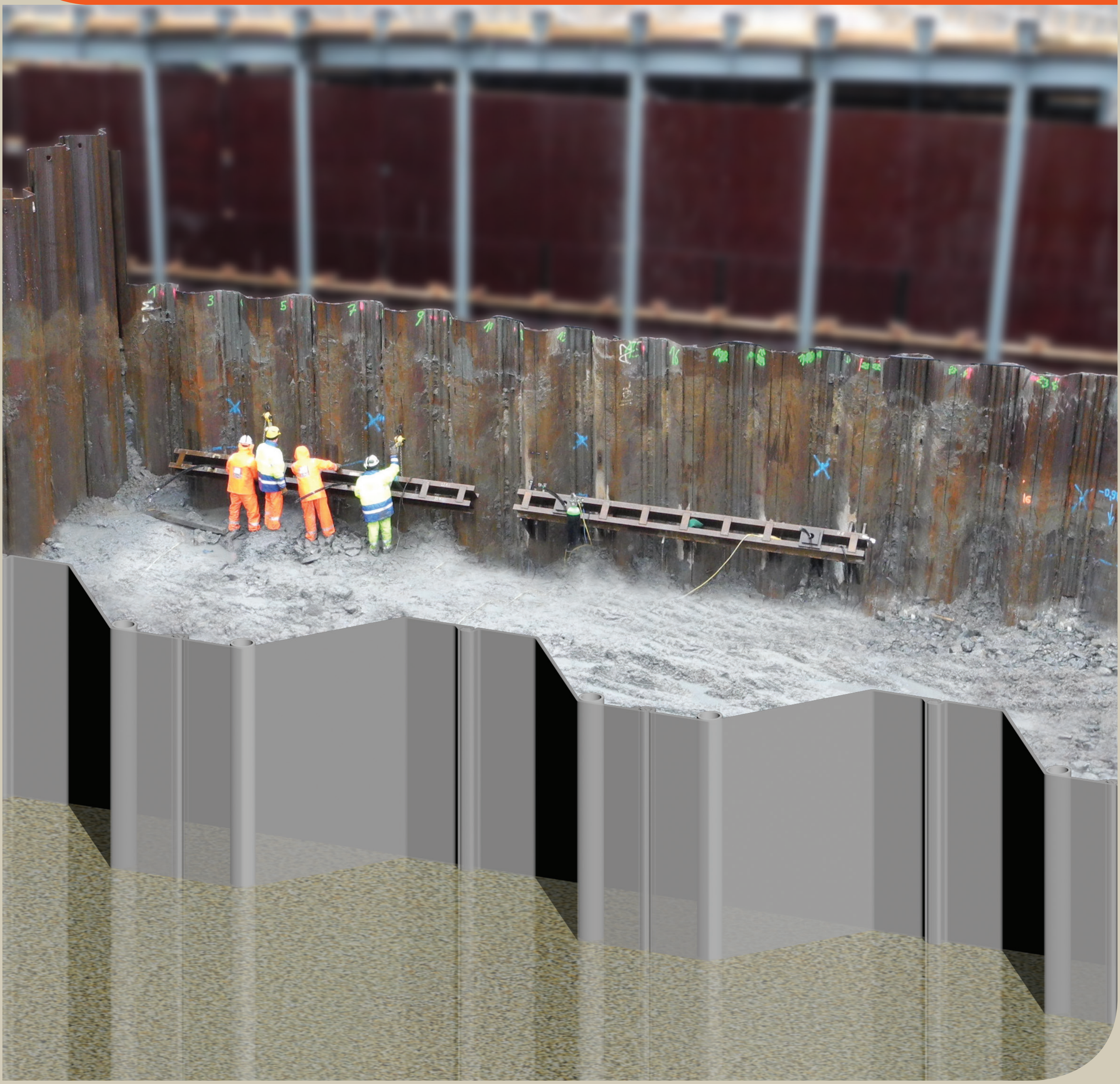
ArcelorMittal Sheet Piling

ArcelorMittal

Rock Bolts

Horizontal toe support for steel sheet piles on bedrock



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1. Introduction

Steel sheet piles retaining walls need to be embedded a minimum depth in the ground in order to generate sufficient passive earth resistance at the bottom of the wall.

However, in Nordic countries the soil consists quite often of soft clay deposits overlying bedrock, and similar ground conditions exist in other countries. Although it is possible to install sheet piles into the bedrock with installation aids such as drilling or blasting of a small trench in the upper layer of the bedrock, it is easier and faster to apply less destructive installation methods.

For excavations in such soft soils with limited thicknesses of soft soil layers above the bedrock, or where the excavation level lies below the bedrock level, it is common practice in Nordic countries to support the toe of the sheet piles with additional rock bolts (dowels).

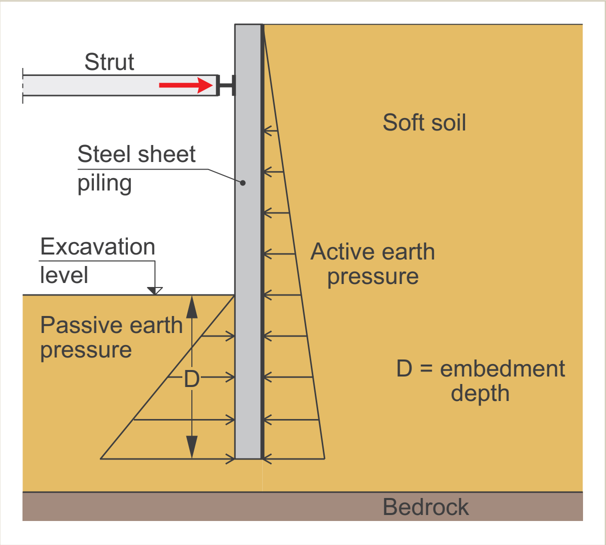


Fig. 1. Typical cross section of a sheet pile wall

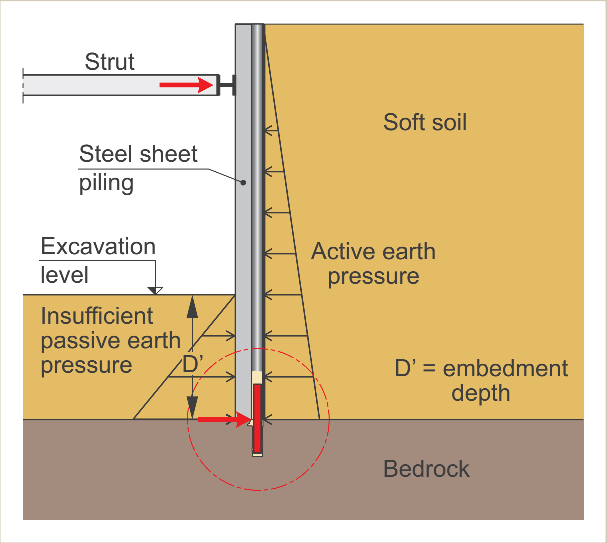


Fig. 2. Sheet pile wall with additional support at toe level (rock bolt)

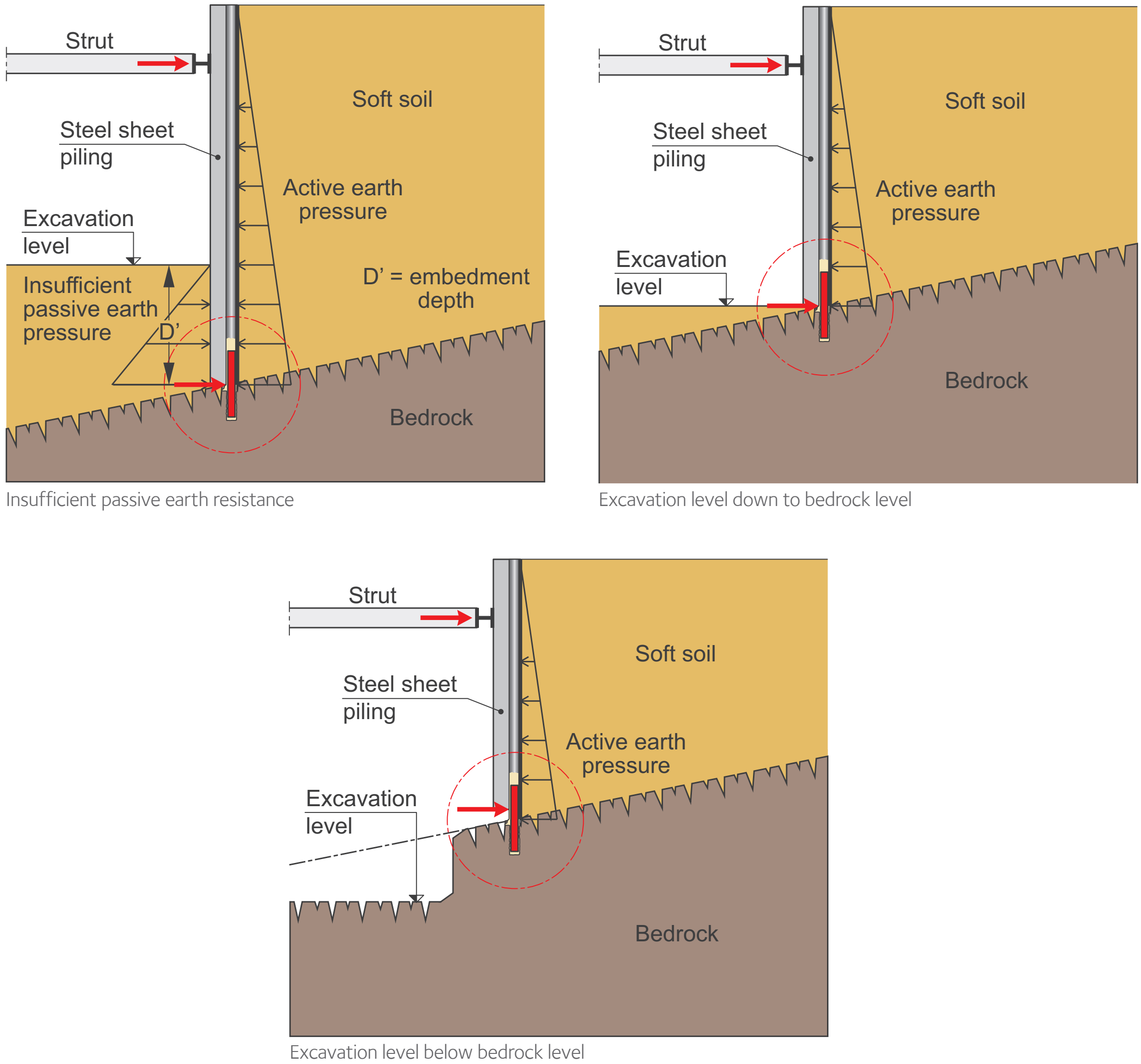


Fig. 3. Sheet pile wall with rock bolts: design cases

The dowels are installed through steel casings and secured into the bedrock before excavation progresses. The casings are welded to the sheet piles prior to driving.

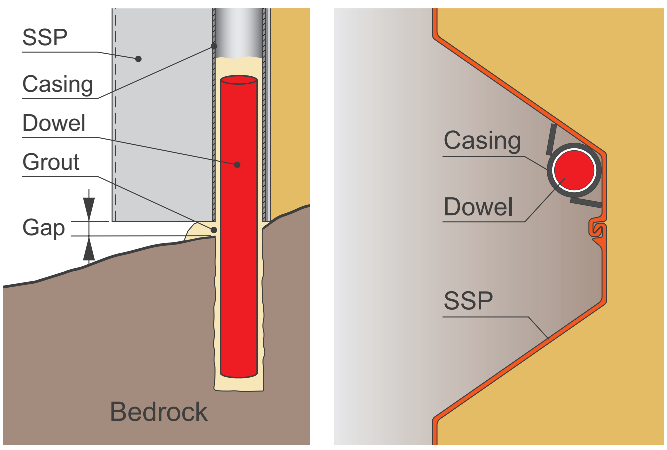


Fig. 4. Sketches of a typical rock bolt system

Pict. 1. Rock bolt on an AZ sheet pile

The main topics of this brochure are the design of rock bolts, the description of practical aspects and of some examples of sheet pile walls supported by rock bolts.

2. General design and installation considerations

The design and installation of rock bolts must be based on a comprehensive geotechnical investigation with detailed information on the location and inclination of the bedrock, both longitudinally and perpendicularly along the future axis of the wall. Borelogs must be drilled along the wall axis.

2.1. Job site investigation and monitoring

Due to the significant influence of the gap between the bedrock and the toe of the sheet piling on the design of the rock bolt solution, it is of major importance to collect reliable data about the bedrock horizon, especially if this horizon is quite irregular with large and / or fluctuating slopes. The estimated bedrock horizon is also required to order the minimum length of each sheet pile.

The distance between boreholes should not exceed 5 m along the sheet pile wall axis, and should be complemented with boreholes to determine the bedrock inclination perpendicular to the wall axis. Some of the boreholes should penetrate at least 3 m into the bedrock, to rule out the possibility of misinterpreting large boulders as bedrock, and to collect sufficient information on the quality of the bedrock.

In most cases, the sheet piles should be chamfered to fit the actual inclination of the bedrock (see Figure 5), so as to minimize the gap between sheet piles and bedrock.

It is also recommended to drive the sheet piles down to the bedrock. If the bedrock surface is jointed or altered, the sheet piles should be chiseled into the bedrock. In any case, a project specific refusal criteria should be defined to prevent excessive damage of the tip of the piles.

Driving logs are mandatory for each sheet pile and should be precise enough to model the level of the toe at the first impact with bedrock, with centimeter accuracy preferably, and after chiseling whenever relevant.

The logs allow determining the slope of the bedrock horizon and hence, they are used to confirm the best position of the rock bolt in order to minimise the gap. However, if the slope of the bedrock horizon changes unexpectedly, then the position of the rock bolts may have to be adapted consequently.

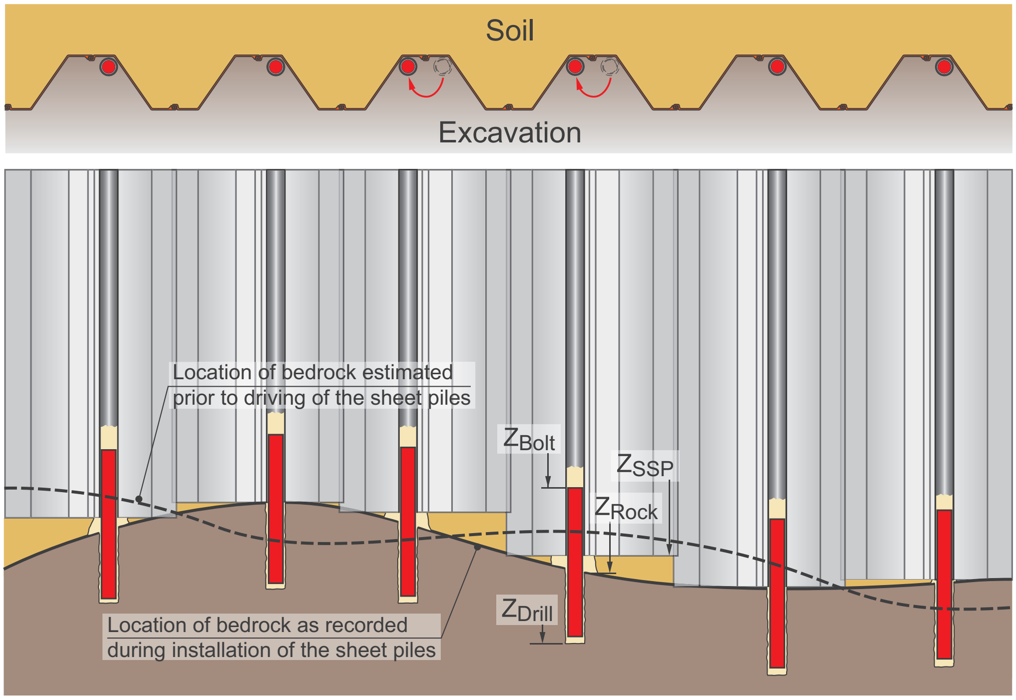


Fig. 5. Optimization of the sheet pile layout based on the bedrock horizon

2.2. Applicability of rock bolts in bedrock

In Norway, rock bolts have been used with success since the 1990's, in rock with different strength conditions. Typical rock strength (uni-axial compressive strength) varies from 50-100 MPa (e.g. shales and phyllites) and up to around 300 MPa (e.g. granite and basalt).

As the uni-axial compressive strength of the rock is seldom tested during the project execution, the bedrock quality is often estimated based on the drilling rate (seconds per meter) when drilling into the bedrock. At drilling rates above 100 – 200 seconds per meter, somewhat dependent of the hammer drill, the rock quality is normally acceptable.

Jointing and fissuring, together with the inclination of the bedrock, can influence significantly the resistance capacity of the rock bolts. Use of rock bolts therefore should be based on previous experience with similar bedrock characteristics.

If the uni-axial compressive strength of the bedrock is below the values mentioned above, acceptable toe support can often be established by driving the sheet piles deep enough down into the bedrock.

3. Design

3.1. General requirements for the design

The overall calculation of the action effects on the retaining wall shall be carried out with a hinged model at the level of the toe support and shall take into account axial forces from battered anchors or from vertical loads.

The following design verifications use the partial safety concept according to the European EUROCODES.

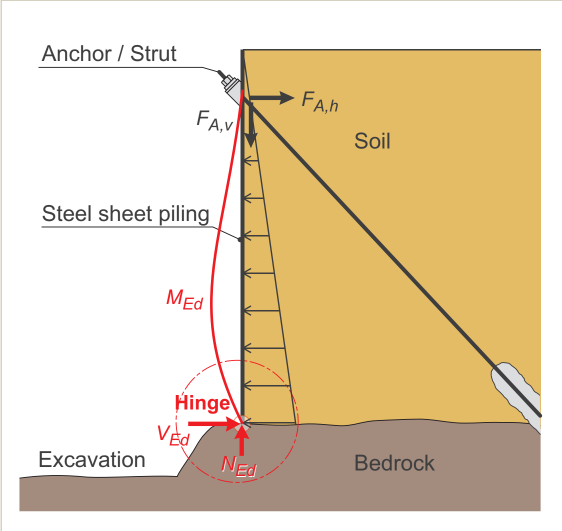


Fig. 6. Rock bolt: design assumptions

3.2. Bolt position and bolt lengths

At least one rock bolt per double AZ sheet pile shall be foreseen. To get more flexibility in case of unpredictable bedrock slopes, a suitable prevention plan would consider a spare casing on each double sheet pile.

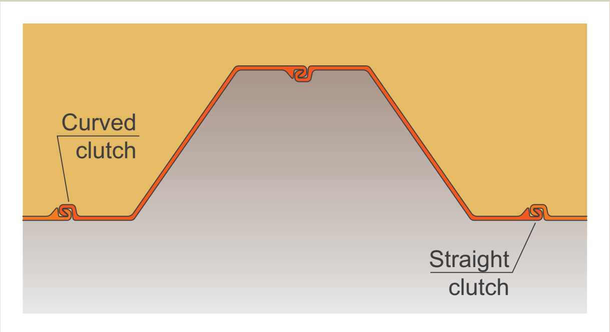
The fixation length (see Figure 8) of the rock bolt in the casing should be at least $L_{F,S} \geq 1.0$ m[1].

The fixation length of the rock bolt in the bedrock should be at least $L_{F,R} \geq 1.0$ m.

Hence, the total length of the rock bolt should be at least $L_{Bolt} \geq 2.0$ m and take into account the predicted gap Δ.

The bolts are always installed on the excavation side.

The preferred solution is a double AZ pile driven with the rock bolts fixed to the flange with the curved clutch (case 1a, see Figure 13).



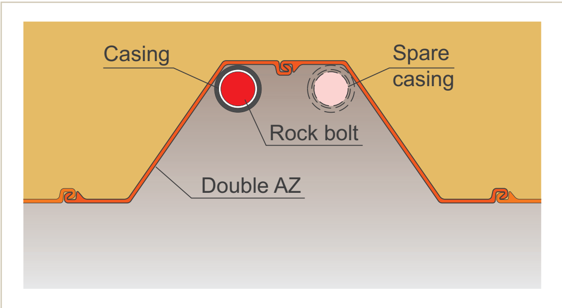


Fig.7. Rock bolt: spare casing in case of unfavourable soil conditions

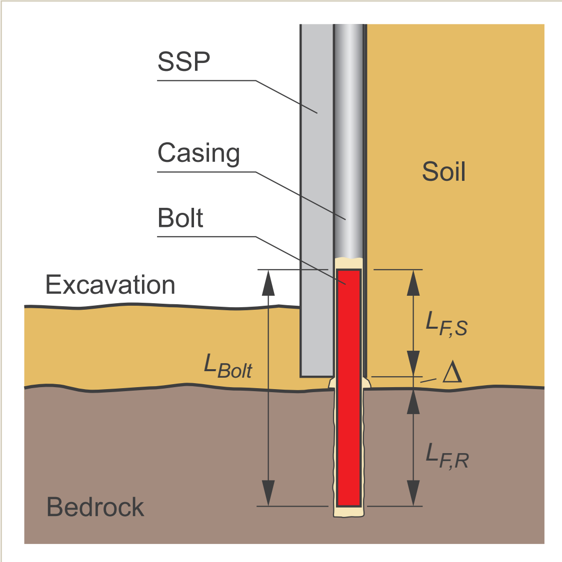


Fig. 8. Rock bolts: definition of the parameters & variables

[1] Smaller fixation lengths $L_{F,S}$ have been analysed in a research project, but since they lead to less cost-effective solutions, ArcelorMittal recommends to use at least 1.0 m

If for practical reasons the rock bolt must be fixed to the flange with the straight clutch, for instance because of critical bedrock inclination, or because of the orientation of the sheet piles, or for other aspects, then following design rules shall be considered

- case 1b: full resistance of the rock bolt provided the central interlock next to the bolt is welded
- case 2: reduced resistance if the welding of the interlock next to the rock bolt is not wished or not cost-effective

In case where the excavation level is below the bedrock level, then the excavation border line should be located at a minimum distance of $X_{Hor} \geq 1.0$ m from the rock bolt axis.

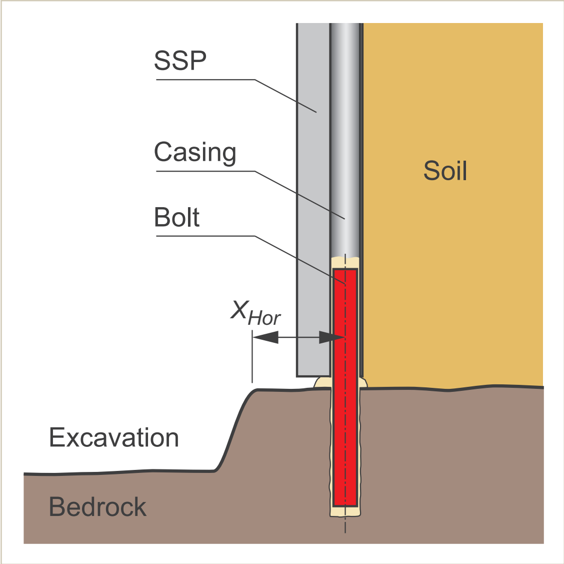


Fig. 9. Minimum distance from the excavation border

3.3. General verification of the sheet pile

The general verification of the sheet piling wall is carried out in line with relevant European standards (for instance EN 1993-5:2007) accounting for the overall action effects

- bending moment resistance $M_{Ed} \leq M_{c,Rd}$
- shear and load introduction at the location of upper anchor or strut
- moment, shear force and axial force interaction
- axial force resistance $N_{Ed} \leq N_{pl,Rd}$
- buckling resistance (if relevant)

Note: the sheet piles should be driven to full contact with the bedrock in case they are submitted to substantial axial forces, so that the axial forces are transmitted from the sheet piles directly to the underlying bedrock.

Additionally, the resistance of the toe support is calculated with following formula

$$V_{Ed} \leq V_{Rd,Toe}$$

$V_{Rd,Toe}$ is the minimum value of two resistances

- rock bolt $V_{Rd,Bolt}$
- local load introduction in the sheet piling $V_{Rd,SSP}$

with

- V_{Ed} design support reaction per double AZ sheet pile
- $V_{Rd,Toe}$ design resistance of the toe support
- $V_{Rd,Bolt}$ design rock bolt capacity per rock bolt
- $V_{Rd,SSP}$ design shear capacity per double AZ pile

So that

$$V_{Rd,Toe} = \min\,(V_{Rd,Bolt}, V_{Rd,SSP})$$

The same design verifications are also applicable if the sheet piles are driven as single piles with one rock bolt on every second pile only.

3.4. Verification of design capacity of the toe support

The rock bolt capacity is given by

$$V_{Rd,Bolt} = r_{Rd,Bolt} \cdot \frac{V_{Pl,Bolt}}{\gamma_{M2}}$$

with $$r_{Rd,Bolt} = \frac{1}{\sqrt{1+1.85 \cdot \left(\frac{\Delta}{D}\right)^2}}$$

and $$V_{Pl,Bolt} = \frac{\pi \cdot D^2}{4} \cdot \frac{f_{y,Bolt}}{\sqrt{3}}$$

where

- $r_{Rd,Bolt}$ dimensionless factor to account for gap Δ
- Δ gap distance between sheet pile toe and bedrock
- D rock bolt diameter
- $V_{Pl,Bolt}$ plastic shear resistance of bolt
- $f_{y,Bolt}$ yield strength of rock bolt

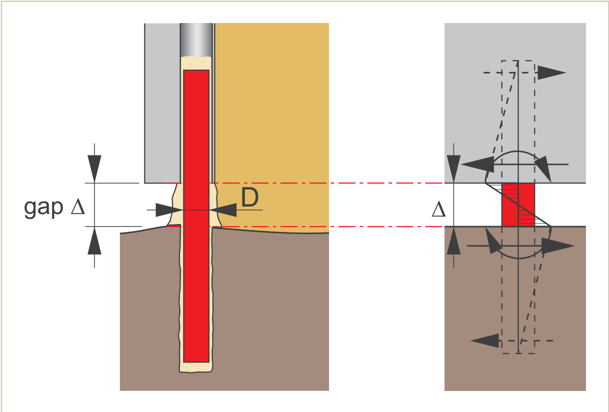


Fig. 10. Rock bolts: effective gap

The Eurocode suggests to use $\gamma_{M2} = 1.25$ as a partial safety factor, but this value may vary by country!

Note that the given capacity takes into account the M/V interaction in the bolt.

Considering the effect of the gap on the rock bolt capacity, a cautious evaluation of the gap Δ should be made based on accurate depth monitoring during job site investigation and during installation time: gap between the sheet pile toe and the bedrock level in relation to the position of the rock bolt and the slope of the bedrock.

The coefficient $r_{Rd,\,Bolt}$ can be calculated or obtained from Table 1 or Figure 11.

$\frac{\Delta}{D}$	$r_{Rd,\,Bolt}$
0.0	1.000
0.1	0.991
0.2	0.965
0.5	0.827
1.0	0.592
1.5	0.440
2.0	0.345
2.5	0.282
3.0	0.238
3.5	0.206
4.0	0.181
4.5	0.161
5.0	0.145

Table 1. Coefficient $r_{Rd,\,Bolt}$ function of the ratio (gap / diameter of bolt)

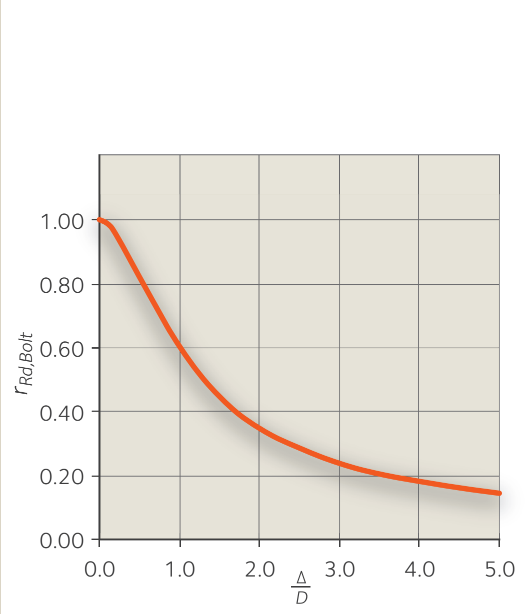


Fig. 11. Coefficient $r_{Rd,\,Bolt}$ function of the ratio (gap / diameter of bolt)

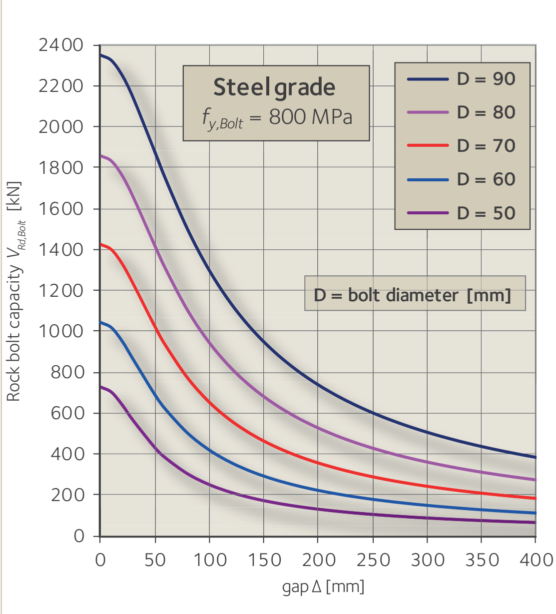


Fig. 12. Rock bolt capacity $V_{Rd,\,Bolt}$ function of the gap for $f_{y,\,Bolt} = 800$ MPa and $\gamma_{M2} = 1.25$

3.5. Typical bolt diameters and steel grades

As a reminder, rock bolts must be installed one meter into bedrock and one meter along the sheet pile. The common length of rock bolts is therefore at least two meters.

Typical bolt diameters vary between Ø 50 and Ø 90 mm. Contractors tend to prefer small diameters bolts with high steel grades (42CrMo4 is most common), which reduces the weight of the rock bolts, and consequently simplifies its handling which is normally done by hand.

Typical steel grades are listed in Table 2. These standards are the most commonly used in Norway, however, other steel grades may be utilised. The differences in quality of the bolts defined in different standards should normally be of little importance for this specific type of application.

Steel grade	Yield strength [MPa][2)]	European standards		
		Grades	Tolerances	Certificates
S 355 J2+AR	315 - 335	EN 10025	EN 10060	EN 10204
42 CrMo4	650	EN 10083	EN 10060	EN 10204
34 CrNiMo6	800	EN 10083	EN 10060	EN 10204

Table 2. Typical European steel grades for rock bolts

[2)] Yield strength depends on the diameter of the bolt. Shown values are valid for diameters 50 – 90 mm

3.6. Relevant cases for the verification of the sheet pile section

Depending on the orientation of the sheet piles, following situations can occur.

The chosen configuration may have a significant influence on the design resistance of the AZ section against the local load introduction from the rock bolt.

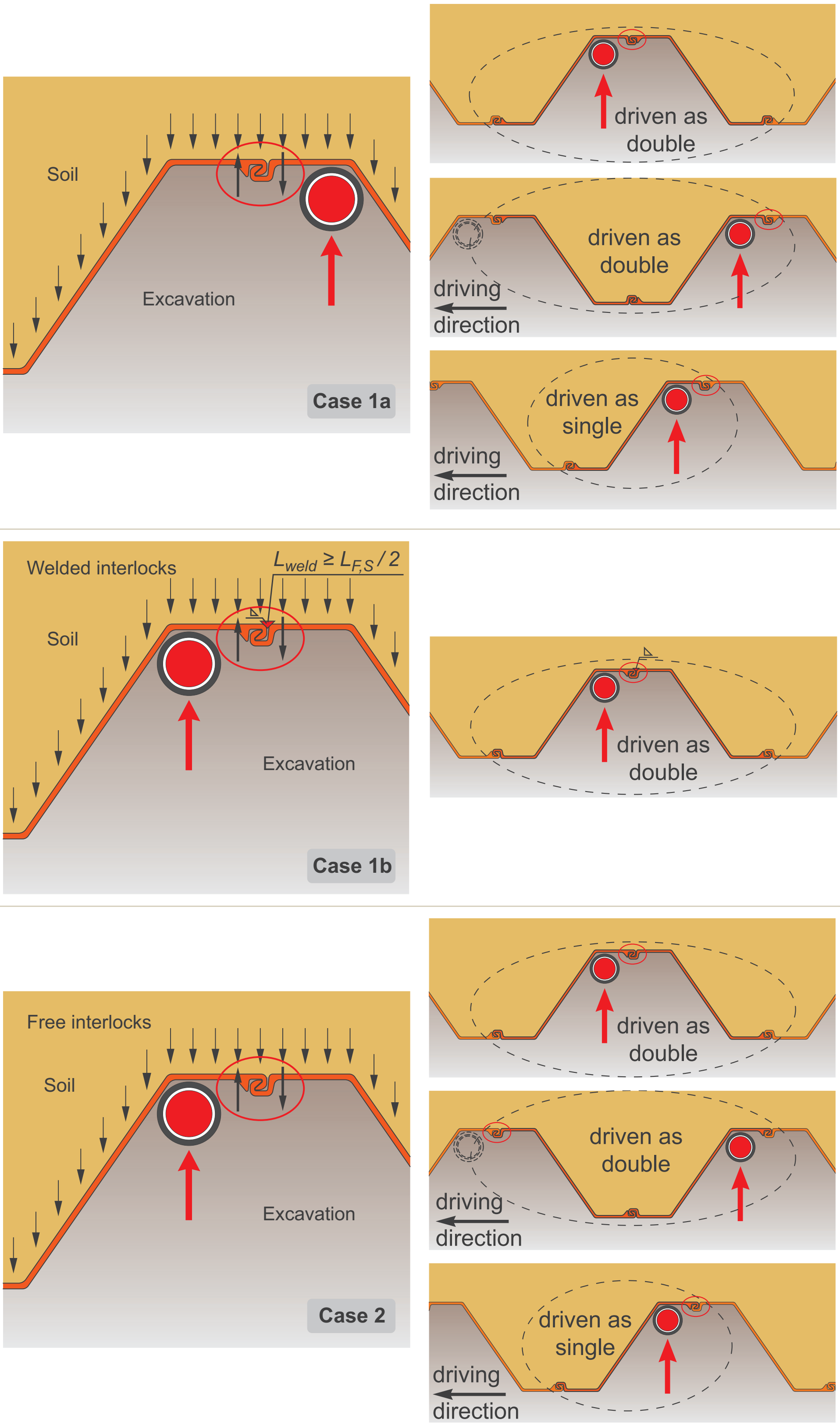


Fig. 13. Position of the rock bolts: possible cases

3.7. Verification of the design capacity of the steel sheet pile section

The design shear capacity of the sheet pile wall is the resistance of an AZ sheet pile against local load introduction via rock bolts, and is given per double AZ pile by

$$V_{Rd,\,SSP} = V_{Rk,\,SSP} \cdot \frac{1}{\gamma_{M0}}$$

with

$V_{Rk,\,SSP}$	characteristic resistance of the AZ-section (per double pile)
γ_{M0}	partial safety factor according to Eurocodes

Note that $V_{Rk,\,SSP}$ is the minimum value of the resistance of the

- web (shear and tension)
- flange (shear and plate bending)
- interlock

The values $V_{Rk,\,SSP}$ have been determined within the framework of a research program (see chapter 7) for two design cases

- case 1:
  - case 1a: rock bolt fixed to the flange with the curved interlock
  - case 1b: rock bolt fixed to the flange with the straight interlock combined with welding of the central interlock next to the rock bolt. In this case, the welding must resist a shear force of $V_{Rd,\,weld} \geq 0.5 \cdot V_{Ed,\,Toe}$ and must have a length of $L_{weld} \geq 0.5 \cdot L_{F,S}$
- case 2: rock bolt fixed to the flange with the straight interlock without welding of the adjacent interlock

3.8. Characteristic resistances of AZ sheet pile sections

Table 3 lists the characteristic resistances $V_{Rk,\,SSP,\,355}$ (kN per pair of pile) for a steel grade S 355 GP, with a fixation length of $L_{F,S} \geq 1.00$ m and for rock bolts with a maximum diameter of 125 mm.

For other steel grades, the characteristic resistance can be calculated with following formula

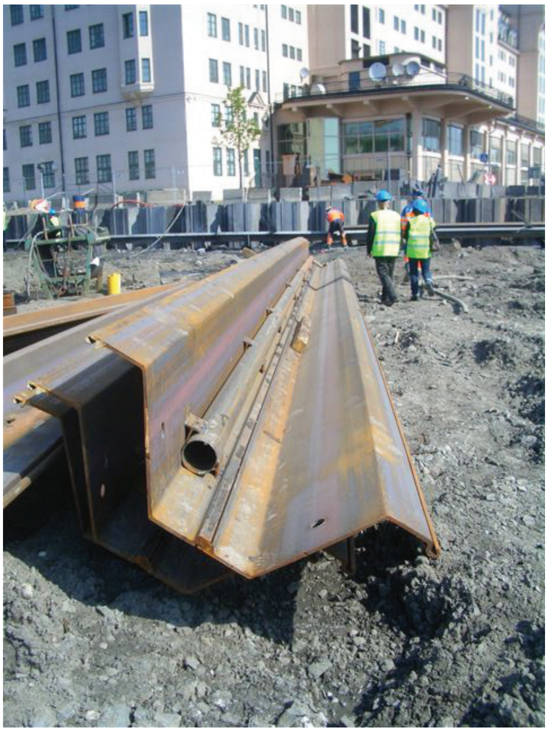
$$V_{Rk,\,SSP} = V_{Rk,\,SSP,\,355} \cdot \frac{f_{y,\,SSP}}{355}$$

with

$V_{Rk,\,SSP,\,355}$	characteristic resistance of the steel sheet pile for yield strength $f_{y,\,SSP} = 355$ MPa
$f_{y,\,SSP}$	yield strength of the steel sheet pile (in MPa)

Note that in case 2 the maximum yield strength that can be considered for the design is 355 MPa.

Please contact ArcelorMittal's engineering department for larger diameters or smaller fixation lengths[3].



[3] The value of $V_{Rk,\,SSP}$ in case 1 is generally slightly higher for diameters below 125 mm

Section	$V_{Rk, SSP, 355}$ [kN]		Section	$V_{Rk, SSP, 355}$ [kN]	
	Case 1	Case 2		Case 1	Case 2
AZ 18-800	595	590	AZ 24-700	1 020	760
AZ 20-800	740	590	AZ 26-700	1 120	760
AZ 22-800	900	590	AZ 28-700	1 210	760
AZ 23-800	855	770	AZ 36-700N	1 110	820
AZ 25-800	950	770	AZ 38-700N	1 210	820
AZ 27-800	1 045	770	AZ 40-700N	1 310	820
AZ 28-750	1 020	795	AZ 42-700N	1 380	820
AZ 30-750	1 120	795	AZ 44-700N	1 480	820
AZ 32-750	1 220	795	AZ 46-700N	1 575	820
AZ 12-770	585	510	AZ 48-700	1 480	820
AZ 13-770	620	510	AZ 50-700	1 575	820
AZ 14-770	655	510	AZ 52-700	1 675	820
AZ 14-770-10/10	685	510	AZ 17[1)]	600	585
AZ 12-700	530	530	AZ 18	720	585
AZ 13-700	595	530	AZ 18-10/10	760	585
AZ 13-700-10/10	625	530	AZ 19[1)]	795	585
AZ 14-700	655	530	AZ 25[1)]	950	770
AZ 17-700	635	570	AZ 26	1 035	770
AZ 18-700	715	570	AZ 28[1)]	1 120	770
AZ 19-700	795	570	AZ 46	1 330	830
AZ 20-700	885	570	AZ 48	1 425	830
			AZ 50	1 520	830

[1)] Section available only upon request

Table 3. $V_{Rk, SSP, 355}$ for AZ sections in S 355 GP, $L_{F,S} \geq 1.0$ m, diameter of bolts ≤ 125 mm

4. Recommendations for the installation

Detailed information and recommendations for the different installation steps and procedures are given in the following sections.

The crucial steps to execute properly the horizontal toe support with rock bolts are

- job site investigation. Accurate determination of the bedrock horizon and slopes
- welding of a casing section to the steel sheet piles prior to the driving
- driving of the steel sheet pile to the depth of the bedrock level. At least part of the sheet pile should be driven to full contact with the bedrock
- drilling into the bedrock using a rock auger through the casing, followed by removal of the soil. Exact depth monitoring is recommended
- depth measurements and installation / removal of a temporary dummy bolt
- grouting of the bottom of the drilled hole. Good quality of the grouting and a sufficient volume to enclose the complete rock bolt after its installation shall be guaranteed
- impact driving of the rock dowels before hardening. Driving may be done with an additional steel bar of the same diameter
- excavation in front of the wall after hardening of the grout

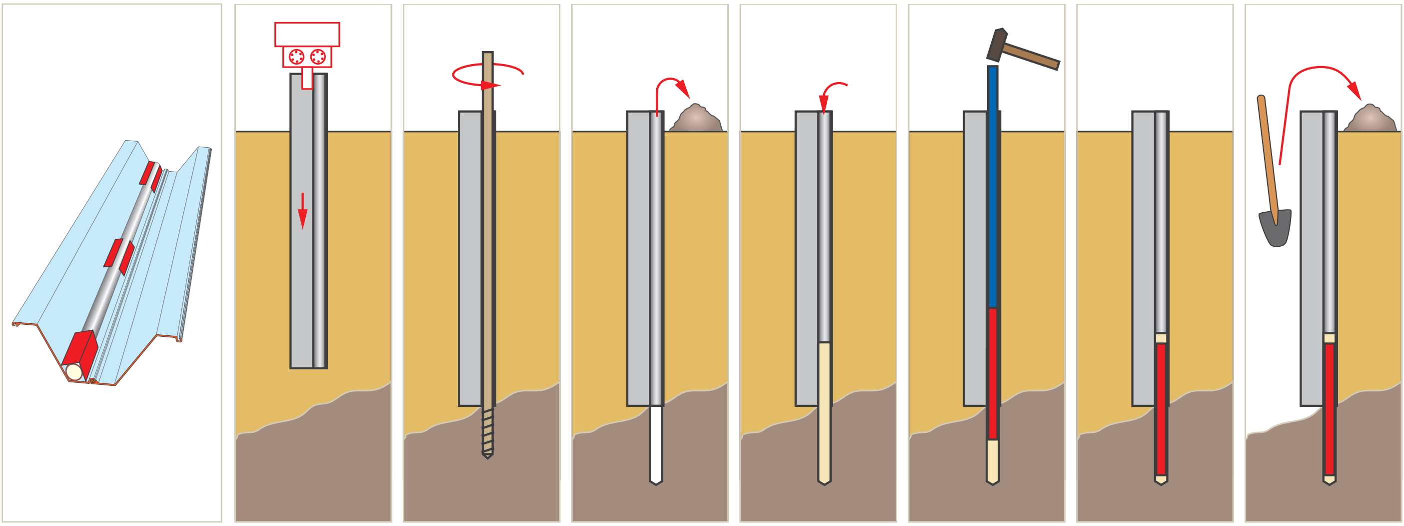


Fig. 14. Execution phases of a rock bolt solution

4.1. Welding details

The most common way is to install the rock bolts through casings welded to the sheet piles. The sheet piles are fabricated prior to the driving as shown in the sketches in Figure 15.

ArcelorMittal recommends these constructional detailing, but alternative solutions may be used.

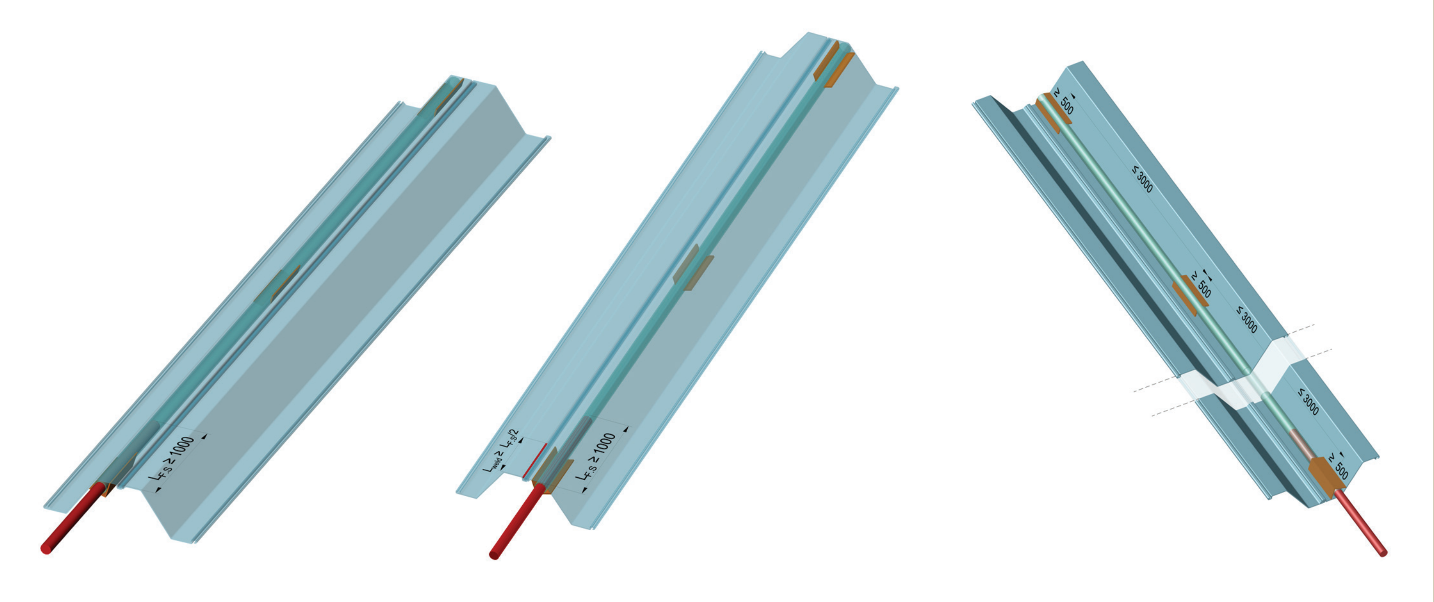


Fig. 15. Recommended fixation of the casings to the sheet pile

To prevent damage, as well as to avoid filling of the casing with soil during driving, the bottom of the casing may be plugged with concrete. This is normally done by welding a short steel tube filled with concrete to the end of the casing (see Figure 16).

The bottom of the casing (concrete plug) should be fixed a few centimeters above the tip of the sheet pile to prevent damage of the casing when the sheet pile reaches bedrock.

Additional protection of the tip of the casing might be contemplated when driving the sheet piles through hard layers, for instance gravel or moraine (see following pictures: welding of stiffeners,...).

The casing / rock bolt should always be fixed at the inner pan of the back flange (i.e. in front, visible from the excavation side, see Figure 17), and preferably in the corner closest to where the sheet pile first hits the bedrock. It shall be ensured that the gap between the bottom of the sheet pile and the bedrock is small, to allow transmitting most of the horizontal support reaction by the means of contact pressures.

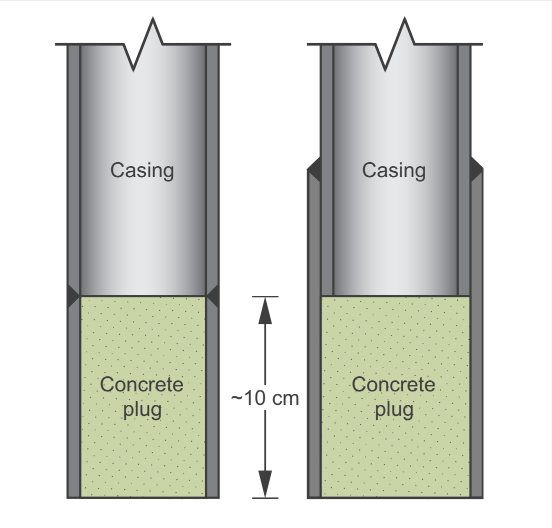


Fig. 16. Plug at the bottom of the casing (steel tube filled with concrete)

Pict. 2. Details of casings

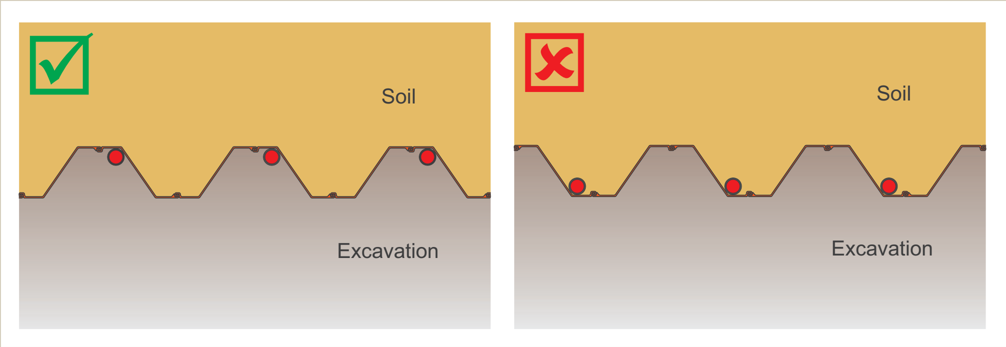
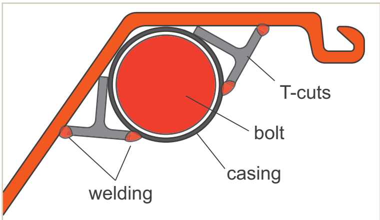


Fig. 17. Correct placement of the casings

A sensible precaution, especially when dealing with a very irregular inclination of the bedrock surface, is to install spare casings on the sheet piles. Thus (additional) rock bolts can be installed in the casings with the smallest gap if necessary.

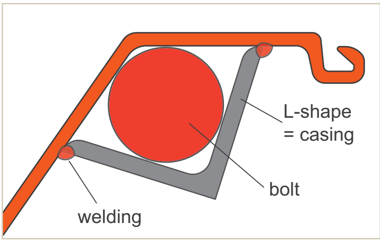
However, if large gaps occur on several adjacent casings then more complex measures must be worked out to ensure a correct toe support.

4.2. Fixation of casings with stiffeners

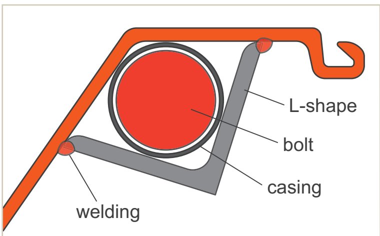


Fastening of casing tube to AZ pile

Proposed T-section	Casing tube diameter [mm]	Bolt diameter [mm]
T 30x30x4.0	70	50
T 45x45x5.5	100	70
T 60x60x7.0	125	90



Continuous L-casing



Protection of casing toe

Sheet pile section	L shapes						
	L80x80x8	L100x100x10	L120x120x12	L140x140x14	L160x160x16	L180x180x18	L200x200x20
AZ 20-800	54	68	82	97	111	126	140
AZ 25-800	54	69	83	98	112	127	141
AZ 30-750	56	71	86	101	117	132	147
AZ 13-770	49	62	75	89	-	-	-
AZ 13-700	50	64	77	91	104	-	-
AZ 18-700	53	68	82	96	-	-	-
AZ 26-700	55	70	84	99	114	-	-
AZ 38-700N	58	73	89	104	120	135	151
AZ 44-700N	58	73	89	104	120	135	151
AZ 50-700	58	73	89	104	120	135	151
AZ 18	55	70	84	99	-	-	-
AZ 26	56	71	86	101	116	-	-
AZ 48	61	77	94	110	126	142	-

Notes

- Table 4 displays only the main sheet pile section of a range. Use the same diameters for the rolled-up and rolled-down derivatives
- L-shapes with other sizes can also be used

Table 4. Maximum bolt or casing diameter (mm) for the AZ sheet pile range (includes tolerances)

4.3. Vertical load transfer

In case of battered anchors or vertical loads on the top of the wall, the vertical loads need to be transferred by the sheet pile wall to the underlying bedrock. To transfer these axial loads from the sheet piles directly to the bedrock it is advisable to drive the sheet piles down to the bedrock.

This can be achieved for instance by chiseling the sheet piles into the bedrock. On the other hand, chiseling of steel sheet piles into the bedrock may damage the sheet pile tip or the casing, which would complicate the subsequent drilling and installation of the rock bolt. Like for any special application, special care must be taken during driving, and for extremely difficult situations, the contractor should resort to an experienced driving crew.

4.4. Drilling of the rock bolt holes

The drill diameter of the hole in the bedrock must be at least 3 mm larger than the diameter of the rock bolt.

4.5. Monitoring of depths

As mentioned above, the effective gap is crucial to the capacity of the rock bolts. The gap must therefore be monitored as accurately as possible.

Hence it is important to determine accurately the distance from the top of the concrete plug to the bottom of the sheet pile (noted (B+C) in Figure 18). The gap Δ can then be calculated as the drilled length from the top of the concrete plug to the impact level of the bedrock, minus the length (B+C).

Experience shows that it is difficult to record the effective gap with an accuracy below ± 3 cm. This implies for instance that a recorded gap of 7 cm lies somewhere between 4 and 10 cm.

After driving and drilling, the recorded toe levels of the sheet piles and top of bedrock should be drawn up in a detailed longitudinal profile (scale = 1:20) and compared to anticipated bedrock levels obtained prior to driving. The purpose is to determine the gaps between the toe of the sheet piles and bedrock. The information must then be compared to the assumptions made for the design of the bolts. If based on the records, the verification demonstrates that the bolts do not have sufficient capacity, additional supporting measures must be taken, preferably before excavation.

Note that the grout should ideally form a cake at the bottom of the sheet pile and thus contribute to a reduction of the effective gap.

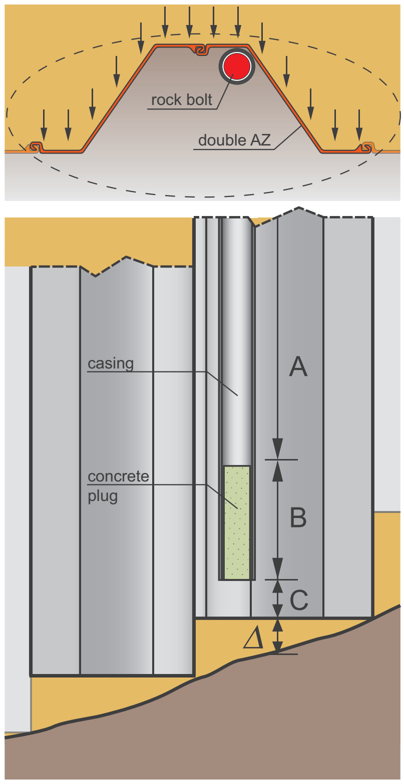


Fig. 18. Determination of the gap Δ

4.6. Grouting and installation of bolts

After flushing out remaining drill cuttings etc. from the hole, a dummy bolt, fastened to a wire is lowered into the hole to verify that the bolt will slide and fit into the hole. The hole is then filled with grout through a hose lowered down to the bottom of the hole. The cement based grout shall have a water / cement ratio of 0.4 or lower. Special additives are normally used to achieve a grout with proper viscosity and setting time.

The rock bolt is then installed, preferably lowered down to the bottom of the hole in a controlled manner. The contractor must verify that the bolt has penetrated all the way down to the bottom of the hole before proceeding with grouting.

In case of a temporary wall, to be able to extract the sheet piles at a later stage, or to avoid axial load on the bolts, the grout should not fill the casing above the bolts. The contractor can apply grease to the upper half of the bolt to limit transfer of axial loads from the sheet pile to the bolt.

4.7. Considerations for the layout

As a reminder, sheet piles are mostly driven as double piles, and the interlocks to be threaded on site should be located on the excavation side.

This configuration allows changing the position of the bolt to the optimal position, as the capacity of the rock bolt toe support strongly depends on the gap between the toe of the sheet piling and the bedrock top.

Additionally, provisions for spare casings may be a good option to be more flexible in case of unanticipated difficulties. Depending on the bedrock slope, especially with steep slopes, the rock bolt may be fixed in either the right or the left corner of the sheet pile. However, in this latter case, a reduction of the resistance may occur (see design case 1 vs. case 2, see Figure 13).

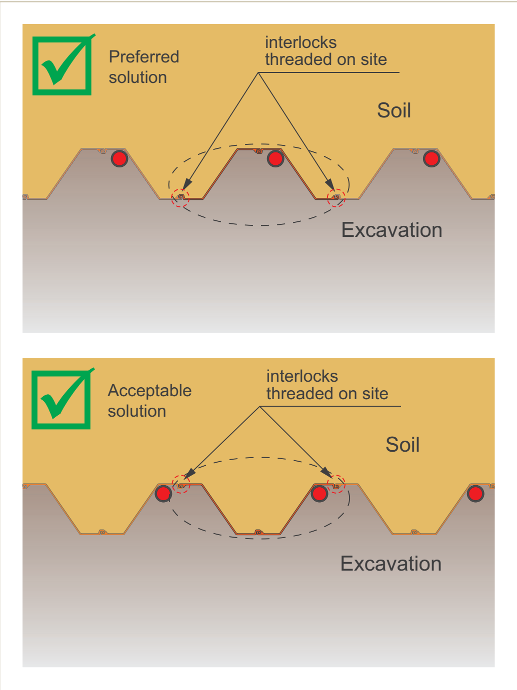


Fig. 19. Layout of AZ piles

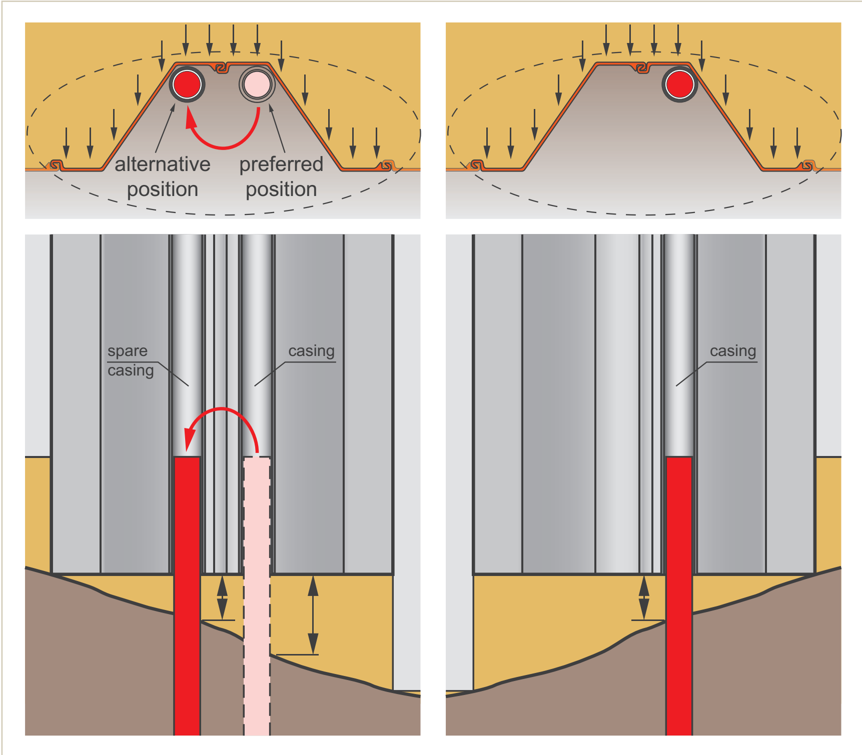
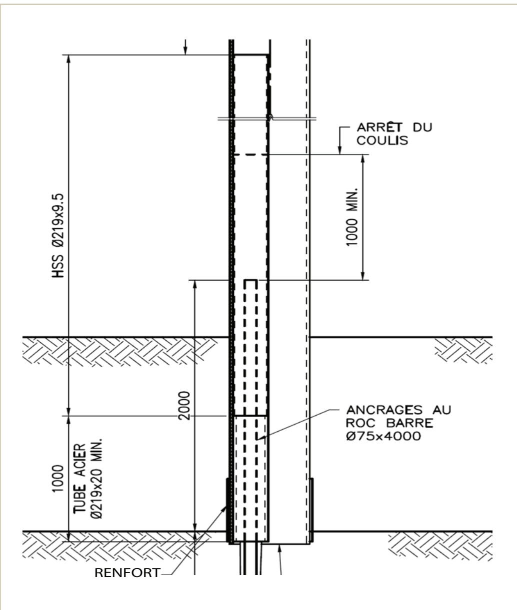


Fig. 20. Spare casings for unexpected cases



4.8. Measures to reduce the gap

As a first solution to reduce the gap the sheet piles shall be driven to a maximum depth to increase the contact with bedrock – at least one edge may penetrate a few centimetres into the bedrock.

Different options may be adopted for a further reduction of the gap in case of steep slopes of the bedrock horizon (see Figure 21)

- change location of the rock bolt fixation (left / right corner)
- flame cutting of lower edge of sheet piles before installation (see Figure 21b)
- staggering of threaded (but uncrimped) double piles, if at all possible with the driving equipment used (see Figure 21c)

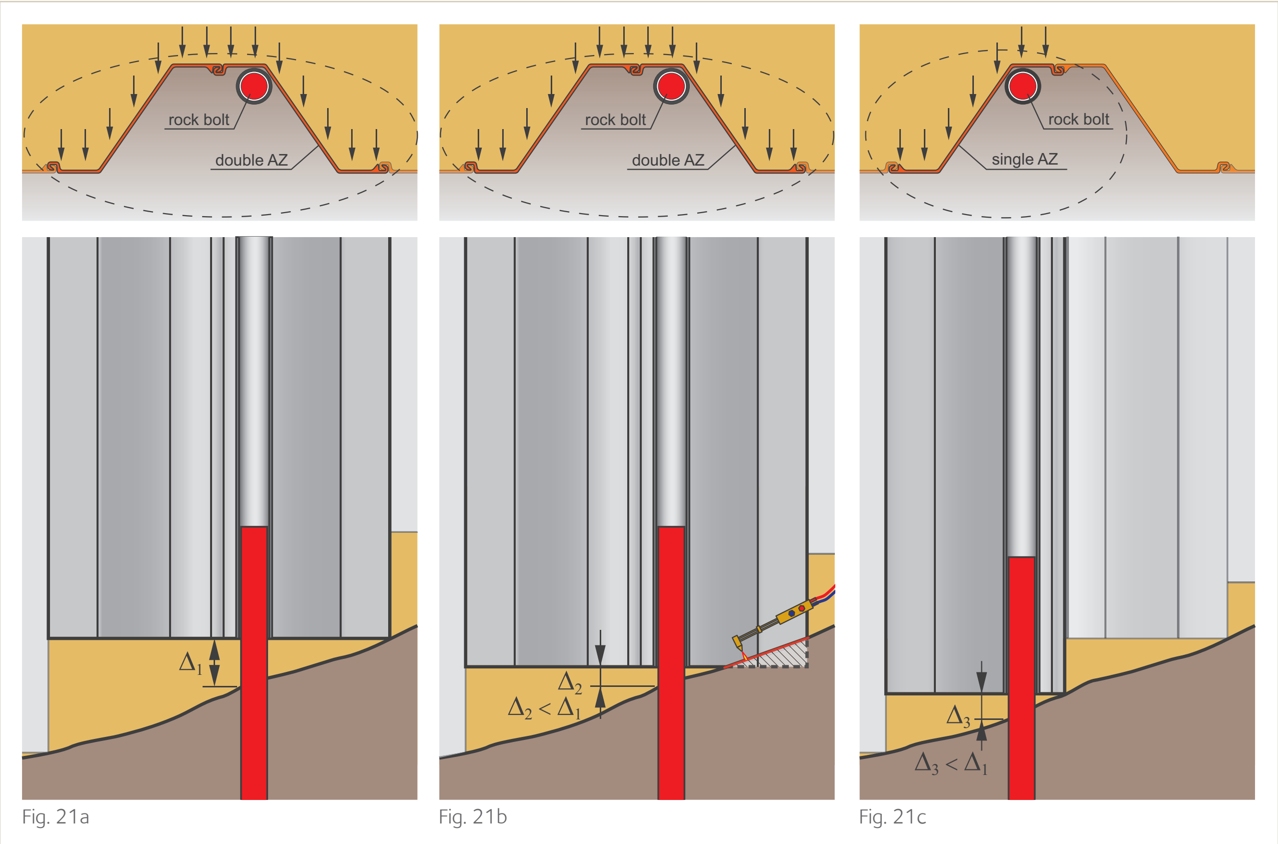


Fig. 21. Possible measures to reduce the gap

5. Additional supporting measures

This chapter covers additional measures often used in connection with rock bolts

Pict. 3. Toe beam. © *Norwegian Public Roads Administration, Grete Tvedt*

5.1. Excavation below bedrock level

If the excavation level is lower than the bedrock level then the axis of the rock bolt should be placed at least 1 m away from the excavation border.

In case of blasting of the bedrock, then the toe of the sheet pile wall must be secured with inclined bolts (as shown in Figure 22) before blasting operations.

It is common to secure the toe of the sheet pile wall with bolts drilled into the bedrock with an inclination of 45°. Bolts must be able to transfer a load equivalent to the load acting on the rock bolts at the same stage.

The inclined bolts are bent against, and welded to the sheet piles over a length of at least 0.5 m. Alternatively the bolts can be cast in a concrete beam along the toe of the sheet pile wall.

In Norway, these additional bolts are normally made of Ø 25 or Ø 32 mm ribbed bars, with steel quality B 500 NC. If the sheet pile wall is permanent, the bolts should either be resistant to corrosion, or be designed taking into account corrosion.

The horizontal shear force determines the bolt diameter. The anchoring length in bedrock should be determined based on the joint set, fissure and cleavage directions in the bedrock. Typical anchoring lengths are 2.0 to 4.5 m. If the loads carried at the toe of the sheet pile wall are large, an alternative solution, whenever possible, would be to replace the inclined bolts with an additional strutting level directly above the toe of the sheet pile wall.

In addition, the exposed rock is usually secured with bolts as the blasting proceeds downwards. Especially with unfavourable joint sets, fissure or cleavage directions the bedrock must be thoroughly examined to determine adequate rock support. Local failure of the bedrock may lead to reduced capacity of the nearest rock bolts, and can also cause progressive failure of the support over a wider area.

Sheet pile walls with battered tie-back anchors are more vulnerable. Indeed, if the bedrock support fails, then the axial forces in the system draw the sheet piles downwards and unload the retaining forces in the battered anchors. The sheet pile wall will then be pressed downwards and inwards, which may increase deformations of the soil behind the wall. In a worst case scenario, a local failure of the bedrock can lead to overloading of neighbouring anchors, resulting in the partial collapse of the sheet pile wall.

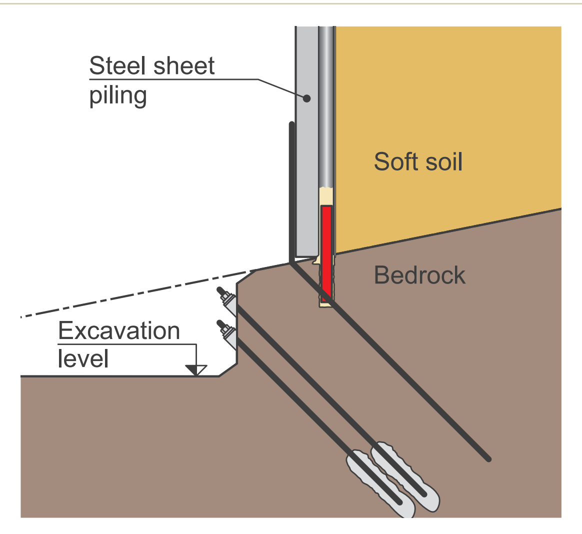


Fig. 22. Excavation level below the bedrock

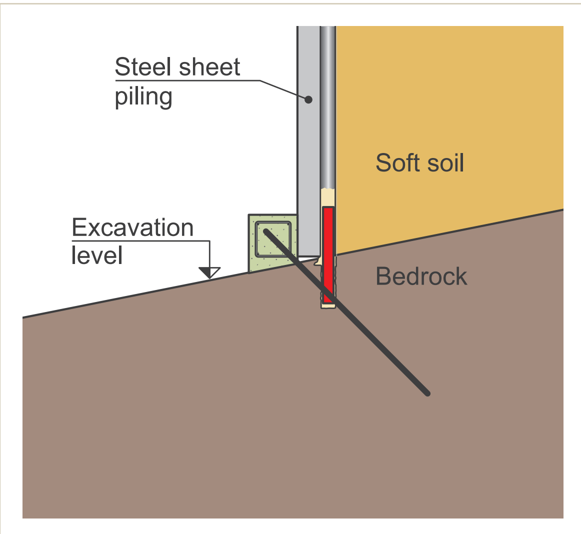


Fig. 23. Toe beam placed at the toe of the sheet pile wall

5.2. Toe beam

Construction of a concrete toe beam along the tip of the sheet pile wall can be useful for the following reasons

- to reduce leakage of ground water at the toe of the sheet pile wall. A concrete beam will contribute to the sealing of the sheet pile / rock interface, and will also provide better counter pressure if injection grouting behind the sheet piles is necessary to obtain further watertightness
- the bedrock is jointed / fissured. A longitudinal reinforced concrete beam will effectively distribute the loads to the bedrock and reduce the risk of progressive failure. The inclined bolts described in the previous section must be cast in the toe beam
- if the sheet pile wall is permanent, a concrete beam at the toe will provide corrosion protection to the rock bolts

An example of a toe beam is illustrated in Figure 23. The beam is reinforced with 4 Ø 16 mm ribbed bars. The longitudinal bars are enclosed with shear reinforcement as shown in the figure. If the bedrock surface is uneven, construction of a toe beam can be rather complex, involving bending of the reinforcement bars and adjustment of the concrete formwork to fit the rock surface (see Picture 3).

5.3. Tightening against fine grained materials or quick clay

Toe beams are commonly used to limit water ingress but they can also prevent washout of fine grained materials through the gaps between the sheet piles and bedrock. Likewise, if there is soft or sensitive clay directly above bedrock, a toe beam will prevent the clay from squeezing in. In both cases the toe beam should be executed as soon as possible after exposure of the bedrock.

Note that to prevent ingress of soil, it is also possible to weld steel plates onto the sheet piles to close the gaps.

Furthermore, jet-grouting along the outside face has been successfully used to close the gaps between the toe of the sheet pile wall and the bedrock, and thus, to reduce potential for leakage as well as soil being washed or squeezed into the excavation.

5.4. Special repair measures

In cases of large gaps, or when the steel sheet piles have not been driven all the way down to bedrock, sufficient toe support with rock bolts may not be achieved with the standard rock bolt solution (pre-mounted casings) described above. Special supporting measures must then be considered.

One solution is to drill down new casings along the sheet piles in order to install additional rock bolts. However, previous experiences when excavating down to the sheet pile / bedrock interface revealed that it is difficult to place the casings with sufficient accuracy.

Moreover, rock bolts installed in casings drilled down after the driving of sheet piles will not be fixed to the sheet piles and their resistance capacity is therefore reduced.

For big gaps between the sheet pile and bedrock, sufficient horizontal support capacity can only be achieved with quite large diameters of rock bolts. Such solutions were already implemented successfully in some projects. For instance, one project was executed with Ø 180 mm steel core piles installed at the back flanges of a sheet pile wall with recorded gaps of 40 to 100 cm.

Another alternative is to install on the excavation side, in front of the back flanges of the sheet pile wall, steel H-beams with casings welded onto the H-beams (see Picture 4). Rock bolts can then be executed to fasten the H-beams in the bedrock. The H-beams will then support the toe of the sheet pile wall. The advantage is that rock bolts of the same diameter as already specified for the sheet pile wall could be used. Use of H–beams is illustrated in Picture 4.

In this specific project the H-beams were also used to strengthen the existing sheet pile wall.

Finally, a practical solution is to improve or alter the strutting of the sheet pile wall. For instance, an additional strut level can be placed near the toe of the sheet pile wall. The excavation can be done in small sections, with section-wise installation of the additional strutting level.

Pict. 4. H-beams with rock bolts supporting a steel sheet pile wall

6. Design example

6.1. Assumptions

Excavation depth 17.50 m

Soft soil (φ_d =25°) layer thickness 15.00 m

Underlying bedrock with slopes of maximum 30%

Sheet pile section[4)]

- AZ 27-800, S 460 AP
  - W_{el} = 2670 cm^3/m
  - $f_{y,SSP}$ = 460 MPa

Partial safety factors and other factors

- γ_{M0} = 1.0
- γ_{M2} = 1.25
- β_w = 0.85 (EN 1993-1-8 2.2.(2))

  can vary by country

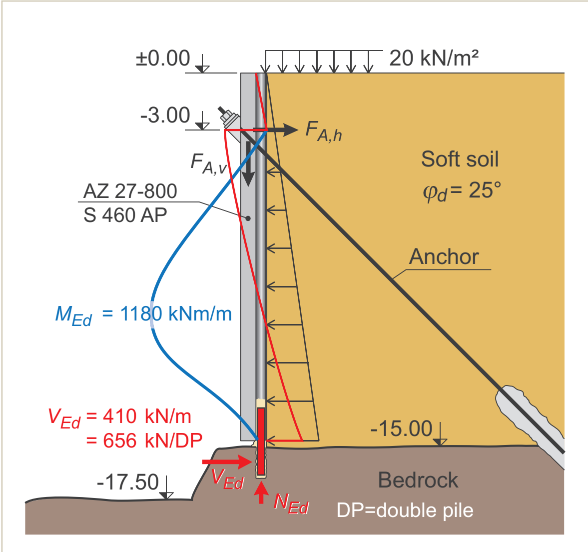


Fig. 24. Geometry of the retaining wall, actions & effects

6.2. Action effects

Geotechnical design results

- M_{Ed} = 1180 kNm/m
- V_{Ed} = 410 kN/m = 656 kN/pair
  (pair = 2 single piles or 1 double pile)

Estimated gap for maximum slope

- max $\Delta_1 \approx$ 190 mm ⇒ 200 mm
- max $\Delta_2 \approx$ 300 mm ⇒ 300 mm

Both values will need to be verified as the direction of the slope, as well as the position of the bolt, may change.

Chosen bolt[4)]:

Ø 90 mm, $f_{y,Bolt}$ = 800 MPa

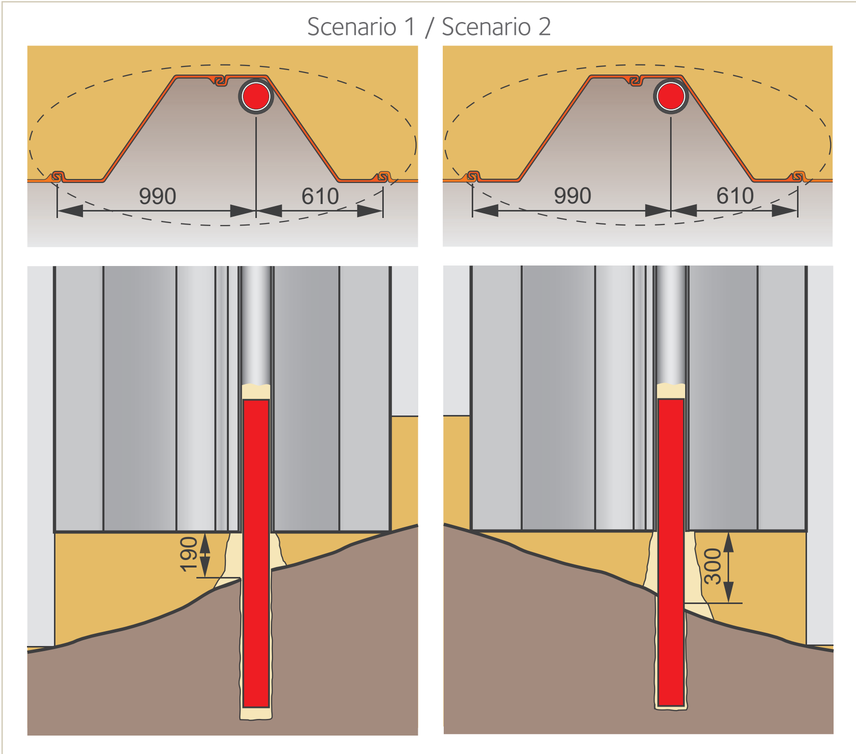


Fig. 25. Section view: estimation of the gaps

[4)] Iterative process

6.3. Verification of bending in sheet piles

With $\gamma_{M0} = 1.0$ and $\beta_B = 1.0$ (AZ sheet piles)

$$M_{c,Rd} = \beta_B W_{el} f_{y,SSP} / \gamma_{M0}$$

$= (1.0 \cdot 2670 \cdot 460 / 1.0) \cdot 10^{-3} = 1228$ kNm/m $> M_{Ed}$

Notes: according to EN 1993-5 [4]

- the AZ 27-800 in S 460 AP is a class 2 section. The design moment resistance of the cross-section $M_{c,Rd}$ could be calculated with the plastic section modulus W_{pl} of 3100 cm^3/m instead of the elastic section modulus W_{el}
- a reduction factor shall be considered if the water pressure on the sheet pile wall is higher than 5 m. Assumption: water pressure is below 5 m at the location of the maximum bending moment M_{Ed}

6.4. Verification of rock bolt capacity

$$V_{Pl,Bolt} = \frac{\pi \cdot 90^2}{4} \cdot \frac{800}{\sqrt{3}} \cdot 10^{-3} = 2938 \text{ kN}$$

with

- $\Delta_1 = 200$ mm $r_{Rd,Bolt} = 0.3141$ $V_{Rd,Bolt} = 738$ kN $> V_{Ed}$ ✓
- $\Delta_2 = 300$ mm $r_{Rd,Bolt} = 0.2154$ $V_{Rd,Bolt} = 506$ kN $< V_{Ed}$ ✗

The chosen bolt is not able to support V_{Ed} if the effective gap exceeds 200 mm.

Solutions

- option 1: choose stronger bolt
- option 2: minimise gap ($\Delta_1 = 200$ mm) by alternating left / right corner for bolt fastening

$\Rightarrow$ chosen option: 2 (for illustrative purposes. Option 1 should be the safest approach)

6.5. Verification of the sheet piles for load introduction through the bolt

The verification checks two possible configurations:
bolt fixed on the flange with

- curved clutch
- straight clutch

In any case $L_{F,S} = 1000$ mm

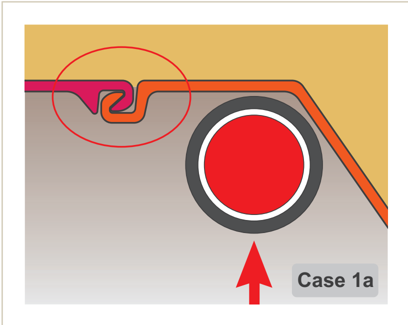
Flange with curved interlock

$$V_{Rk,SSP} = V_{Rk,SSP,355} \cdot \frac{f_{y,SSP}}{355}$$

From Table 3, case 1

$$V_{Rk,SSP} = 1045 \cdot \frac{460}{355} = 1354 \text{ kN}$$

$$V_{Rd,SSP} = \frac{V_{Rk,SSP}}{\gamma_{M0}} = \frac{1354}{1.00} = 1354 \text{ kN} > V_{Ed}$$ ✓



Flange with straight interlock

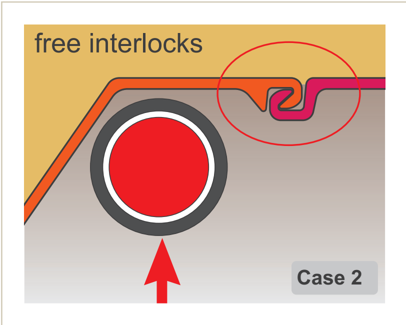
2 configurations are possible

Free interlock

From Table 3, case 2

Reminder: if $f_{y,SSP} > 355$ MPa then $V_{Rk,SSP} = V_{Rk,SSP,355}$

$$V_{Rd,SSP} = \frac{V_{Rk,SSP}}{\gamma_{M0}} = \frac{770}{1.00} = 770 \text{ kN} > V_{Ed}$$ ✓



Welded interlock

$V_{Rd,\,SSP} = 1354$ kN $> V_{Ed}$ *(see above)* ☑

Welding design

Try $a_w = 6$ mm, $L_{weld} = 500$ mm

Simplified method from
Eurocode EN 1993-1-8: $F_{w,\,Ed} \leq F_{w,\,Rd}$

with $$F_{w,\,Rd} = a_w \cdot \frac{f_u}{\sqrt{3}\,\beta_w\,\gamma_{M2}}$$

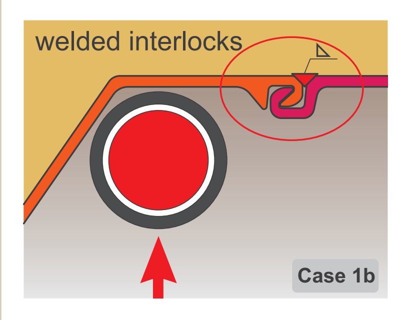
For a steel grade S 460 AP: $f_u = 550$ MPa and $\beta_w = 0.85$

Hence

$$F_{w,\,Rd} = 6 \cdot \frac{550}{\sqrt{3} \cdot 0.85 \cdot 1.25} = 1793 \text{ N/mm}$$

$$\Rightarrow V_{Rd,\,weld} = L_{weld} \cdot F_{w,\,Rd} = 500 \cdot 1793 \cdot 10^{-3} = 897 \text{ kN}$$

$$\geq \frac{V_{Ed}}{2} = \frac{656}{2} = 328 \text{ kN}$$ ☑



6.6. Solution

- AZ 27-800 in S 460 AP
- Rock bolt Ø 90 mm with $f_{y,\,Bolt} = 800$ MPa
- Minimise gap ($\Delta_1 \leq 200$ mm) by alternating as required by bedrock slope left / right corner for bolt fastening.

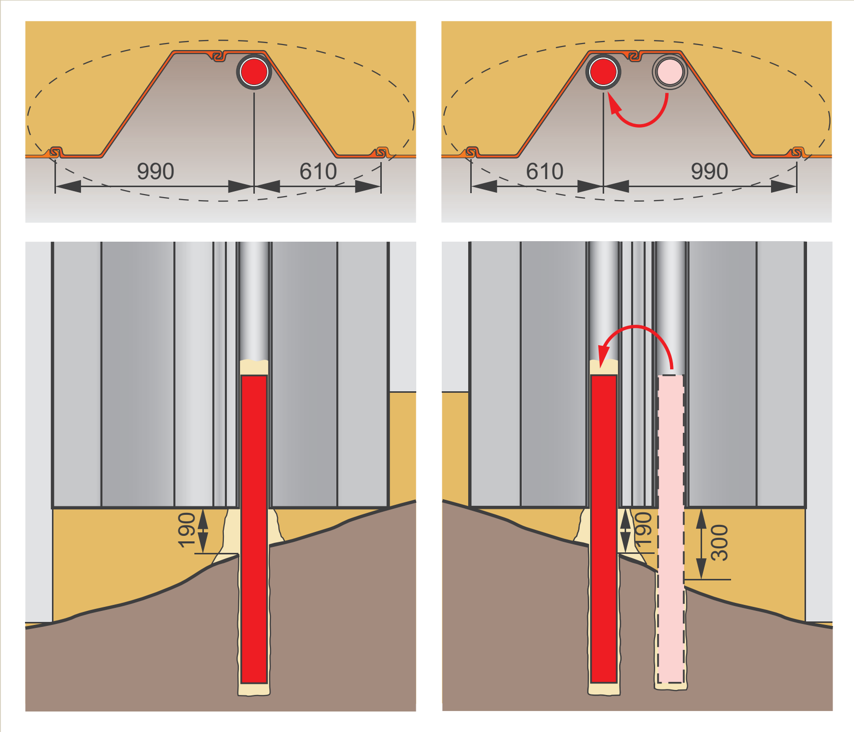


Fig. 26. Final solution: minimize gap

7. Background knowledge

Although the system had been used in the past numerous times, reliable background knowledge on the behaviour of the rock bolt and the steel sheet piling for the specific boundary conditions was gathered within a major R&D project chaired by NGI (Norwegian Geotechnical Institute).

The research project was realised in 2007-2008 and comprised extensive laboratory testing and numerical finite element (FE) simulations which allowed developing a series of design guidelines for the toe support of steel sheet piles by rock bolts.

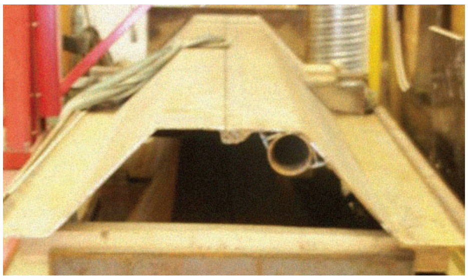
The laboratory testing was carried out horizontally and the bedrock was simulated by pre-cast concrete blocks.

Within the frame of the numerical studies the main parameters were analysed in detail.

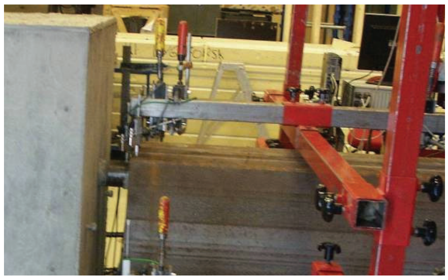
The knowledge gained from this research program allowed developing a safe-sided design approach and design verifications based on the framework of existing standards including EN 1993.

The present brochure is based on this safe-sided design approach. Due to the assumptions made in the proposed formulas, which have been confirmed by laboratory tests and FE simulations, the results are only valid for ArcelorMittal's AZ steel sheet pile range.

Concrete block to simulate bedrock

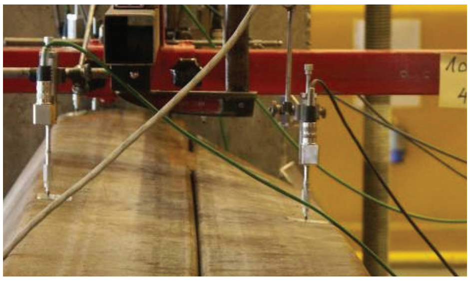


AZ specimen with tube casing fixed with T-shapes



AZ supported by rock-bolt, grouted in tube casing and fixed in pre-cast concrete with a gap of 100 mm

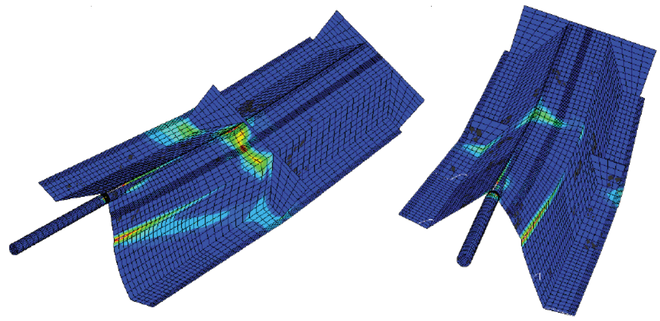
Test set-up on span-floor with displacement controlled load introduction at mid-span



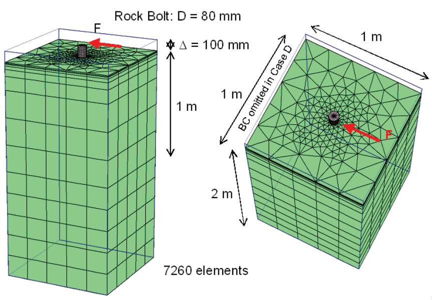
Twisting of the cross-section (limited locally to the sheet piling toe) due to off-centre support

Plastification of the rock bolt

Pict. 5. Pictures of laboratory tests performed by the NGI



Back-calculation of tests



Simulation of Bolt-Rock-interaction

8. Bibliography

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[2] A new verification method for toe support of sheet pile walls driven to bedrock. Kort, A, Karlsrud, K, Nordic Geotechnical Meeting, Sandefjord, Norway, Sept. 2008. Proceedings, 2008, pp 300-307.

[3] Norwegian Public Roads Administration. Handbook 026E, General specifications 2. Standard specification texts for bridges and quays. Principal specification 8. March 2009.

[4] EN 1993-5: 2007. Eurocode 3 - Design of steel structures - Part 5: Piling. CEN.

IMPORTANT NOTE

Data in this brochure is only valid for AZ steel sheet piles manufactured by ArcelorMittal.

Latest info on the production of steel sheet piles can be found in the catalogue "Steel Sheet Piling | General catalogue". ArcelorMittal.

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