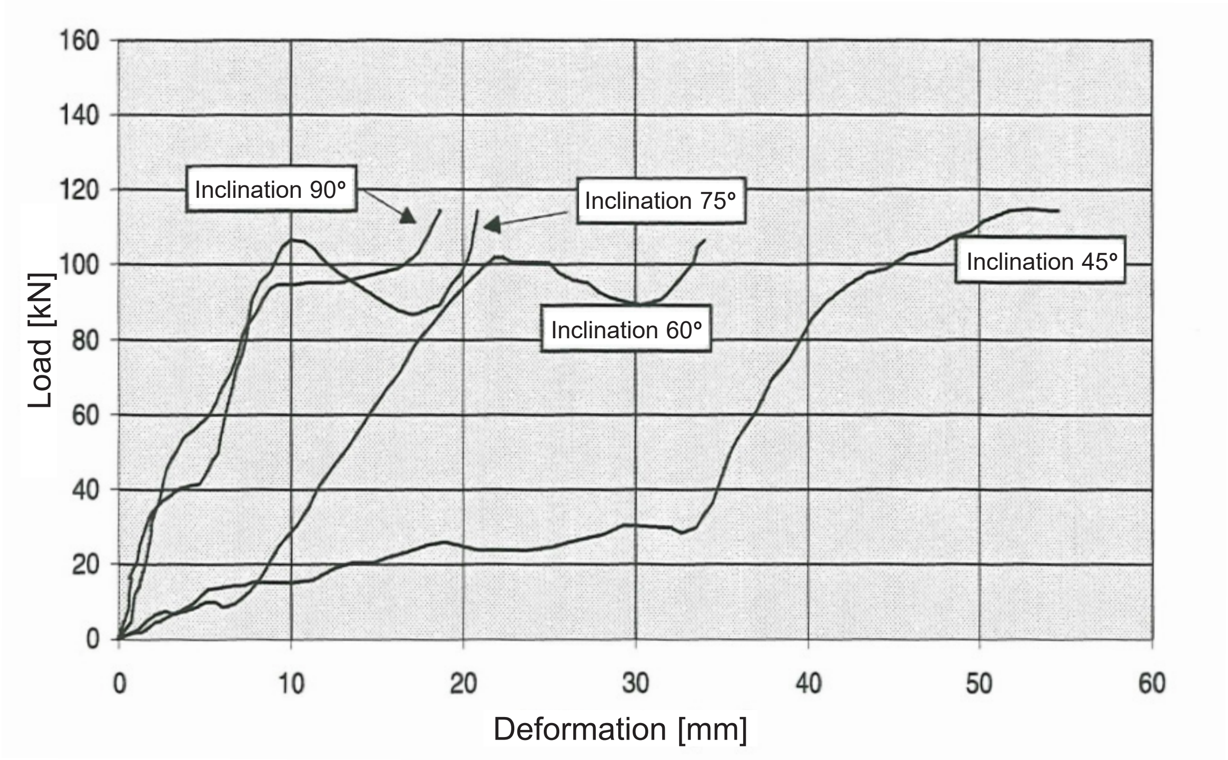


Figure 5.6 Load/deformation curve for end-anchored bolt with dome-shaped spherical plates with different angles between the plate and bolt hole /10/.

5.3 Systematic bolting

5.3.1 Systematic, unpretensioned bolting

In connection with the blasting of underground caverns with an almost circular roof, it is assumed under certain conditions that a parabolically shaped self-supporting vault will be formed, where the fractured rock is primarily exposed to compressive stresses. An assumed unstable rock mass below the compressive zone can be stabilised using fully embedded, untensioned bolts extending at least 1 metre inside the lower limit of the compressive zone; see Figure 5.7.

5.3.2 Bolt lengths in the case of systematic, unpretensioned bolting

Indicative bolt lengths (L) can be determined based on the tunnel width (D) using the following equation (after /1/).

(4) $L = 1.40 + 0.184D$

The bolt lengths can be reduced out towards the abutments; see Figure 5.6. For practical reasons, this is only applicable in the case of relatively large widths, e.g. more than 10 metres.

Equation (4) is indicative and general. When determining bolt lengths, consideration must also be given to the local rock conditions.

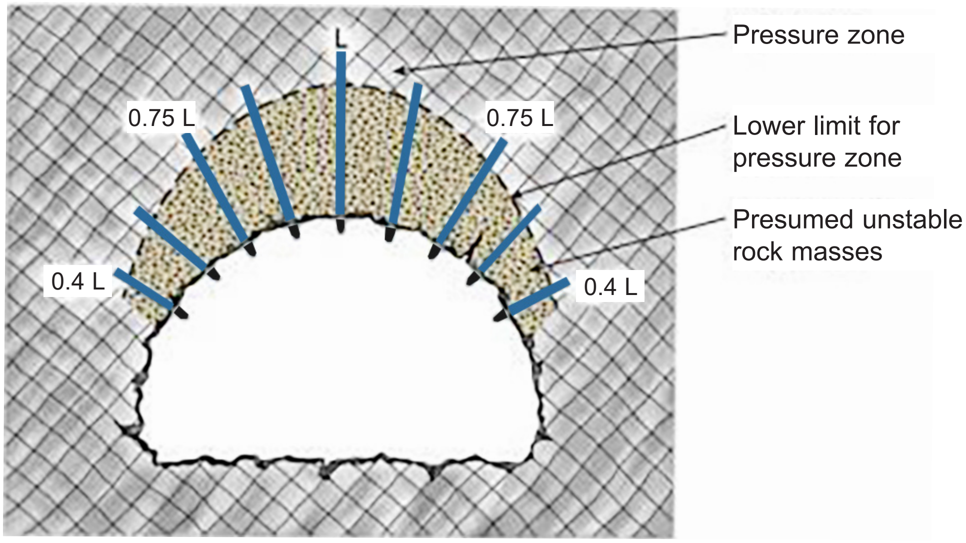


Figure 5.7 Decreasing bolt lengths towards the abutments

5.3.3 Bolt spacing in the case of systematic, unpretensioned bolt

In practice, it is common to choose bolt patterns with equal spacing between the bolts in each row and the bolt rows, where the bolt spacing is:

$c/c = 1.0 - 2.5\ m$

Depending on the fracturing, a different spacing between bolt rows and bolts can also be chosen for each row. Bolt patterns are assessed on the basis of rock conditions and are largely based on experience. The bolt spacing and any use of other stabilisation methods in addition to bolts will vary with rock conditions and the safety level that is required for the rock facility concerned.

5.3.4 Systematic, pretensioned bolting

Pretensioned bolts can be used to form a compression arch in the rock; see Figure 5.8. This assumes that the bolts are arranged systematically with a given spacing and degree of pretensioning. In order to form a compression arch with pretensioned bolts, the following conditions must be met (after /1/, /2/).

$L / a \approx 2$
$a \leq 3e$
$T \approx 0.5 - 0.8K$

where:
L = Bolt length
a = Bolt spacing
e = Mean fracture spacing
T = Pretensioning force
K = Breaking capacity of the bolt

The ability of the bolts to significantly affect the stress picture in the rock is often very limited. The formation of a compression arch will be limited to schistous/layered rocks and unstressed rock with little tension /2/.

To form a compression arch, the bolts should be of equal length. Indicative bolt lengths (L) can be determined based on the tunnel width (D) using the following equations /1/, /21/):

(4) $$L = 1.4 + 0.184D$$

(5) $$L = 1.6\sqrt{1.0 + 0.012D^2}$$

Equations (4) and (5) are indicative and general, and result in different bolt lengths. Equation (5) gives shorter bolt lengths than (4) and should therefore only be used in exceptional cases. The equations indicate the range of variation in bolt lengths that should be used to form a compression arch. Bolt lengths are also assessed based on the local rock conditions.

End-anchored bolts can result in poor anchoring in heavily fractured rock.

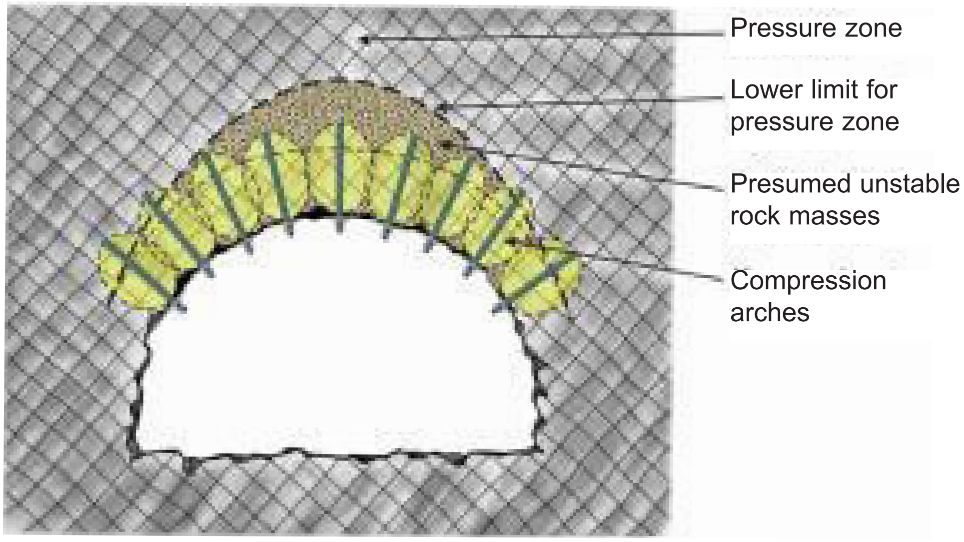


Figure 5.8 Formation of a compression arch using pretensioned bolts

5.4 Bolting in rock walls and cuttings

In principle, there are no major differences between the dimensioning of bolts in tunnels and the corresponding process for rock walls and cuttings. However, in high walls or rock cuttings and rock slopes, the friction on the fractures (shear strength) is often of great importance, and extensive stabilisation may be necessary if this is not taken into account. In addition, consideration should be given to the fact that the bolts are often orientated obliquely in order to prevent movement along a fracture plane. Embedded bolts are better suited to absorbing shear deformation than end-anchored bolts.

The stabilisation of walls and rock cuttings using bolts often entails locking shear movements along fracture planes by securing what are presumed to be unstable blocks to adjacent stable rock.

The securing of unstable blocks that can slide on a fracture plane can be considered to be static. The number of bolts needed to stabilize the block can be expressed by equation (6); see Figure 5.9.

(6)

$$n = \frac{G\,(F \bullet \sin\beta - \cos\beta \bullet \tan\varphi) + U \bullet \tan\varphi - cA}{B\,(\sin\alpha \bullet \tan\varphi + F \bullet \cos\alpha)}$$

where: n = Number of bolts
G = weight of loose or presumed unstable block or collection of blocks
F = Safety factor (e.g. 1.5–2, partly depends on the facility's safety level)
B = Load-bearing capacity of the bolt e.g. the flow load of the bolt upon stretching)
φ = Angle of friction of the fracture/gouge
α = Angle between the bolt and the fracture plane (recommended 30–50°)
β = Angle of dip of the fracture plane
c = Fracture/gouge cohesion
A = Area of the fracture plane’s sliding surface
U = Fracture water pressure

Figure 5.9 Stabilising a presumed unstable block in a rock cutting

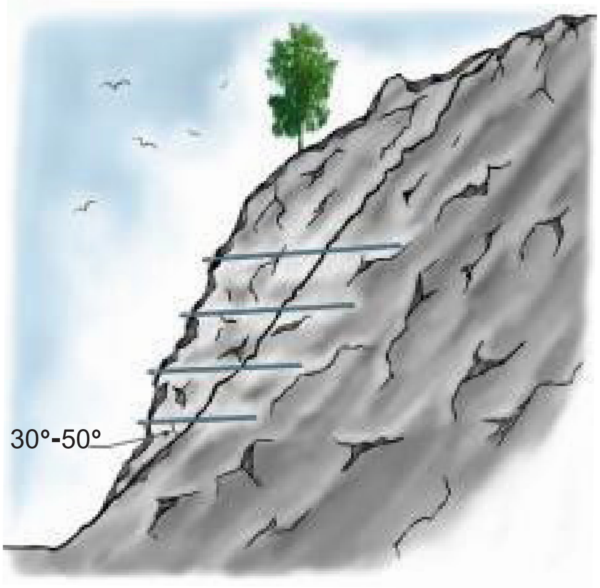


Figure 5.10 Recommended angle between bolt and fracture plane

In connection with major stabilisation works and the use of anchors, pretensioning of the anchors can be utilised to increase the friction on the fracture surfaces. Formulae have been developed based on friction theory and empirical studies (see for example /22/, /23/).

5.4.1 Bolt orientation in the case of bolting in rock walls and cuttings

Bolts should be inserted so that the tensile capacity is utilised. The recommended angle between bolt and potential sliding plane is 30–50° (see Figure 5.10) after /24/, /25/. The dimensioning strength of a rebar bolt (fully embedded) can then be assumed to be utilised to the greatest extent possible, upon tensile and oblique loading.

There is some uncertainty associated with the dimensioning strength of bolts when they are subjected to pure shear in the rock (90° between the bolt and potential sliding plane) /24/, /25/, /26/. This partly depends on the nature of the fracture surface and thus the fracture sequence, along with the type of bolt. The dimensioning strength of a rebar bolt is approximately halved if it is subjected to pure shear.

If bolts are used as end anchors, consideration must be given when selecting a bolt angle to the fact that bolt plate/rock surface can only have a maximum deviation relative to the bolt orientation of 20° from the normal.

5.4.2 Risk assessment of cuttings

All rock cuttings are associated with some risk, as the original stability of the rock has been altered. All rock cuttings with a height of >10 m should be assessed as a separate object throughout the planning, construction and operation phases.

This assessment should include:

- an overall evaluation, including an assessment of overall stability (dedicated mapping of the rock in the cutting and surrounding area, preferably using the Q method)
- specific risk assessment, including calculations of possible blocks as shown in equation (6)
- described design and safety measures, with detailed descriptions of the length and orientation of bolts and any other measures such as anchors or simply the bringing down of larger blocks
- expert follow-up and documentation.

We stress that documentation similar to that described in Chapter 7 can also be used for surface stabilisation.

In the risk assessment, consideration must be given to the functional requirements applicable to the cutting. Functional requirements for rock cuttings on heavily trafficked roads and/or high-speed roads/ railway lines should indicate very little tolerance for failure/falling blocks/landslides.

6. Control methods

6.1 Visual checks during execution

The installation procedure for the individual bolt type concerned must be followed. See the description of the installation process in Chapters 3 and 4 and/or the supplier's description/product description.

Checks on fully embedded bolts are carried out by observing grout emerging from under the plate as a completion test, in addition to documentation of grout usage and the correct bolting grout. No grout should flow out when the grouting equipment is disconnected. Each bolt should be marked to indicate that it has been grouted.

Before starting bolting works, the contractor should check the consistency of the bolting grout by installing a bolt in a transparent plastic pipe of a similar dimension to the bolt hole. This could be done using either a combination bolt or, for example, a grout-embedded rebar bolt (the Bergjet method). During the construction period, this exercise should be repeated at regular intervals. Excessively thin mortar can be identified by the fact that it flows out of the plastic pipe. Incorrect execution can become apparent through non-filling of the plastic pipe.

6.2 Visual checks of completed bolting

The completed bolting, i.e. bolt type, quantity and location, must be compared against the specified stabilisation class.

Checks must be made to ensure that the angle between the bolt and the rock surface is not less than the recommended minimum angle, and that the hemisphere rests correctly against the plate.

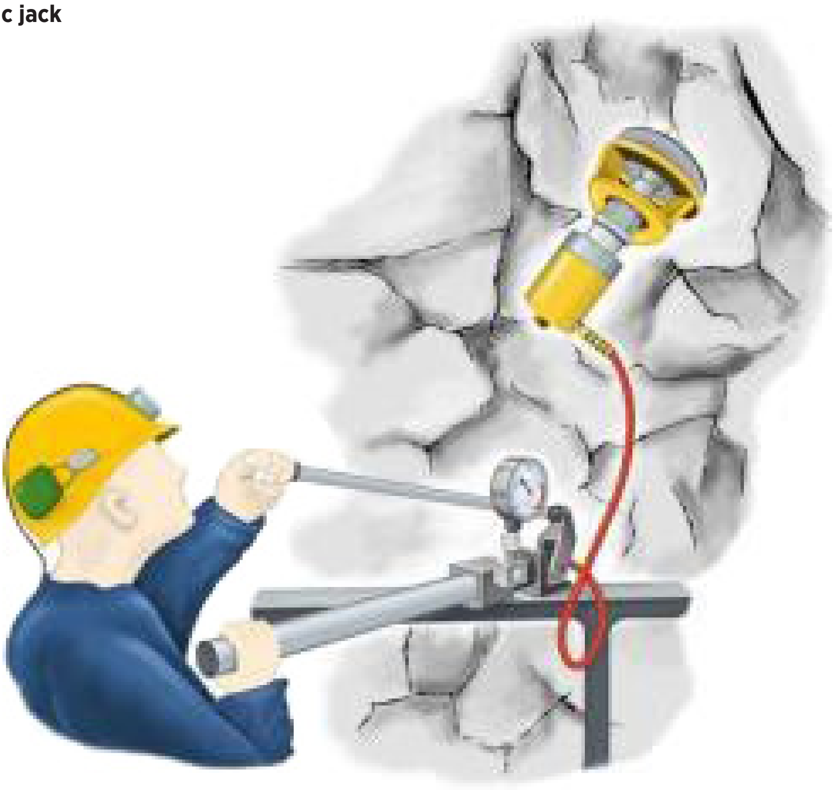
Checks can be performed on pretensioning along with the calibration/checking of pretensioning equipment (impact wrench) by placing a hydraulic jack between the rock surface and the end plate. To ensure that the friction in the threads is as even as possible, the threads should be lubricated with a suitable lubricant, such as wax.

6.3 Checking of anchoring via pull tests

Pull testing using a hydraulic jack is used as a means of checking end-anchored bolts. It is important that the pull testing is performed by skilled personnel.

It is common practice to pull the bolt to a given upper limit, such as 50–70% of the bolt's character-

Figure 6.1 Test pulling using a hydraulic jack



istic strength (yield strength). The pulling is carried out using a special hydraulic jack (see Figure 6.1). Experience indicates that anchoring with polyester is a satisfactory method for use when the bolt can be pulled to 4-5 tonnes without sinking.

Efforts must be made to pull the bolt in the bolt direction. If necessary, it should be built up under the cylinder. If possible and justifiable with regard to stability, the plate should be removed before pull testing to avoid damaging the plate.

Tensile testing can also be performed by pulling the bolt until it fails. This indicates the precise capacity of the anchoring or bolt. The method is destructive, as the bolt is destroyed and must be replaced.

6.4 Checking of embedding through drilling

The bolt and surrounding rock are drilled out using core drilling equipment (see Figure 6.2). This drilling method is time-consuming and expensive. Adjustment is made on the basis of the projecting part of the bolt. As a result of drilling deviations and requirements regarding accuracy when setting equipment, it is difficult to obtain good results with drilling lengths in excess of 2 metres. Drilling out bolts is a destructive method and the bolt must be replaced.

Bolts that have been in situ for a prolonged period of time can be drilled out to investigate durability with regard to corrosion and degradation of the grout or polyester compound, etc.

Figure 6.2 Drilling out a bolt

7. Documentation

This chapter is intended as a guide and covers the various documentation tools that are available for bolting. The aim is to raise awareness of the tools and aids that are available, and to demonstrate the possibility of fully digitising documentation.

A description is given of the various tools and aids, along with how data is collected and where this data is useful. Documentation is a control tool for use during and after construction, and is just as important in day-to-day operations as it is in final documentation. It is recommended that stabilisation bolts be recorded with quantity, type, length, position and direction. The purpose of documenting the type (length and size) and location (coordinates and angle) of bolts is to ensure that documentation is established of what has been placed where, and what types and lengths of bolts have been used to provide stabilisation.

The aim must be to gather all tunnel data in model-based documentation, and to use this data actively during the construction and operating phase. In Norway, active efforts are being made to digitise the final documentation with BIM. Going forward, it will be important to establish a method for seamlessly recording bolts from drilling logs and bolting logs in such a model. Several projects are in the process of doing this and will lead to a new way of documenting bolting.

7.1 Definitions

There are some important terms and definitions in tunnel terminology which should be explained in order to understand what assumptions are made when converting a three-dimensional object and folding it out to form a two-dimensional plane

The fold-out principle

The tunnel profile is folded out so that the distance along the profile matches the arch length in the theoretical blasting profile. The viewing angle of the folded-out profile is as if it had been viewed from the outside/above (as indicated by the eye in Figure 7.1). In order to fold it out, a fixed point must be established which the tunnel will be based on when laid flat. This is done by determining four main points; transition wall/invert, wall centre, abutment and centre of the roof. The centre of the roof is then the centre of the tunnel. (Ref /27/)

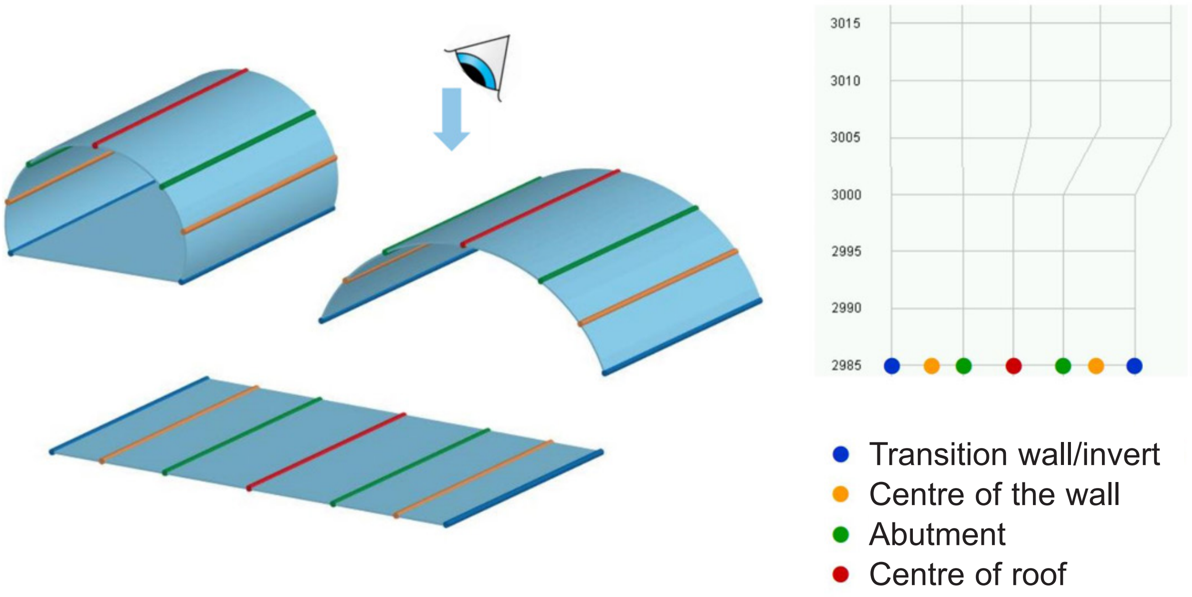


Figure 7.1 The fold-out principle, where the tunnel centre line is the centre of the roof. On the right is the folded-out profile as it appears in 2D. The colour codes refer to the corresponding lines /27/.

Map coordinates and tunnel coordinates

Coordinates in a tunnel are fundamental for tunnelling and rock stabilisation. Coordinates are used to determine the location of objects (bolts and bolt holes) at a fixed point (pile number). In the case of tunnels, two coordinate systems are used, one global and one local. These are also known as map coordinates and tunnel coordinates.

Figure 7.2. shows the tunnel coordinates, where h is indicated as "up" **a** is the pile number, and **b** is the distance from the centre line to the side. An example is that the pile number (**a**) = 420, side (**b**) = -9.5m and height (**h**) is 10m.

Figure 7.3 shows the map coordinate system, where **Z** is indicated as "up", **X** is east and **Y** is north. A coordinate system is required in order to use map coordinates. EUREF89 UTM (Universal Transversal Mercator) has been used in Norway since 2009. There are currently three official EUREF89 zones in Norway, UTM 32, UTM 33 and UTM 35, the UTM projection has a scale factor of 0.9996 in the central meridian. This means that a distance measured in the terrain must be corrected by up to 400 ppm (parts per million) or 4cm/100m. The "measurement error" depends on the distance from the central meridian, in order to be converted to a distance in the map plane. The EUREF UTM coordinate system is good enough for most structures and roads. The challenges lie in the staking-out of construction projects with strict tolerance requirements, e.g. regarding the joining of building components /28/.

The solution to this problem was to introduce a new secondary official projection, EUREF89 NTM (Norwegian Transversal Mercator) with zones 5 – 30. This coordinate system will have a maximum scale correction within the zone width of 11 ppm in Southern Norway and 5 ppm in the far north of the country. The coordinate system will then satisfy all practical purposes where conventional measuring equipment is used /28/.

In the case of tunnel operations, tunnel coordinates are primarily used for contours and lines, while almost all data generated by machinery during construction uses a map coordinate system.

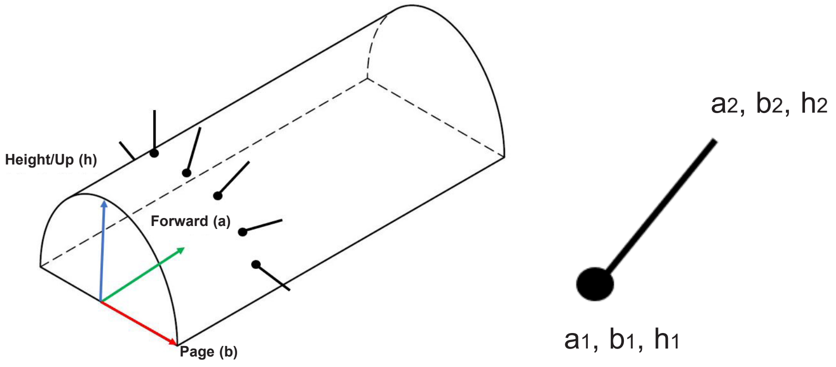


Figure 7.2. Tunnel coordinate system (left) where a is the pile number, b is the distance from the centre line to the side, and h is the height and normal of the centre line. Bolt (right) shows the tunnel coordinates with collaring point (a1, b1, h1) and bottom (a2, b2, h2).

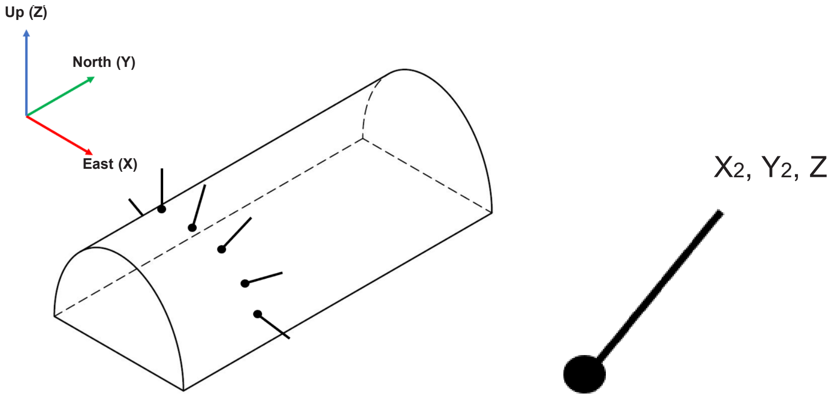


Figure 7.3. Tunnel with map coordinate system (left) east is X, north is Y and up is Z. Bolt (right) shows map coordinates with collaring point (X1, Y1, Z1) and bottom (X2, Y2, Z2).

Tunnel profile

Figure 7.4. shows two-dimensional tunnel profiles with a normal lateral slope.

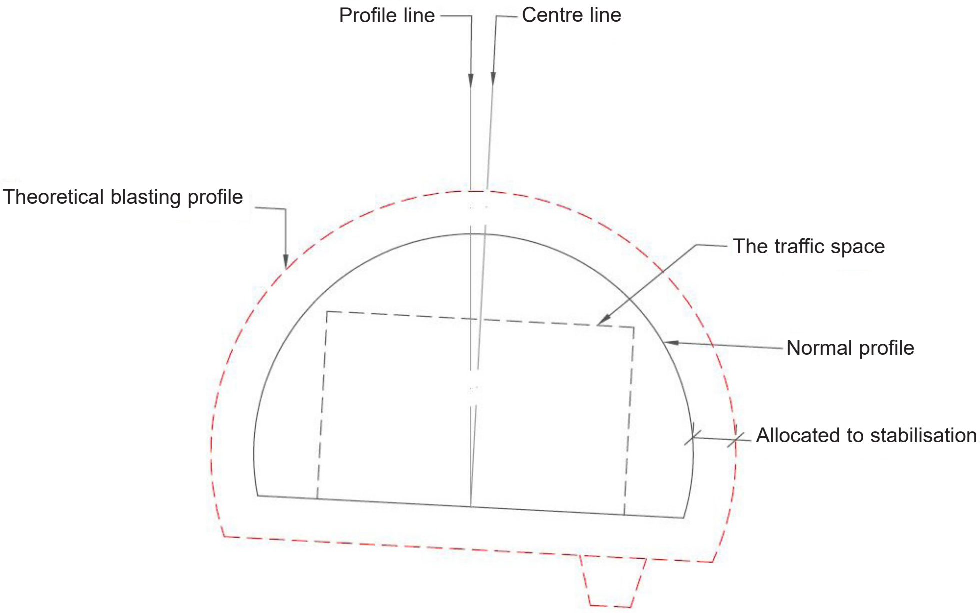


Figure 7.4 Schematic tunnel profile. The dashed red line indicates the theoretical blasting profile with lateral slope.

7.2 Methods for recording rock stabilisation

There are five main methods for recording bolts, and it may be appropriate to combine several such methods in order to obtain a good overall picture.

Manual documentation

This is the traditional method of documenting bolting. The bolt pattern, length and type are determined based on the Q value of the surrounding rock. The log itself is prepared by a bolting foreman who passes it on to the quality control engineer, who in turn checks that it has been completed as ordered.

Drilling log from drilling rig

A navigated drilling log can provide information on the position, direction and length of the bolt holes, with (X, Y, Z) coordinates for the collaring point and hole direction. However, the drilling log cannot provide information on whether a bolt has actually been inserted in the hole, or whether a bolt that is shorter than the length of the hole has been inserted.

Surveying using a total station theodolite

Surveys using a total station theodolite can provide information on the collaring point of the bolt itself with (X, Y, Z) coordinates, but not direction or length. Assuming that the bolt holes which do not contain bolts are not surveyed, it will be clear that a bolt has been inserted in this hole.

Recording using a camera

Images provide a visual overview of the bolts in an area, but will not normally be sufficient to enable coordinate lists to be produced. The bolts are shown without a defined direction and length, but the angle of the bolts with respect to the bolt plate can provide an indication of the direction.

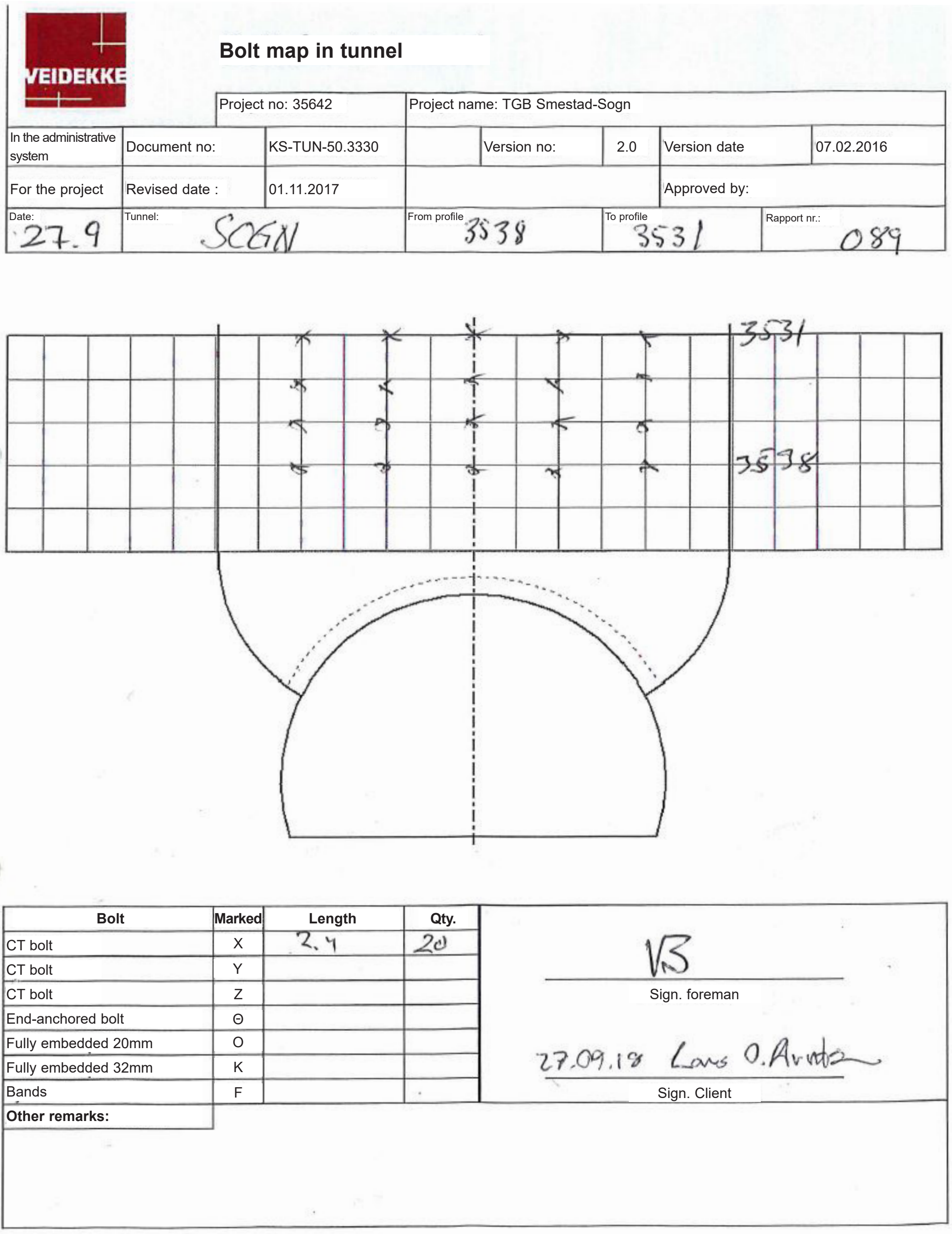
Model-based documentation

Over time, more and more requirements have been imposed on final documentation, and the major construction clients now often stipulate that model-based methods must be used in the planning, design and construction of projects.

7.2.1 Manual mapping

The current practice for checking bolting is sample-based, and the view that quality control engineers do not need to check everything if the rock is of good quality. In the case of critical zones or poor rock, everything should be checked, and additional bolts are often ordered retrospectively. When a quality control engineer performs an inspection, the number of bolts in the tunnel is counted for each blast round and compared against bolt reports from the contractor (see Figure 7.5.)

Alternatively, the bolt reports are summarised in a more general logbook (see the example in Figure 7.6.)



Bolt map in tunnel

		Project no: 35642	Project name: TGB Smestad-Sogn			
In the administrative system	Document no:	KS-TUN-50.3330		Version no: 2.0	Version date	07.02.2016
For the project	Revised date :	01.11.2017			Approved by:	

Date: 27.9	Tunnel: SOGN	From profile 3538	To profile 3531	Rapport nr.: 089

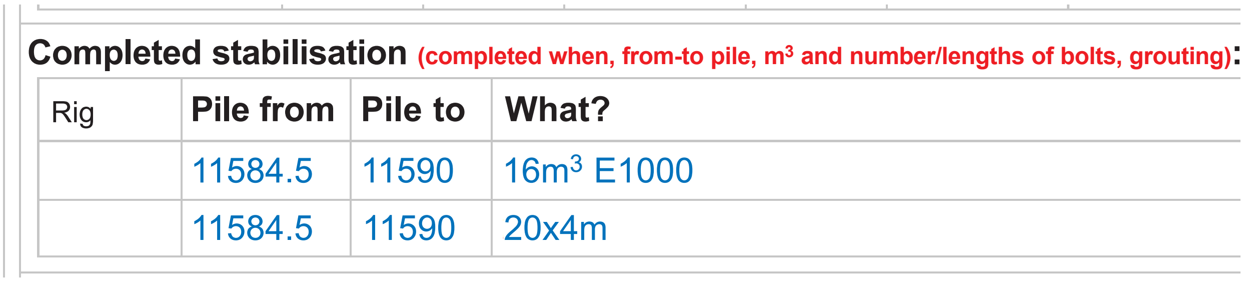
Bolt	Marked	Length	Qty.
CT bolt	X	2.4	20
CT bolt	Y		
CT bolt	Z		
End-anchored bolt	Θ		
Fully embedded 20mm	O		
Fully embedded 32mm	K		
Bands	F		

VB
Sign. foreman

27.09.18 Lars O. Arntzen
Sign. Client

Other remarks:

Figure 7.5. A traditional bolting report (with permission from Veidekke).



Completed stabilisation (completed when, from-to pile, m^3 and number/lengths of bolts, grouting):

Rig	Pile from	Pile to	What?
	11584.5	11590	16m^3 E1000
	11584.5	11590	20x4m

Figure 7.6. Example of a logbook (with permission from the Norwegian Public Roads Administration).

7.2.2 Drilling log from drilling rig and survey using a total station theodolite

Drilling logs and surveyed bolts can provide map and tunnel coordinates. Figure 7.7. is based on a drilling log, and shows a folded-out two-dimensional map of bolt holes, where length is indicated using colour codes shown in Table 7.2., and the lines radiating out from the dot show the orientation of the bolt holes. Table 7.1. shows an extract from a coordinate list. The list contains both tunnel coordinates and map coordinates for the bolts in the red circle in Figure 7.7. The pile number and contour length are used to place the bolt hole on the folded-out bolt hole map. The contour length is determined based on the location of the bolt hole relative to the centre line (black). The values on the left are negative, while those on the right are positive. The red lines on either side of the bolt log represent the transition from wall to invert. The map coordinates are determined based on the parameters North, East and Up. The collaring point indicates where the bolt hole starts and the bottom will be where the bolt hole ends.

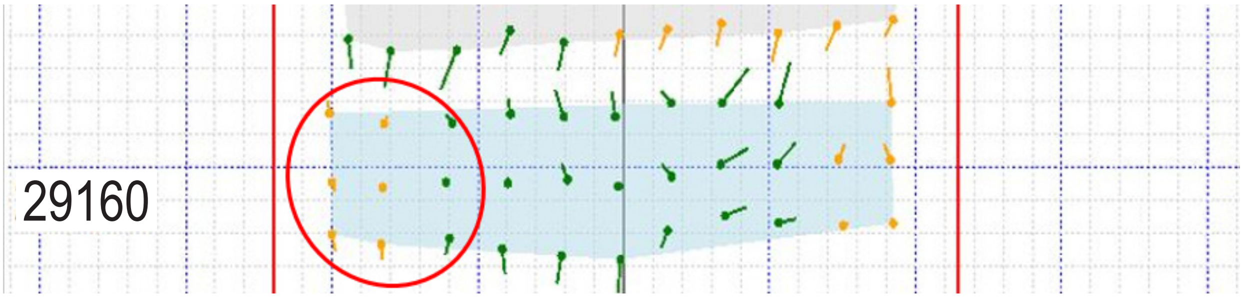
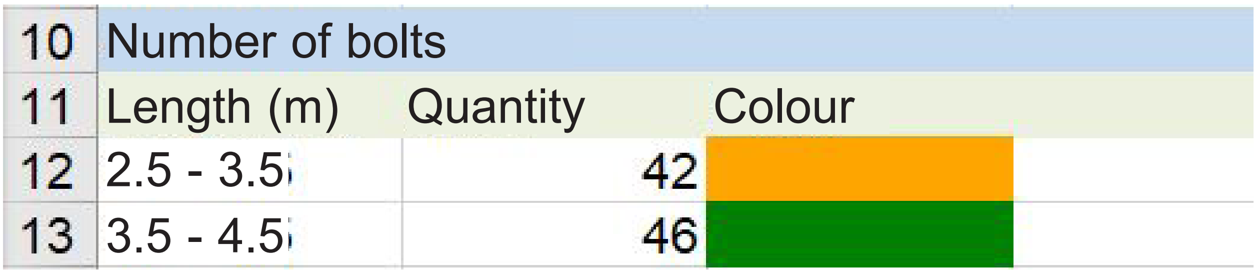


Figure 7.7. Example of two-dimensional bolt map /29/

Coordinates								
Pile	Length (m)	Collaring point - North	Collaring point - East	Collaring point - Up	Bottom - North	Bottom - East	Bottom - Up	Contour length
29162.045	3.201	1552533.8	84744.319	-218.587	1552533.1	84747.437	-218.592	-9.996
29160.466	3.19	1552532.5	84743.366	-218.626	1552531.5	84746.406	-218.637	-9.997
29158.364	3,205	1552530.4	84742.89	-218.573	1552528.8	84745.67	-218.418	-10.078
29158.678	3.193	1552530.7	84743.022	-220.595	1552529.3	84745.82	-221.222	-8,203
29160.618	3.2	1552532.8	84743.165	-220.401	1552531.7	84746.115	-220.997	-8.253
29162.354	3.192	1552534.2	84744.166	-220.36	1552533.5	84747.245	-220.777	-8.302
29162.176	4.203	1552534.6	84743.022	-222.618	1552533.7	84746.448	-224.899	-5,966
29160.458	4,192	1552532.9	84742.461	-222.562	1552531.6	84745.807	-224.743	-6,088
29158.659	4.203	1552531.3	84741.585	-222.729	1552529.8	84744.772	-224.967	-5.872

Table 7.1. Map and tunnel coordinates for the two-dimensional bolt map shown in Figure 7.7.



10	Number of bolts		
11	Length (m)	Quantity	Colour
12	2.5 - 3.5	42	🟧
13	3.5 - 4.5	46	🟩

Table 7.2. The length of the different bolts indicated by colour codes /29/

Looking at the bolt log in 3D, e.g. in a 3D PDF, can be a very useful way of orientating oneself in relation to how the bolt holes are drilled in the tunnel. Figure 7.8 shows a bolt map in 2D, where three red rings marking the same bolt holes are shown in 3D in Figure 7.9 in the same area of the same tunnel. The bolt holes themselves are colour-coded based on a Measurement-While-Drilling (MWD) interpretation.

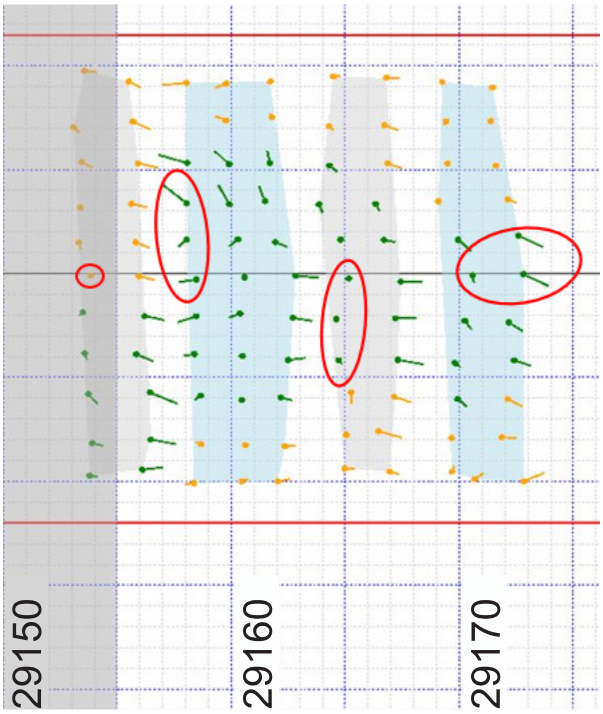


Figure 7.8. 2D bolt map, here marked with red rings around bolts shown in Figure 7.9. in 3D. /29/.

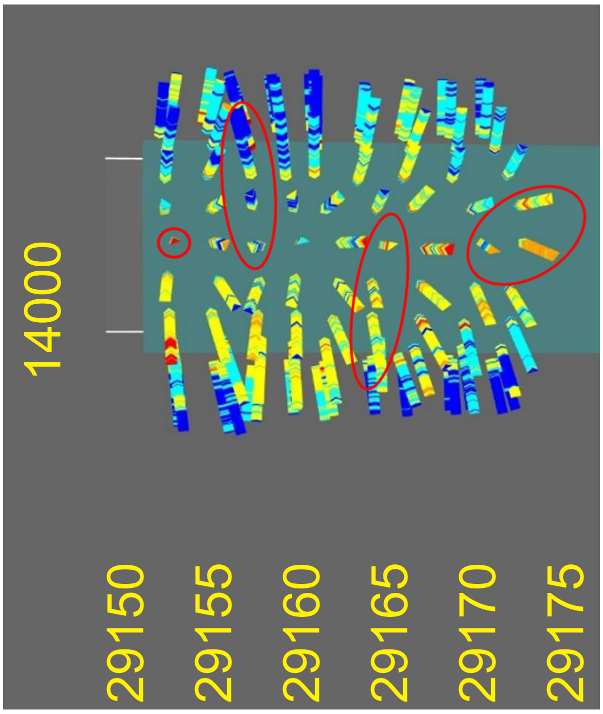


Figure 7.9. 3D visualisation of drilling log. Red rings mark the same bolts as in Figure 7.8. /29/

Bolt hole maps can also show the direction of bolt holes and reveal any deviations from the requirement for bolts not to exceed a 20^0 deviation from the normal on the theoretical contour (see Figure 5.5). Figure 7.10 shows an area where the bolt holes have been poorly drilled in relation to the 20^0 deviation requirement, but has an area where they are almost radial on the theoretical contour.

There may be a number of reasons why a bolt hole shows that it exceeds 20^0 normally on the theoretical blasting profile. The main reason is what the actual blasted profile looks like, and it is then important to determine whether there are protruding rocks and overbreak in the profile. In Norwegian tunnels, efforts are made to maintain a mean overbreak of 0.35 m. If a bolt hole is then drilled in order to insert a bolt in an area with protruding rocks or overbreak, the collaring point and bottom will not end up being radial to the theoretical blasting profile, even though it may be radial to the actual blasting profile. There are several ways of checking and visualising this. Figure 7.11 shows a flat map from profiles, while Figure 7.12 shows a transverse profile, which makes the bolt holes from the theoretical contour clearly apparent. Here, you quickly gain an overview of what the roof and walls look like. It is possible to add bolt holes so that it becomes clear where the bolt has been inserted.

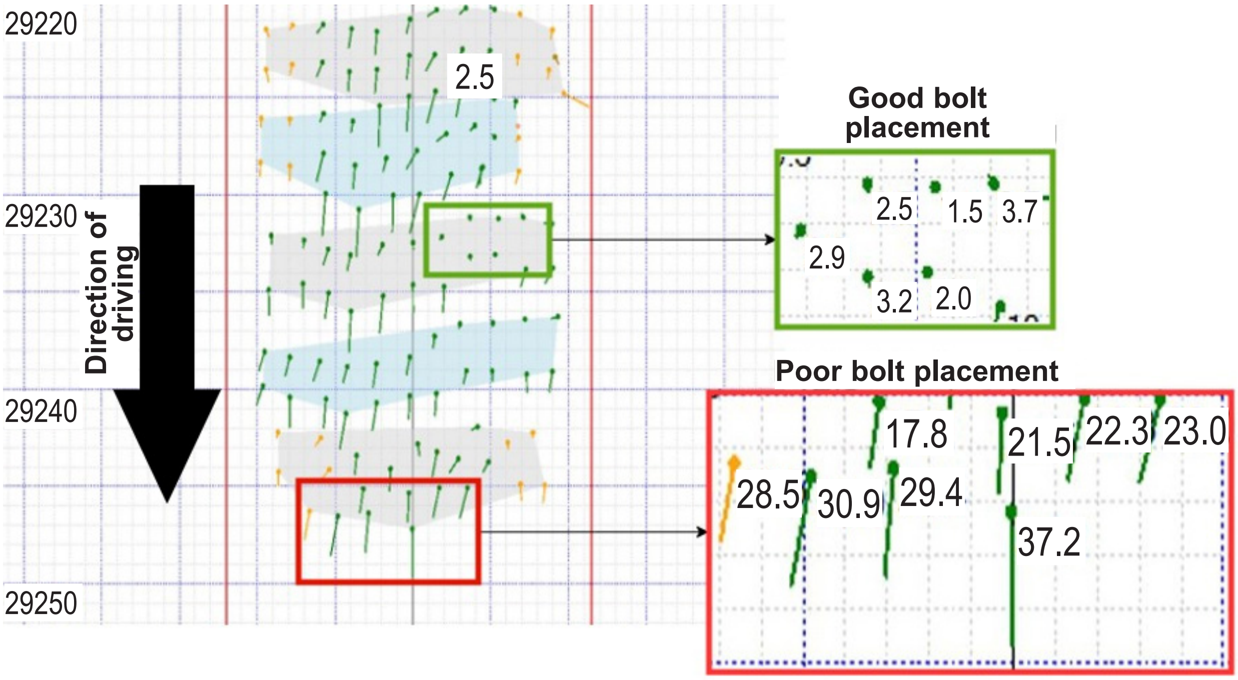


Figure 7.10. Bolt map with degrees deviation from radially inserted bolts, compared with the theoretical contour /29/

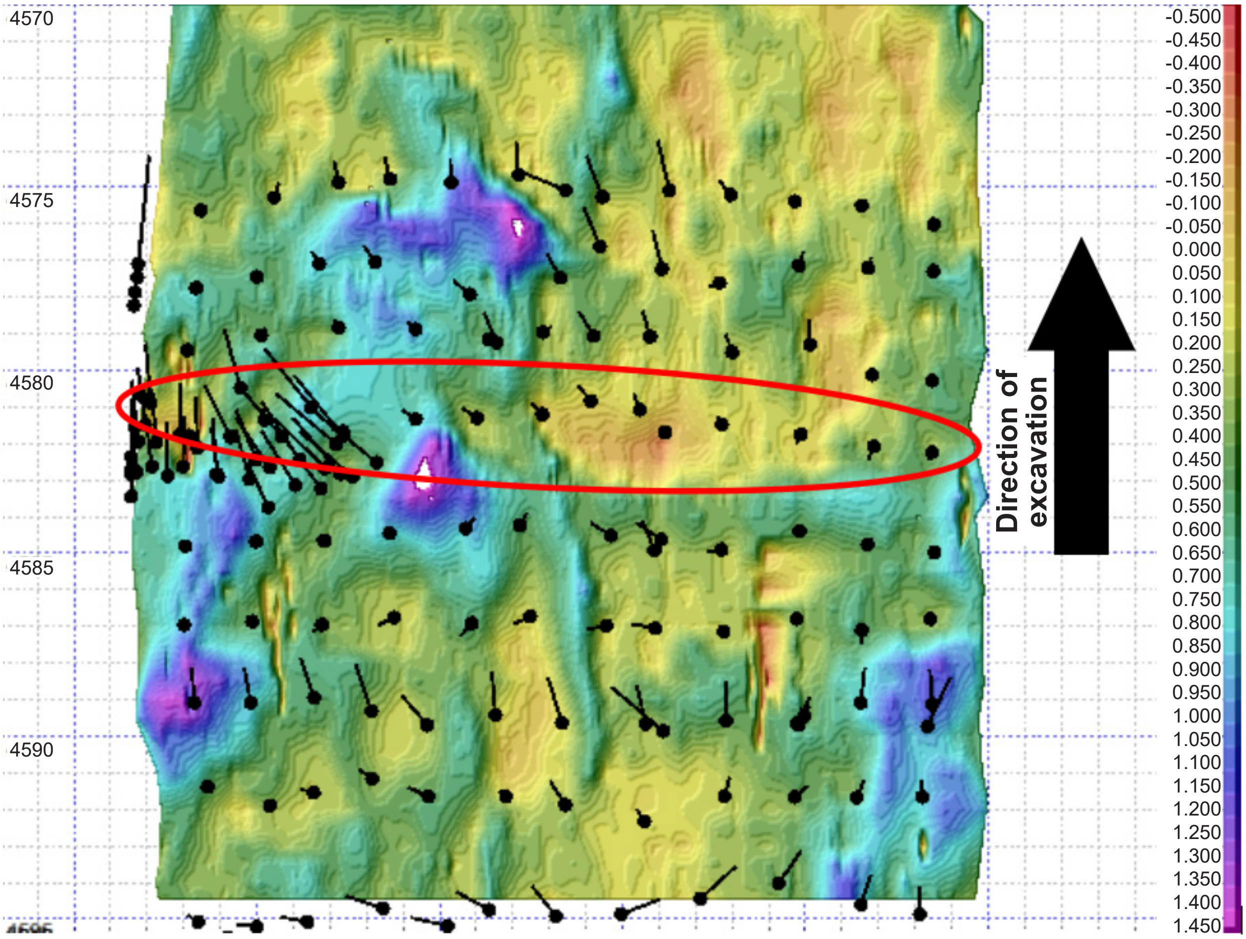


Figure 7.11. The flat map shows deviations from the theoretical blasting profile. Red indicates the theoretical blasting contour, blue-violet is bedrock above the theoretical blasting profile (cavities), while holes in tunnel will lie within the theoretical blasting contour (protruding rock). The red circle indicates the transverse profile shown in Figure 7.12. /29/

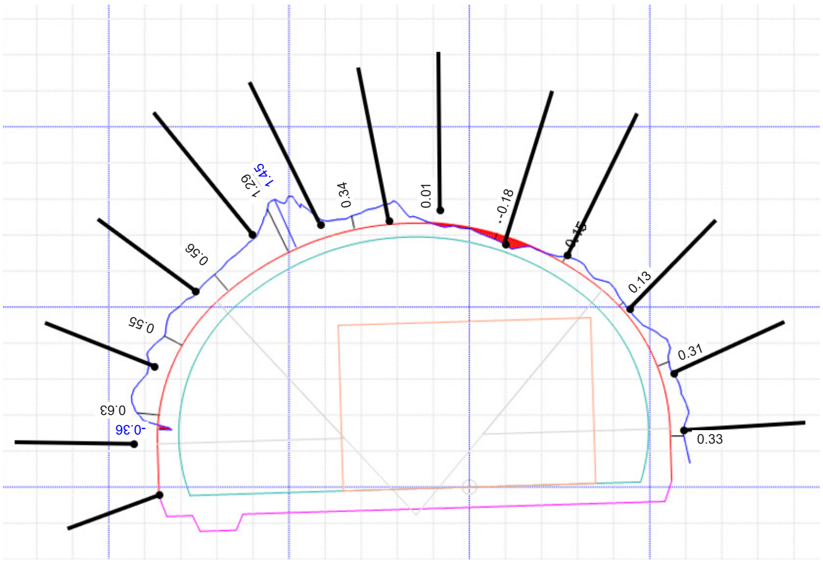


**Figure 7.12.
Theoretical blasting contour (green) versus actual blasting contour (red). The protruding rock is shown in red /29/.**

7.2.3 Recording using a camera

Photographs can be taken using an ordinary handheld camera, or a special camera designed to be fitted to drilling and spraying rigs; see Figure 7.13. The advantage of using a fixed camera is that it is possible to fix the angle of the images, so that they are the same every time, and tunnel equipment is fitted with working lights which provide good lighting conditions for photography.

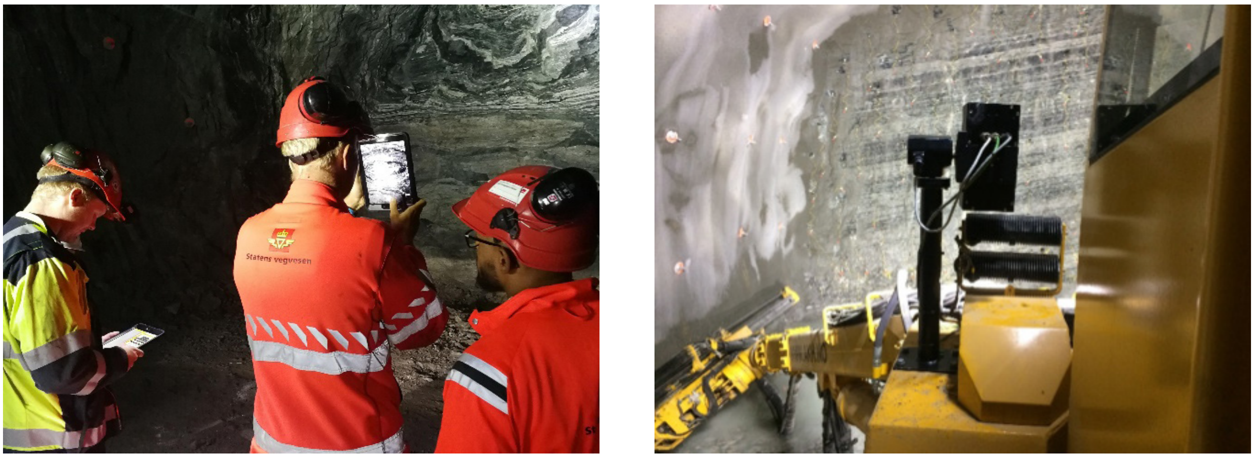


Figure 7.13. It can be documented using a handheld camera, in this case a tablet (left) or a fixed camera on a drilling or spraying rig (right).

Figure 7.14 presents a series of images showing a roof before and after bolt installation. In the series of images in the "before" row, red spray-paint indicates where the bolts are to be installed. The "after" row shows bolts inserted on the red paint marks. These photographs provide a quick overview of what is to be inserted and whether all the bolts have been inserted. You can also check protruding rocks and overbreak, along with the position of the bolt in the actual blasted tunnel profile.

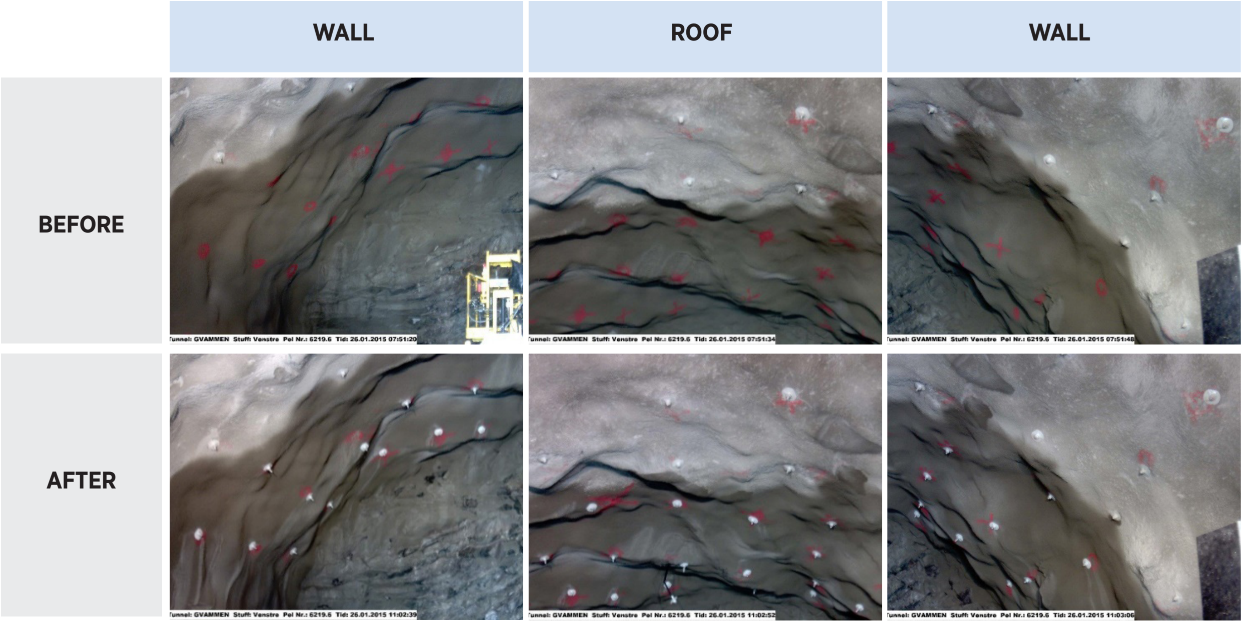


Figure 7.14. The top row shows bolt position markings in red on fresh sprayed concrete. The bottom row shows the same area with the bolts in position. In this case, paint has been sprayed for each blast round. At the front of the photograph is a previous blast, while the newly inserted bolts are from the last blast round. The photograph is taken from pile number: 6219.6, Gvammen – Århus, 2015.

Figure 7.15 shows how to combine a fixed camera which provides high-resolution images with scans from profiles which provide the bolt coordinates and data from MWD. The image shows the actual contour and bolt holes.

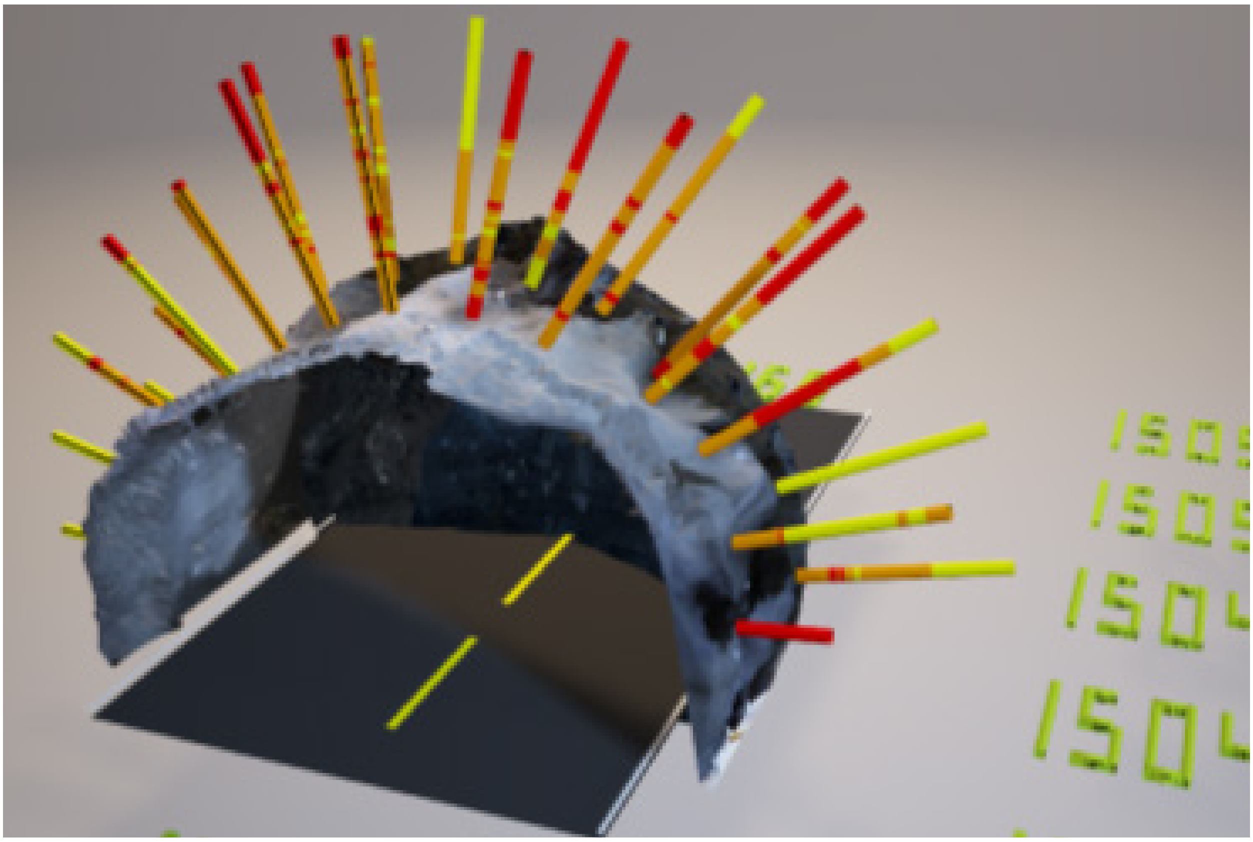
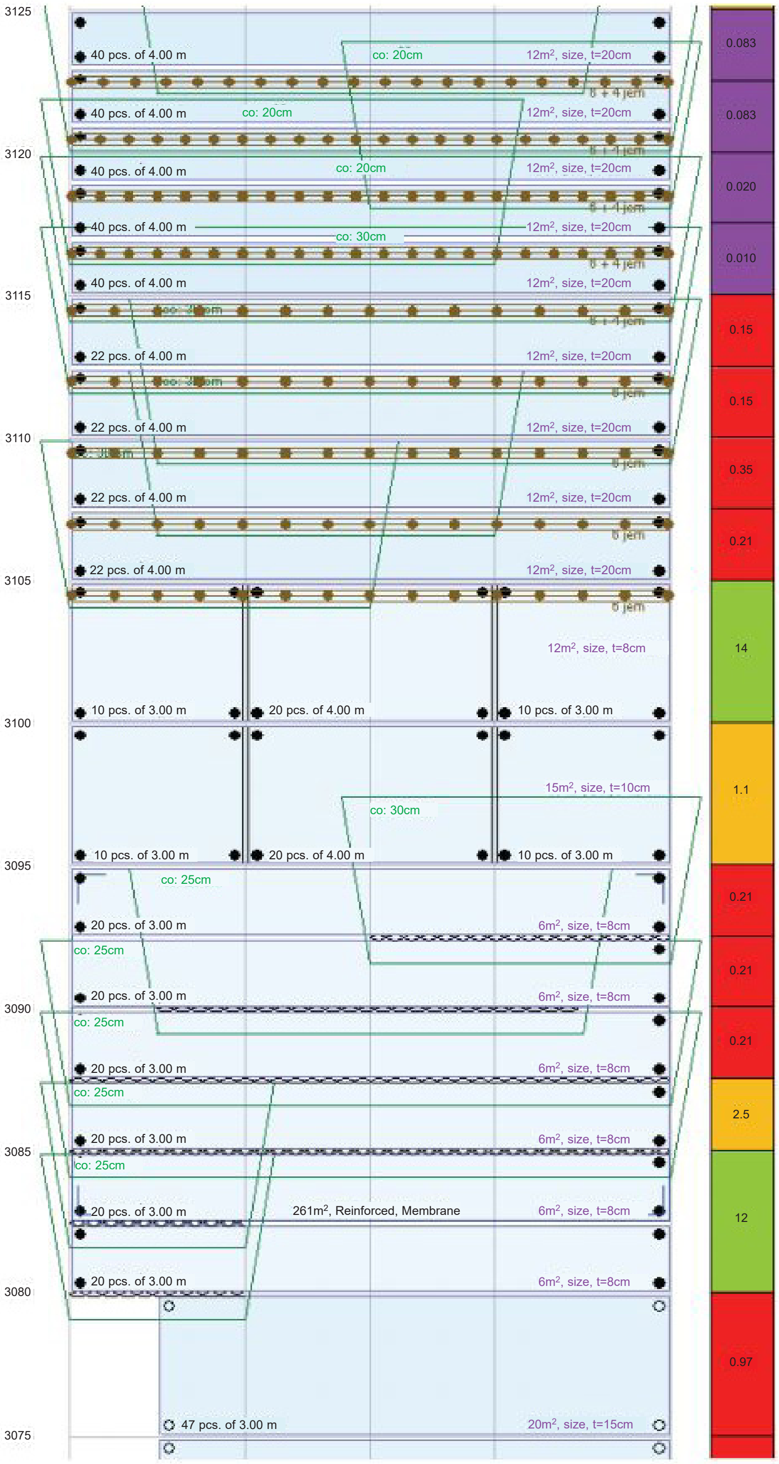


Figure 7.15. High-resolution images collected by a fixed camera on a drilling rig. The images of the tunnel were created based on a profile scan. Bolt holes from MWD were then added.

7.3 Final documentation

It is recommended that stabilisation bolts be recorded with quantity, type, length, position and direction. Where measures to ensure stability during work are included in permanent stabilisation measures, all bolts must be documented. It is recommended that final documentation be submitted with collated data from the entire project. There are various ways of collecting data for documentation of rock stabilisation. The most commonly used software and companies in Norway are NovaPoint Tunnel, Rockma, Bever Control AS and Gemini.



Tunnel driving with 2.5 and 2 m blast rounds. Stabilisation with spiling and arches on the tunnel face, along with sprayed concrete and bolts.

The description on some of the spiling bolts has been moved to make them more visible.

Stabilisation using combination bolt 3 m in wall and 4 m in roof, along with sprayed concrete.

The description for sprayed concrete has been moved so that it does obscure the description of the bolts.

Tunnel driving with 2.5-metre blast rounds. Stabilisation using spiling with the suspension of bands and bolts. Reinforced waterproof casting behind the tunnel face due to wide zone with swelling clay.

Stabilisation using end-anchored bolt due to rock spalling

Figure 7.16. An example of what a complete set of bolt documentation might look like /27/.

NovaPoint Tunnel

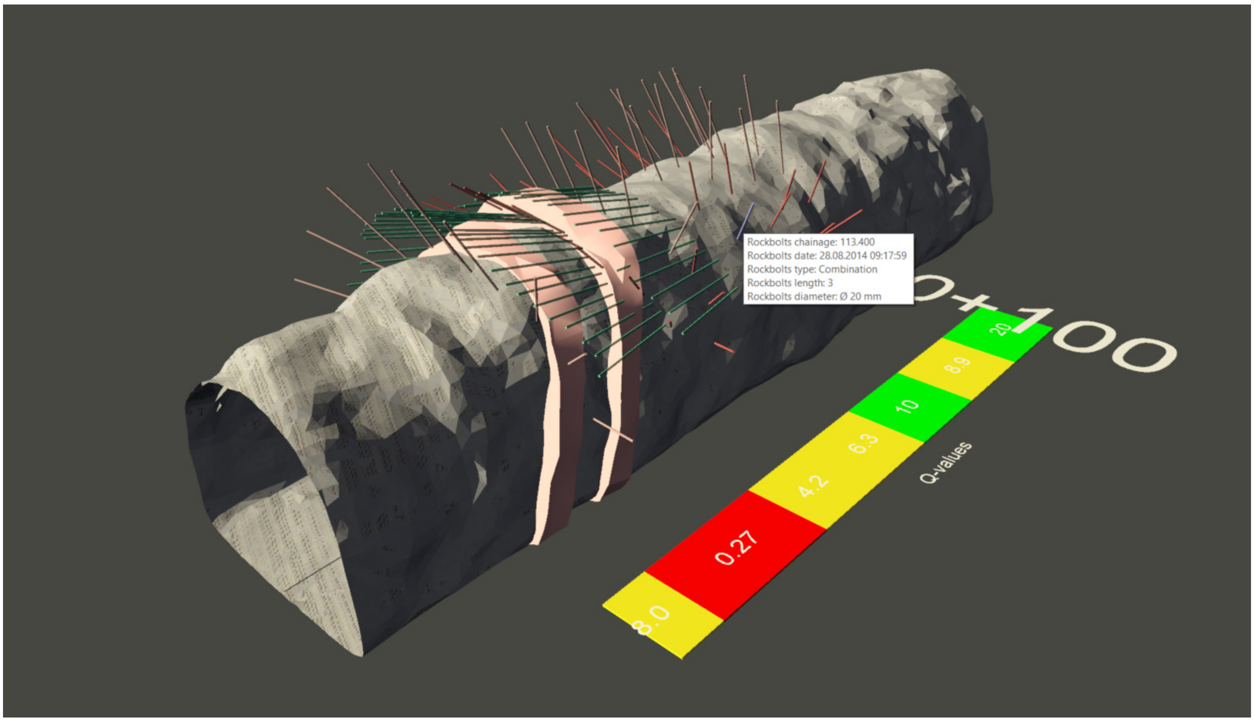
NovaPoint Tunnel is a software product designed for detailed tunnel modelling and is used to record and report geological conditions and rock stabilisation. Figure 7.16 shows how the bolts are presented in NovaPoint Tunnel. Figure 7.16 shows documented rock stabilisation in the report. Bolts at the tunnel face are shown as black borders with a circle at each corner. If the circle is open, the bolt is end-anchored. If it is solid, the bolt is an embedded/combination bolt, while crosses indicate other types of bolt. Spiling is indicated by green trapezoids. The height/length of the trapezoid corresponds to the bolt length that is inserted. Sprayed concrete is indicated by blue borders shown with a pale blue filling. The fill colour indicates the thickness, with 8 cm as the palest and 40 cm as the darkest. Lattice girders are the brown lines which are connected on each side, while the brown circles indicate the number of bolts. Bands are indicated by a link in black. They are inserted as start and end points. NovaPoint presents the bolts as a quantity, rather than a precise position.

Model-based documentation:

Today, all the major construction clients require model-based methods to be used for the planning, design and construction of future projects. This is increasingly being stipulated as a requirement, along with a requirement for "as-built" documentation to be model-based. This indicates a transition from drawing-based deliveries to drawing-less model-based projects, where the coordination model is pivotal. This is creating new opportunities in terms of the planning, execution and documentation of bolting. Advantages of model-based bolting documentation include:

- Bolt quantities can be calculated directly from the model, and revised in accordance with current conditions
- The actual placement of the bolts can be readily visualised, and it is possible to make assessments of the execution and quality of bolting.
- Bolting can be seen in conjunction with other stabilisation measures, tunnel geometry or geological conditions
- It provides relatively accurate final documentation, which can be useful in connection with the refurbishment of existing facilities nearby or the planning of new facilities.

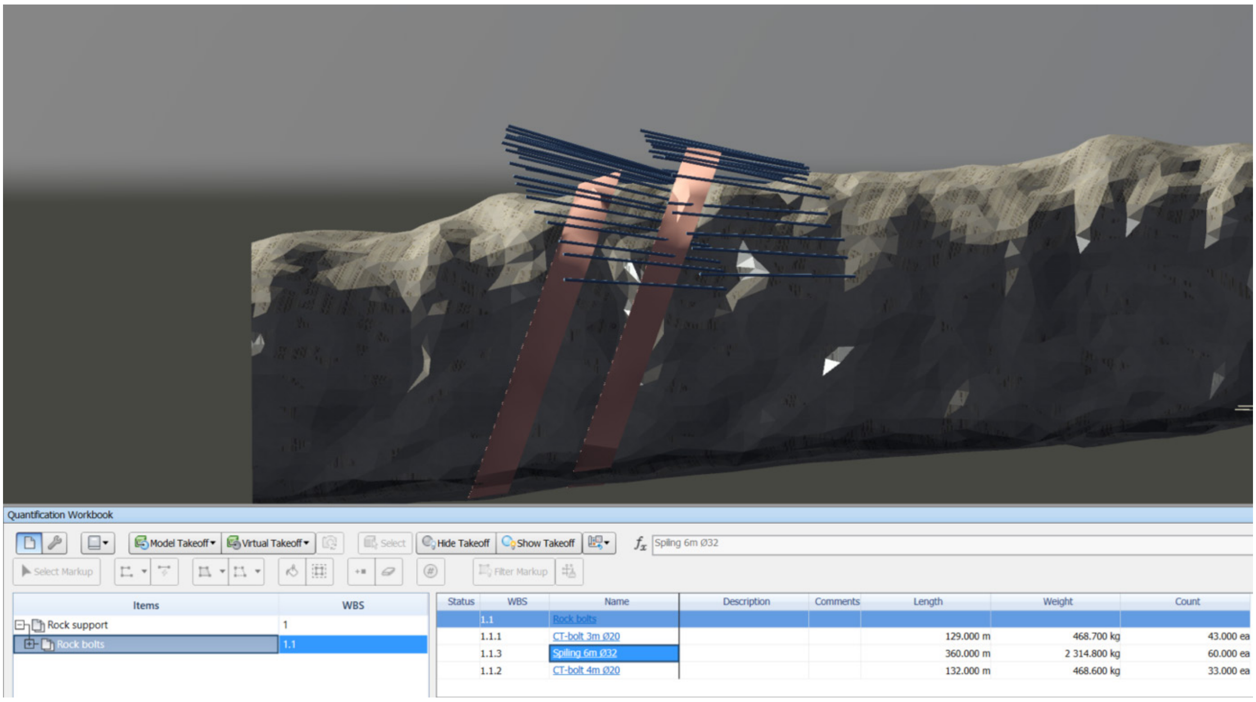
Large amounts of data are currently being collected from facilities across Norway. Much of this data provides a good basis for the automatic creation of a bolting model. The example below shows a bolting model, where the bolt geometry is automatically generated based on MWD data, and compared against profile scanning and Q mapping in a combined model (see Figure 7.17). It is possible to see how data can be linked to the bolt geometry. In addition to making each individual bolt searchable, this opens up possibilities as regards quantity calculations and ID tagging and, in the long term, it will be possible to include the properties of bolts for use in operation and management. The model below was generated in Autocad Civil 3D.



Rockbolts chainage: 113.400
Rockbolts date: 28.08.2014 09:17:59
Rockbolts type: Combination
Rockbolts length: 3
Rockbolts diameter: Ø 20 mm

Figure 7.17. Modelling of bolts based on MWD data. The model is georeferenced and can readily be compared with other data (Retrieved from Bane NOR, 2018).

Figure 7.18 shows how a model can be used for quantity calculations. You quickly get an overview of the bolts that have been inserted. Having a common model of a facility means that there is always an overview of the status at any given time. Experience from the Follo Line indicates that, if good updating procedures are established at an early stage, most of the data will already be in place, so keeping a model up-to-date will present no greater challenges than the current, widely used Novapoint solution. It will also be beneficial to include the MWD model so that it is loaded into the same model and can help to provide a more complete picture.



Spiling 6m Ø32

Items	WBS
Rock support	1
Rock bolts	1.1

Status	WBS	Name	Description	Comments	Length	Weight	Count
	1.1	Rock bolts					
	1.1.1	CT-bolt 3m Ø20			129.000 m	468.700 kg	43.000 ea
	1.1.3	Spiling 6m Ø32			360.000 m	2 314.800 kg	60.000 ea
	1.1.2	CT-bolt 4m Ø20			132.000 m	468.600 kg	33.000 ea

Figure 7.18. Example of a quantity calculation in a model. The figure shows the number of spiling bolts inserted upon passing a weakness zone. In turn, this can, for example, be linked to the process code for further use in connection with final settlement (Retrieved from Bane NOR, 2018).

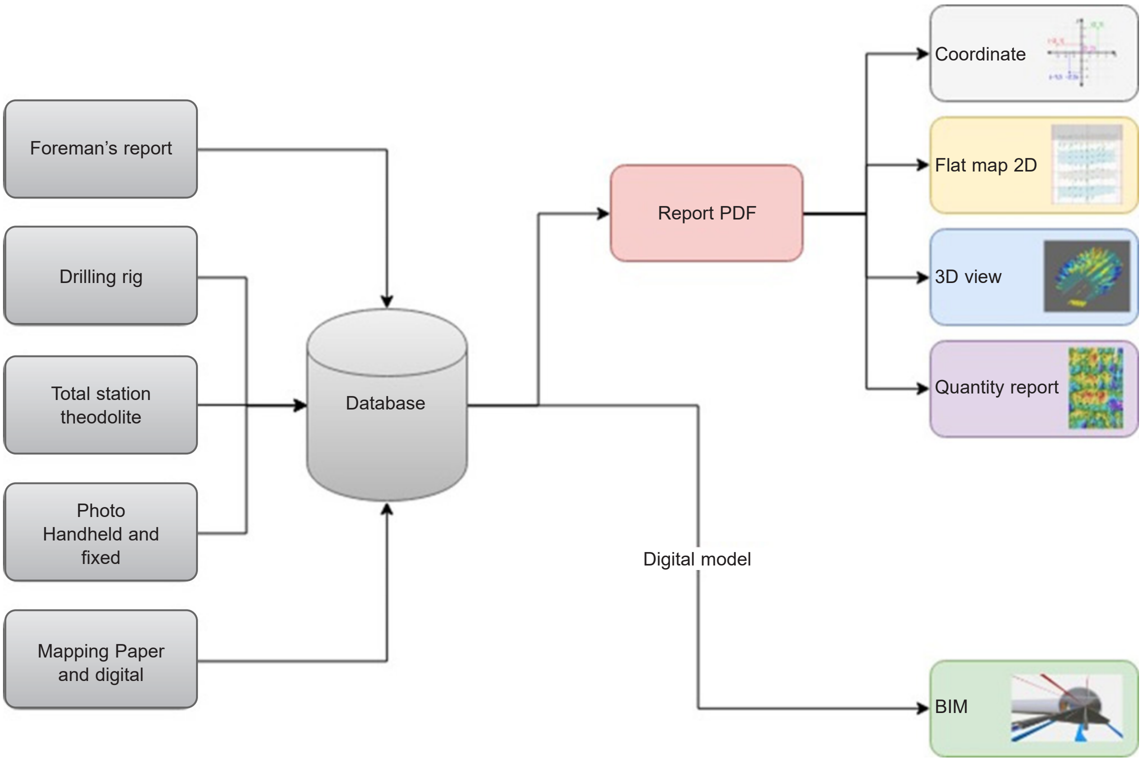


Figure 7.19. A flow chart showing sources which are entered in a database and can then be reported in PDF format using different display formats and/or entered in a digital model.

7.4 Measurement-While-Drilling (MWD) data as a by-product of bolt drilling

Most tunnel boring rigs used in transportation projects today must be fitted with equipment for MWD logging. This means that data concerning rock quality can also be obtained via bolt holes, and can be used to determine whether inserted bolts are sufficiently long to pass through recorded weakness zones. It will also be possible to assess whether the bolt can be secured to good quality rock for end-anchoring. This information can be used to assess whether the stabilisation measures that have been carried out are sufficient. An example of MWD interpretation in a bolt hole is shown in Figure 7.20. A blue vein can clearly be seen intersecting the tunnel. This can create difficult end-anchoring conditions and must be taken into account.

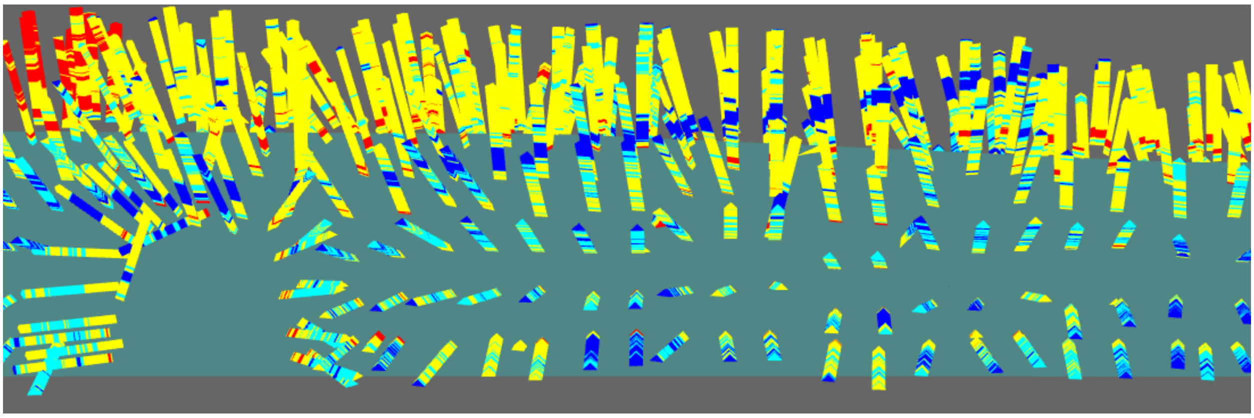


Figure 7.20. The red colour in the MWD interpretation indicates weak rock (poor), while the blue colour indicates hard rock, and the yellow indicates the normal value (the host rock). It is possible to see that there is some variation in the anchoring of the bolts. Soknedalstunnelen/Trøndelag 2018 /29/.

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