Substructure: Design and construction. Frost

1 Purpose and scope

This chapter deals with the design of the substructure with regard to frost.

The chapter describes which factors affect frost penetration, as well as which requirements are imposed on the materials that may be used in the frost protection layer. It is particularly important that well graded materials are used so that the embankment is dense enough to prevent internal air convection. This particularly applies to blasted rock/crushed stone. Well graded materials containing an element of sand/gravel will also be capable of ensuring a moisture level at the base of the frost foundation, something which is regarded as beneficial. The chapter must also be seen in correlation to [Underbygning/Prosjektering og bygging/Drenering|kap. 11 Drenering]].

2 Frost

2.1 Frost susceptibility

Soil types may be divided into four classes according to their load-bearing capacity during the spring thaw period:

T1	Non frost-susceptible
T2	Slightly frost-susceptible
T3	Averagely frost-susceptible
T4	Very frost-susceptible

Mal:Textbook material

Soils used in the frost zone must be of the type 'Non-frost- susceptible'. Frost susceptibility is assessed based on the material's grain uniformity. (Refer to Table 1.).

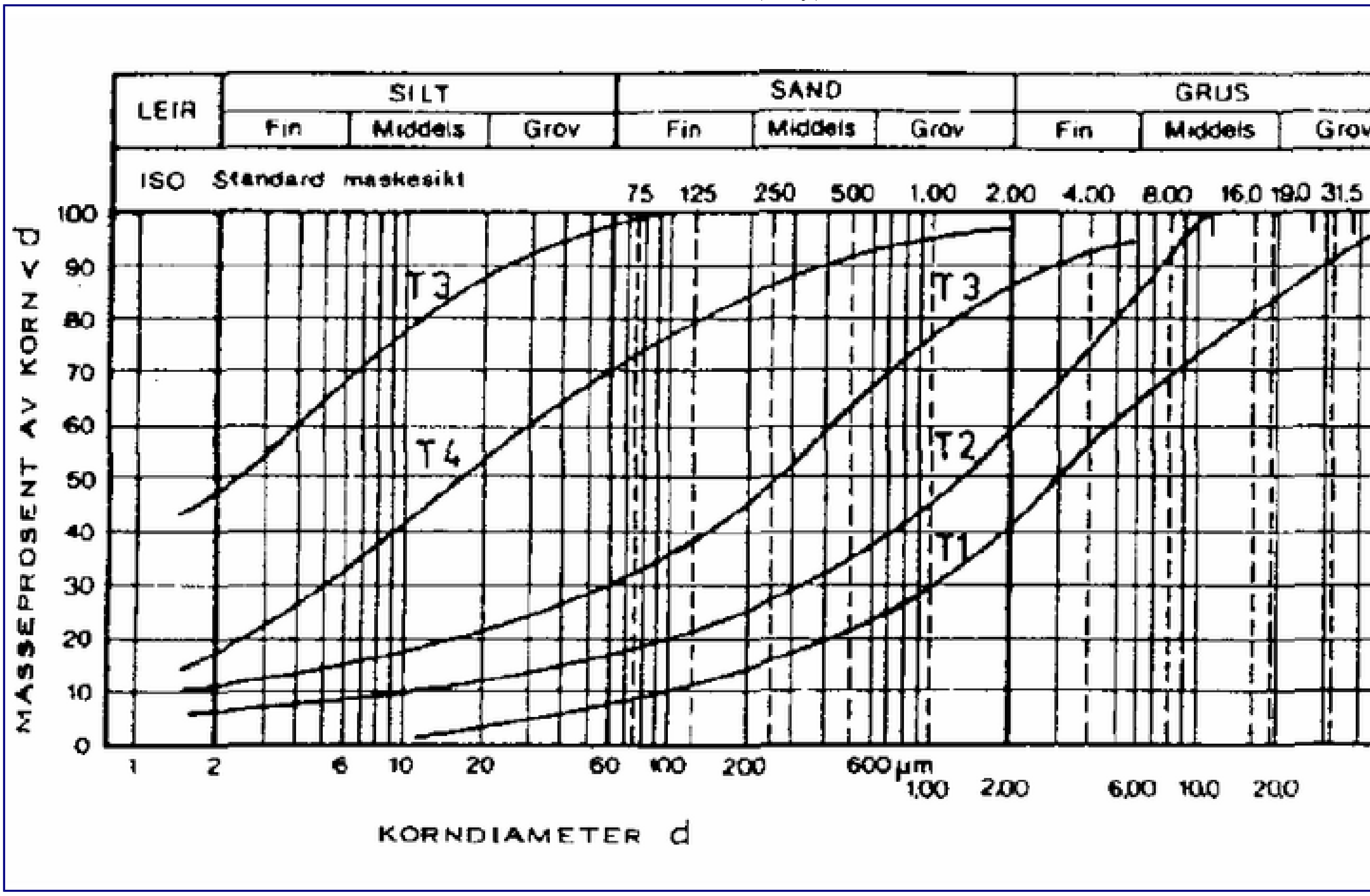
The frost criteria may be expressed thus: 'For a material to be non-frost-susceptible, the mass percentage of the material < 0.02 mm must not be greater than 3% based on material that passes through a 19 mm strainer'.

Peat Marshy ground

Tabell 1: Frost susceptibility classification

		Mass percentage (of material < 19.0 mm)					
Designation	**Frost class**	**< 0.02 mm**	**< 0.2 mm**	**Soil examples**			
Non-frost-susceptible	T1	≤ 3 %		Sand Gravel			
Moraine (sandy, gravelly)				Slightly frost-susceptible	T2	> 3 - ≤ 12 %	Sand Gravel
Averagely frost-susceptible	T3	> 12 %	< 50 %	Sand Moraine (clayey) Clay with more than 40% < 0.002 mm			
Very frost-susceptible	T4	> 12 %	> 50 %	Clay with less than			

40% < 0.002 mm
Silt
Moraine (silty)

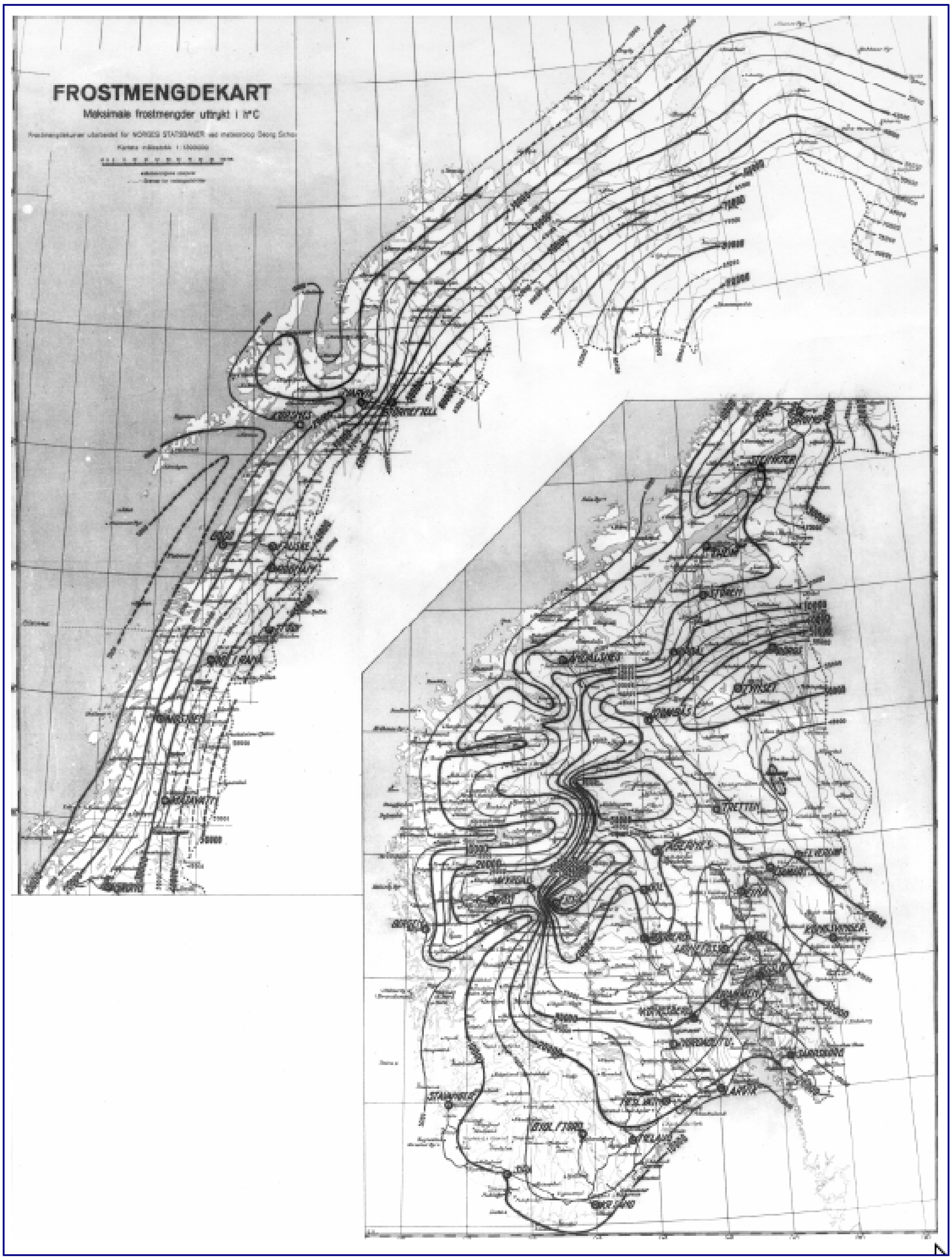


Figur 1: Examples of grain size distribution curves for soils within the various frost groups

2.2 Design frost level

Frost penetration into the ground is dependent on the frost levels expressed in h°C (hourly degrees) and the ground's properties. Figure 2 shows a chart of maximum frost levels (F_{100}) for the whole of Norway. Figures 3, 4 and 5 show the design curves for the frost protection layers shown.

Figure 2 should be used for pre-engineering purposes only. For detail planning, an assessment of local temperature conditions should be carried out along the course of the line. Frost levels specified in Statens vegvesens vegnormal nr. 018 Vegbygging may be used.



Figur 2: Maximum frost levels for Norway

3 Frost protection layer

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3.1 The functions of the frost protection layer

The frost protection layer must

- prevent penetration of frost to the formation and subsoil

- prevent internal convection within the substructure
- where possible, ensure a high level of moisture in the layer above the formation
- ensure sufficient load-bearing capacity and stability

3.2 Materials in the frost protection layer

The frost protection layer must be made up of effective friction materials, i.e. well graded, well draining and frostproof (T1-materials, cf. Table 1). Approved materials are described in sections 3.2.2–3.2.5.

3.2.1 Implementation and inspection

Implementation and inspection are the same as for materials in the reinforcing layer, refer to kap. 6 Banelegeme, avsnitt 3.4 og 3.5.

3.2.2 Blasted rock and crushed stone

Stones must be well graded, with grain uniformity coefficient $C_u = d_{60}/d_{10} \geq 15$. Machine ballast without a sand/gravel fraction is unsuitable for use in the frost protection layer for technical reasons relating to frost.

The maximum permitted stone dimension is 500 mm, though not greater than 2/3 of the layer thickness that is distributed.

Filling with quarry dust to the extent that the stones 'float' is not permitted, and no more than 3% of material may be less than 0.02 mm, based on material under 20 mm.

For the design of frost protection layers of blasted rock, refer to avsnitt 4.6.

3.2.3 Sand and gravel

A frost protection layer of gravel materials must comprise well graded materials from natural gravel deposits. The material may contain stone but the maximum grain size must not exceed 150 mm. Sand must generally not be used in the formation except as a filter layer.

3.2.4 Lightweight aggregate and foam glass

The use of lightweight aggregate and foam glass for stabilising purposes is discussed in chapter 8, Stability. It may also be appropriate to use these materials for frost insulation, often with the added purpose of providing a beneficial stabilising or subsidence-reducing effect, or other effect. If such materials are used on an embankment, the frost protection layer will be omitted.

When using lightweight aggregate or foam glass, the design frost level must always be set to F_{100}.

The thickness of a layer of lightweight aggregate or foam glass designed in consideration of frost should be oversized by 20% in order to compensate for the penetration of stones into the layer.

3.2.4.1 Materials

Requirements for materials are as specified for lightweight aggregate and foam glass in Underbygning/Prosjektering_og_bygging/Stabilitet. Table 2 contains an example of thermal conductivity parameters for dry lightweight aggregate. Table 3 contains an example of thermal conductivity parameters for dry foam glass. Thermal conductivity that is more beneficial than that stipulated in the design value must not be used.

Tabell 2: Material requirements, lightweight aggregate

Material	Density, dry (kg/m^3)	Thermal conductivity, dry (at -5°C) (W/mK)	Comments
Lightweight aggregate	Max. 400	0.12 (Design value 0.15)	Ext. grading 0–32 mm

Foam glass || Max. 300 || 0.11 (Design value 0.15) || Ext. grading 10–50/60 mm

Tabell 3: Material requirements, foam glass

Material	Density, dry (kg/m^3)	Thermal conductivity, dry (at -5°C) (W/mK)	Comments

3.2.4.2 Implementation

Layers of lightweight aggregate or foam glass for frost insulation are distributed on the formation. The requirements for the implementation of frost protection layers with these materials are equivalent to the requirements for embankments comprising the same materials, refer to Underbygning/Prosjektering_og_bygging/Stabilitet.

3.2.4.3 Inspection

Inspection is generally the same as for embankments of lightweight aggregate or foam glass, refer to Underbygning/Prosjektering_og_bygging/Stabilitet. In addition:

- the layer thickness must be inspected with particular care
- the distribution of rock material on top of the light backfill must be undertaken with care in order to avoid deformations and larger rocks penetrating the insulation layer.

3.2.5 Extruded polystyrene (XPS)

A frost foundation of extruded polystyrene (XPS) should not be used. Exceptions may be made where there are special technical and/or economic factors.

The design frost level must always be set at F_{100} when XPS is used as frost insulation.

The minimum permissible board thickness is 60 mm.

Only CFC-free and HCFC-free boards may be used.

Specifications and material requirements are stipulated in Table 4. Thermal conductivity that is more beneficial than that stipulated in the design value must not be used.

Tabell 4: Specifications and material requirements, extruded polystyrene

Material	Density, dry (kg/m^3)	Compressive strength (at 5% def.) (kPa)	Thermal conductivity, dry (at -5°C) (W/mK)
Extruded polystyrene, XPS	Min. 38	Min. 400	0.025 (Design value 0.037)

3.2.5.1 Implementation

The boards must be protected against mechanical damage from gravel/stones. This is achieved with fine gravel or sand/gravel to a thickness of 5–10 cm, including the underside if stones are used beneath the boards. The boards must be laid close together, and without any gaps between them. The exception to this are the wedge sides at each end of an insulated section. For the design of the required gravel layer thickness beneath the insulation (XPS), refer to Underbygning/Vedlikehold/Banelegeme/vedlegg 6.a.

3.2.6 Expanded polystyrene (EPS)

Expanded polystyrene (EPS) is primarily used for stabilisation purposes. Also refer to Underbygning/Prosjektering og bygging/Stabilitet. In such cases, the EPS slabs will also form part of the frost protection layer. The thickness of the EPS layer will then normally be a minimum of one slab thickness, i.e. 0.5 m and further frost protection layers are therefore usually unnecessary.

3.3 Sealing side slopes

To prevent the intrusion of cold air, the side slopes must be sealed. Refer to chapter 6, Ballast bed.

4 Frost dimensioning

The frost protection layer must be designed according to local frost levels measured in freezing degree hours. The rationale for the choice of design frost level is that, statistically, no more than one total freezing of the substructure, resulting in a suspension of service, will occur in a 100 year period.

Definition of frost level F_{10}, F_{20} and F_{100}

- F_{100} is frost level taken from Figure 2
- $F_{20} = 0.85 \cdot F_{100}$
- $F_{10} = 0.75 \cdot F_{100}$

4.1 Main lines

Table 5 shows frost levels that form the basis of different quality classes for a main line:

Tabell 5: Requirements for the design frost level for the various quality classes for a main line

Quality class	Design speed, V_{dim}	Design frost level, F_d
K0 - K1	$V_{dim} \geq 125$ km/h	F_{100}, i.e. regarded as being exceeded once in the course of a 100 year period
K2 - K4	45 km/h $\leq V_{dim} \leq 120$ km/h	F_{20}, i.e. regarded as being exceeded once in the course of a 20 year period
K5-lines	Vdim ≤ 40 km/h	F_{10}, i.e. regarded as being exceeded once in 10 years

The design speed (V_{dim}) is the speed that all technical installations must satisfy as a minimum. V_{dim} stipulates the design speed for a whole line or parts of the line. In selecting V_{dim}, it is also important to take future railway standards into account.

4.2 Branch lines

Branch lines are designed for F_{100} with reductions.

4.3 Factors affecting frost penetration

Many factors affect frost penetration in a railway structure. A list of the most important factors is shown in Table 6.

Tabell 6: Factors that affect frost penetration in a railway structure

Climatic conditions	Line construction	Superstructure and substructure material

- Climatic zone
  - frost level in the air
  - annual average temperature
- Ground temperature
- Relationship between frost level in the air and the embankment's surface
- Previous summer temperature
- Previous autumn precipitation
- Snow and wind conditions
- Local variations in climate
- Cloud cover or clear sky

- Drainage
- Cross-section design
- Layer thickness
- Sealing ditch slopes
- Cutting depth
- Subsoil
- Water channels
- Underpasses
- Culverts

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- Dry bulk density and porosity depending on:
  - grading:
    - d_{maks}
    - fines content
    - open/sealed structure
    - degree of compaction:
    - compaction work
    - thickness upon distribution
- Water content
- Rock type

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A number of factors, such as annual average temperature and frost level, may be measured and quantified even though these factors may also vary significantly over a given section of line. Other factors, such as dry bulk density and maximum grain size, will be dependent on implementation and inspection, d_{max}. Certain factors have major annual variations.

4.3.1 The effect of the various factors on frost resistance

4.3.1.1 Grading of material

An open structure may result in unfavourable internal convection in the substructure, i.e. that coarse-grained single graded materials are unfavourable.

4.3.1.2 The embankment's water content

Increased water content results in an increase in thermal conductivity in the embankment. This is because water has greater thermal conductivity than air and also because the water acts as 'bridges' for the heat flow between the stone particles. At the same time, increased water content will lead to more latent freezing heat being emitted when water in the materials freezes. Thus, high water content in the frost protection layer is beneficial.

4.3.1.3 Ground temperature

The temperature 10 m below ground is virtually constant and almost equal to the local annual average temperature. Thus, a lower annual average temperature will result in increased frost penetration. The annual average temperature will also vary locally, and is, for example, lower on north-facing slopes than south-facing slopes.

4.3.1.4 The relationship between air temperature and temperature on the surface of the embankment during the summer

The surface temperature will usually be the same, or lower than the air temperature, as opposed to what is found on an asphalted road surface. During the winter, as a result of radiation emitted, the surface temperature will be lower than the air temperature.

4.3.1.5 Dry bulk density of rock material in the reinforcing layer and frost protection layer

High dry bulk density and low porosity in the rock material increases the thermal conductivity. Based on the thermal conductivity alone, the frost penetration should increase with an increase in dry bulk density. Rock material with high dry bulk density, however, is more well graded and usually contains significantly more fines than porous rock material. Dense rock material therefore has a greater capacity to retain moisture. Well graded materials are also beneficial in terms of avoiding internal air convection. Thus, on the whole, dense rock material with a high fines content is best suited as a frost protection material. Table 7 shows the suitability of blasted rock as a frost protection material.

Tabell 7: Blasted rock as a frost protection layer in railway installations. Suitability depends on grain composition

Structure		**Fines content/moisture**	
Grading/porosity	**Grain size**	**Low fines content/dry**	**High fines content/earth-moist (but not frost-susceptible)**
densely graded/low porosity	fine blasted	very suitable	very suitable
	coarse blasted	suitable	very suitable
open graded/high porosity	fine blasted	unsuitable	suitable
	coarse blasted	unsuitable	unsuitable

4.4 Prerequisites for frost dimensioning

When designing for frost, consideration must be given to the fact that the surface temperature during the winter is generally lower than the air temperature 2 m above ground, where air temperature measurements are taken. When using the design curve for blasted rock, this is included.

Reference is made to 'Frost action in ground' no. 17 for estimating climatic loads. In respect of frost dimensioning of railways, the winter surface temperature is calculated based on the method stipulated for asphalted roads. The summer surface temperature is calculated based on the air temperature during an ordinary summer.

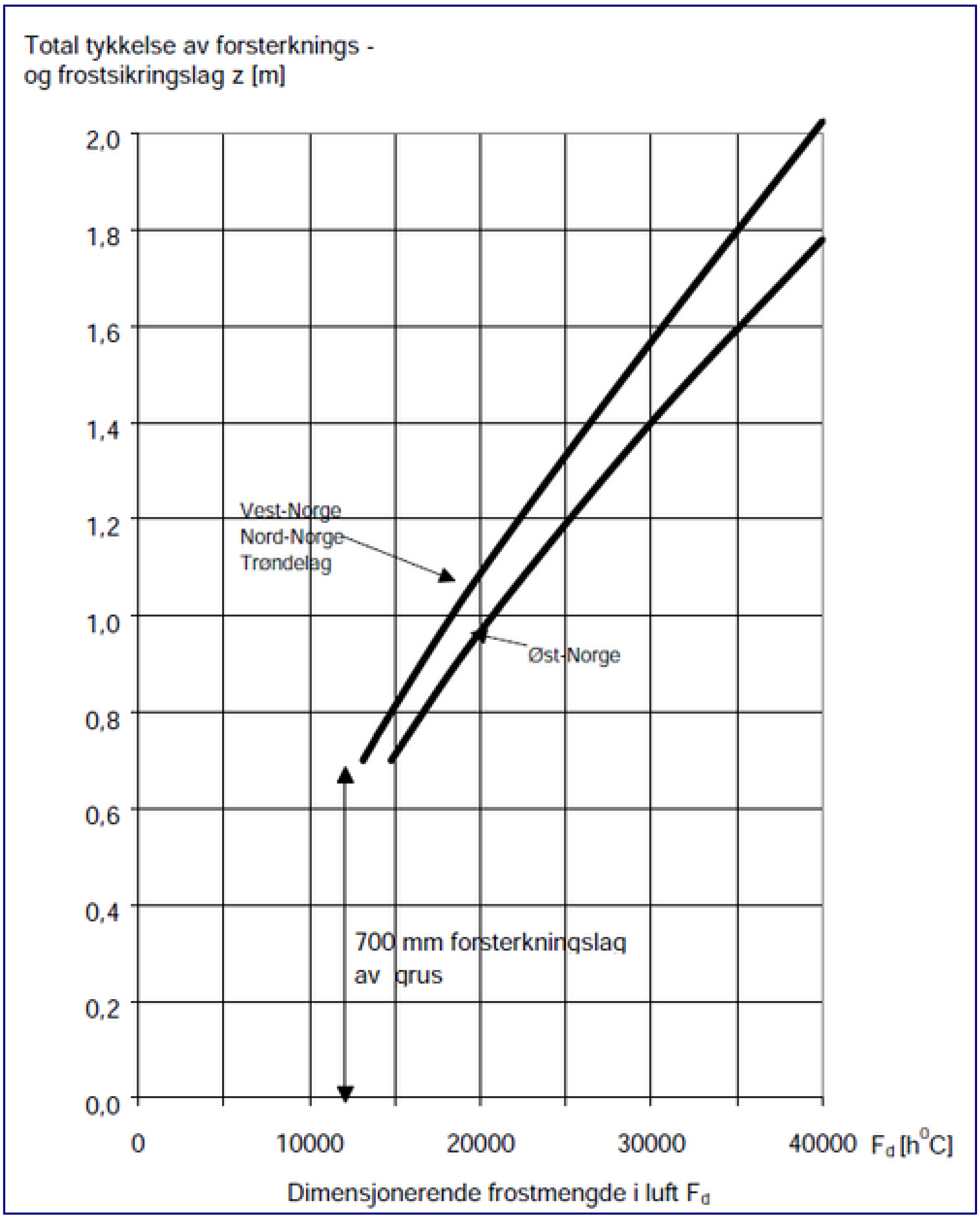
The insulating effect of snow layers is not taken into account when frost dimensioning.

It must always be assumed that the formation has been drained when frost dimensioning.

In the case of a single-track line, the width of the frost protection layer at the top must be at least 5.0 m. In the case of a double-track line, or a line comprising several tracks, the frost protection layer must be at least 2.5 m on either side of the centre of the track.

4.5 Design of frost protection layer of gravel

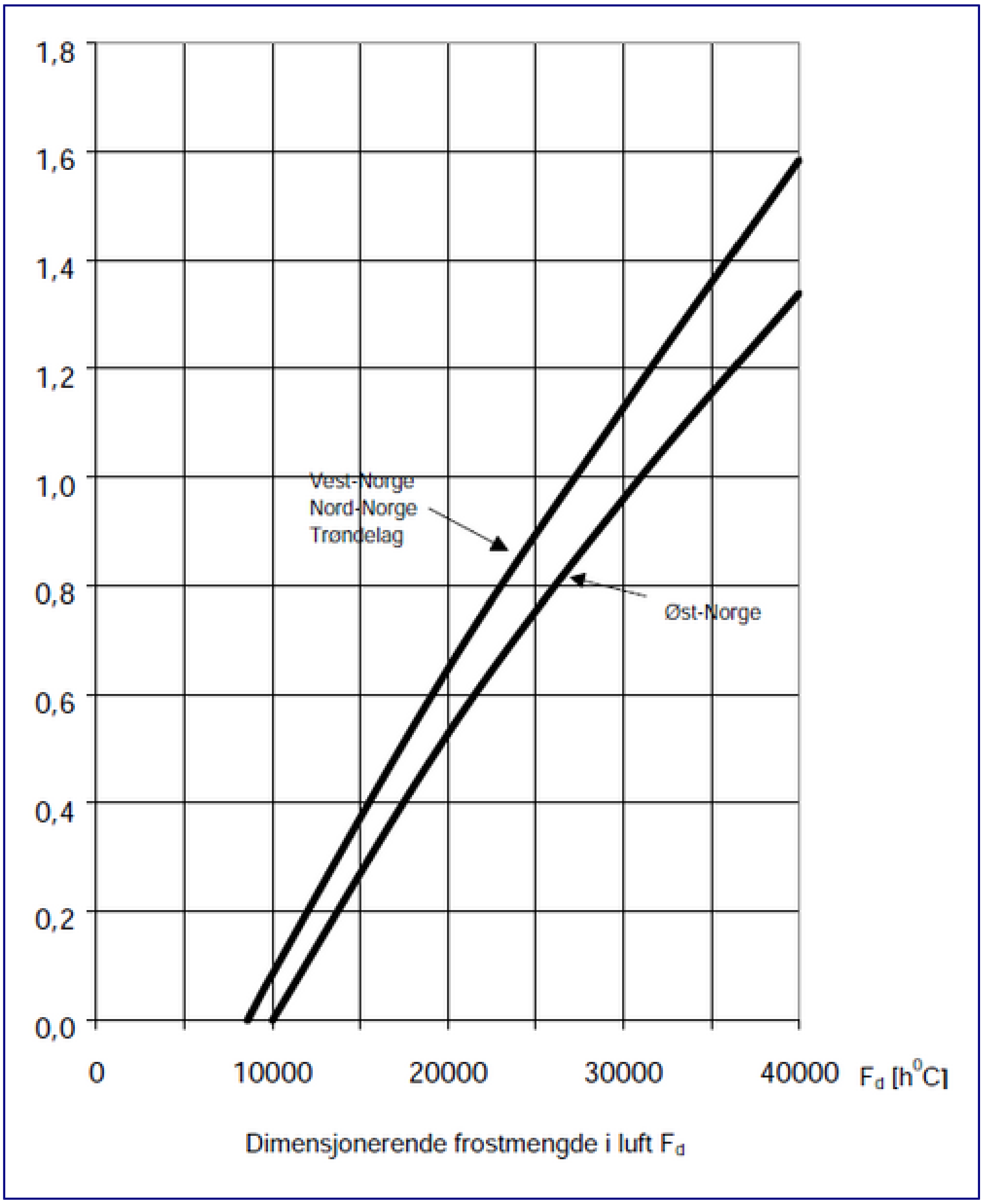
The total thickness of a reinforcing layer and frost protection layer comprising sand or gravel under ballast is designed in accordance with Figure 3. Design curves have been formulated for Norwegian conditions in accordance with UIC sheet no. 719. The conditions in Eastern Norway are more favourable compared to the rest of the country due to the greater store of summer heat in Eastern Norway. In a frost-technical context, sand in the filter layer is regarded as gravel.



Figur 3: Design curves of total thickness, z, of reinforcing layer and frost protection layer of gravel

Figure 4 shows design curves for a frost protection layer of gravel, based on the assumption that a

700 mm reinforcing layer of blasted rock will also be used.



Figur 4: Design curves for frost protection layer of gravel, in addition to 700 mm reinforcing layer of blasted rock

4.6 Design of a frost protection layer of blasted rock

When designing a frost protection layer of blasted rock it is crucial to show due care and consideration to the fact that the thermal properties are generally unstable and that significant variations may occur in the properties, both locally and from site to site.

In order to safeguard against extremely unfavourable properties, a curve equal to 1.6 x Z_{gravel}, as specified in Table 6, may be used. The curve applies to designing the thickness of a frost protection layer and reinforcing layer of blasted rock, based on the assumption that the following points have been satisfied:

- rock material is well graded so that internal convection, for example, is prevented
- the surface and ditch slopes of the ballast bed have been sealed, so that heat loss through convection and frost penetration from the side is reduced to a minimum. For

[Underbygning/Prosjektering_og_bygging/Frost#Tetting_av_sideskråninger|tetting av sideskråninger]], refer to section 3.3.

The design curve applies to the relevant concept with a 700 mm reinforcing layer of stones of 0 - 300 mm and a frost protection layer of stone with a maximum stone dimension of 500 mm, or up to 2/3 of the layer thickness.

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The input data for the design curve is a 100 year frost level in the atmosphere.
The effect of the temperature difference between the air and the surface is
included in the curve specified in Figure 5.
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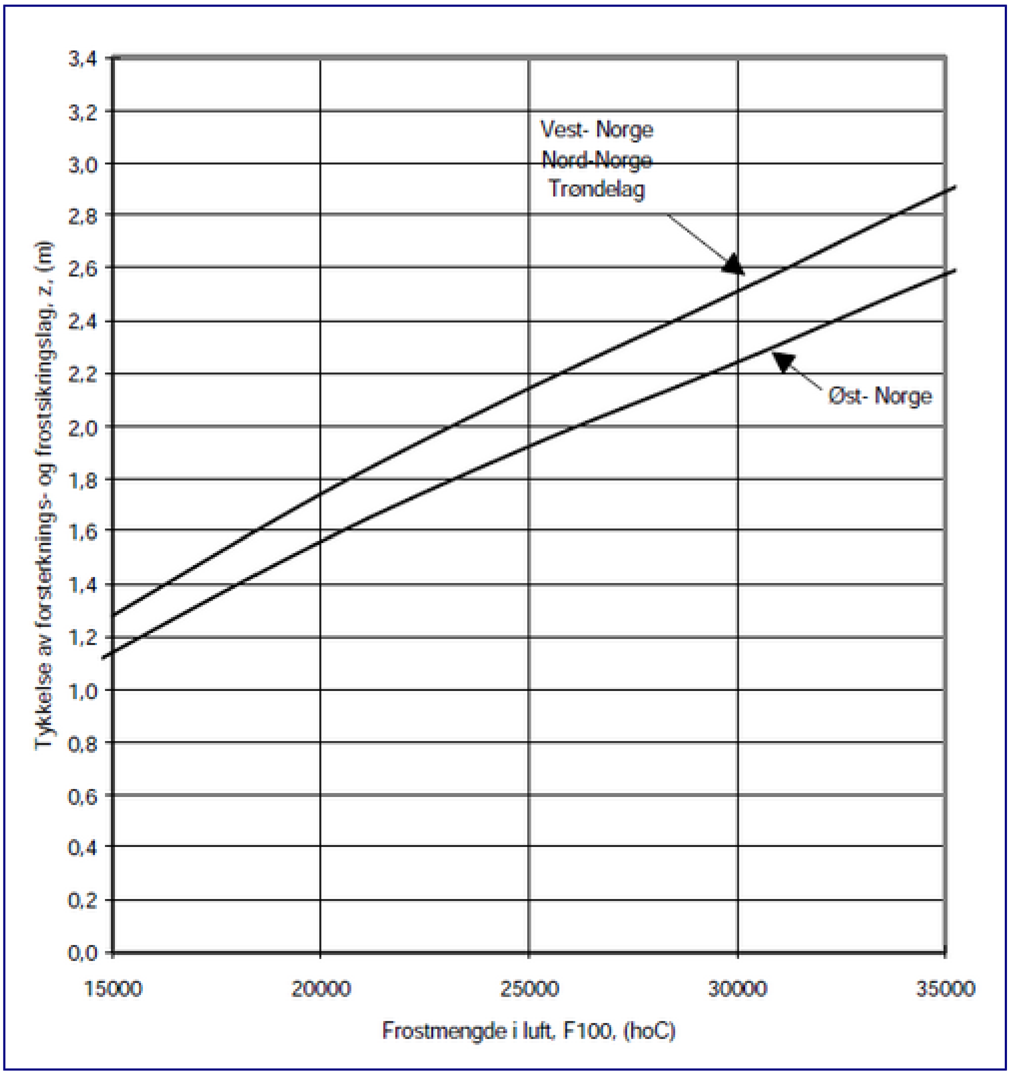
Still, there is no doubt that the use of blasted rock for frost protection engenders a greater degree of uncertainty than alternative solutions using gravel, insulation products or a heat-accumulating bottom layer. The following factors have not been included in the design curve:

- 'stone cavities' as a result of separation through improper laying or single graded materials
- large stones (may create thermal bridges throughout the embankment)
- internal convection as a consequence of open structures in the blasted rock material (the requirements for the use of well graded materials in avsnitt 3.2.2 will, however, take this effect into account)

If particularly favourable materials are used, the layer thickness may be calculated separately. If particularly unfavourable materials are used, the layer thickness must be calculated separately.

Ensuring a high degree of moisture at the base of a frost foundation of blasted rock will improve frost resistance. This may be achieved, for example, by adding a gravel bed or filter layer of sand.

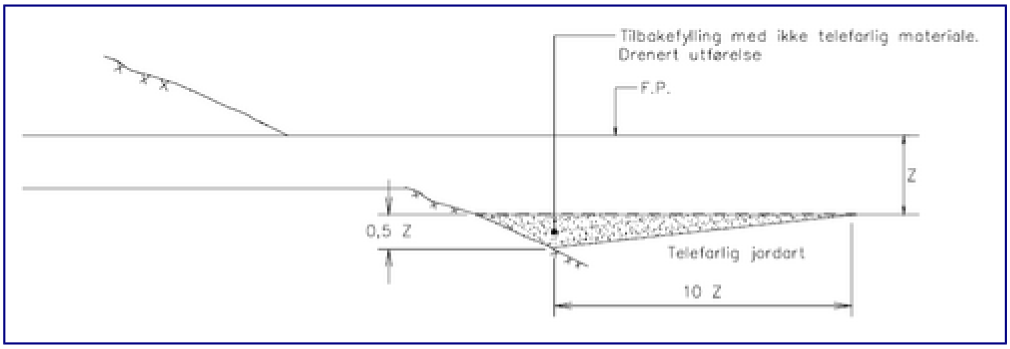


Figur 5: Design curve of total thickness of reinforcing layer and frost protection layer of blasted rock

5 Frost protection in special conditions

6 Rock cutting

Generally, deep blasting in rock cuttings should be performed to the same depth as spoil extraction from adjacent earth cuttings. Because frost propagates faster and deeper in rock than in uncompacted materials, a wedge with non-frost-susceptible materials must be included over a specified length closest to the rock cutting, as shown in Figure 6. The depth must be set to 0.5 · Z, where Z represents the thickness of the reinforcing layer and frost protection layer. The length of the wedge is normally set to 10 · Z.



Figur 6: Wedging of frost protection layer at point of transition to rock
If, in exceptional cases, rock cuttings are not deep blasted, the rock surface must be laid bare and cleaned of quarry dust and all frost-susceptible material before backfilling takes place. Insulation with XPS must be considered, in addition to wedging.

6.1 Frost protection of water channels, culverts and underpasses

In respect of water channels, culverts and underpasses, the structure's size will affect the required thickness of the frost protection layer.

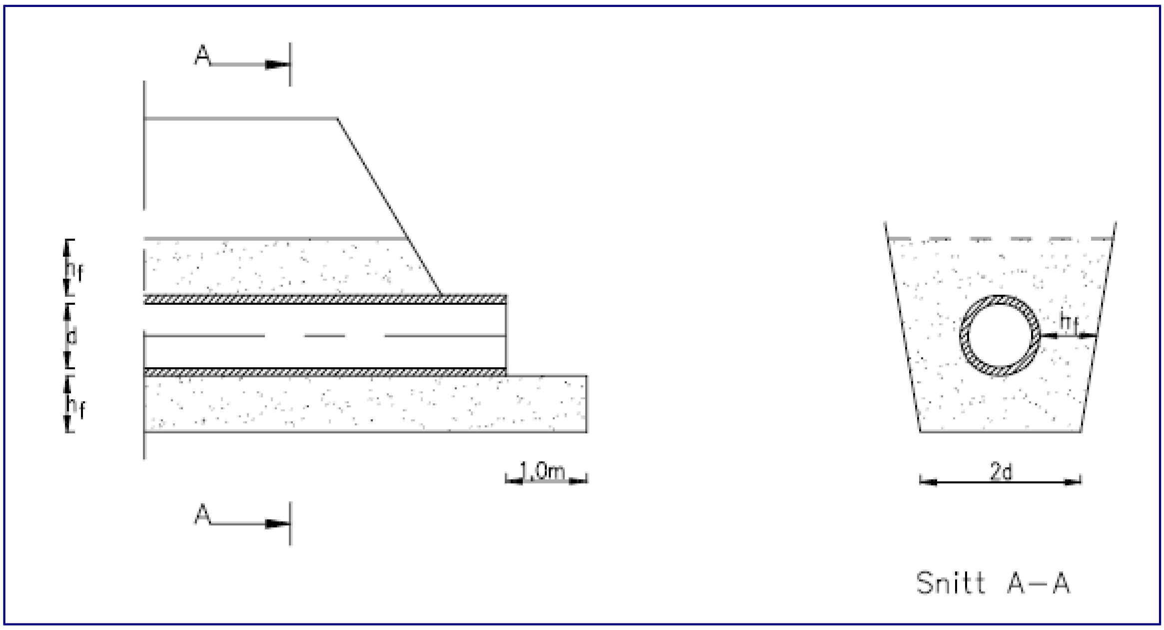
Frost will penetrate the actual channel and should usually be expected to affect the whole length. The thickness of the frost protection layer, h_f, is dependent on the cross-section of the channel.

Refer to Table 8.

Tabell 8: Thickness of frost protection layer, h_f

	Maximum internal height or width, d (m)	Thickness of frost protection layer, h_f (m)			
				1.0	$h_f = 0.3 \cdot d (Z + 0.5)$
Water channel, culvert, underpass	> 0.6		5.0		
				d > 1.0	$h_f = (0.3 + 0.1d) (Z + 0.5)$

Z (m) equals the total thickness of the reinforcing layer and the frost protection layer in accordance with avsnitt 4.



Figur 7: Frost protection of water channels

6.2 Retaining walls

The foundations of retaining walls must be frost-free in accordance with the maximum permissible frost level (F_{100}) regardless of the standard of the line. Non-frost-susceptible backfill materials must be used in the frost zone. The thickness of the layer is h_f. (Refer to Figure 8.).

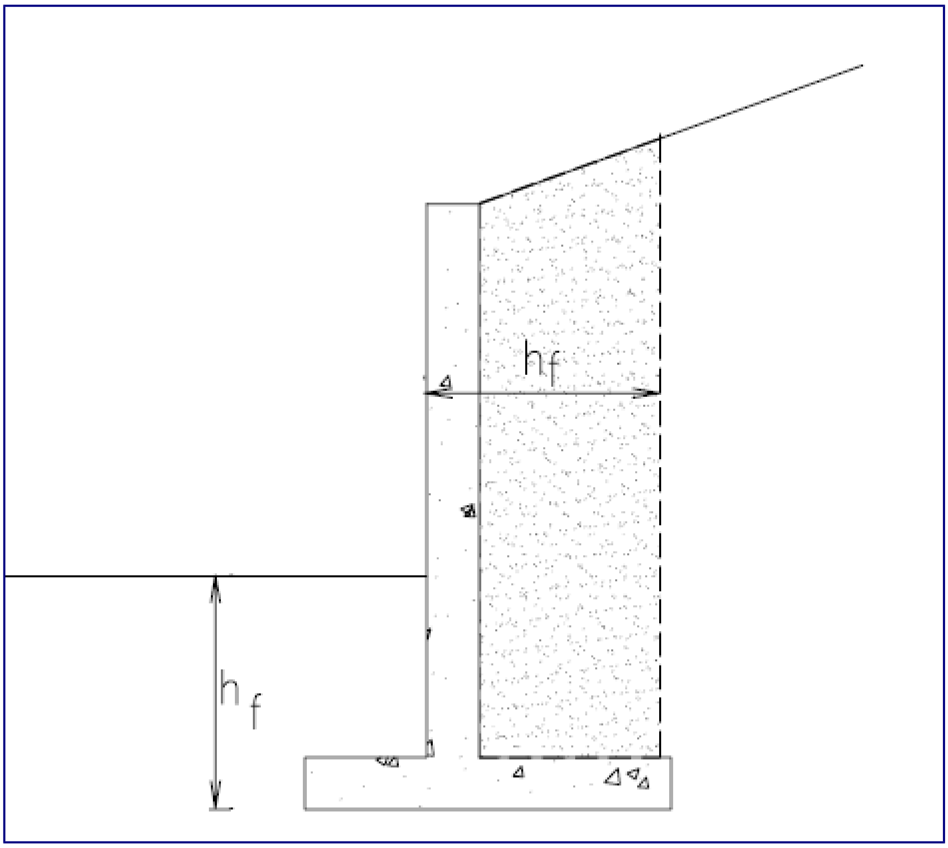
Stones larger than 300 mm are not permitted. The work must be conducted in such a way as to ensure that the rock material does not damage the structure during infill. If the retaining wall is designed for traffic loads, the backfill material must be compacted with a plate compactor.

If the rock material is too open to prevent the penetration of fines, fibre membrane must be used on the soil.

Cf. also Underbygning/Prosjektering og bygging/Stabilitet.

h_f (m) = Z + 0.5

Z (m) equals the thickness of the reinforcing layer and the frost protection layer in accordance with avsnitt 4.



Figur 8: Example of frost protection of a retaining wall