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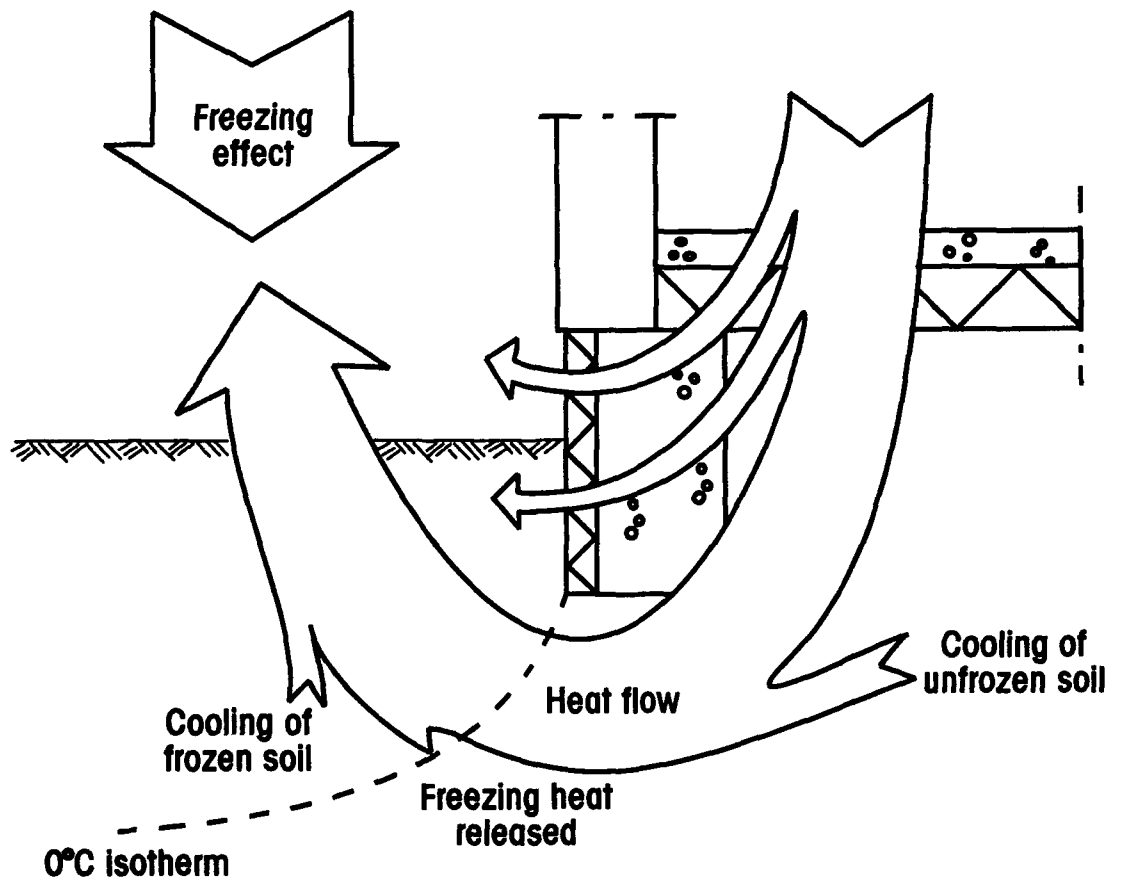
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European Foundation Designs for Seasonally Frozen Ground

Omar Farouki

March 1992

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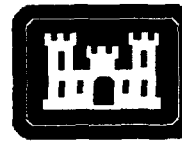
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For conversion of SI metric units to U.S./British customary units of measurement consult ASTM Standard E380, Metric Practice Guide, published by the American Society for Testing and Materials, 1916 Race St., Philadelphia, Pa. 19103.

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**U.S. Army Corps
of Engineers**
Cold Regions Research &
Engineering Laboratory

European Foundation Designs for Seasonally Frozen Ground

Omar Farouki

March 1992

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PREFACE

This report was prepared by Dr. Omar T. Farouki, Senior Lecturer, Department of Civil Engineering, The Queen's University of Belfast, Northern Ireland. Funding for this work was provided by the Office of the Chief of Engineers under Program Element 6.27.84A, Project 4A762784AT42, Task BS, Work Unit 013, *Improve Design Criteria for Foundations in Cold Regions*. This report was technically reviewed by Lawrence Danyluk and Frank Sayles, both of CRREL.

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CONTENTS

	Page
Preface	ii
Introduction	1
Background	1
Design criteria	6
Freezing index	6
Mean annual temperature	8
Soil frost susceptibility	8
Frost penetration	8
Critical isotherm	13
Foundation depth.....	15
Factor of safety.....	16
Slab-on-grade foundations.....	16
Principles	16
Use of slab-on-grade foundations.....	18
Factors influencing frost penetration	21
Thermal considerations for buildings and foundations.....	25
Foundation depth and ground insulation	40
Protection against moisture from the ground.....	49
Slab-on-grade construction.....	51
Thermal insulation materials	53
Foundations with a crawl space or basement	53
Introduction	53
Heat flow conditions	56
Frost penetration	56
Floor temperature and thermal insulation	58
Foundation depth.....	59
Foundation wall insulation.....	62
Thermal insulation of basement walls	65
Drainage and thermal insulation	65
Foundation of basements	66
Frost problems	66
Frost protection of unheated buildings	68
Introduction	68
Frost load	69
Necessary thermal insulation	71
Variable heated and cold buildings.....	84
Designs with open foundations	86
Background from Frost I Jord project	86
<i>Building Details</i> guidelines for concrete piers.....	90
Frost protection during winter construction	91
Introduction	91
Design freezing index.....	92
Necessary thermal insulation.....	93
Some practical measures	95
Frost protection of building ground.....	96
Retaining walls and bridge foundations.....	99
Frost forces on walls	99
Design for frost protection.....	100
Insulation properties and use	101
Properties and use conditions	101

	Page
Ground insulation and its placement.....	105
Examples of insulation use	105
Retrofit of insulation	109
Conclusion.....	110
Literature cited.....	112

ILLUSTRATIONS

Figure

1. Maximum freezing index contours in Norway	5
2. Freezing index contours for F_{50} for Finland	6
3. Less stringent design values for the freezing index in Finland	6
4. Temperature zones in Sweden	7
5. Damping of temperature distribution in the ground by insulation	8
6. Mean annual temperatures in Norway (1931–1960)	9
7. Mean annual temperatures in Finland (1931–1960)	10
8. Contours for maximum frost depths in Norway	11
9. Influence of freezing index and snow cover thickness on frost depth	12
10. Frost penetration depth in frost-susceptible soil in Sweden	12
11. Design values for mean snow depth over a winter for Finland	12
12. Average frost-free depth for foundations of unheated structures on frost-susceptible soil in Finland, neglecting snow cover effects	13
13. Heave forces acting at right angles to the frost front	13
14. Frost penetration depth using -1°C as the critical isotherm	14
15. Frost I Jord frost criterion and definition of foundation depth z_g	14
16. Frost protection principle in Finland using a 0°C isotherm limitation	14
17. Example of finite-element mesh for determining isotherms	15
18. Slab-on-grade foundation, showing foundation depth h	16
19. Slab-on-grade foundation with edge-expanded concrete slab	17
20. Slab-on-grade foundation with separate slab and foundation walls	17
21. Combination slab-on-grade and basement foundation in sloping terrain	18
22. House on broken stone fill in sloping terrain	18
23. Foundation and slab cast as one unit and reinforced, acting together to distribute the wall loading over a larger area on wet ground	19
24. Slab-on-grade design used in the Skjetten development	19
25. Use of outside insulation on the foundation wall, guiding heat down to the foundation	20
26. Use of horizontal ground insulation to keep frost away from the foundation	20
27. Frost penetration near a heated building with a slab-on-grade foundation	20
28. Types of floor slabs.....	20
29. Position of the -1°C isotherm at different times	21
30. Relationship between outside temperature variation and frost penetration at a foundation	21
31. Influence of floor insulation R_1 on frost penetration depth for two cases	22
32. Effect of removing floor insulation where horizontal ground insulation is used	22
33. Influence of foundation wall insulation R_2 on frost penetration	23
34. Influence of pedestal height h on frost penetration depth	23
35. Frost penetration depth as a function of the distance from a corner	24
36. Cold bridge effect with a concrete foundation wall	24

	Page
37. Foundation design that has no cold bridge	25
38. Heat losses from a house with a slab-on-grade foundation	26
39. Heat loss from the ground during the freezing process	27
40. Poorly insulated floor, giving a lower floor temperature but some heat to frost-protect the foundation wall	27
41. Well-insulated floor, giving a higher floor temperature but little heat to frost-protect the foundation wall	27
42. Cold bridge, giving an uncomfortable floor temperature	28
43. Heating cable in the floor, giving a satisfactory floor temperature up to the outer wall	28
44. Heat flow through the floor and wall	28
45. Foundation designs investigated in the Danish study	29
46. Traditional Danish slab-on-grade house foundation	29
47. Foundation wall of expanded clay blocks	29
48. Results of the heat flow analysis in the Danish study	30
49. House foundation and three progressively improved versions	30
50. Slab-on-grade design on which the computer analysis of floor temperature is based	31
51. Effect of variation in air temperature on floor temperature at points 0.3 and 1.0 m from the outer wall.	31
52. Edge-stiffened concrete slab with insulation on top of the slab	32
53. Edge-stiffened concrete slab with insulation cast into the slab	32
54. Edge-stiffened concrete slab with insulation under the slab	33
55. Concrete slab with ground insulation and a foundation wall of light-weight clinker blocks on a concrete footing	33
56. Recommended U -values for slab-on-grade foundations for buildings heated to at least 18°C	34
57. Division of construction into layers and fields	35
58. Curves for determining floor insulation thickness from U -values	36
59. Recommended location of insulation in association with a foundation wall	38
60. Types of foundation wall	39
61. Effect of ground insulation on isotherms	40
62. Freezing zone's influence on ground construction	40
63. Frost penetration at a corner of a building	41
64. Frost penetration 0.8 m from a corner of a building	41
65. Frost penetration at a corner of a building when foundation wall insulation is used.	41
66. Frost penetration 0.8 m from a corner of a building when foundation wall insulation is used	42
67. Frost penetration at a corner of a building when foundation wall insulation is extended 0.3 m into the ground	42
68. Frost penetration 0.8 m from a corner of a building when foundation wall insulation is extended 0.3 m into the ground	42
69. Oblique frost forces at a corner of a building	42
70. Oblique frost forces 0.8 m from a corner of a building	43
71. Frost penetration at a corner of a building when foundation wall insulation is extended 0.3 m into the ground and a heating cable is used	43
72. Frost penetration at a corner of a building when foundation wall insulation is extended 0.3 m into the ground and ground insulation is used at the corner	43
73. Frost penetration at a corner of a building when the foundation protrudes by a distance a	43

	Page
74. Example of calculated temperature distribution at a foundation	44
75. Placement of ground insulation	45
76. Ground insulation at corners and outside an unheated small room	46
77. Ground insulation along all walls, at corners and outside an unheated small room	46
78. Thermal resistance of ground insulation according to foundation depth and local freezing index	47
79. Location of heating cable	48
80. Position of the damp-proof course for floors with damp-proof floor coverings	49
81. Concrete slab with internally insulated concrete foundation wall	50
82. Concrete slab with externally insulated concrete foundation wall	50
83. Concrete slab with foundation wall of light aggregate concrete	51
84. Light floor with foundation wall of light aggregate concrete	52
85. Light floor and concrete slab with expanded edge	52
86. Wood-surfaced floor with edge-expanded concrete slab	53
87. Foundation with a crawl space	54
88. Cold crawl space ventilated with outside air, usually through openings in the foundation wall	54
89. Warm crawl space ventilated with heated inside air	54
90. Combination of crawl space with basement and slab-on-grade in steep terrain	55
91. Ventilation of a crawl space through the ceiling	55
92. Foundation wall cast in concrete	56
93. Heat flow through a cold crawl space under a heated building	56
94. Isotherms for a long building	57
95. Isotherms for a square building	57
96. Recommended thermal insulation vs design freezing index for a floor structure over a cold crawl space to obtain a floor surface temperature of at least 17.5°C with an inside temperature of 21°C	58
97. Crawl space foundation on non-frost-susceptible ground	59
98. Foundation depth for cold or unheated buildings	59
99. Minimum foundation depth for a crawl-space foundation under a continuously heated building on frost-susceptible soil	61
100. Design of frost protection for heated structures with crawl spaces.	62
101. Placement of insulation with reduced foundation depth	62
102. Effect of insulation on isotherms for a floor structure with a crawl space	63
103. Design curves for the <i>U</i> -value of a 2.5-m-high concrete basement wall with the same thickness of Roofmate SL/Perimate DI Styrofoam above and below ground	64
104. Design curves for the <i>U</i> -value of a 2.5-m-high concrete basement wall with the extra insulation thickness under the ground	64
105. Design curves for the <i>U</i> -value of a 6-m-high insulated concrete basement wall with the top 0.5 m above the ground	64
106. Alternate designs for basement wall drainage	65
107. Replacement of steeply inclined frost-susceptible material by coarse draining material	65
108. Protection and drainage of a basement wall.	66
109. Recommended design of a basement foundation where one basement wall is exposed to outside air	67
110. Horizontal component of frost heave acting on a basement wall when the soil surface is inclined	67

	Page
111. Inclined frost heave along a basement wall when there is a snow-free zone along the wall	67
112. Thermal insulation limiting frost penetration so that the frost-susceptible soil under the structure does not freeze	68
113. Different values for F_d for the foundation wall and the floor	69
114. Reduction factors for the freezing index in Finland	71
115. Width of ground insulation for cold structures	72
116. Typical positions of ground insulation to protect a slab, a foundation wall and a column	73
117. Effect of ground insulation position on the isotherms for a cold structure ...	73
118. Drainage layer under a floor and foundation wall	74
119. Necessary thickness of Styrofoam as a function of design freezing index and mean annual temperature	75
120. Frost protection of a foundation wall and slab	75
121. Frost protection of a foundation and slab cast as one unit	76
122. Frost protection of a small building such as a garage or free-standing shack	76
123. Frost protection of a foundation for large loading using inside formwork ...	76
124. Frost protection of a foundation for large loading using no inside formwork	76
125. Frost protection of a column foundation with a wall girder	77
126. Extra frost protection at a corner	77
127. Omission of frost protection of the floor if the inside temperature stays above 0°C	78
128. Dangerous design with a foundation wall	78
129. Dangerous design with a column foundation	78
130. Building where only the foundation wall is frost protected	79
131. Frost protection of the foundation for a levegger wall, atrium wall or foundation strip	79
132. Frost protection of a cantilever wall	79
133. Frost protection at a corner and end of a foundation	80
134. Alternative treatments of a retaining wall	80
135. Frost protection of columns and column foundations	81
136. Differential movement between cold and heated parts of a building	82
137. Examples of frost protection of heated buildings and their cold parts	82
138. Frost protection of an exterior cellar staircase	83
139. Frost protection of a foundation for an entrance staircase	84
140. Frost protection of a landing and stairway with a closed-in entrance	85
141. Frost protection of a garage entrance drive	85
142. Designs for heated or cold buildings that are satisfactory with regard to frost penetration requirements	86
143. Houses on piers, which are especially suited to places with steep or rolling terrain or ground with bad drainage	86
144. Recommended U -values for floor structures	86
145. Frost heave and sidegrip	87
146. Pier taken down to the frost-free depth and anchored against the lifting force from ice sidegrip	87
147. Types of open foundations	88
148. Necessary footing size for carrying the load of a pier	89
149. Necessary footing area for anchoring against sidegrip	89
150. Section of pier with a footing	90

	Page
151. Elevated house to keep it dry in wet conditions	90
152. Anchoring of beam to columns.....	90
153. Pier positions to give approximately the same load on each pier under a bearing wall	91
154. Horizontal heave forces on a vertical structure	92
155. Estimation of a partial design freezing index	92
156. Necessary insulation thickness for frost protection with expanded polystyrene insulation	95
157. Thicknesses of thermal insulation and drainage material that give frost protection, together with the necessary width b of the ground insulation outside the foundation wall	95
158. Foundation placed on ground insulation	96
159. Example of cast-in-place pier	96
160. Calculations of frost penetration in undisturbed ground with no insulation	97
161. Calculations of frost penetration with 50-mm-thick insulation 9.20 m wide; thermal conductivity of insulation = 0.046 W/mK	97
162. Calculations of frost penetration with 100-mm-thick insulation 9.20 m wide; thermal conductivity of insulation = 0.046 W/mK	97
163. Insulation extended 1.0–1.5 m outside the area that should be frost-protected	99
164. Proposal for design values for frost pressure, based on observations	99
165. Frost protection of retaining walls and bridge foundations	100
166. Insulation with a pile foundation for a retaining wall	101
167. Temperature difference caused by insulation	101
168. Necessary insulation thickness as a function of required thermal resistance and insulation's thermal conductivity	102
169. Possible arrangements of floor layers	103
170. Design thermal conductivity of expanded polystyrene for frost protection under different use conditions	104
171. Design thermal conductivity of extruded polystyrene for frost protection under different use conditions	104
172. Design thermal conductivity of light aggregate for frost protection under different use conditions	104
173. Design thermal conductivity of mineral wool for frost protection under different use conditions	105
174. Method of placing insulation for frost protection as a foundation is being constructed	106
175. Examples of protection of ground insulation	106
176. Types of slab-on-grade construction showing insulation	107
177. Types of slab insulation	107
178. Leca foundation wall and ground insulation	107
179. Foundation design using two layers of extruded polystyrene, an edge-expanded concrete slab and ground insulation of extruded polystyrene	108
180. Recommended thickness of polystyrene ground insulation for Sweden	108
181. Foundation with crawl space and leca foundation wall	108
182. Alternative placement of insulation for a narrow strip foundation	108
183. Dimension of insulation for foundations of cold structures in Sweden	109
184. Effect of ground insulation on 0°C isotherm	109
185. Recommended thicknesses of ground insulation in Sweden	110

TABLES

Page

Table

1. Correction factor for maximum frost depth in Norway	8
2. Conversion coefficients for frost depth in Finland	10
3. Greatest heat flow through floor surface in a square building 10 × 10 m situated in Stockholm	26
4. Relationship between floor surface temperature and internal heat transfer resistance R_i	30
5. Thermal resistance of the ground R_j	34
6. Floor insulation thicknesses satisfying regulations	35
7. Recommended increase in insulation thickness for various values of maximum freezing index	37
8. Maximum allowable U -values and minimum thermal resistances for the floors of heated and partly heated structures with slab-on-grade foundations	37
9. Approved least thermal resistance of edge insulation	38
10. Necessary foundation wall insulation of expanded polystyrene or mineral wool for three floor heights	38
11. Minimum foundation depth with ground insulation only at the corner and outside an unheated small room	45
12. Necessary ground insulation with a foundation depth of 0.4 m	46
13. Heated structures (inside temperature $\geq 17^\circ\text{C}$) frost-free foundation depth in frost-susceptible soil for slab-on-grade foundations with insulation outside the foundation wall	47
14. Necessary cable power for frost protection	48
15. Maximum allowable U -value and minimum thermal resistance for floor structure of heated and partly heated buildings with crawl space	58
16. Lifting force transmitted by sidegrip to unprotected piles or piers with diameter 200 to 350 mm in dry crust clay	59
17. Reduction factor β with respect to frost penetration depth for a foundation construction below a heated building with a floor construction above an enclosed crawl space ventilated by outside air	60
18. Frost-free foundation depth in frost-susceptible soil for a heated structure with a crawl space	62
19. Thickness of insulation under a foundation wall associated with a crawl space	63
20. Thermal resistance of the ground R_j for a basement outer wall with a fill height H (m) above the basement floor	64
21. Reduction factor for uninsulated floor construction laid on the ground	66
22. Guidelines for choosing F_d for frost protection of construction and ground, permanently or during the building period	70
23. Maximum frost heave	70
24. Necessary thermal resistance R_o with frost insulation to prevent frost heave under cold insulated structures	71
25. Thermal resistance of ground insulation for protection of cold structures ...	72
26. Frost protection with expanded polystyrene and underlying drainage material	74
27. Correction factor for insulation thickness given in Table 26 with use of other insulation material	75
28. Necessary insulation width outside a foundation wall	75
29. Necessary insulation width for protection of a foundation wall	78
30. Necessary insulation width for protection of a column foundation	78

31. Friction between a pile and the under-the-frost zone	88
32. Necessary size of square pier footing for anchoring against frost sidegrip for various specific loads	91
33. Necessary thermal resistance R_0 with frost insulation for winter covering of uninsulated construction and building ground	93
34. Thermal resistance of insulation for protection of building ground	94
35. Necessary insulation width b outside the foundation wall	95
36. Necessary insulation thickness with use of winter material	98
37. Density, compressive strength and thermal conductivity of insulating materials	102
38. Properties of materials used in building construction	105

LIST OF SYMBOLS

b	Width of ground insulation
d	Thickness of drainage layer or other material
F	Freezing index ($h^{\circ}C$)
F_d	Design freezing index
F_{100}	Maximum freezing index in 100 years
h	Height of top of foundation wall, or bottom of floor structure, above outside ground level (the pedestal height)
h_o	Frost penetration depth in undisturbed ground
H	Outside soil height above the basement floor
MAT	Mean annual temperature ($^{\circ}C$)
Q-2	Two-dimensional heat loss through floor and wall
R	Thermal resistance of a homogeneous plane material layer in the floor
R_e	Thermal resistance of existing structure
R_g	Thermal resistance of air space in the floor structure
R_i	Internal heat transfer resistance (inside air to floor surface)
R_j	Thermal resistance of the ground underlying the building
R_o	Thermal resistance of insulation layer
R_t	Thermal resistance of the floor structure
R_T	Total thermal resistance of the floor structure against the ground (i.e. including the effect of the underlying ground)
R_1	Thermal resistance of floor insulation (m^2K/W)
R_2	Thermal resistance of foundation wall or edge beam insulation
R_3	Thermal resistance of ground insulation
t	Thickness of insulation
t_o	Insulation thickness as obtained from Figure 58
T_{in}	Internal temperature in building ($^{\circ}C$)
T_m	MAT averaged over a 30-year period
T_{out}	External air temperature ($^{\circ}C$)
U-value	Heat loss per unit area from part of a structure (W/m^2K)
v	Ventilation rate from a crawl space
z_g	Foundation depth
z_f	Frost penetration depth
β	Reduction factor applied to h_o
λ	Thermal conductivity (W/mK)
λ_p	Practical value of thermal conductivity

European Foundation Designs for Seasonally Frozen Ground

OMAR T. FAROUKI

INTRODUCTION

Foundations in cold regions need to be adequately designed against frost action. Otherwise damage may result from the heave of freezing soil under and around the foundations. In particular, the foundation depth should extend below the depth of frost penetration in frost-susceptible soil.

This report draws from the design codes and practices in Europe, particularly the Scandinavian countries, where the problems are most intense and where considerable experience has evolved related to specific foundation designs against frost action. Personal visits and contacts with designers in Scandinavia provided additional information.

In recent years the tendency has been to use shallow foundations with associated insulation that utilizes some of the heat from the building to reduce the depth of frost penetration at the foundation. The background to this is described in the next section, and the various design criteria used in Scandinavian practice are then detailed. The report then considers designs of slab-on-grade foundations according to the guidelines of Norway, Sweden and Finland. These specify the required insulation, taking into account factors influencing frost penetration and foundation depth.

Designs of foundations with a crawl space or basement are then described. Requirements for insulation are given and frost problems discussed, including possible sidegrip of freezing soil adjacent to foundation or basement walls.

A section on unheated buildings shows how designs against frost action for these cases are based on the principle of limiting the loss of soil heat that is stored in the ground during the summer. This is done by insulating under the building; horizontal insulation boards are laid on top of a coarse drainage layer.

Designs with open foundations, such as piers and piles, are then described, sidegrip being an

important consideration. The following sections consider protection against damage that may arise during winter construction and deal with frost protection of retaining walls and bridge foundations.

The report then looks at insulation properties and gives examples of insulation use. The concluding section emphasizes some of the main points in current Scandinavian foundation design and considers research requirements.

BACKGROUND

Foundation design in areas of frost depends on the choice of an appropriate foundation depth and protection of the foundation from the effects of frost, particularly where there is frost-susceptible soil. Harmful frost action arises under certain conditions. Frost must penetrate down to frost-susceptible soil, and sufficient water must be available to feed ice lens formation and growth in this soil at an adequate rate. Ice lenses produce forces that are usually directed at right angles to the frost front. These forces can be very large and can lead to heaving of all or parts of the foundation as the soil freezes below. The magnitude of the heave forces cannot generally be determined. It is impractical to fully restrain heave, so one should design so that it does not take place at all. In practice this means that any frost-susceptible soil that can affect the foundation must be insulated so it will not freeze or that it must be replaced by non-frost-susceptible material or that water is prevented from being supplied to the freezing front.

Frost damage can also arise from "sidegrip" occasioned by the lateral shearing stress exerted by the freezing soil on adjacent foundations, such as foundation walls or strips, columns or posts. There is then a tendency for these to be lifted up by shearing forces acting along their side surfaces; this is counter-

acted by the weight of the foundation, by the load it carries and by anchorage below the frost line.

In certain cases, freezing of frost-susceptible soils can produce horizontal forces, causing the buckling of basement walls, retaining walls and the like. These forces are difficult to estimate and should be prevented from occurring by suitable design, by insulation, by preventing capillary water from rising to the freezing front, or if possible, by lowering the ground water level in the vicinity of the wall.

In the Scandinavian countries there have been many instances where foundations have been based at reduced depths and protected by insulation. A reduced depth is one that is shallower than the frost-free depth in undisturbed ground. Such a shallow depth has usually been used with "light" buildings that exert only a small bearing pressure on the underlying ground. These include buildings of a large extent, such as warehouses, if the bearing pressure is sufficiently reduced by means of spread foundations. Heavy structures that exert large bearing pressures generally require deeper foundations extending to firm soil layers or to rock. The foundation depth is then usually greater than the frost-free depth, and problems due to frost action do not arise.

In Sweden, foundations with reduced depths were built since around the 1920s, and by 1975 about 50,000 houses with "slab-on-grade" had been built and generally functioned satisfactorily (Torgerson 1975). They had a concrete slab more or less at grade level and an edge beam or foundation wall transferring the main building load to ground at a shallow depth. However, foundation depths for light buildings varied from a value of 0.25 m all the way down to the full frost-free depth in undisturbed ground.

The Swedish building standards of 1967 (SBN 1967) specified a foundation depth of 0.25 m as a general rule for the whole country. However, this depended on certain conditions being satisfied, and local circumstances could necessitate a deeper foundation. Where frost-susceptible soil existed, the foundation depth had to be increased sufficiently so that no damage occurred from frost heave or sidegrip. This meant that factors influencing frost penetration had to be considered and due regard given to heat from the building, the soil's characteristics, ground water conditions, drainage and insulation. Then one could determine how much the foundation depth could be reduced in comparison with the frost-free depth in undisturbed ground.

The guidelines in SBN (1967) were based partly on experience relating to a large number of com-

pleted buildings and partly on temperature measurements and theoretical calculations, e.g., by Adamson and others in 1964. However, the theoretical basis was somewhat unsatisfactory, partly because of the difficulty at that time of mathematically analyzing the problem of heat flow in the foundation soil area. Modern computer techniques enabled this problem to be solved in sufficient detail with the determination of temperature distributions for different building designs and climatic conditions. The effects of various factors (e.g. insulation placed at various locations) on frost penetration were assessed by Adamson et al. (1971, 1973) and Adamson (1973). This eventually led to revision of SBN (1967) to produce the 1980 version of the Swedish building standards (SBN 1980).

Norwegian experience with slab-on-grade designs came later than for the Swedes. Methods of construction based on a reduced foundation depth began to be used in Norway around 1950, and test houses with slab-on-grade foundations were built in 1955. A survey by Skaven-Haug (1961) of 432 Norwegian municipalities showed that the recommended minimum foundation depths varied from 0.75 m (in Kristiansund) to 1.88 m (in Finnmark), with a mean value of about 1.45 m. Foundations with reduced depths were less expensive due to easier and less costly foundation methods and possible economies in materials. The economic advantages could be substantial in the case of an integrated multiple house development, especially if prefabricated techniques could be used, as was done in the Skjetten development completed in 1972.

The limited Norwegian practical experience with light buildings was assessed around the late 1960s when Thue (1973) surveyed 25 different designs of slab-on-grade construction with insulation. The survey showed that there was no frost damage after occupation and heating of the buildings but that slight damage occurred where there were connections to unheated auxiliary buildings or extensions, such as car ports. The most important conclusion from the survey was that it was essential to protect the construction operation and the foundation during the winter; otherwise damage due to frost was liable to occur. Swedish practical experience was also assessed, and although cases in Sweden showed rare occurrence of damages, one must bear in mind possible differences between Norway and Sweden as regards soil conditions and climatic effects. In Sweden, as in Norway, there were some damages associated with unheated accessories to heated buildings that could have been avoided by allowing free movement of the associated cold

section. Also, in Sweden there were cases of a "cold bridge" (a path of low resistance to heat flow) at the connection between the foundation wall, the floor and the outer wall in a heated house, leading to excessive heat losses and uncomfortable floor temperatures.

The results of such surveys and assessments were taken into account in the Norwegian building guidelines, which came into effect in 1970. Before that, in the building code regulations of 1949, the requirement was that foundations had to go down to the frost-free depth (in undeveloped ground during a hard winter) or to frost-resistant rock. There was no differentiation between foundations of heated buildings such as houses and foundations of unheated buildings or other structures.

The Norwegian regulations that came into force in 1970 stipulated that the foundations be built so that no damage occurs from frost action, neither from heave nor from sidegrip arising from frost-susceptible soil. This implies that, as long as this requirement is satisfied, the foundation depth may be less than the frost-free depth in undisturbed ground. Additionally, protection is required against the rise of moisture and water vapor into the building. Also, the joint between the floor and the foundation wall and outer wall must not form a cold bridge.

The 1970 rules were based on fundamental principles. The requirement was a "finished product" conforming to these principles, while the decision process and detailed design were left to the engineer.

The change in the building regulations opened the way to nontraditional foundation designs. The basic idea in placing a foundation at a reduced depth is to limit the frost penetration near the foundation by using the heat escaping from the building or the heat released from the associated soil on cooling and freezing (known as soil heat). This soil heat is stored in the ground during the summer. Insulation placed horizontally in the soil limits release of the soil heat to outside air during the cold season, so this heat is available to prevent the foundation area from getting too cold.

In the case of a heated house, the idea is to place adequate insulation at appropriate locations (e.g. at the foundation wall) so as to guide the escaping heat towards the base of the foundation, thereby preventing frost from penetrating near the base. To reduce the foundation depth it may also be necessary in certain cases to use artificial sources such as heating cables, but the economics of this would have to be justified.

Measures based on these ideas ensure that no

harmful effects arise from any frost-susceptible soil below the reduced frost penetration level. These concepts give protection from frost action, are comparatively easy to carry out, and lead to cost savings. The result has been that shallow foundations are usually used in Norway for light buildings.

To develop a set of guidelines for design against frost action, the Frost I Jord project was initiated in Norway around 1970 and continued until about 1976. The project was a coordinated venture between the Technical University in Trondheim and the Norwegian Building Research Institute (NBI) in Oslo, with others, such as consulting engineers, providing input. The important results of Adamson and his co-workers in Sweden on slab-on-grade and crawl space foundations were utilized and formed a basis for some of the results of the Frost I Jord project.

At the Institute for Building Technology (University of Trondheim), Thue (1974) considered that design against frost action can be approached on one of three levels. The first and simplest level is to produce a set of approved schematic designs for each of the four climatic zones in Norway. On the second level one develops a simplified procedure for calculations relating to a certain scheme. The user can quickly check whether a certain design solution is satisfactory from the thermal point of view. The third level is the highest and most complex method, whereby the transient heat conduction equation is solved by a finite-element computer technique with appropriate boundary conditions. This level would apply when a high safety factor is required and great detail is important. It also applies to complicated or extreme construction for which simpler methods are not applicable.

The computer programs developed by Thue are a powerful tool for analyzing heat flow associated with foundations in the ground. They produce a plot of the isotherms in the soil around the foundation of a particular building under given climatic influences taking into account any heat contribution from the building, the latent heat of fusion and the change in thermal conductivity of the soil on freezing. From the resulting location of the critical isotherm, the optimum insulation can be designed according to its material type, position, thickness and other dimensions. The important criteria are the depth of frost penetration in the ground around the foundation and the floor surface temperature inside the building.

The work of Thue and others at Trondheim was continued by Torgersen and others at NBI in Oslo and by consulting engineers like Algaard. The Frost

I Jord project produced a series of publications bearing the same name and culminating with *Frost I Jord*, No. 17, 1976. This issue brought together all the previous theoretical and practical experience in an extensive and comprehensive report that is considered by Scandinavian engineers to be a reliable guide for design against frost action in soils. It contains chapters written by experts on different aspects of foundation design.

Based on the results of the Frost I Jord project, NBI started publication in 1978 of a set of design sheets, the *Bygghjelp* (*Building Details*). These sheets also had input from the Norwegian building industry and took into account comments on previous guidelines. The sheets contain guidelines that were revised as necessary, the latest appearing in modified form in 1987. They have been simplified and directed to the people doing the building work. They are not considered as law but are accepted by local authorities and the building industry as sensible and reliable guidelines to follow. They are widely used in Norway by engineers, architects and builders for reference and design in their offices and by engineers and contractors on building sites.

The *Bygghjelp* sheets propose guidelines that have a built-in safety factor, although this is difficult to quantify. For standard cases the guidelines can save time, since there is no need to carry out a design using a computer program or some other method. In Norway, frost protection is generally based on the sheets, and specific computer designs are rare. For example, in 1987, NBI performed only one computer test of the heat losses associated with different slab-on-grade designs.

Although there had been prior research on frost effects in Finland, particularly in the mid-1970s, the Finnish guidelines of 1979 on foundation design against frost action were largely based on the results of the Norwegian Frost I Jord project with some amendments to suit local conditions in Finland. With the exception of Lapland, the Frost I Jord results were found to be generally applicable to most of Finland. However, more insulation is required under Finnish climatic conditions. The intent of installing insulation is to reduce frost damage, but some designers or contractors did not follow the guidelines properly, so damage has occurred in certain cases.*

* Personal communication with S. Saarelainen, Technical Research Center of Finland, Espoo, 1986.

On the basis of investigations of frost damage and experience with completed foundations, the 1979 guidelines were revised and new guidelines published in 1987 by the Geotechnical Laboratory of the Technical Research Center of Finland (VTT). This new "code" amended the 1979 code and introduced some changes, in particular stressing the necessity for extra insulation at corners of structures and the importance of continuous insulation under a foundation wall so that there is no cold bridge effect. The 1987 code also referred to the mean snow cover during winter rather than the maximum snow depth and suggested using a reduction factor to allow for snow cover in relation to unheated structures.

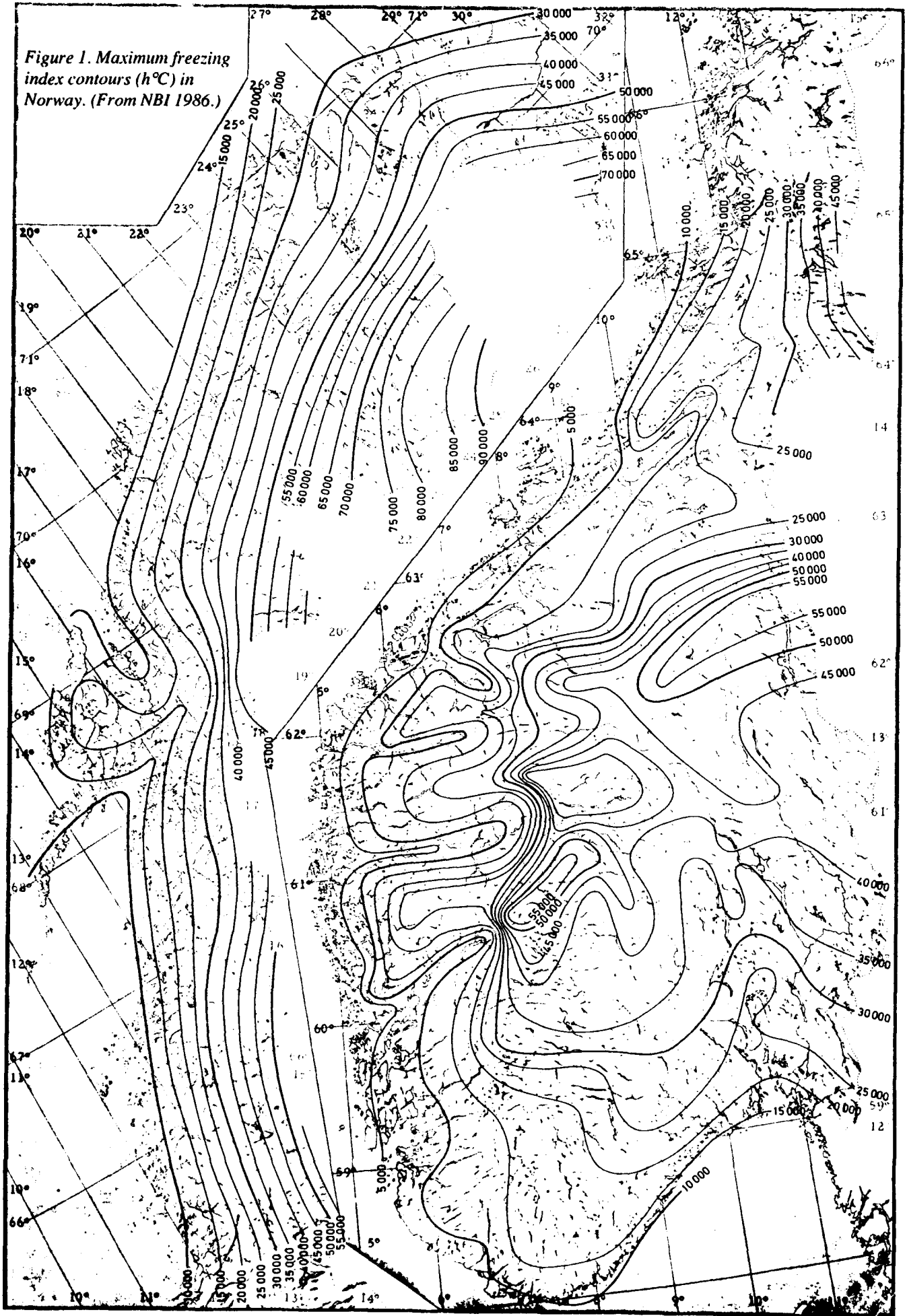
With regard to the economics of foundations, individual cases may need to be investigated specifically to determine the most economical foundation. In Austria the general preference is to place the foundation 0.2–0.5 m deeper using additional concrete rather than insulation. Contractors are not fond of using insulation because of the risks involved if it deteriorates with moisture uptake.* On the other hand, with the vast experience in using insulation in the Scandinavian countries, there is general confidence in its use and proper functioning over the life of a structure. During the 1970s the slab-on-grade method came to be generally applied in Norway because of its economy. As many as 50,000–100,000 houses have so far been built by this method with very good results (NBI 1986).

In Finland it is estimated that a single private house, constructed with a slab-on-grade foundation and insulation, can entail a saving of 200 to 300 Finnish marks (\$50 to \$75) per square meter (of foundation area) as compared with a foundation that extends down to the frost-free depth in moraine.** The latter case would involve extra expense due to additional excavation, additional time and the disposal of unwanted excavated material. The savings take into account the cost of the insulation and its installation. Considerable savings can thus result if a large development is carried out with many buildings involving similar shallow foundations. This agrees with the Norwegian experience as in the famous Skjetten project.

* Personal communication with H. Brandl, Technical University, Vienna, Austria, 1987.

** Personal communication with S. Saarelainen, 1986.

Figure 1. Maximum freezing index contours (h°C) in Norway. (From NBI 1986.)



DESIGN CRITERIA

Freezing index

The freezing index F at a locality represents the amount of frost occurring over a year and, in Scandinavia, is expressed as the product of the degrees Celsius below 0°C and the number of hours of frost conditions ($10,000\text{ h}^{\circ}\text{C} = 750^{\circ}\text{F days}$). F varies from year to year, and a suitable design value F_d needs to be chosen depending on the particular application.

In Norway the maximum F_d value used is F_{100} , which is the maximum freezing index occurring in 100 years. Contours of this maximum freezing index are given for different parts of the country in Figure 1 based on station records for more than 100 years. Lower values of F_d may be used in certain cases, e.g. F_{10} , F_5 or F_2 corresponding to the highest freezing index occurring in 10, 5 or 2 years, respectively.

In Finland the maximum value of F_d used is F_{50} , which may be found from Figure 2 for a particular locality. Less stringent design values of F_{20} , F_{10} , F_5 or F_2 (Fig. 3) are sometimes used for particular applications.

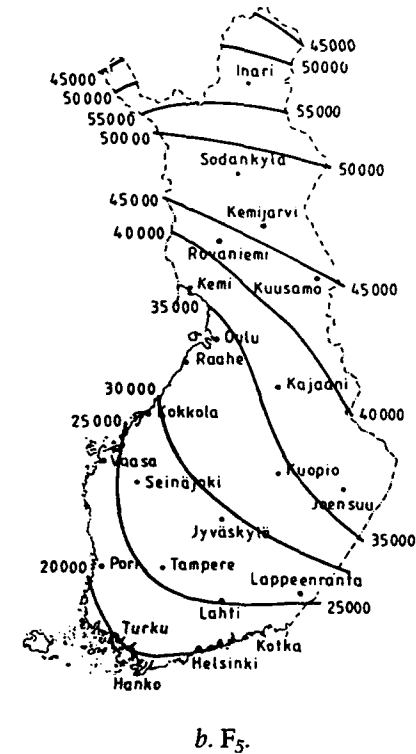
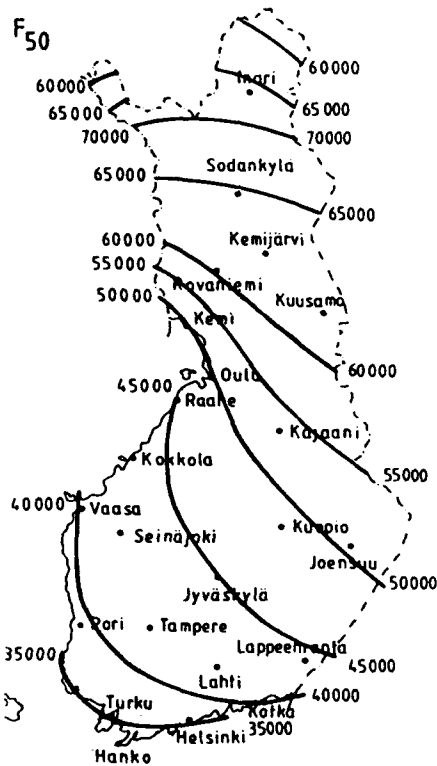
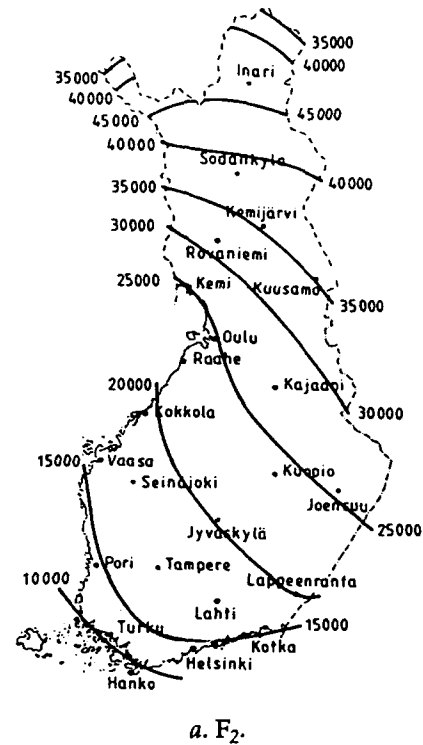
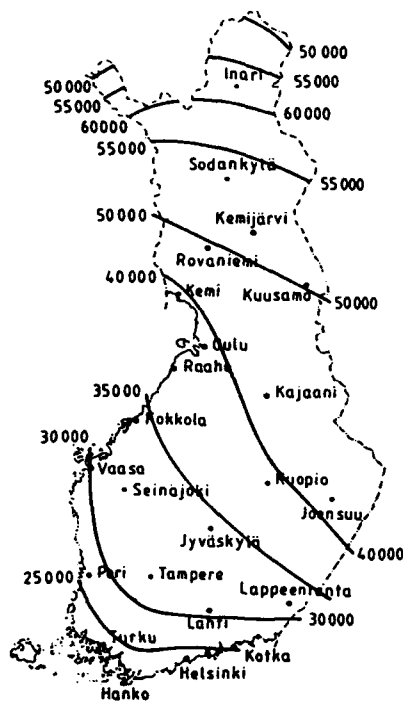
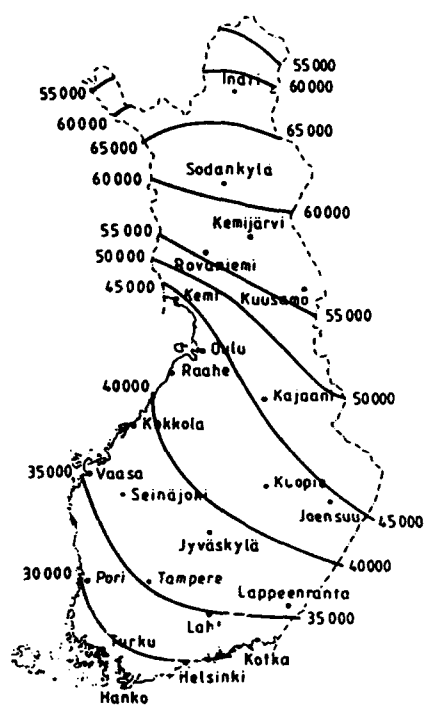


Figure 2. Freezing index contours for F_{50} for Finland. (From VTT 1987.)

Figure 3. Less stringent design values for the freezing index in Finland. (From VTT 1987.)



c. F₁₀.



d. F₂₀.

Figure 3 (cont'd).

The Swedish standards (SBN 1980) imply a maximum design freezing index of around F_{50} , since the frost penetration depth h_0 used in design corresponds roughly to the maximum frost depth in a 50-year period. Rather than using a freezing index, the Swedish standards refer to four temperature zones in Sweden ranging from the coldest zone I in the north of the country to the warmest zone IV in the south (Fig. 4). The zones do not have specific parameters such as the mean temperature and length of winter. They are used, for example, in specifying wall and floor insulation required to achieve an acceptable indoor climate.* In Norway

* Personal communication with S. Knutsson, Luleå University of Technology, Sweden, 1988.

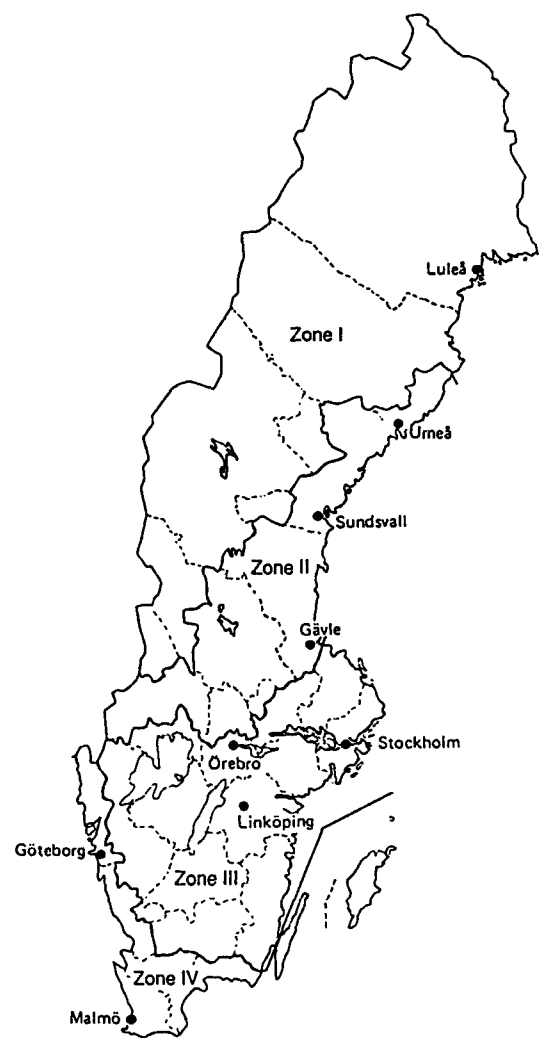


Figure 4. Temperature zones in Sweden. (From SBN 1980.)

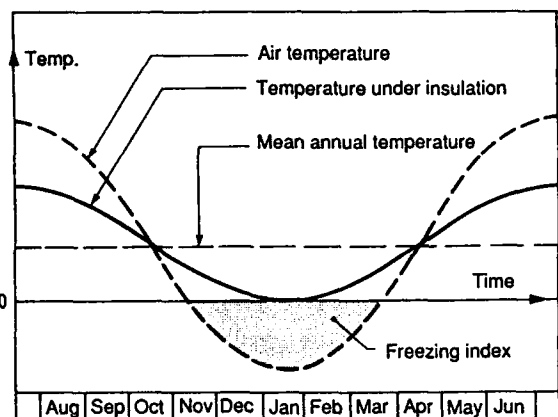


Figure 5. Damping of temperature distribution in the ground by insulation. (From NBI 1987.)

such specifications (e.g. describing the highest acceptable heat loss through building parts) are now the same for the whole country. Previously four temperature zones had been specified in the building code of 1981.*

In Denmark, a design freezing index of 12,000–15,000 h°C was chosen on the basis of the very severe winter of 1941–42, which corresponded to an occurrence of once or twice in a 100-year period (Porsvig 1986).

Insulation placed horizontally in the ground, i.e. ground insulation, limits frost penetration and reduces the effective freezing index under the insulation. Figure 5 shows the damping of the temperature distribution under the insulation. Correctly designed ground insulation should damp the temperature distribution so much that no frost occurs below the insulation.

Mean annual temperature

The mean annual temperature (MAT) of air at a locality is important in connection with the design of insulation placed in the ground outside the foundation. MAT is a measure of the soil heat stored in the ground over the summer warming period (Skaven-Haug 1972). Ground insulation retards the loss of this heat, so frost penetration is reduced. MAT also influences the extent of frost heave. MAT values are given in Figure 6 for Norway and in Figure 7 for Finland for the period 1931–1960.

* Personal communication with S.-E. Torgersen, Norwegian Building Research Institute, Oslo, 1988.

Soil frost susceptibility

Soil frost susceptibility is generally based on grain size distribution with various classifications (Chamberlain 1981). For example, there are three classes of susceptibility according to Swedish criteria. The Norwegian classification according to the State Road Board has four classes of susceptibility. In Austria frost susceptibility criteria are the same for building foundations as for road construction and have worked well over the last 15 years.* To reduce the risk of damage, a detailed assessment of the foundation soil's frost susceptibility and the ground water conditions is required.

Frost penetration

The frost penetration in free (i.e. undisturbed) ground h_0 is an important design criterion, as is the extent of its reduction by the effect of a building and its foundations. The frost depth is influenced by MAT, the geothermal gradient, the type of ground, its degree of saturation and the snow cover. For Norway, Figure 8 shows the maximum frost depth in undisturbed sandy gravel without a snow cover. Correction factors are applied for other materials as shown in Table 1, the factor for sandy gravel being taken as 1.0. No correction is usually made for the soil's water content, although the effect of this could be significant in some cases.

Table 1. Correction factor for maximum frost depth in Norway (Fig. 8). (From Frost I Jord 1976.)

Material	Correction factor
Stone	1.4
Sand/gravel	1.0
Silt	0.85
Clay	0.7
Turf	0.33

Figure 9, from the Finnish guidelines (VTT 1987), gives a rough estimate of the expected frost depth in different soil types depending on the freezing index and the presence of a snow cover. This cover is normally present almost all winter except for relatively short periods of variable melting in fall and spring. Due to uneven accumulation of snow at a building and its removal from trafficked areas,

* Personal communication with H. Brandl, 1987.

Standard normals of air temperature, Norway
Meteorological Institute,
Oslo (°C).

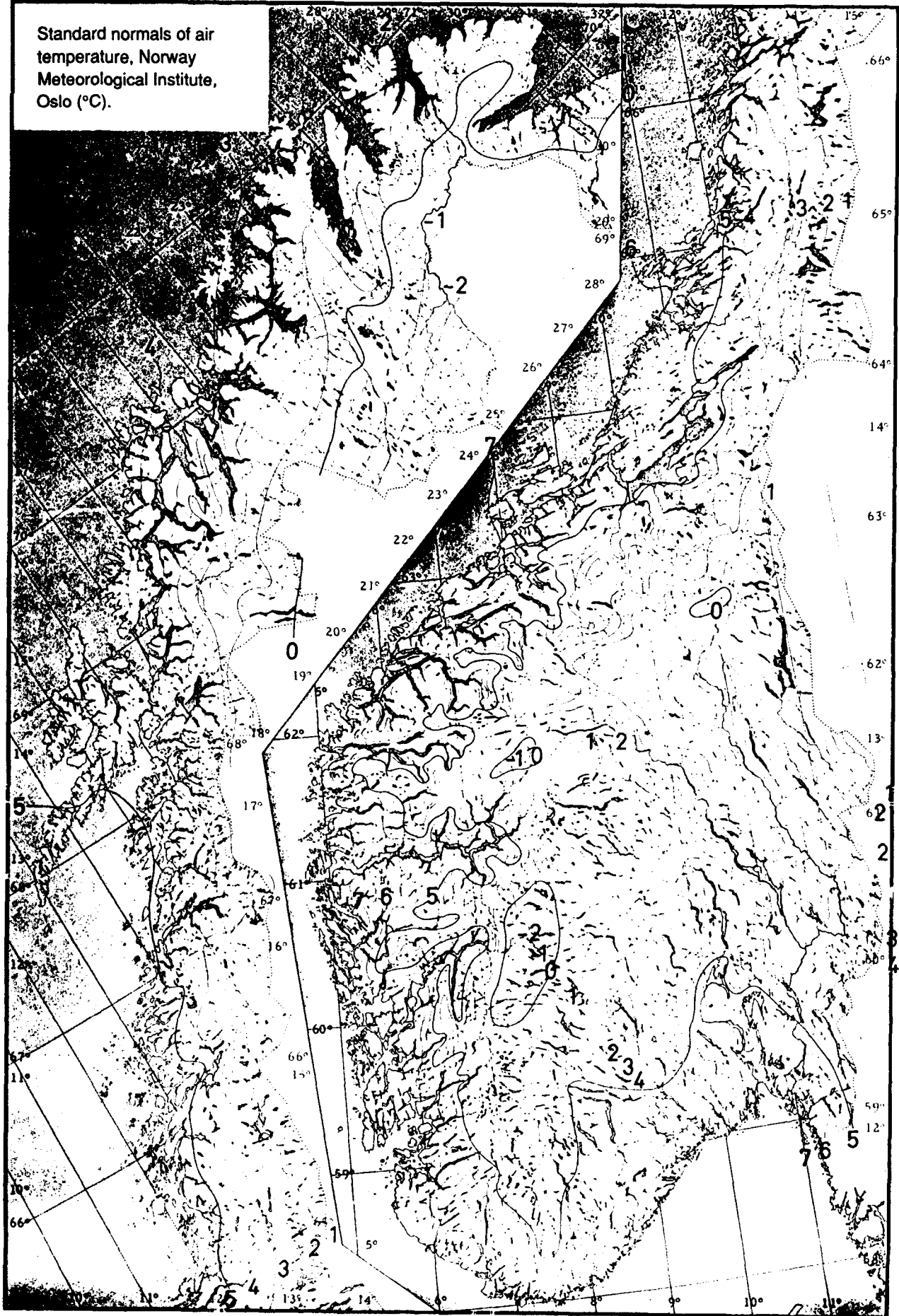


Figure 6. Mean annual temperatures in Norway (1931-1960). (From Frost I Jord 1976.)

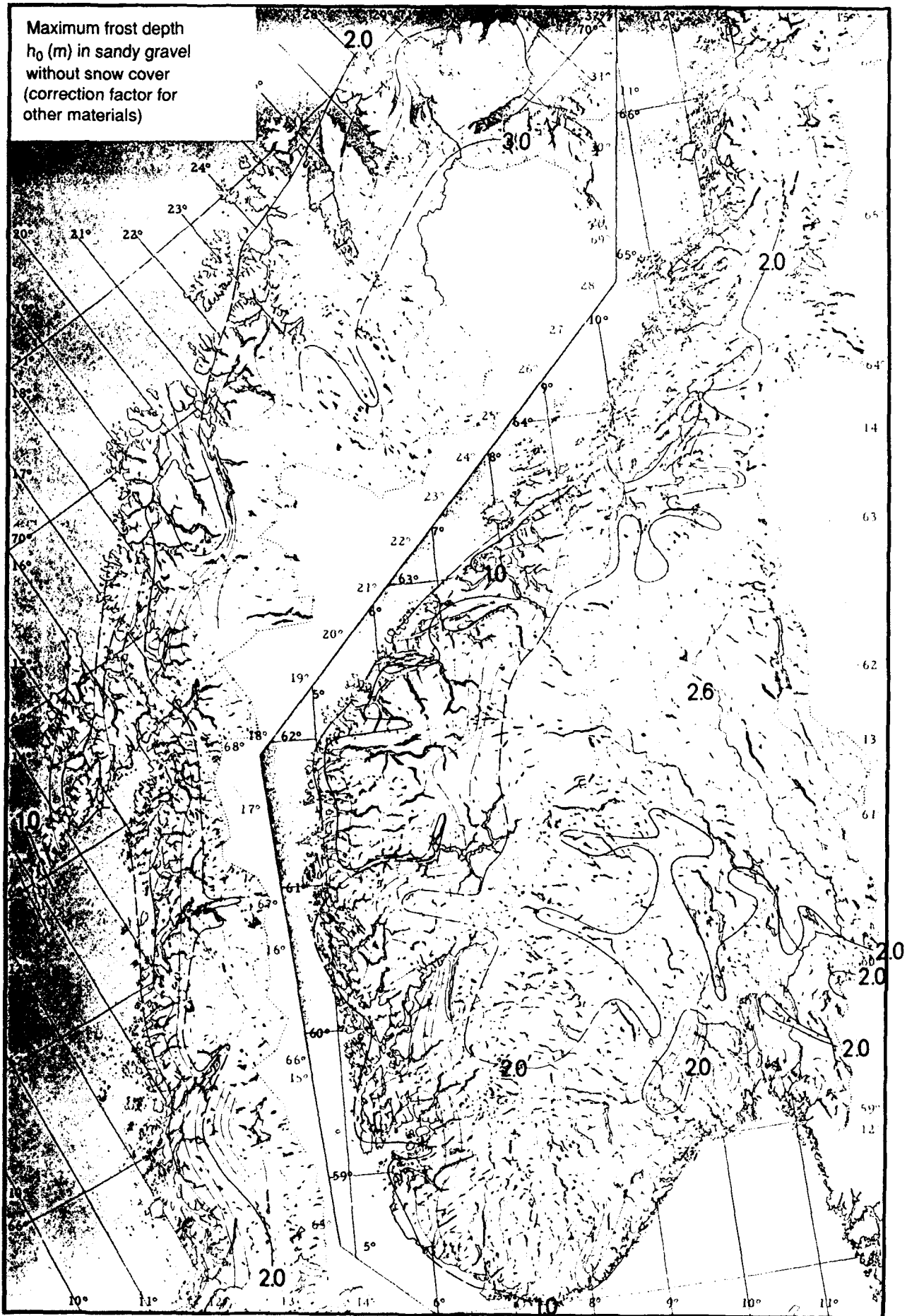


Figure 8. Contours for maximum frost depths in Norway. (From Frost I Jord 1976.)

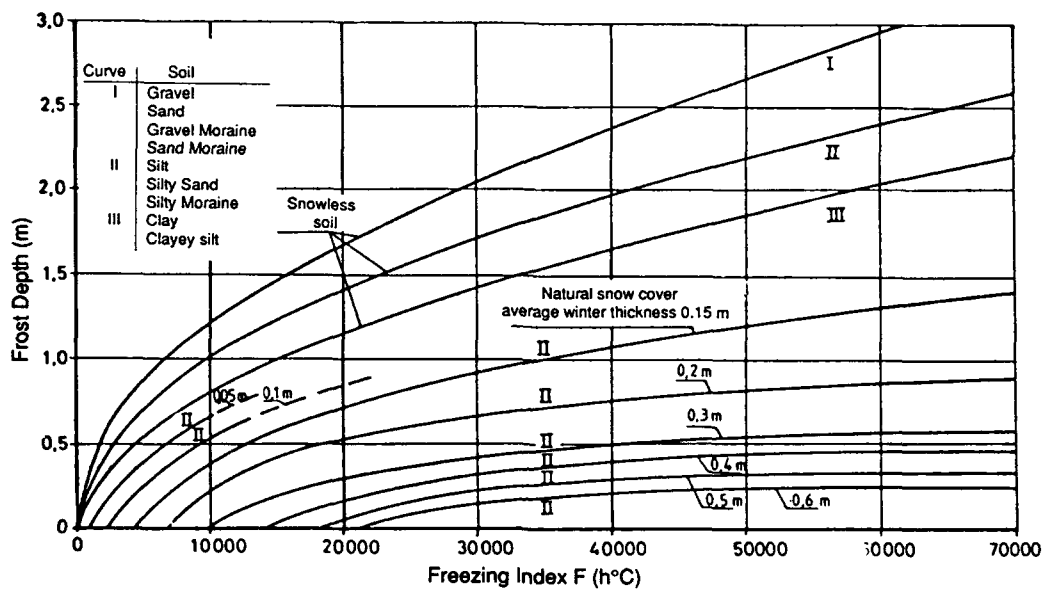


Figure 9. Influence of freezing index and snow cover thickness on frost depth. (From VTT 1987.)

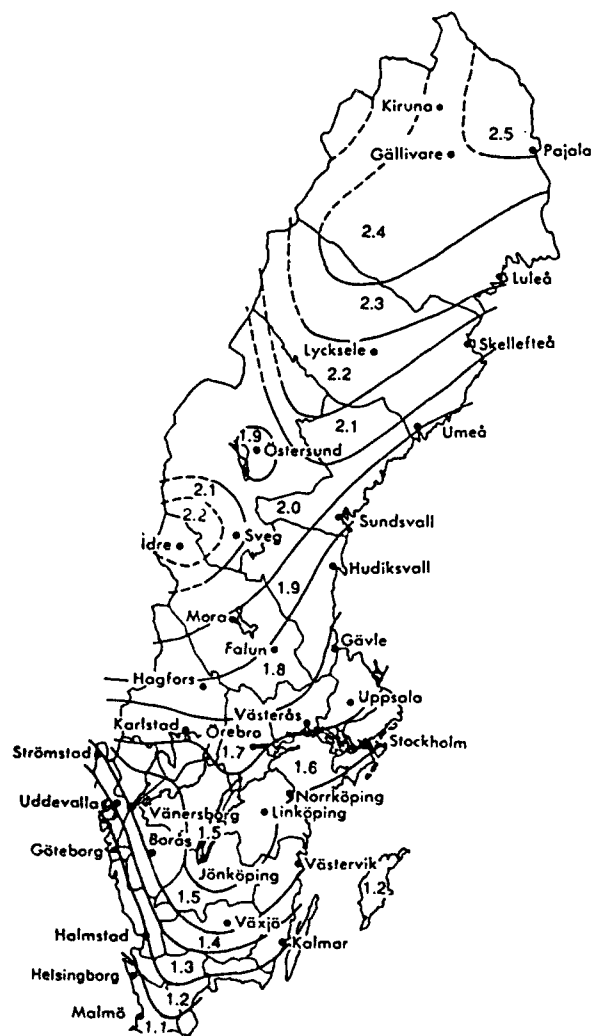


Figure 10. Frost penetration depth (in meters) in frost-susceptible soil in Sweden. (From SBN 1980.)

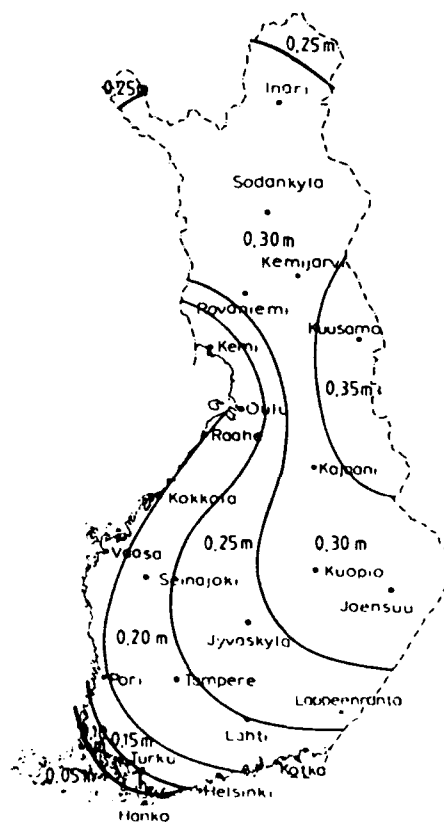


Figure 11. Design values for mean snow depth over a winter for Finland. (From VTT 1987.)

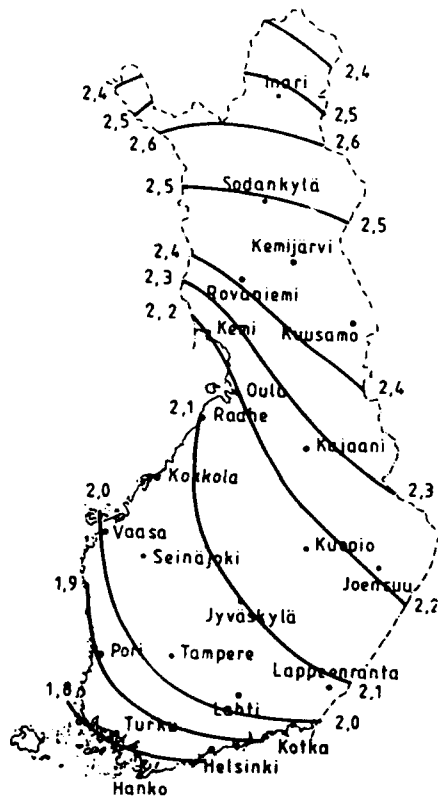


Figure 12. Average frost-free depth (in meters) for foundations of unheated structures on frost-susceptible soil in Finland, neglecting snow cover effects. (From VTT 1987.)

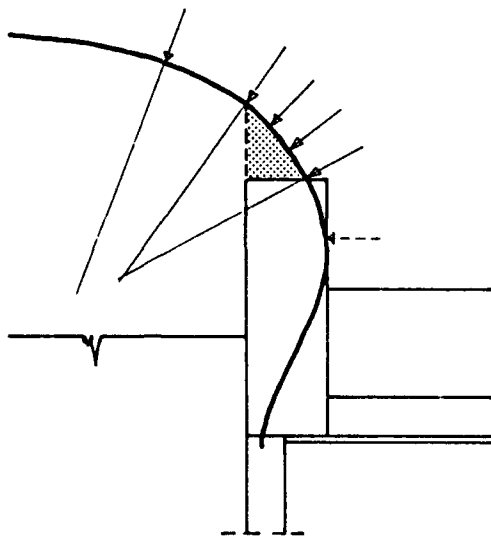


Figure 13. Heave forces acting at right angles to the frost front. (From Kløve and Thue 1972.)

gether with the design freezing index to estimate the frost depth from Figure 9.

Where snow cover is to be neglected in Finland, the frost-free foundation depth can be found from Figure 12. According to the guidelines, this figure applies to unheated structures such as stores, garages, sheds, masts, exterior staircases and supporting columns or walls. It gives the frost-free depth occurring once in 50 years for silt, silty sand or silty moraine (Soil II of Fig. 9).

In case one wishes to use a less-stringent design freezing index (occurring once in less than 50 years) and the foundation soil is different from soil II, the corresponding F_d for a Finnish locality is first found from Figure 3 and then applied to the appropriate (snowless) curve in Figure 9 to determine the frost-free depth.

Critical isotherm

Since there is usually a significant depression of the freezing point of water in soil, Adamson et al. (1973) suggested that the critical isotherm should be taken as that representing a temperature of -1°C . At that temperature, it is common to find some unfrozen bound water still present in fine-grained soils, together with ice lenses that have formed in water-saturated soil. Ice lenses generally follow the isotherms; the forces produced are therefore mainly at right angles to the isotherms (Fig. 13), but they tend to incline towards the direction of least resistance.

Accordingly, in their analysis Adamson et al. took the frost penetration depth as the vertical distance from the outside ground surface to the point of intersection of the -1°C isotherm with the downward extension of the inside edge of the foundation wall (i.e. the intersection with the vertical $x = 0$ in Fig. 14). Whereas Thue (1974), working in Norway, originally used the 0°C isotherm as the critical isotherm, the definitive Norwegian Frost I Jord report (Torgersen 1976a), followed the Swedish work of Adamson and fixed on the -1°C isotherm as the appropriate design isotherm. The requirement was that this isotherm should not penetrate under the foundation to an extent greater than one third the foundation width (Fig. 15). Only a very small amount of the frost-susceptible soil then freezes, so no damage is caused to the foundation. In Norway this criterion implies that the foundation depth will vary from about 0.4 m to about 1.2 m from the mildest to the coldest region (up to a design freezing index of 60,000 h°C) where no ground insulation is used for extra protection.

The design practice in Finland is to regard the 0°C isotherm as being critical. This introduces an

extra safety factor as compared with Swedish or Norwegian practice. Figure 16 shows the basic design principle or criterion used in Finland. As shown, the 0°C isotherm must not fall within the 2:1 load spread area beneath the foundation, i.e. the prism formed by two boundaries, the gradient of each being 2:1 (vertical to horizontal). Since the soil in this area would not freeze, there should be no adverse heave effects.

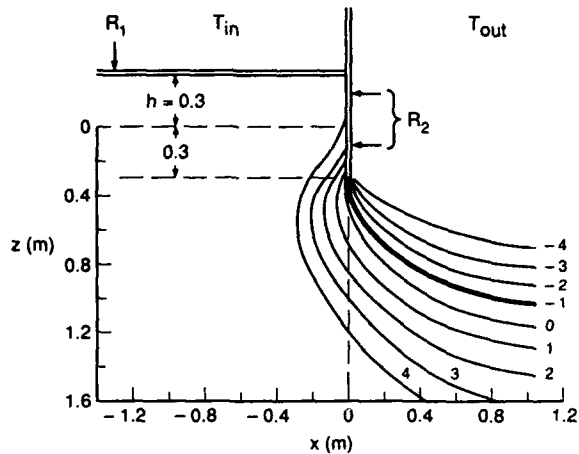


Figure 14. Frost penetration depth using -1°C as the critical isotherm. Its intersection with $x = 0$ (the inside boundary of the foundation wall) gives the assumed frost penetration depth. (From Adamson et al. 1973.)

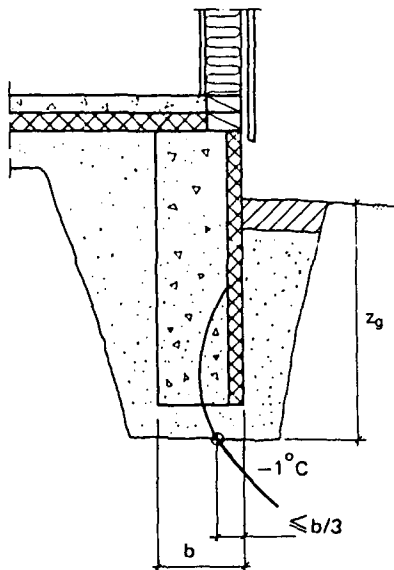


Figure 15. Frost I Jord frost criterion and definition of foundation depth z_g . (From Torgersen 1976a.)

Whereas the Swedish criterion of Adamson et al. (1973) requires that the -1°C isotherm should not penetrate beyond the inner edge of a foundation wall, the Finnish criterion specifies that the 0°C isotherm should not penetrate beyond the outer edge of a foundation (Fig. 16a) or a foundation wall (Fig. 16b). This further limitation of the Finnish design method contributes to another increase in safety factor as compared with Swedish and Norwegian methods.

The 1987 Finnish guidelines give an example of a finite-element method used to estimate the temperature distribution for a slab-on-grade foundation (Fig. 17). In the case illustrated, the slab has increased insulation near the foundation wall, which has inside insulation. Ground insulation is used with non-frost-susceptible material above and below it, and this material is also present below the floor and foundation wall. The heat flow analysis is based on transient and nonlinear

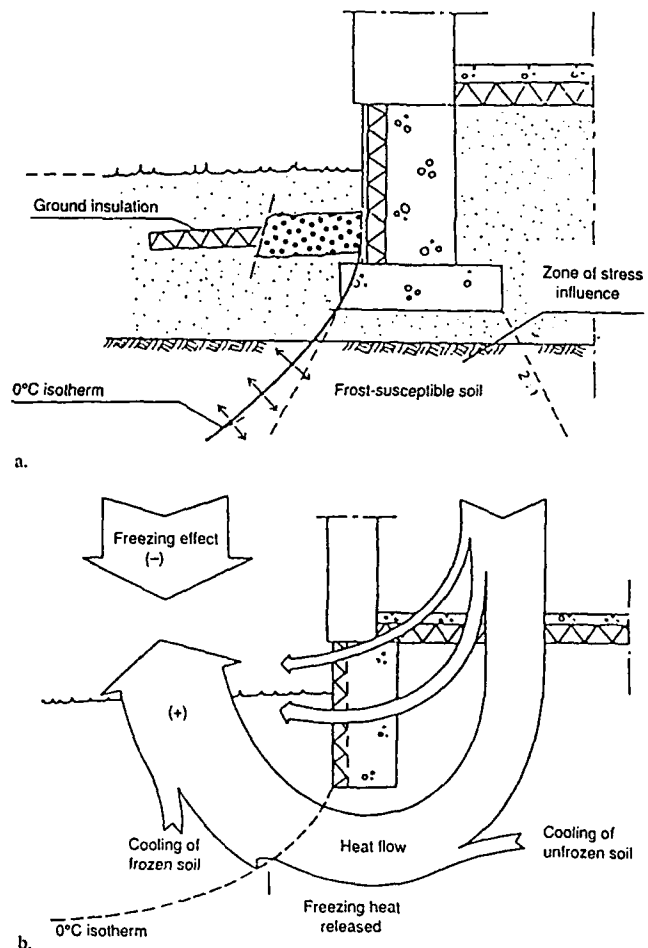


Figure 16. Frost protection principle in Finland using a 0°C isotherm limitation. (From VTT 1987.)

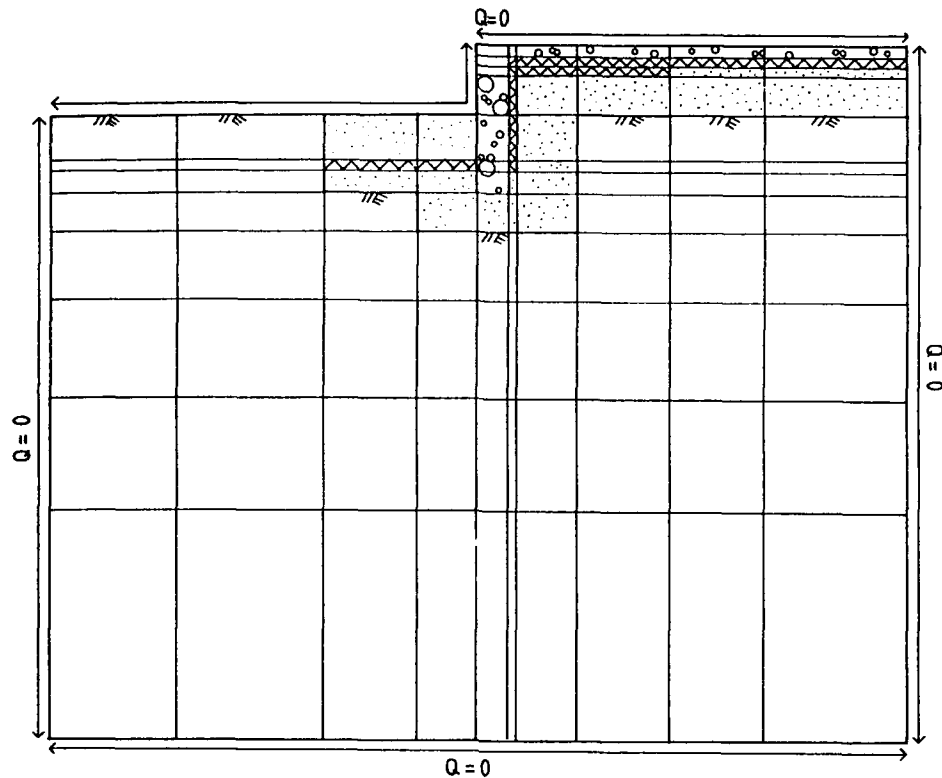


Figure 17. Example of finite-element mesh for determining isotherms. (From VTT 1987.)

conditions, the nonlinearity being due to the generated heat of freezing. A computer program is used to calculate the temperature at the nodes of a typical finite-element mesh for the boundary conditions shown, requiring:

- The dry unit weight and moisture content of the coarse material and the underlying soil, from which the rate of production of latent heat of freezing is calculated;
- The specific heat and thermal conductivity of each material component in the model;
- An estimate of temperature conditions at the initial time point of the calculation procedure;
- The outside temperature conditions corresponding, for example, to the design winter; and
- Other boundary conditions.

The isotherms can then be determined, and if the 0°C isotherm has an unfavorable location, the insulation is increased and the analysis repeated.

Foundation depth

Foundation depths in Norway, Sweden, and Finland will be discussed later in connection with slab-on-grade designs and foundations with crawl spaces. In other European countries, foundations

are usually placed at the frost-free depth if the ground is frost susceptible.

In Austria the general rule is that the foundation must be below the frost-free level with an added safety factor depending on the type of structure. The greater the sensitivity of the structure to frost effects, the deeper the foundation should be. Foundation depths have ranged from 1.2 m (for a small house) to 2.2 m. The local climate has a large effect, and in one case there was 3 m of frost. There is reluctance to use insulation to reduce the foundation depth.*

The specification in Czechoslovakia is also that the base of the foundation must be below the frost depth. The standard prescribes a general minimum depth of foundation of 0.8 m, but this is increased to 1.2 m in cohesive soils where ground water is less than 2.0 m below the surface. The minimum foundation depth is further extended to 1.4 m below ground level if the soil is cohesive and liable to shrinkage.** On the other hand, if the soil is non-

* Personal communication with H. Brandl, 1987.

** Personal communication with J. Ctvrticka, Prumstav Pardubice, Pardubice, Czechoslovakia, 1987.

frost-susceptible, the foundation depth can be a minimum of 0.4 m. For regions in Czechoslovakia having a freezing index greater than 15,000 h°C, the foundation depth is to be increased from the general value of 0.8 m specified by the Czech standard.* Recently there have been attempts in Czechoslovakia to build foundations shallower than the standard specification by designing thermal insulation for protection, but no details are available.

The rule of thumb in West Germany, based on experience, states that the foundation depth should normally be 0.8 m but extended to 1.2 m in mountain areas. No thermal insulation appears to have been used in association with foundations.**

The case of Denmark is interesting since it shows the lack of rationality in some procedures. According to Porsvig (1986) the foundations of old Danish buildings (of light construction in 1 or 2 stories) were carried out a hundred or more years ago with a foundation depth of 0.3 to 0.45 m. These buildings, which were not founded on deposits liable to settlement, have shown no signs of damage that can be attributed to frost heave of the foundations. A hundred years later Danish tradition changed so that foundations were placed deeper under the ground, i.e. 0.6 to 0.9 m. This perhaps resulted from the introduction of a new floor construction method, a foundation with crawl space. After the winter of 1941-42, the Danish standards stated that the frost-free foundation depth should be 0.9 m or more! However, while the statement is that this depth should normally be between 0.9 and 1.2 m, depending on the soil's frost susceptibility, the actual depth can be less if there is a heat contribution to the foundation soil or if insulation is placed or drainage measures applied. A smaller foundation depth is allowed with free-bearing foundation structures if there is no damage from freezing of the soil under the foundation. Notwithstanding these guidelines, it is understood in Danish practice that a designer is allowed to use a particular foundation method if it can be justified.

Factor of safety

In Swedish and Norwegian practice the effect of snow cover is neglected, and this builds in a safety factor in the design. This is also the case in Finnish

* Personal communication with I. Gschwendt, Research Institute of Civil Engineering, Bratislava, Czechoslovakia, 1987.

** Personal communication with H. Jessberger, Ruhr University, Bochum, West Germany, 1986.

design practice for heated buildings, but allowance is made for the effect of snow cover in certain types of cold structure. Other factors that influence the safety factor in the design process are:*

- Selection of the probability level of the design winter at the location, i.e. the design freezing index;
- Selection of the thermal conductivity value of the insulation material in use considering the risk of increasing moisture content in the long term and aging effects of the insulation; and
- Evaluation of the frost susceptibility of the local ground.

Because these factors may have opposing effects, an extra safety margin has not been included in Finnish design, the probability being small that all risks are mobilized together. Designing structures is an art of varying uncertainty, but there is no evidence to indicate failure of frost design in Finland. Rather, in the analyzed damage cases, the thermal behavior agrees with the thermal analysis used in design.

SLAB-ON-GRADE FOUNDATIONS

Principles

A slab-on-grade foundation has been increasingly used for light buildings because of its relative ease of construction and its economy. It involves placing a slab, often of concrete (e.g. Fig. 18), more or less on existing ground or on suitable coarse

* Personal communication with S. Saarelainen, 1988.

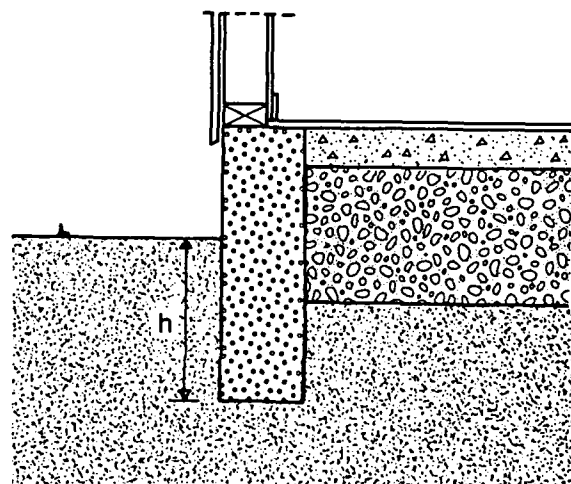


Figure 18. Slab-on-grade foundation, showing foundation depth h . (From Kløve and Thue 1972.)

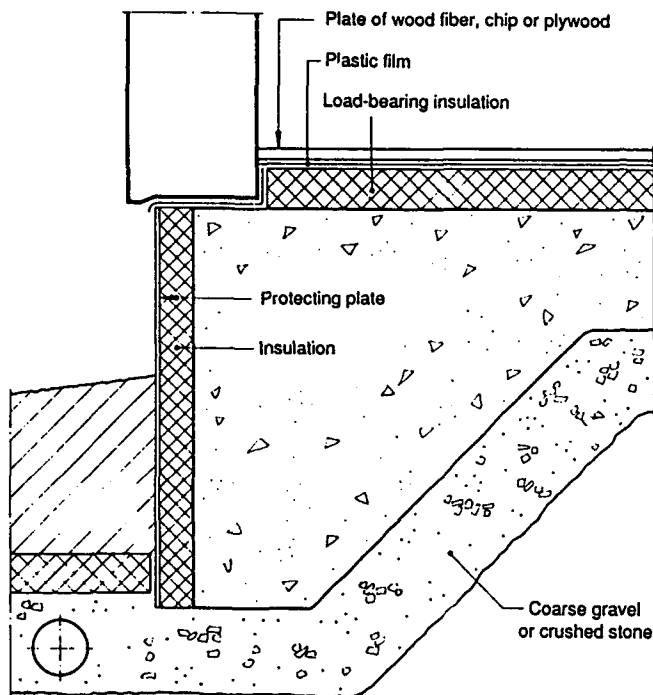
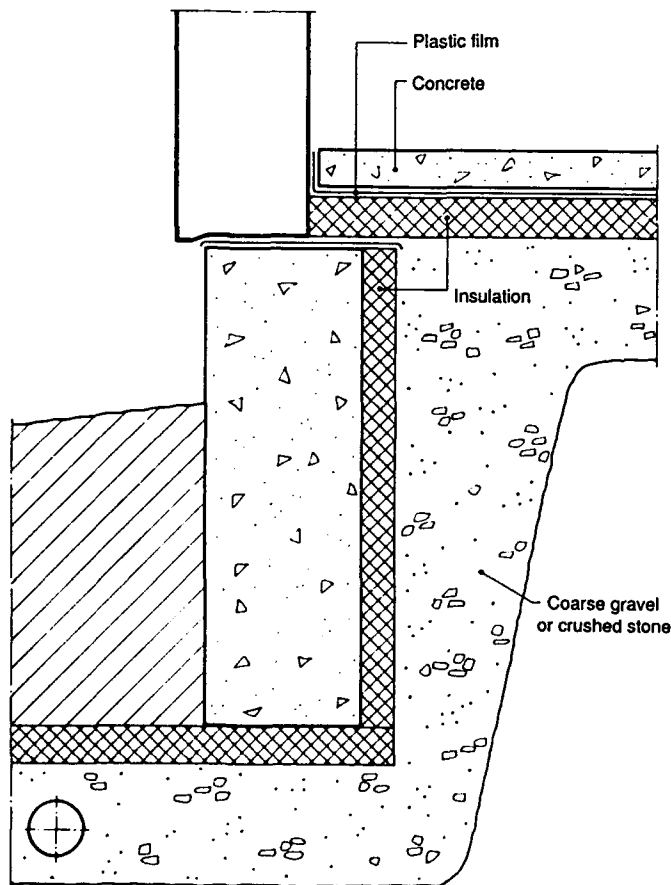


Figure 19. Slab-on-grade foundation with edge-expanded concrete slab. Such a slab gives more load spread with poor foundation conditions. (From NBI 1979b.)



material, with the associated foundation wall ("ringwall," or perimeter wall) based above the frost level in undisturbed ground. With such a shallow foundation there is safety from frost action because frost penetration near the foundation can be reduced in one or more of three ways:

- By the heat escaping from the building (mainly through its floor), this heat being guided towards the foundation area as much as possible;
- By the use of external ground insulation, generally placed horizontally near the foundation wall, to limit the loss of soil heat to the atmosphere and thereby reduce the depth of frost penetration at the foundation; and
- By the use of an artificial heat source such as a heating cable.

Design against frost action in the case of slab-on-grade foundations is closely linked with requirements for thermal insulation of the floor of the building (i.e. adequate floor surface temperature) and also requirements for protection of this floor against the effects of moisture and water vapor from the underlying soil.

A slab-on-grade foundation is generally one of two types, depending on the way in which the weight of the bearing walls is transferred to the ground:

- A slab with thickened edges cast integrally (Fig. 19); or
- Separate slab and foundation walls (Fig. 20).

In the first case the interaction between the edge beam and the slab has the advantage of distributing the load over a greater area, thus reducing the bearing pressure and consequent settlement. However, the slab would be subject to great strain and possible cracking if the edge beam settles. In the second case the slab can be entirely free of the foundation walls or it can be supported. Since there is no continuity between the slab and foundation walls, the slab undergoes less strain than in edge-reinforced slabs. Provision should be made for differential settlement between the slab and the wall.

Figure 20. Slab-on-grade foundation with separate slab and foundation walls. (From NBI 1979b.)

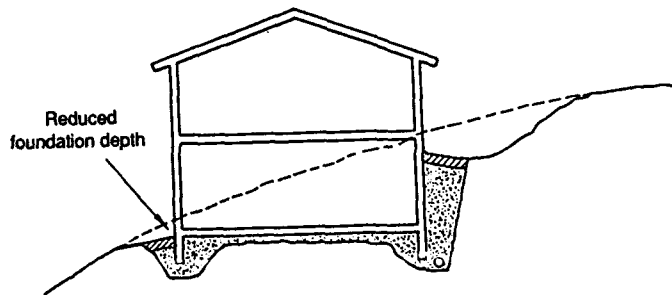


Figure 21. Combination slab-on-grade and basement foundation in sloping terrain. (From NBI 1986.)

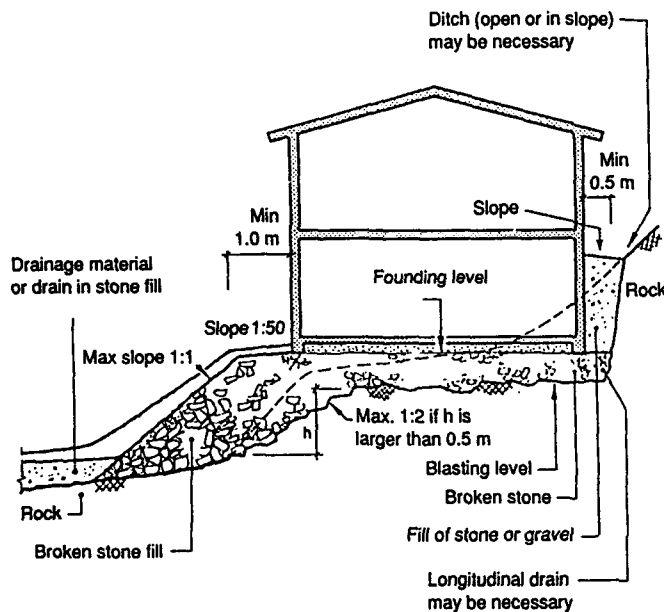


Figure 22. House on broken stone fill in sloping terrain. (From NBI 1986.)

Separate slabs are simpler both with regard to construction and in statical terms. They are also better at allowing for minor ground irregularities. In contrast to Sweden, most houses built in Norway as slab-on-grade have used separate slabs and foundation walls. The Swedish emphasis on edge-reinforced slabs is partly because Sweden includes a number of low-lying areas containing extremely wet clay, so settlement is a very real problem and load spread is necessary. However, the interaction between the slab and the thickened edge has sometimes resulted in cracked slabs, and special reinforcement has been required to withstand the stresses due to considerable settlement. In Norway, on the other hand, normal slab reinforcement is sufficient, and concrete foundation walls are generally 20 cm thick with no footings. Foundation walls of clinker bricks are also used (Torgerson 1975).

Use of slab-on-grade foundations

The slab-on-grade foundation method can provide a shallow foundation where excavating for a

deeper foundation would be more difficult or costly or could lead to drainage problems (e.g. arising from a high ground water level). In the past 10–20 years, houses with shallow foundations in Norway have often been the only kind not to exceed the cost limits set by the Norwegian National Housing Bank. It is expected that, in the foreseeable future, the slab-on-grade method will continue to be common (NBI 1986).

Site and terrain conditions

Founding a slab directly on existing ground requires practically flat terrain with a level difference under 0.5 m. Any fill required must be well compacted so as to resist further compression later. Filling and compacting frozen soils under winter conditions can cause large settlements during spring thaw.

Slab-on-grade foundations are not suited to ground with marked differences in level. However, in steeply sloping ground it can be feasible and economical to build a combination slab-on-

grade with a basement (Fig. 21). In this way the foundation depth at the front edge is reduced. This can be done where the ground consists of soil or rock, and it results in a considerable extension of the usable floor area of the building.

In rocky ground an economical foundation can be carried out by using compacted broken stone obtained from site blasting (Fig. 22). The particle size and gradation should be controlled to obtain a dense fill. With adapted cut-and-fill in sloping terrain, one can economize in the mass balance for each house such that the earthwork is kept to a minimum.

In hilly terrain the slab-on-grade method could be feasible for large construction projects where a rational cut-and-fill technique can be followed to minimize earthworks, as was done in the Skjetten development near Oslo. As a result the amount of excavation was considerably less than with other types of foundation.

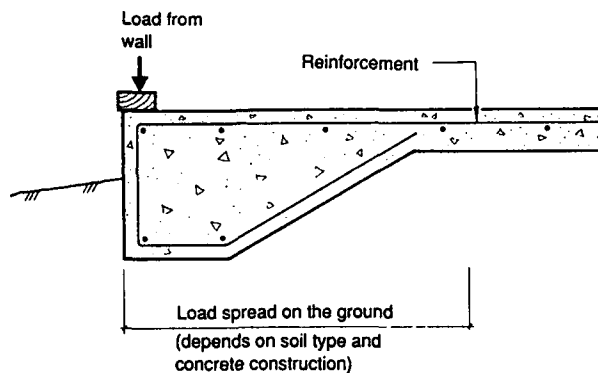


Figure 23. Foundation and slab cast as one unit and reinforced, acting together to distribute the wall loading over a larger area on wet ground. (From NBI 1986.)

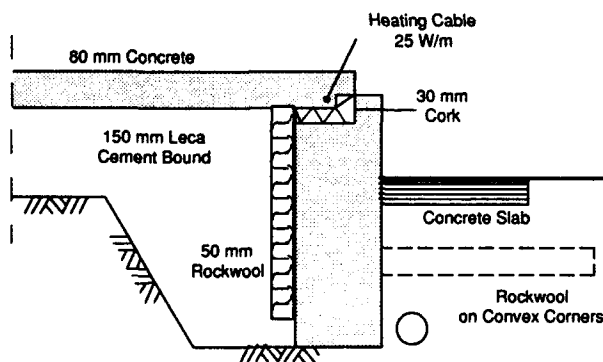


Figure 24. Slab-on-grade design used in the Skjetten development. (From Eiesland 1972.)

Soil conditions

An evaluation should be made to see if the soil is frost susceptible because this influences the foundation depth and thermal insulation procedures. In Norway a dry crust layer occurs over large areas, leading to special design considerations. It is a very hard top layer, usually clay or silty clay, with a thickness of 2–4 m. It exhibits a system of fine cracks from drying and shrinkage and is often very susceptible to frost heaving.*

Any topsoil and organic soil must be removed prior to building. Small buildings, such as one- or two-story houses, can usually be supported on a foundation wall without footings. However, if the ground bearing capacity is too low, the need for a footing must be specially evaluated. With wet clay it may be necessary to spread the wall loading over a large area on the ground. As previously mentioned this can be achieved by casting the foundation wall and slab as one integral unit with reinforcement to get joint action (Fig. 23). Such a construction must be specially designed with regard to concrete thickness and required reinforcement.

In the case of wet underlying soil it is often necessary to use a separation layer between this soil and the drainage layer under the slab. The separation layer can consist of 50–100 mm of sand or a synthetic fiber mesh, acting as a filter to prevent the overlying drainage layer from clogging up.

The Skjetten development

The Skjetten development near Oslo is an example of a large-scale project involving slab-on-grade foundations for row houses (Eiesland 1972). It was constructed in 1970–1972 on an extensive site with undulating terrain. The ground level was optimally adjusted using a computer program to give cut or fill areas suitable for slab-on-grade foundations. The particular foundation design is shown in Figure 24; the slab consists of 80 mm of concrete lying on 150 mm of stabilized (i.e. cement-bound) light expanded clay aggregate called Leca. This has thermal insulation properties and also acts as a moisture and vapor barrier. It has an important function in the period after construction, allowing the concrete slab to cure downwards after an impervious floor covering has been placed on the slab.

It is important in such foundations that there should be no cold bridge effect at the junction between the slab and a foundation wall. In this

* Personal communication with S.-E. Torgersen, 1988.

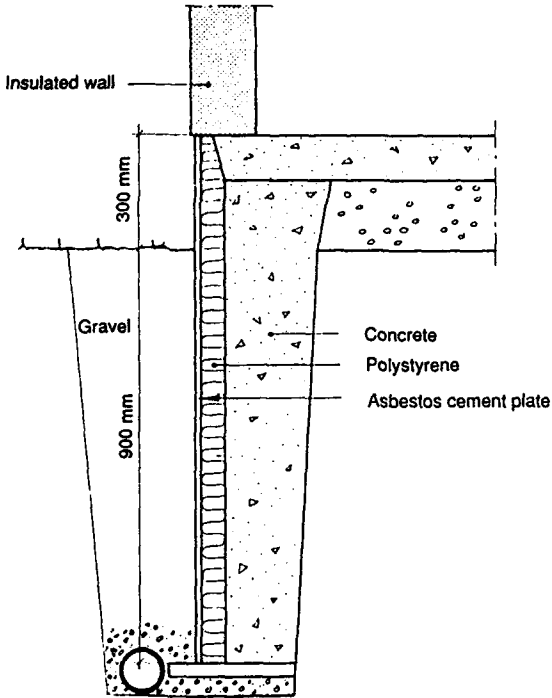


Figure 25. Use of outside insulation on the foundation wall, guiding heat down to the foundation. There is no cold bridge effect. (From Færøyvik 1972.)

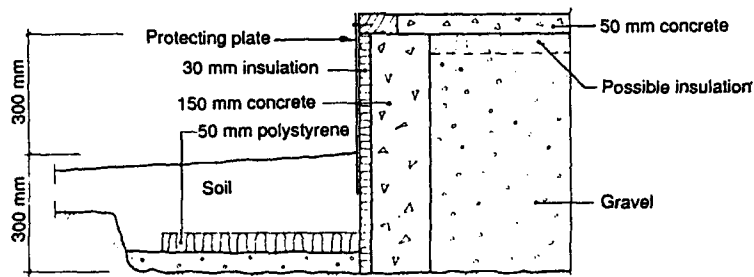


Figure 26. Use of horizontal ground insulation to keep frost away from the foundation. (From Færøyvik 1972.)

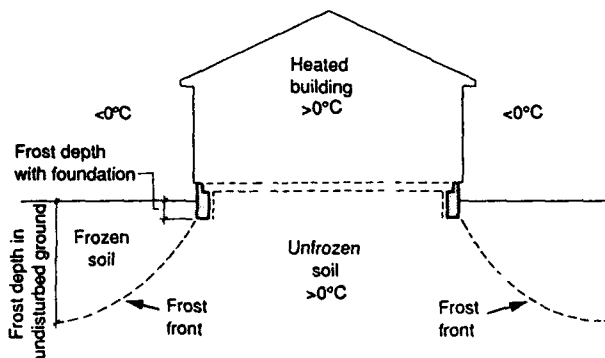
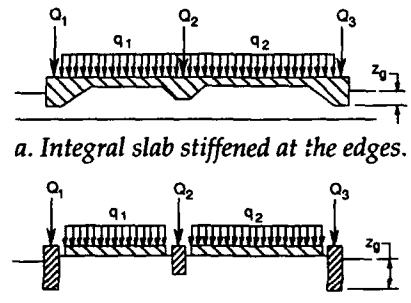


Figure 27. Frost penetration near a heated building with a slab-on-grade foundation. (From NBI 1986.)

design a cold bridge was inhibited by placing 30 mm of cork insulation between the slab and the concrete foundation wall, as shown in Figure 24. Also a heating cable supplying 25 W/m was placed in the floor near the floor and wall joint.

Vertical insulation, placed on the inside of the foundation wall, consisted of 50 mm of Rockwool (a mineral wool). This insulation guides heat from the house down toward the foundation base. In spite of this, Færøyvik (1972) pointed out there was still some cold bridge effect below the insulation, which could be obviated by using designs such as in Figure 25 and Figure 26. In the Skjetten scheme the use of outside, instead of inside, insulation on the foundation wall was indeed considered. Although outside insulation would have been thermally more effective, it was rejected on practical grounds because of the difficulty of applying insulation protection to the particular Skjetten foundations where distinct changes in levels occurred.

The reduced foundation depths in the Skjetten scheme were calculated from a complicated formula taking into account the duration of the frost period, the inside temperature of the house, the thermal conductivities of frozen and unfrozen soil, latent heat and other factors. Construction contin-



a. Integral slab stiffened at the edges.

b. Slab with edge beams taking the wall loads.

Figure 28. Types of floor slabs. (From Adamson et al. 1973.)

ued in winter, and detailed thermal studies were carried out to determine necessary protection in the cold period (Eiesland 1972).

The development was carried out in an area where there was a considerable thickness of dry crust material in which traditional deeper foundations would have been more costly. The scheme gave substantial economic benefits, but the design would require variation to suit the conditions of specific small schemes or individual houses.

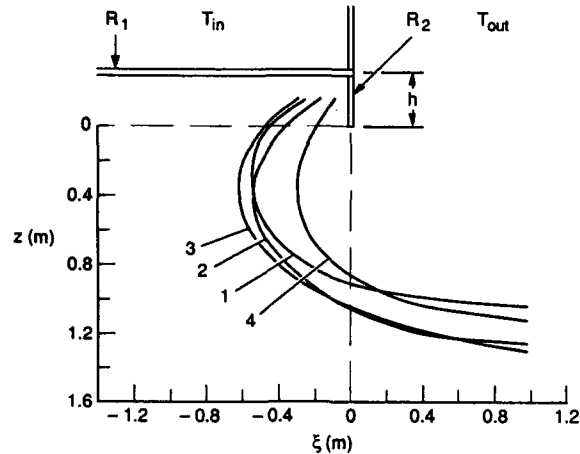


Figure 29. Position of the -1°C isotherm at different times. (From Adamson et al. 1973.)

- Line 1: 2 weeks after the lowest outside temperature ($T_{out} = -12.5^{\circ}\text{C}$)
- Line 2: 4 weeks after the lowest outside temperature ($T_{out} = -11.0^{\circ}\text{C}$)
- Line 3: 6 weeks after the lowest outside temperature ($T_{out} = -8.0^{\circ}\text{C}$)
- Line 4: 9 weeks after the lowest outside temperature ($T_{out} = -3.7^{\circ}\text{C}$)

Factors influencing frost penetration

As compared with undisturbed free ground, frost penetration near a slab-on-grade foundation (for a heated building) is less (Fig. 27), and its extent depends on the following factors. These were investigated in Sweden by Adamson et al. (1973) and in Norway by the Frost I Jord project, which was partly based on the computer results of Thue (1973). The studies of Adamson et al. applied to the two foundation types shown in Figure 28, but the Norwegian work reported by Torgersen (1976a) involved theoretical analysis of slabs separate from the foundation walls.

Climate

In their computer analysis Adamson et al. (1973) assumed the outside temperature T_{out} to vary as a cosine function of time t according to Janson (1968):

$$T_{out} = T_m + T_a \cos \omega t \quad (2\pi\omega = 1 \text{ year}) \quad (1)$$

where T_m is the annual mean value of air temperature (over a 30-year period) and the amplitude T_a is chosen such that the resulting freezing index equals F_{50} .

Different climatic conditions were considered, covering the range of temperature zones I to IV in Sweden (Fig. 4). In one case the greatest frost penetration under the foundation wall occurred four weeks after the lowest outside temperature (Fig. 29).

The Frost I Jord report (Torgersen 1976a) considered a similar cosine outside temperature distribution and a distribution based on the mean daily temperature but giving the same freezing index (Fig. 30). Computer calculations showed that the resulting magnitude of the frost depth at a foundation was practically the same for each temperature

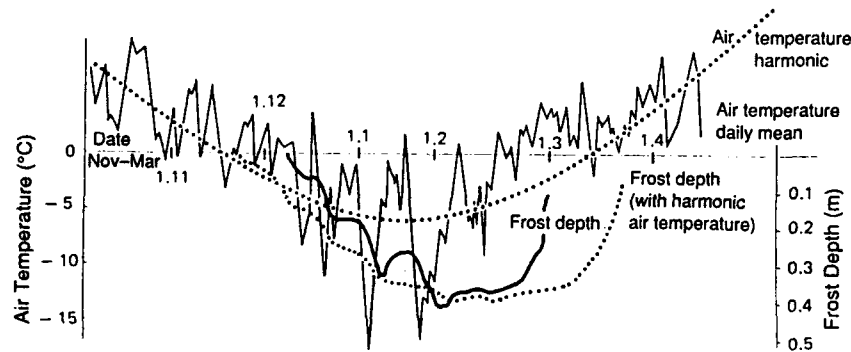


Figure 30. Relationship between outside temperature variation and frost penetration at a foundation. (From Torgersen 1976a.)

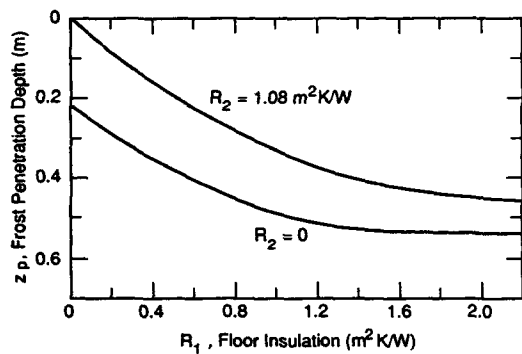


Figure 31. Influence of floor insulation R_1 on frost penetration depth for two cases. The insulation R_2 of the foundation wall applies to its part above ground. The pedestal height was 0.3 m. (From Adamson et al. 1973.)

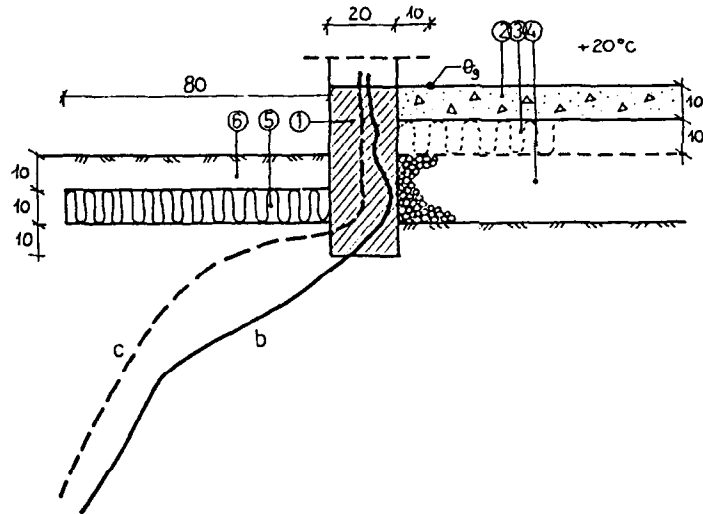


Figure 32. Effect of removing floor insulation where horizontal ground insulation is used. The 0°C isotherm shifts from b to c. (From Kløve and Thue 1972.)

distribution. It was deduced that the freezing index is the decisive parameter as regards the depth of frost penetration at a specific site. The climatic influence can therefore be represented by a local freezing index, while the mean annual temperature plays only a small role in the case of a well-insulated slab-on-grade foundation. The freezing index for design is taken in Norway to be the greatest value in a 100-year period, i.e. F_{100} .

Snow cover

In one case of their analysis, for example, Adamson et al. found that natural snow cover reduced frost penetration from 0.5 m for snow-free ground to 0.0 m. However, snow is often removed from areas near a building, and the insulation effect of any snow present is usually neglected in the design of slab-on-grade foundations for heated structures in Sweden, Norway and Finland.

Size of building

Adamson et al. showed that frost penetration at a corner for a building with overall dimensions of 4x4 m was approximately the same as for a building that is 10x10 m. In the middle of the outer wall, frost penetration is insignificantly larger in the case of the smaller building. The results were thus applicable to buildings with a smaller dimension equal to 4 m or more. This agreed with the stipulation of the 1967 Swedish building standards con-

cerning the application of certain design requirements to buildings with widths of at least 4 m. Smaller buildings would need to be analyzed specifically.

Floor insulation

The Swedish study of Adamson et al. showed the effect of the floor insulation thermal resistance R_1 on the frost penetration z_p for two cases (Fig. 31). In one case there was no edge (or foundation wall) insulation (i.e. $R_2 = 0$) and in the other case the edge insulation had a thermal resistance R_2 of 1.08 m² K/W. With more floor insulation the depth of frost penetration increases in each case because less heat escapes to the foundation area. An increase in R_1 from 1.0 to about 2.15 m²K/W, however, causes only a small increase in the frost penetration. If R_1 is increased above 2.15 m²K/W there is an insignificant increase in frost penetration.

An uninsulated floor would give the best protection against frost, but some insulation is necessary to provide a comfortable floor temperature. Figure 32 illustrates the effect of removing floor insulation in a case where horizontal ground insulation is used. Without floor insulation the critical isotherm shifts from position b to c, which is much less likely to cause frost damage to the foundation but increases heat loss, requiring extra inside heat (Kløve and Thue 1972).

Associated with frost-susceptible soils, the required thermal resistance of the floor insulation is

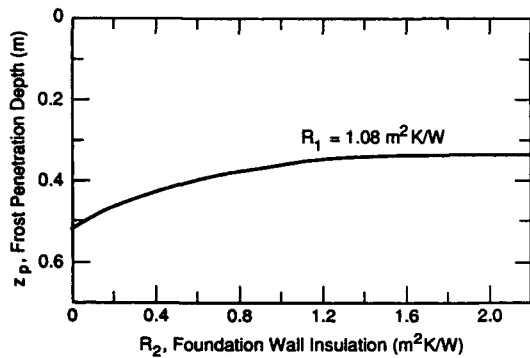


Figure 33. Influence of foundation wall insulation R_2 on frost penetration. The floor insulation R_1 is $1.08 \text{ m}^2\text{K/W}$. The insulation on the foundation wall is placed only above ground. The pedestal height is 0.3 m . (From Adamson et al. 1973.)

in the region of $1.0\text{--}2.0 \text{ m}^2\text{K/W}$ depending on the climate. This is equivalent to about $40\text{--}80 \text{ mm}$ of expanded polystyrene. If the freezing index is $50,000 \text{ h}^\circ\text{C}$, an increase in floor insulation from 1.0 to $2.0 \text{ m}^2\text{K/W}$ means an increase of frost penetration of about 20% but with an energy savings (Torgersen 1976a).

Foundation wall insulation

Vertical foundation wall insulation is used to limit the heat loss from the building and particularly to help guide the heat towards the foundation base thus reducing the frost penetration (Fig. 31). For a given freezing index this reduction continues until the thermal resistance of the insulation R_2 increases to about $1 \text{ m}^2\text{K/W}$ (equivalent to about 40 mm of expanded polystyrene or 0.25 m of light clinker blocks). Adamson et al. (1973) found that if the insulation was increased further, there was no appreciable effect on the extent of frost penetration (Fig. 33). There is little point in having too high a value of R_2 .

However, the place where the insulation is put is significant. External insulation gives less frost penetration than insulation placed internally on a foundation wall. An advantage of inside insulation is that it does not need protection as does outside insulation.

Thue (1974) showed that using inside insulation without floor insulation gave similar heat loss results to insulating the floor together with providing outside insulation. This means that the increase in heat loss through the perimeter resulting from moving insulation from the outside to the inside of a foundation wall is practically equal to the reduction in heat flow to the foundation resulting from

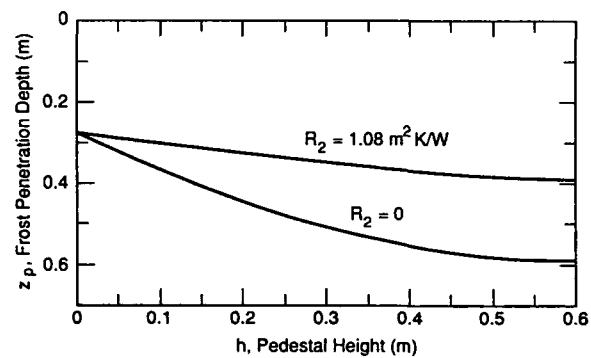


Figure 34. Influence of pedestal height h on frost penetration depth. The floor insulation R_1 is $1.08 \text{ m}^2\text{K/W}$. The insulation R_2 on the foundation wall is placed only above ground. (From Adamson et al. 1973.)

insulating the floor. However, protection from frost action on the perimeter foundation is reduced by moving the insulation inside.

The results of Adamson et al. (1973) showed that a foundation wall composed of light clinker blocks reduced frost penetration in one case to 0.37 m , compared with a penetration of 0.60 m for a foundation wall of concrete or hollow concrete blocks. A concrete wall acts as a thermal bridge conducting heat outwards rather than directing it down towards the foundation base, thus leading to a greater frost penetration. The greater thermal resistance of a foundation wall composed of light clinker means that it may not require additional thermal insulation, as does a foundation wall of concrete.

Height of the foundation wall above ground level

The vertical distance from the floor surface of a building to the outside ground surface may be termed the pedestal height. If this height is increased, there is more exposure and more heat will be lost without benefitting the foundation. Frost penetration at the foundation therefore increases (e.g. Fig. 34), necessitating more insulation of the foundation wall. The edge or foundation wall should therefore not be made unnecessarily high.

The Swedish building standards (SBN 1980) state that extra insulation of a foundation wall is required if the pedestal height is greater than 0.3 m and that this height should not exceed 0.6 m . The Norwegian *Building Details* (NBI 1986) require special protection if the floor lies higher than 0.6 m over the outside ground. The Finnish guidelines (VTT 1987) also consider designs for a pedestal height up to 0.6 m , with greater values requiring special treatment.

Ground insulation

Ground insulation placed horizontally (or sometimes obliquely) in the soil outside the foundation has a strong influence in reducing frost penetration by limiting the release of soil heat. Such insulation is therefore especially suitable for extra protection

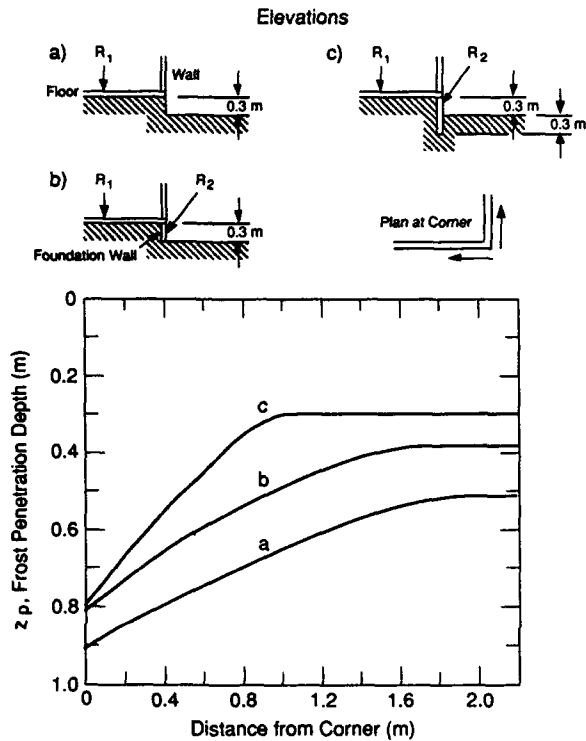


Figure 35. Frost penetration depth as a function of the distance from a corner. $R_1 = R_2 = 1.08 \text{ m}^2\text{K/W}$. (From Adamson et al. 1973.)

against frost at a corner of a building, where exposure is more severe, or near a cold section situated at an outer boundary. It is also desirable around the whole of the building in an especially cold climate requiring additional frost protection. The insulation width is usually up to 1.0 m, with a thermal resistance of 1.0–1.5 $\text{m}^2\text{K/W}$. There is little point in having too much ground insulation since this is not likely to cause much further reduction in frost penetration, as shown by the computer results of Thue (1974).

At a corner of a building there is exposure to frost from two sides, and frost penetration is consequently deeper than in the middle of an outer wall. Adamson et al. (1973) showed that the penetration is often double or more at a corner. Figure 35 illustrates the increase in frost penetration as a function of distance from the corner. It was found that the corner effect disappeared completely in southern Sweden at about 1–1.5 m from a corner and in northern Sweden at about 2 m from a corner. Extra ground insulation is thus required at corners, particularly for places with a high freezing index; this is recognized in Swedish, Norwegian and Finnish guidelines.

Cold bridge effect

Figure 36 shows an example of a foundation design that was much used in Finland because of its ease of construction. It resulted in many cases of frost damage during the severe winter of 1984–85 because frost penetrated under the foundation wall, as can be seen from the position of the 0°C isotherm. This resulted from the cold bridge effect occasioned by the fact that the insulation is

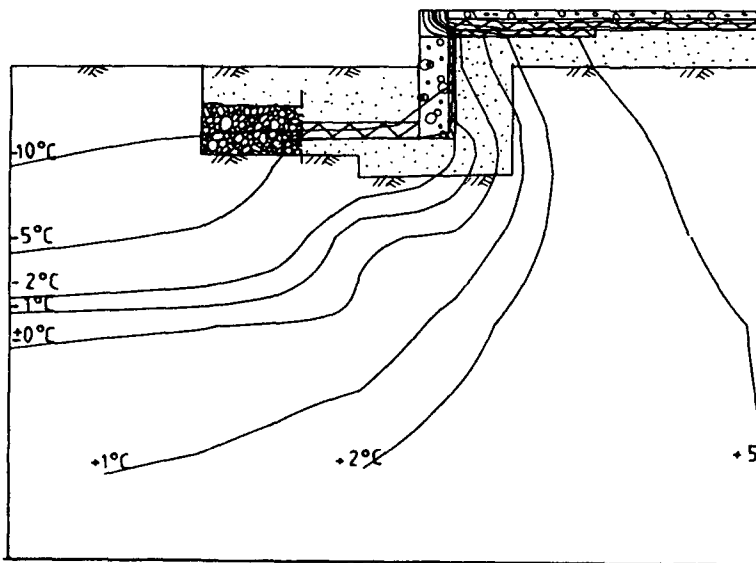


Figure 36. Cold bridge effect with a concrete foundation wall. The isotherms are for a freezing index of 57,000 h°C , a foundation depth of 0.5 m and a floor structure thermal resistance of $2.0 \text{ m}^2\text{K/W}$. (From VTT 1987.)

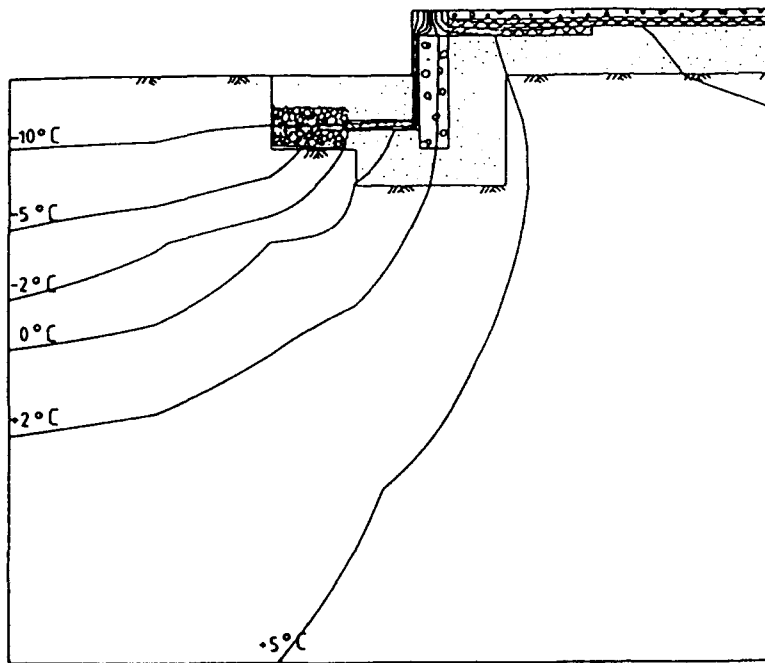


Figure 37. Foundation design that has no cold bridge. The isotherms are for a freezing index of 37,000 h°C, a foundation depth of 0.5 m and a floor structure thermal resistance of 1.0 m²K/W. (From VTT 1987.)

not continuous under the concrete foundation wall. The damage could have been prevented by having designs such as shown in Figure 37 or, in south Finland, by building the foundation wall of light expanded clay aggregate instead of concrete.* With a design as illustrated by Figure 37, the cold bridge is broken and the 0°C isotherm does not approach the bottom outer edge of the foundation wall.

Thermal considerations for buildings and foundations

Thermal insulation of the floor should be designed so that the floor temperature is not lower than 16°C. Too low a floor temperature would not be comfortable and could result in condensation at the surface of the floor. The floor surface temperature depends particularly on the inside temperature of the building, the heat flow across the floor and other heat losses from building walls and foundation walls.

To save energy there has been a tendency in recent years to lower the inside temperature below the guideline value assumed in design, and this has resulted in damage. A lower inside temperature would require more floor insulation or a lower foundation depth or both because the design depends on heat from the building.

Heat flow from a building

Adamson's study. Adamson (1973) reported the results of computations assuming nonstationary and stationary heat flows related to long rectangular buildings and square buildings. Heat flows and floor temperatures were calculated for 19 two-dimensional cases applying to long buildings and for 14 three-dimensional cases applying to square buildings. In the latter, heat flow downwards cannot be considered two-dimensional. The two types of slab-on-grade foundations shown in Figure 28 were analyzed. The inside temperature of the building was generally assumed to be 20°C. The variables considered were geographical position (giving the outside temperature), floor slab insulation, insulation of the bottom wall unit (i.e. the edge beam or foundation wall) and external horizontal ground insulation. The heat flow across the floor was analyzed by a forward-difference finite-element method, which gave the isotherms at a certain time after the lowest outside temperature.

In the case of long buildings the isotherms were represented for a vertical section parallel to the shortest dimension of the building. For square buildings the isotherms were those occurring in the vertical plane through a diagonal. The cases studied corresponded with those used in the studies of frost penetration and required foundation depth. The results of Adamson's computations based on stationary heat flow agreed well with those on the basis of nonstationary flow, within a zone about 1 m from an external wall. In the middle of the floor,

* Personal communication with H. Kivikoski, Technical Research Center of Finland, Espoo, 1986.

Table 3. Greatest heat flow through floor surface in a square building 10 × 10 m situated in Stockholm. Coordinates x and y are parallel to the sides and measured from the center of the plan. (From Adamson 1973.)

y (m)	Greatest heat flow (W/m^2) at the point x, y				
	$x = 0.50$	2.30	3.25	4.20	4.85 m
0.5	3.1*	3.6	4.9	7.8	12.7
2.30	3.6	4.3	5.5	8.1	12.9
3.25	4.9	5.5	6.4	8.8	13.3
4.20	7.8	8.1	8.8	10.8	14.2
4.85	12.7	12.9	13.3	14.2	16.4

*Values in boldface refer to a diagonal of the building.

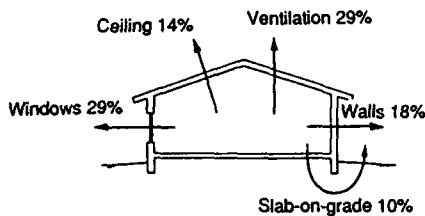


Figure 38. Heat losses from a house with a slab-on-grade foundation. (From Torgersen 1976a.)

heat flow was much higher in a square building than in a long building of the same width because of three-dimensional flow in the former case. Comparison of the combined thermal resistance values of the floor construction and underlying soil in the two cases showed a considerably higher value in the case of the long building, because heat has to travel a longer distance down from the middle of the floor and around the bottom of the foundation.

For a square building an illustration of the heat flow at different points of the floor is given by Table 3. This shows how the heat loss increases from the middle of the floor to an external wall. Heat loss also increases from the middle of an external wall to a corner.

It was also shown that the thermal resistance between a point on the floor surface near an external wall and a point on the ground surface outside the building is practically independent of the boundary temperature in the ground and the outside air temperature. This means that the results of the computations have wide general applicability.

Frost I Jord project (Torgersen 1976a). In a typical Norwegian house with slab-on-grade construction, the percentage heat losses during the winter half of the year, shown in Figure 38, increase as the outside temperature drops. Only about 10% of the total

heat loss from the building is represented by the heat loss through the floor, the actual percentage depending on the effectiveness of the insulation of the house above the ground. The heat loss through the floor passes through the ground below and rises towards the outside air by means of an approximately semicircular path. The effect is to reduce the frost depth near the foundation compared with the frost depth in undisturbed ground (Fig. 27). An important aspect of design is to use a floor insulation that will allow the requisite amount of heat to flow towards the foundation base, thereby reducing frost penetration under the foundation wall.

Some of the heat loss from the floor attempts to follow other paths, such as through the connection between the floor and the foundation wall (where a cold bridge could form) or farther down across the foundation wall. Interruption of the possible cold bridge and adequate vertical insulation of the foundation wall would guide most of the heat lost from the floor to the underside of the foundation wall. Insulation of the foundation wall is described later. Additional protective measures include installing heating cables or heat ducts in the floor area near the connection with the foundation wall or placing horizontal ground insulation in the soil outside the wall to reduce frost penetration.

Ground insulation inhibits the release of the soil heat, which is stored in the soil during the summer half of the year and is available to retard the downward advance of frost. As the outside temperature continues to drop below $0^{\circ}C$, the soil heat is gradually given up as the unfrozen soil cools, as it releases latent heat when it freezes, and as the frozen soil cools further. Compared to the soil heat, the geothermal heat from the Earth's interior is insignificant. Figure 39 shows the importance of the latent heat given up on freezing.

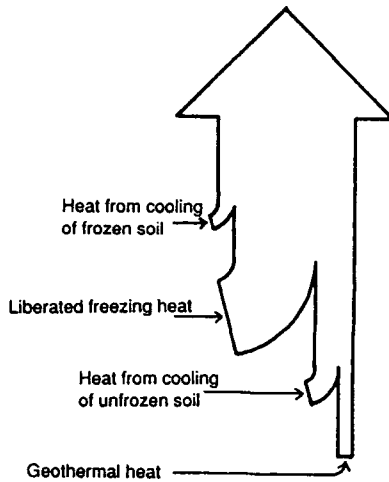


Figure 39. Heat loss from the ground during the freezing process. (From Kløve and Thue 1972.)

Where there is frost-susceptible ground, heating of the building is assumed to be continuous in the cold season, giving an inside temperature of 18°C. Heating can be reduced temporarily, e.g. for a 3-week vacation during winter, but the inside temperature in this case must be at least 5°C.

Heat flow from the floor of a building depends on the thermal resistance it encounters. Modern insulation material with a large thermal resistance can be used to reduce the heat flow. The underlying soil also has a thermal resistance that depends on its properties and the length of the heat flow path through it. As shown by Adamson (Table 3) the largest heat flow across a floor occurs near the outer walls because flow paths to the outside air are short. In the middle of the floor the heat flow is much less because heat has to traverse long distances through the ground before it can reach outside air. In this case the total thermal resistance along the heat flow path will be dominated by the ground's thermal resistance while floor insulation plays a smaller role. The effects of floor insulation can be seen by comparing Figures 40 and 41. In Figure 40 the insulation has a low thermal resistance, and heat flow across it is therefore large. The floor surface temperature is reduced, but the frost boundary does not advance very deep at the foundation wall because of the effect of the large heat flow contribution from the floor. On the other hand, in Figure 41 the floor insulation has a large thermal resistance, which restricts heat loss across it and thereby maintains a higher floor surface temperature. As a result the frost boundary ad-

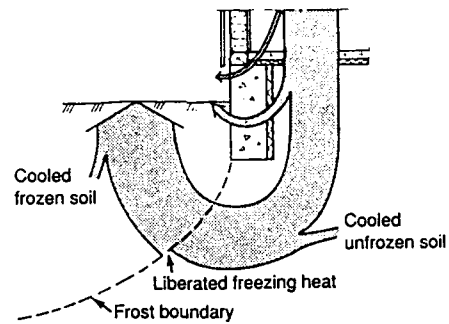


Figure 40. Poorly insulated floor, giving a lower floor temperature but some heat to frost-protect the foundation wall. (From Torgersen 1976a.)

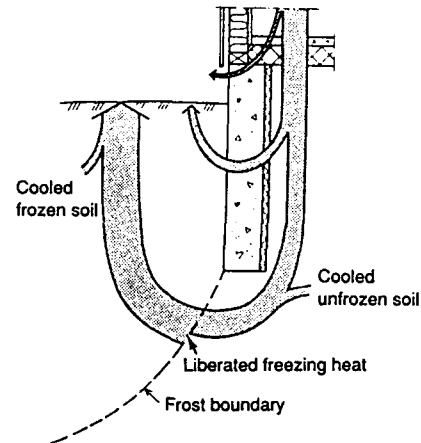


Figure 41. Well-insulated floor, giving a higher floor temperature but little heat to frost-protect the foundation wall. (From Torgersen 1976a.)

vances deeper down at the foundation wall, so the foundation depth increases.

The starting point in the slab-on-grade design process is to find the necessary floor insulation such that an acceptable floor surface temperature can be obtained. One must then make sure that the frost boundary does not advance too deep and that the chosen foundation design is not likely to be damaged by frost action. Great care should be taken to assure interruption of a possible cold bridge at the junction of the floor, the foundation wall and the outer wall (Fig. 42), and airtightness should be ensured.

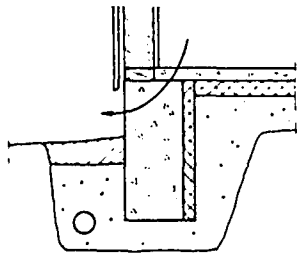


Figure 42. Cold bridge, giving an uncomfortable floor temperature. (From Torgersen 1976a.)

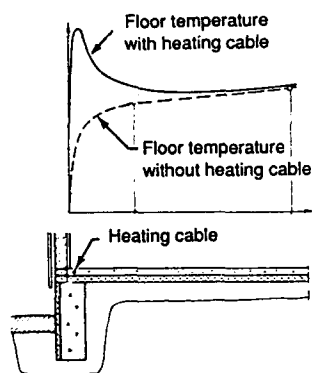


Figure 43. Heating cable in the floor, giving a satisfactory floor temperature up to the outer wall. (From Torgersen 1976a.)

A heating cable in the floor along an outer wall gives a comfortable floor temperature all the way out to that wall if the floor is well insulated. Insulation on its own would usually not suffice to produce a comfortable temperature in a floor strip within 0.3 m of the outer wall (Fig. 43).

Danish heat flow analysis. From a recent investigation by the Thermal Insulation Laboratory (1982) in Denmark, Figure 44 shows two-dimensional heat losses through the floor and wall as compared with one-dimensional heat flow determined according to the relevant Danish standards giving rules for calculating heat loss from buildings. The two-dimensional heat loss Q_2 can be almost three times the values indicated by the Danish standards. By comparison, the work of Adamson (1973) considered only one-dimensional heat loss through the floor (and loss through the foundation wall) ap-

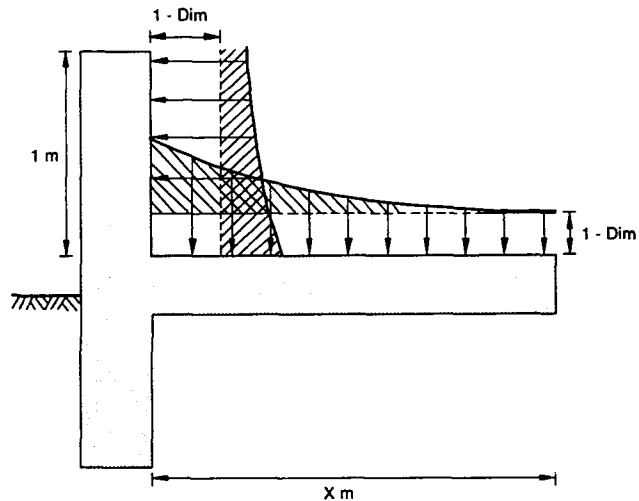


Figure 44. Heat flow through the floor and wall. (From Thermal Insulation Laboratory 1982.)

parently without including heat loss through the building wall above the floor.

The Danish study, titled "The Low-Energy House Project," analyzed foundation designs for energy conservation houses. Different slab-on-grade foundation designs were studied (Fig. 45), offering a variety of technical solutions to the problem of cold bridges. From about 1960 most single-family houses in Denmark have been one-story houses without basements and built with slab-on-grade foundations. The connection between the floor, the external wall and the foundation wall often resulted in severe cold bridges. The traditional type of foundation for Danish slab-on-grade houses is shown in Figure 46, and a design that has recently been used is given in Figure 47. (It has not been Danish practice to install external ground insulation.)

For each of the designs in Figure 45, computer calculations were made to obtain the two-dimensional heat flow. The calculated values of Q_2 , together with the associated insulation, are shown in Figure 48 for each of the designs. The results showed the considerable importance of effective vertical perimeter insulation extended to the correct depth. An illustration of this is a design shown in Figure 49a, which has an extremely well insulated floor but a high heat loss due to continuous concrete between the slab and a foundation wall. In Figure 49b there is an improvement resulting from the replacement of the unusually thick concrete slab by an ordinary 100-mm slab. Separation of the floor slab from the inner part of the foundation wall

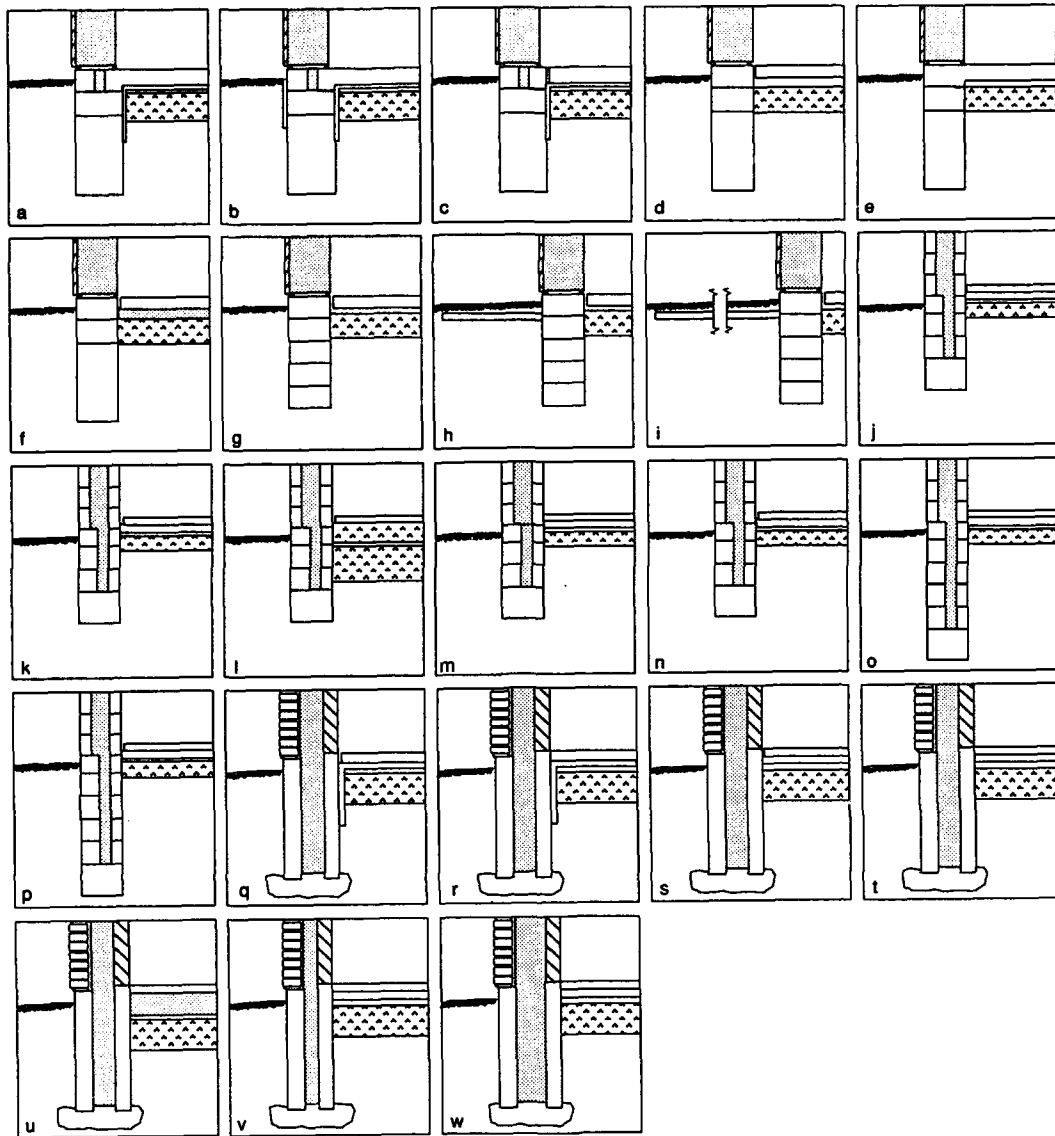


Figure 45. Foundation designs investigated in the Danish study. (From Thermal Insulation Laboratory 1982.)

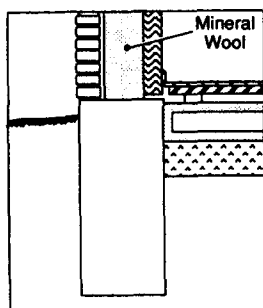


Figure 46. Traditional Danish slab-on-grade house foundation. (From Thermal Insulation Laboratory 1982.)

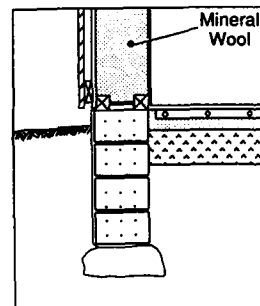


Figure 47. Foundation wall of expanded clay blocks. (From Thermal Insulation Laboratory 1982.)

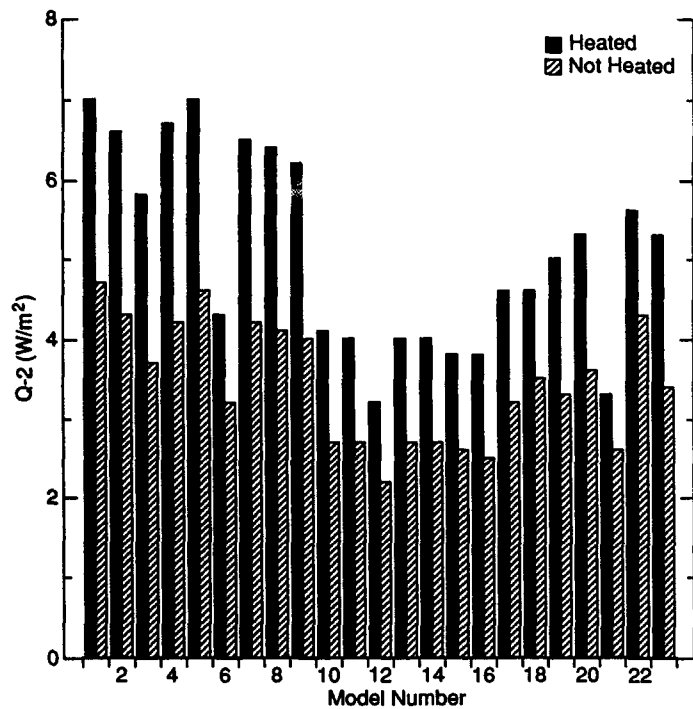


Figure 48. Results of the heat flow analysis in the Danish study. (From Thermal Insulation Laboratory 1982.)

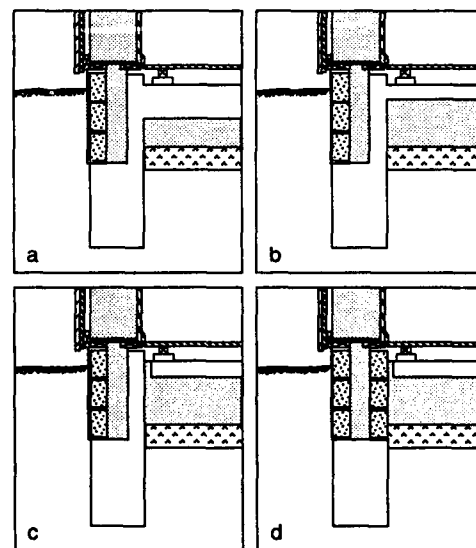


Figure 49. House foundation and three progressively improved versions. (From Thermal Insulation Laboratory 1982.)

by introducing mineral wool (Fig. 49c) gives a further slight reduction in heat loss. A more significant reduction results when the inner part of the foundation wall is replaced by blocks of expanded clay concrete (Fig. 49d). The resulting heat loss is only about half the heat loss with the construction of Figure 49a.

Internal heat transfer resistance

A very important thermal factor is the heat transfer resistance R_i ($\text{m}^2\text{K}/\text{W}$) affecting heat flow from the inside air to the floor surface. It depends on the surface material and the air velocity, and its reciprocal is the heat transfer coefficient ($\text{W}/\text{m}^2\text{K}$), which Adamson (1973) stated was lower (i.e. R_i was higher) than usually assumed in previous design calculations. Measurements showed that in corner rooms of single-story heated buildings, the heat transfer coefficient between the room air and the floor surface was $1.5\text{--}2.5 \text{ W}/\text{m}^2\text{K}$. The lower value corresponds to an R_i value of $0.67 \text{ m}^2\text{K}/\text{W}$ and applies to the middle of the floor. The higher figure corresponds to an R_i value of $0.4 \text{ m}^2\text{K}/\text{W}$ and applies to the part near the corner of an external wall.

It is important to be able to determine the appro-

Table 4. Relationship between floor surface temperature and internal heat transfer resistance R_i . (From Adamson 1973.)

Distance from outer wall (mm)	Floor temperature ($^{\circ}\text{C}$)		
	$R_i = 0.40$	0.29	$0.14 \text{ m}^2\text{K}/\text{W}$
0	11.6	13.0	15.3
10	11.7	13.1	15.5
30	12.0	13.5	15.9
90	12.7	14.1	16.6
200	14.3	15.1	17.4
300	14.9	15.7	17.9
500	15.5	16.8	18.7
1000	17.8	18.7	19.9

prate value of R_i because it influences the floor surface temperature markedly, as shown in Table 4. This table gives the temperature at different distances from an outer wall depending on the chosen value of R_i . The inside air temperature is assumed to be 21°C .

Where there is little ventilation and doors are closed, R_i may be as high as $0.65 \text{ m}^2\text{K}/\text{W}$, but with normal ventilation and heating R_i is about $0.40 \text{ m}^2\text{K}/\text{W}$. The Norwegian standards NS 3031 (NBR 1986) give a value of $0.13 \text{ m}^2\text{K}/\text{W}$ for R_i .

Effect of climate

In the Norwegian study reported by Torgersen (1976a) related to the construction shown in Figure 50, a computer study was made of the influence of changes in the outside air temperature on floor temperature at points 0.3 and 1.0 m from an outer wall (Fig. 51). These results applied to the winter of 1965–66 in Oslo, which was the coldest for 30 years, and data for the mean air temperature over each 5-

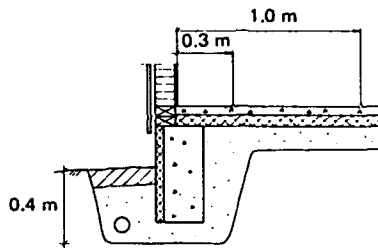


Figure 50. Slab-on-grade design on which the computer analysis of floor temperature is based. (From Torgersen 1976a.)

day period was input. The dotted curve represents a harmonic (cosine) curve for the outside air temperature. The computer program assumes a different air temperature distribution but one that gives the same value of the freezing index F . The resulting effects on the floor temperature variation are about the same. The conclusion is that it is sufficient to represent the climate's influence by the local freezing index, which is the significant parameter, whereas the mean annual temperature has an insignificant influence on the floor temperature of a well-insulated slab. The design freezing index is taken in Norway to be F_{100} , the maximum F value in a hundred-year period.

Effect of insulation

The computer study of Adamson (1973) showed that edge beam or foundation wall insulation and floor insulation have a large influence on heat flow near the beam or wall and therefore an important influence on the floor temperature.

Concrete slab with edge stiffening. Calculations of floor temperature were made for different cases where the floor slab insulation is laid above the slab

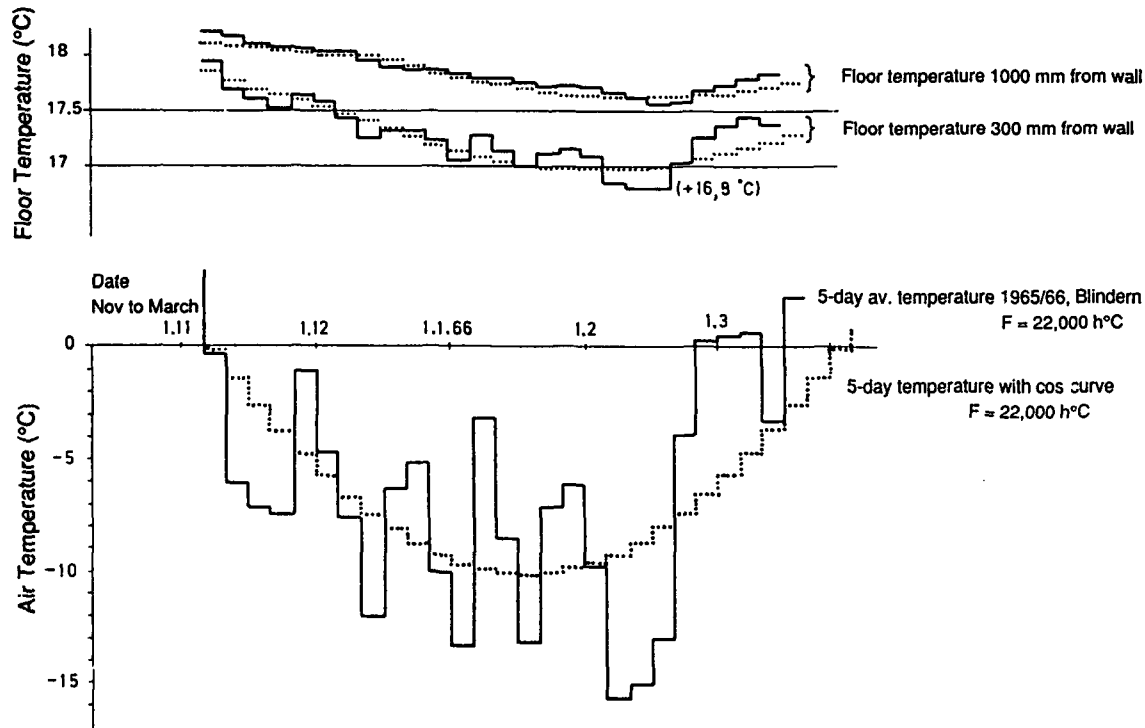


Figure 51. Effect of variation in air temperature on floor temperature at points 0.3 and 1.0 m from the outer wall. (From Torgersen 1976a.)

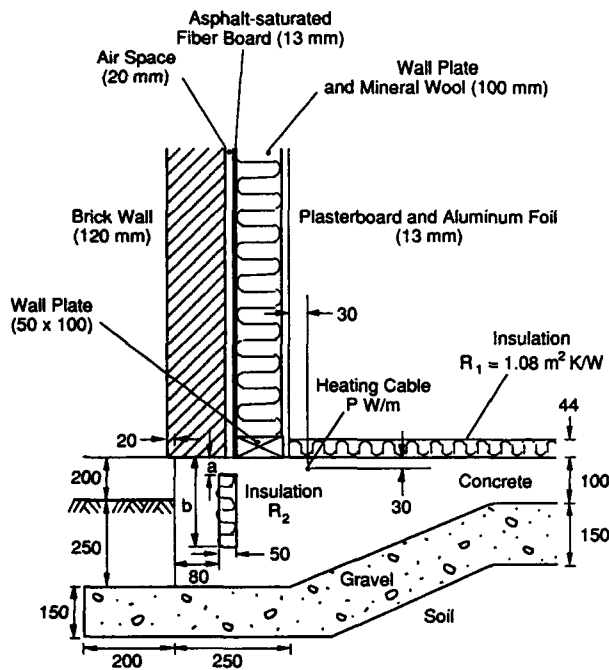


Figure 52. Edge-stiffened concrete slab with insulation on top of the slab. (From Adamson 1973.)

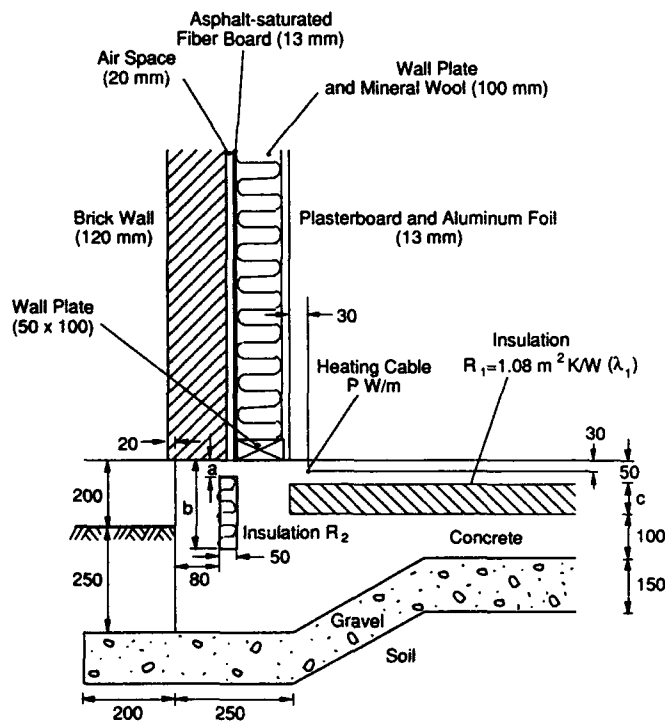


Figure 53. Edge-stiffened concrete slab with insulation cast into the slab. (From Adamson 1973.)

(Fig. 52), cast into the slab (Fig. 53) or laid under the slab (Fig. 54). Taking comparable cases illustrated by these figures (cases 104, 143 and 171, respectively), the first case gave the highest floor temperature near an external wall, and the second case gave the lowest floor temperature near the external wall. As expected, the floor temperature decreases considerably towards an external wall. In one case, for example, the temperature dropped from 17.5°C at about 0.9 m from an external wall to 8.2°C at this wall. The room occupation zone is assumed to begin 0.3 m from an external wall, and the temperature at this point should be at least 16°C for comfort. A heating cable producing 20 W/m and placed near an external wall can give acceptable floor temperatures up to that wall (Fig. 43).

Concrete slab in combination with strip foundation. In the case of a concrete slab with separate foundation walls, the effects of thermal insulation laid on top or underneath the slab and the effects of different wall constructions were also studied. The foundation walls were assumed to consist of either hollow concrete blocks or lightweight clinker blocks on a concrete footing. An example with the latter type of foundation wall is shown in Figure 55, where an external wall has brickwork facing and inner stud panels. One computation showed a drop in floor temperature from 18.3°C at about 0.8 m from the external wall to 13.4°C at this wall. This is more favorable than the case mentioned above, where the concrete slab has edge stiffening.

Ground insulation. The influence of ground insulation (placed as in Fig. 55) was also studied and found to be negligible in causing a rise in floor temperature. Also, frost penetration into the footing would not be reduced much because of thermal conduction from the outside through the concrete.

Thermal insulation of floors

The floor thermal insulation and the ground's thermal resistance strongly influence the floor's surface temperature, but while a designer has little influence on the ground's thermal resistance, the floor thermal insulation can be prescribed to ensure a satisfactory floor temperature.

The necessary thickness of floor insulation is determined from the prescribed U -value of the floor construction (i.e. slab, covering and floor insulation). The requirements for U -values for slab-on-grade construction are given in Chapter 53 of the Norwegian building code

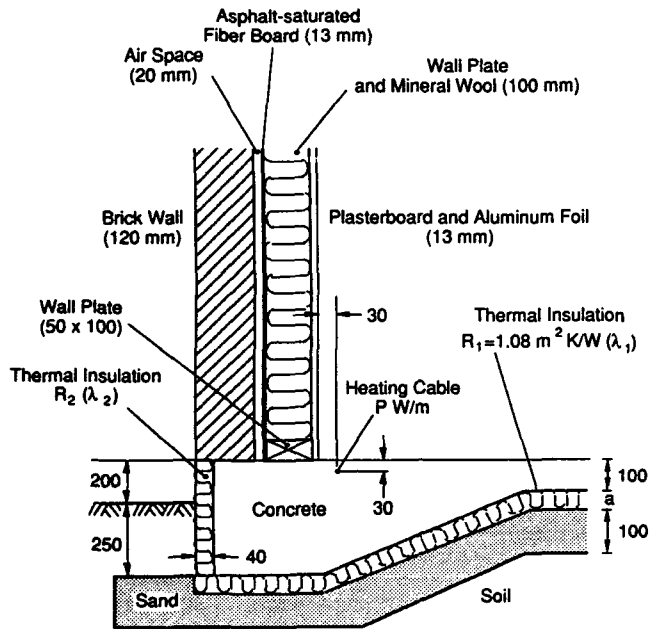


Figure 54. Edge-stiffened concrete slab with insulation under the slab. (From Adamson 1973.)

for heated buildings (NBI 1986). The requirements apply to a 1-m-wide strip of the floor bordering an outer wall, and also to the average for the whole floor. These requirements should be regarded as the minimum requirements for thermal insulation; it can often pay to insulate better. To avoid problems with low floor temperature in colder regions of Norway, U -values are recommended in the *Building Details* (NBI 1986), as shown in Figure 56. These values apply to buildings that are heated to at least 18°C . There are different curves depending on whether the underlying ground is clay, other soil or rock. The local freezing index is applied together with the appropriate curve to obtain the recommended U -value. (Figure 1 shows the maximum freezing index in different parts of Norway.)

Determination of insulation thickness according to Norwegian standards. The required floor insulation can be determined according to the rules given in NS 3031 (NBR 1986). This gives values for the average ground thermal resistance R_g

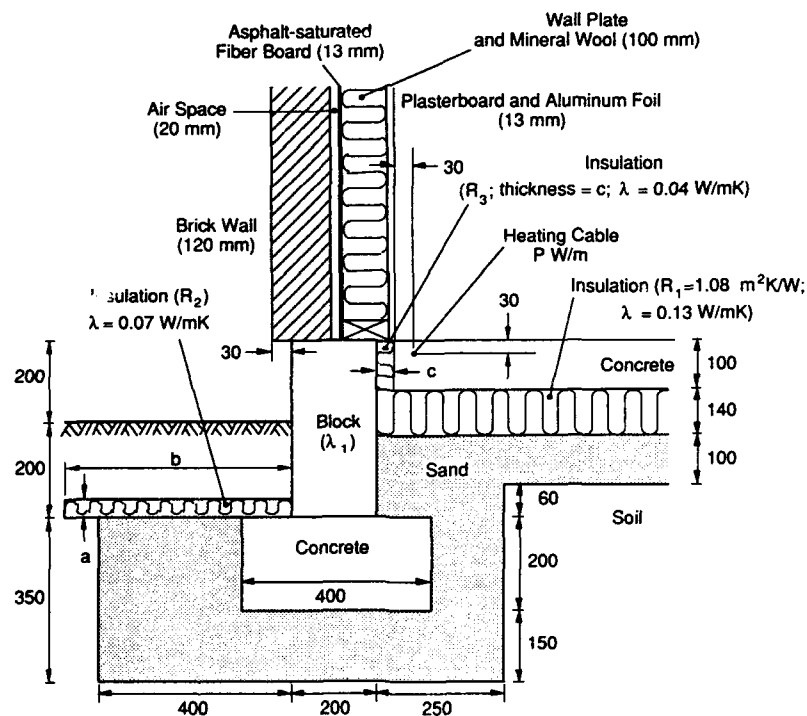


Figure 55. Concrete slab with ground insulation and a foundation wall of light-weight clinker blocks on a concrete footing. (From Adamson 1973.)

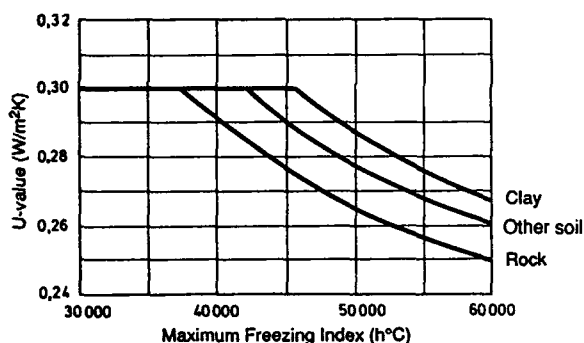


Figure 56. Recommended U-values for slab-on-grade foundations for buildings heated to at least 18°C. (From NBI 1986.)

Table 5. Thermal resistance of the ground R_j . (From NBR 1986.)

Construction	Thermal resistance R_j (m^2K/W)		
	Clay	Other soil	Rock
Slab-on-grade up to 0.6 m above grade			
0–1 m from an outer wall	1.1	0.9	0.5
1–3 m from an outer wall	3.0	2.3	1.5
3–6 m from an outer wall	4.2	3.2	2.2
Over 6 m from an outer wall	6.0	4.8	3.5
Additional resistance for a floor of depth h (m) below grade	$1.4 h$	h	$0.7h$

depending on the type of ground (clay, rock or other) and the distance from an outer wall as shown in Table 5.

The total thermal resistance R_T for the construction against the ground is then calculated from the formula

$$R_T = R_j + R_t \quad (2)$$

where R_t is the thermal resistance of the composite floor structure against the ground. The floor structure will often consist of a floor cover and a slab with underlying plastic film and insulation. The slab may be homogeneous consisting of concrete or wood material, but it could be of composite construction consisting, for example, of wood and mineral wool and including air spaces.

R_t is the thermal resistance of the composite floor from surface to surface and is expressed as

$$R_t = \sum R + \sum R_g \quad (3)$$

where R is the thermal resistance (m^2K/W) of a homogeneous plane material layer in the floor and R_g is the thermal resistance of an air space.

The thermal resistance R across a continuous homogeneous plane material layer is calculated according to the expression

$$R = d/\lambda_p \quad (4)$$

where d is the material thickness (m) and λ_p is the

practical value of the thermal conductivity (W/mK) for the material layer. NS 3031 gives tabulated values of the thermal conductivity of insulation materials and other materials that may be used. It also gives appropriate values for the thermal resistance of a "plane unventilated air layer."

In determining the thermal resistance of a floor construction that consists of homogeneous and nonhomogeneous plane material layers, the composite construction is divided into fields, with heat flowing at right angles to each field, as shown in Figure 57. Upper and lower bounds for the thermal resistance are then calculated and the mean value taken. The upper bound is calculated on the assumption that heat flow paths across the fields are parallel, so that no heat crosses from one field to the next. The lower bound is based on the assumption that different materials in a layer "blend together," i.e. that there is no thermal resistance between the different materials in a layer. Details of the procedure of calculation are given in NBR (1986).

By using these rules the total thermal resistance R_T of a slab-on-grade construction (including the effect of the underlying ground) can be calculated. This can be done for different fields of the floor according to the distance from an outer wall.

The U -value (W/m^2K) for the slab-on-grade construction is simply the reciprocal of R_T :

$$U = 1/R_T \quad (5)$$

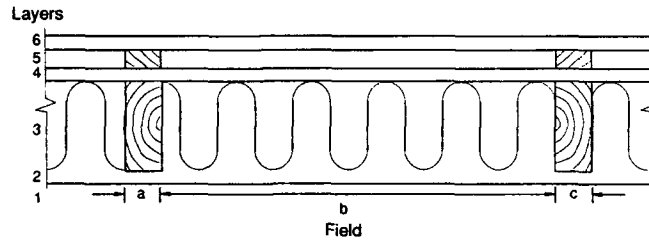


Figure 57. Division of construction into layers and fields.
(From NBR 1986.)

and represents the heat flow per unit cross-sectional area per unit temperature difference along the flow path.

Figure 56 gives recommended U -values for an inside temperature of 18°C , depending on the locality's maximum freezing index and ground type. The floor insulation thickness can then be selected so that the total U -value of the slab-on-grade construction, calculated according to NS 3031 rules, is satisfactorily related to the recommended U -value from Figure 56 (i.e. the allowable U -value is not exceeded).

Use of figures in Norwegian Building Details (NBI 1986). A quick method of determining a suitable thickness for the floor insulation is simply to use the appropriate curve in the figure from the *Building Details* (Fig. 58). Each set of curves applies to a particular field of the floor relative to an outer wall. The given curves for different ground conditions are according to NS 3031. The curve for clay applies to pure clay, while the middle curve should be used for other soil materials and for broken stone. The soil layer thickness below the floor must be at least 2.0 m; with thinner layers over a rock underlayer, one may interpolate between the curve for the actual soil type and that for rock. With a drainage layer under the floor consisting of at least 150 mm of crushed rock or coarse gravel, one can allow a thermal resistance of $0.2 \text{ m}^2\text{K}/\text{W}$, which is equivalent to 8 mm of floor insulation. The required floor

insulation thickness obtained from Figure 58 can then be reduced by 8 mm.

In Figure 58 it is assumed that the floor insulation is polystyrene or mineral wool with a practical thermal conductivity of $0.036 \text{ W}/\text{mK}$. It is also assumed that the thermal resistance of the foundation wall is at least $1.0 \text{ m}^2\text{K}/\text{W}$, for example, a concrete foundation wall with at least 40 mm of polystyrene or mineral wool or a 250-mm-thick foundation wall consisting of blocks of light clinker. A 50-mm concrete slab is assumed, with a floor covering and plastic film underneath, giving a combined thermal resistance of $0.11 \text{ m}^2\text{K}/\text{W}$.

For insulation material with a practical thermal conductivity λ_p different from $0.036 \text{ W}/\text{mK}$, the insulation thickness t (mm) can be calculated from

$$t = t_o \lambda_p / 0.036 \quad (6)$$

where t_o is the insulation thickness in accordance with Figure 58.

Small houses. It is normal in a small house (less than 4 m wide) to insulate the whole floor with the same insulation thickness. The building code demands a U -value not exceeding $0.3 \text{ W}/\text{m}^2\text{K}$ for a 1-m-wide border area of the floor along an outer wall. Table 6 (from *Building Details*) can be used to determine the required thickness of insulation, and this is then applied in Figure 58a to determine the U -value, which should not exceed $0.3 \text{ W}/\text{m}^2\text{K}$.

Table 6. Floor insulation thicknesses satisfying regulations. (From NBI 1986.)

Insulation material	Practical thermal conductivity (W/mK)	Insulation thickness (mm)		
		Clay	Other soil	Rock
Polystyrene or mineral wool	0.036	50(40)	60(50)	70(60)
Loose light clinker	0.20	250	300	400

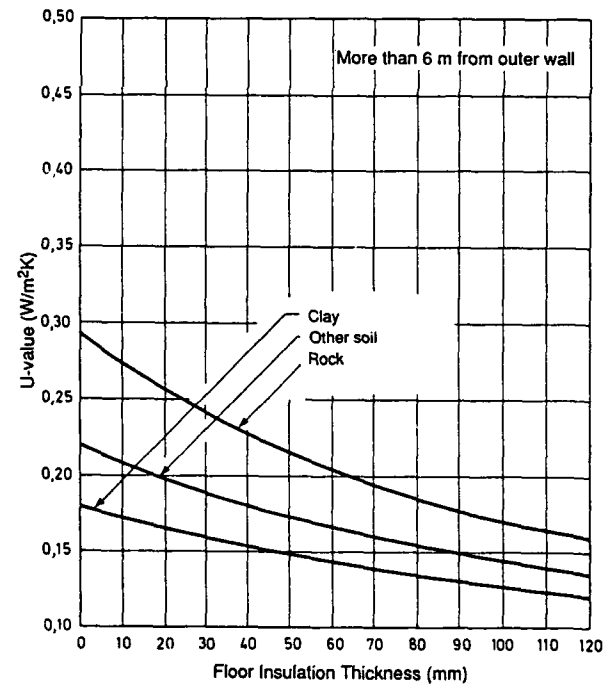
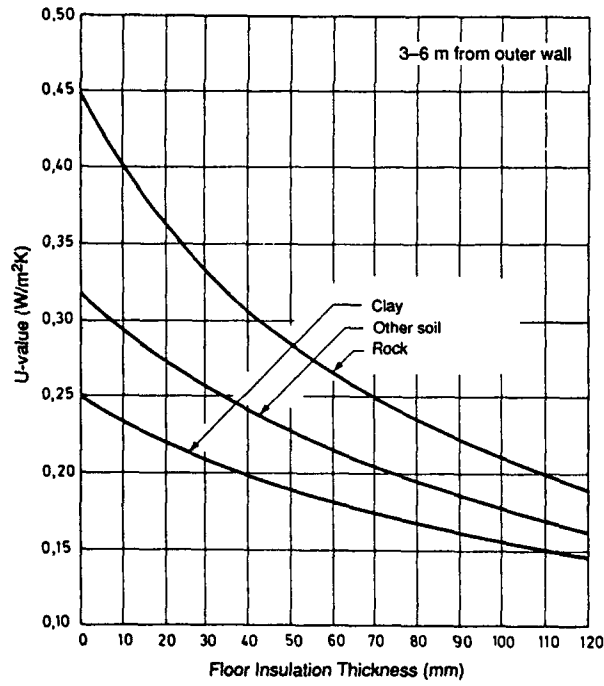
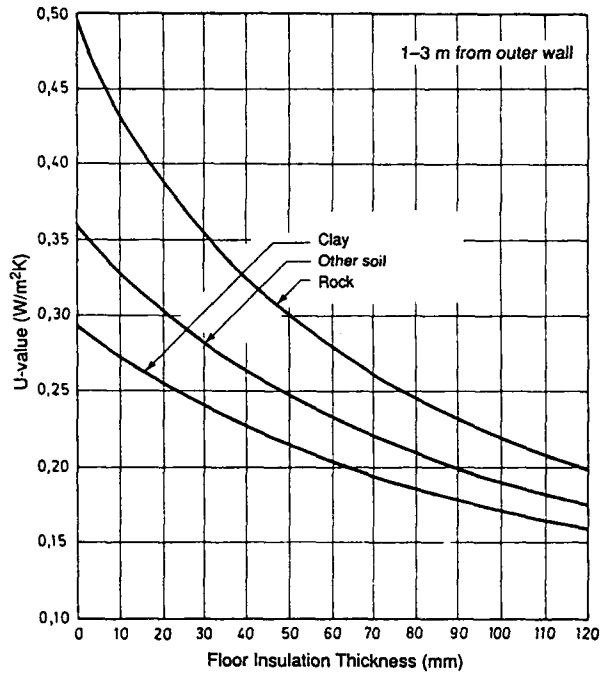
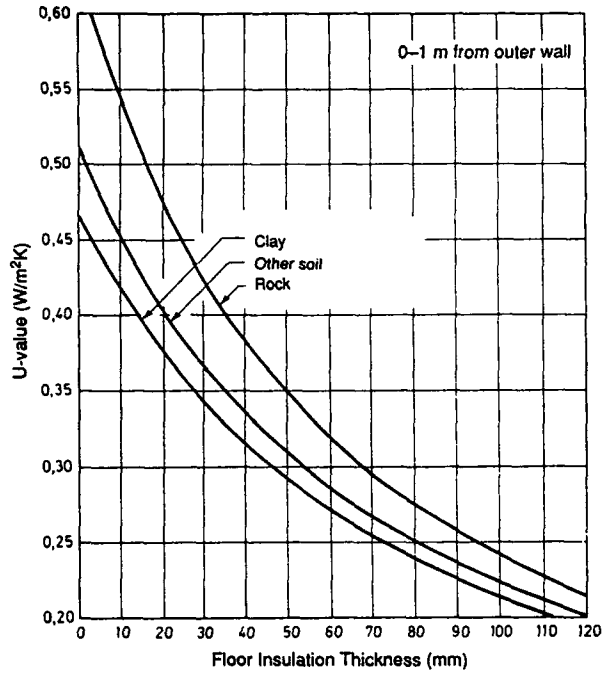


Figure 58. Curves for determining floor insulation thickness from U-values. (From NBI 1986.)

Table 6 gives values of insulation thicknesses of polystyrene and mineral wool that are satisfactory according to the regulations. The numbers in parentheses apply to slab-on-grade constructions with at least 150-mm-thick drainage layers of crushed rock or coarse gravel under the insulation, the thickness of which can accordingly be reduced. In colder regions (freezing indexes above 40,000 h°C), the recommended insulation thicknesses should be increased by the amounts given in Table 7 to avoid a reduced floor temperature. This assumes sufficient foundation wall insulation as provided by a concrete foundation wall with at least 40 mm of polystyrene or mineral wool, or a foundation wall consisting of 250-mm-thick blocks of light clinker.

Table 7. Recommended increase in insulation thickness for various values of maximum freezing index. (From NBI 1986.)

Ground type	Recommended increase (mm)		
	$F_{100}=40,000$	50,000	60,000 h°C
Clay and other soil	0	10	20
Rock	10	20	30

Large buildings. For large buildings (greater than 4 m wide) the necessary thickness of floor insulation, in accordance with the required U -value for a 1-m-wide border area along an outer wall, is determined from Figure 58. Also, the average U -value for the whole floor should be checked against the actual requirement.

For a floor construction the average U -value can be calculated according to the formula

$$U_m = \frac{A_a U_a + A_b U_b + A_c U_c + A_d U_d}{A_a + A_b + A_c + A_d} \quad (7)$$

where U_a, U_b, U_c and U_d are the U -values for the floor fields from Figure 58 and A_a, A_b, A_c and A_d are the areas of these fields.

Swedish standards (SBN 1980). SBN (1980) simply states that the thermal resistance of an outer edge strip of a floor construction (with no heat gains from heating pipes) should not exceed 3.3 m²K/W. The normal U -value requirement for a slab-on-grade construction is 0.30 W/m²K, and the maximum U -value is 0.40 W/m²K. These values apply for the four temperature zones in Sweden. The maximum U -value is higher than the allowable value of 0.30 W/m²K specified in Norway.

Finnish guidelines. The Finnish guidelines (VTT 1987) give the maximum allowable U -value and minimum thermal resistance for a slab-on-grade foundation with a heated or partly heated room. As shown in Table 8 a maximum U -value of 0.36 W/m²K is specified for all areas of the floor construction below a heated room (intermediate between the Norwegian and Swedish values). The specified thermal resistance of a slab-on-grade floor structure in Finland is higher for the 1-m border area than for the inner part of the floor.

Comparison. The Norwegian method of determining the floor insulation thickness is more detailed, since it takes into account the underlying foundation material and considers four areas of the floor according to their distance from an outer wall. However, for a small house the same thickness of insulation is used over the whole floor.

Foundation wall insulation

The effects of foundation wall insulation on frost penetration and floor temperature were described earlier. Figure 59 shows alternative locations of insulation recommended by the Finnish guidelines (VTT 1987). The foundation wall itself may be

Table 8. Maximum allowable U -values and minimum thermal resistances for the floors of heated and partly heated structures with slab-on-grade foundations. (From VTT 1987.)

Floor structure	Max. allowable U -value (W/m ² K)		Thermal resistance (m ² K/W)	
	Heated room	Partly heated room	Heated room	Partly heated room
1-m floor and ground border areas	0.36 (0.45)*	0.45 (0.65)	2.6 (2.1)	2.1 (1.4)
Other areas	0.36 (0.45)	0.45 (0.65)	1.4 (-)	0.9 (-)

* Values in parentheses apply to industrial structures and warehouses.

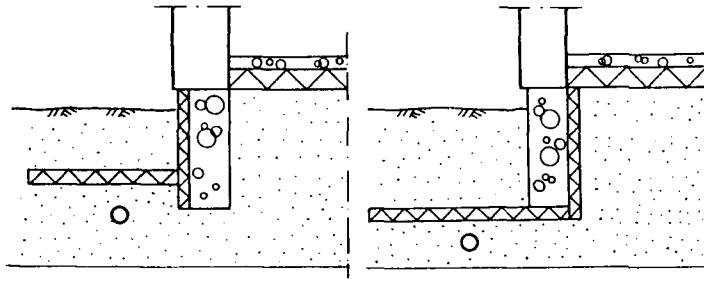


Figure 59. Recommended location of insulation in association with a foundation wall. (From VTT 1987.)

Table 9. Approved least thermal resistance of edge insulation. (From SBN 1980.)

	Thermal resistance (m^2K/W)	
	Temperature zones I and II	Temperature zones III and IV
Floor with heating along external wall	1.00	0.80
Floor without heating along external wall	1.60	1.20

Table 10. Necessary foundation wall insulation of expanded polystyrene or mineral wool for three floor heights. If the floor's height above the ground is more than 600 mm, the foundation wall should be frost-protected according to the guidelines in NBI (1987). (From NBI 1986.)

Maximum freezing index ($h^\circ C$)	Insulation thickness (mm)		
	Floor height: ≤ 300	450	600 mm
$\leq 30,000$	40	50	60
40,000	50	60	70
50,000	60	70	80
60,000	80	90	100

made of material with good insulation properties like light clinker blocks, or only some part of the foundation wall may be composed of such blocks (Fig. 49d).

The Swedish building standards (SBN 1980) give approved values for the minimum thermal resistance of edge (or foundation wall) insulation associated with a slab-or-grade foundation as shown in Table 9.

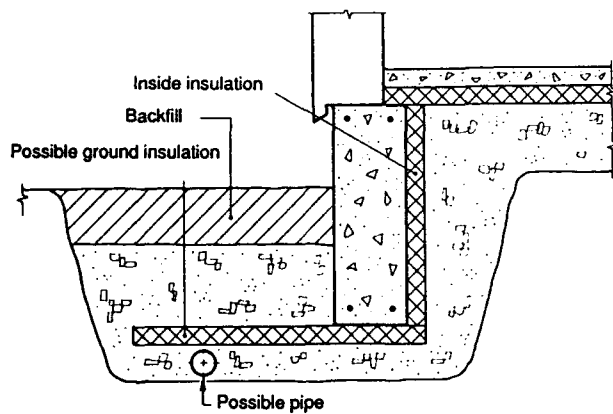
The Norwegian *Building Details* (NBI 1986) require the whole foundation wall to be insulated to obtain frost protection. The thickness of insulation depends on the locality's maximum freezing index (F_{100}) and on the pedestal height (i.e. the height of the floor surface above the prepared ground level). Table 10 gives recommended thicknesses of insulation for a foundation wall of concrete insulated with expanded polystyrene or mineral wool. A

foundation wall of 250-mm light clinker blocks can be taken as equivalent to 40 mm of polystyrene or mineral wool. If the insulation requirement according to Table 10 is larger than that, this type of foundation wall should be additionally insulated.

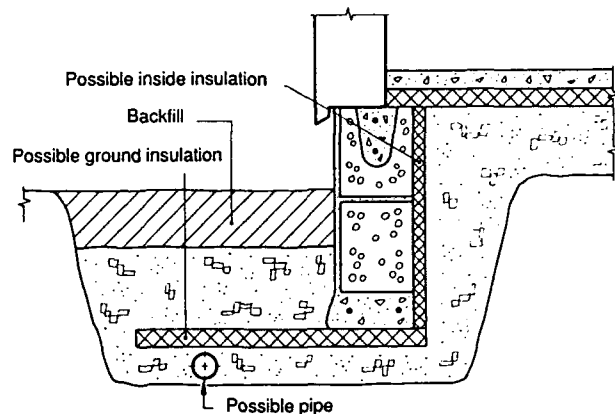
Examples of insulating foundation walls with inside or outside insulation (or both) are given in Figure 60. One example shows a foundation wall built with light clinker blocks using inside insulation (Fig. 60b). Foundation wall insulation should consist of a board of polystyrene with a density at least 20 kg/m^3 or a board of mineral wool with a density of at least 90 kg/m^3 .

Ongoing Danish research. As part of the Danish energy research program, an analysis is being done on the necessary foundation depth of existing and future buildings in relation to frost protection assuming no foundation insulation, outside foundation insulation only and inside foundation insulation only. The analysis is based on the following conditions (Porsvig 1986):

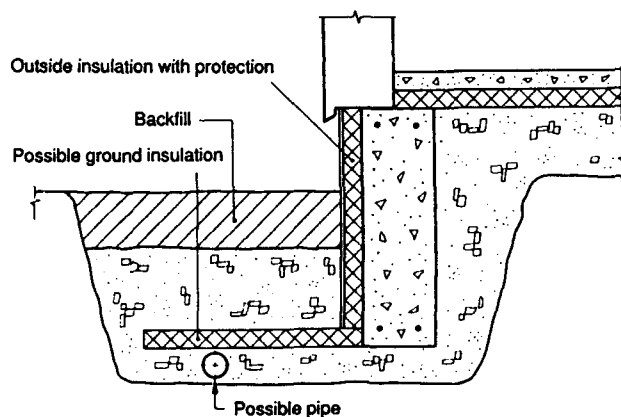
- Two typical foundation soils, namely saturated moraine and partly saturated sand (these occur at foundation depths in about 70% of Denmark);
- A heated building insulated according to the present Danish standards;
- A frost influence corresponding to an outside temperature variation like that of the exceptionally cold winter of 1941–42; and
- A constant soil temperature of about $8^\circ C$ over a depth of 10 m.



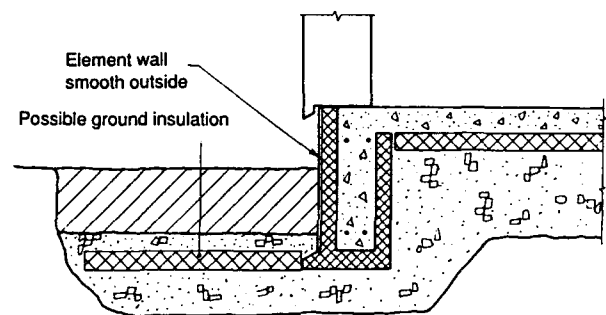
a. Cast foundation wall with inside insulation.



b. Built foundation wall with light aggregate blocks on cast concrete footing, possibly with extra inside insulation.



c. Cast foundation wall with outside insulation with a protected surface.



d. Cast foundation wall in elements of polystyrene with a smoothed outside.

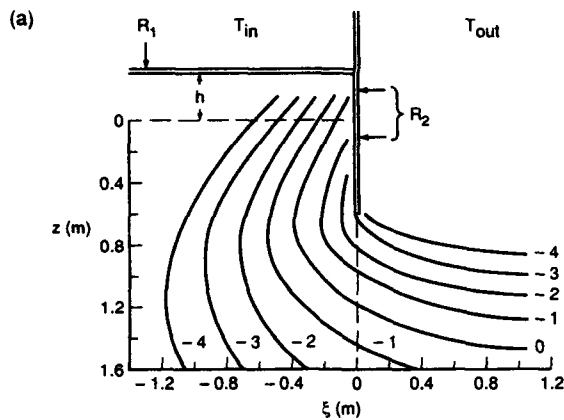
Figure 60. Types of foundation wall. (From NBI 1986.)

The project includes computer calculations of temperature conditions around part of a construction composed of outer wall, foundation and floor. The part of the outer wall considered is bounded by a horizontal section at a height of 1 m above the floor level. The included floor surface is bounded by a vertical section at a distance of 2 m from the internal face of the wall. The foundation depth is varied between 0.4 and 0.9 m under the ground surface. The influence of insulation on the outside or inside of the foundation is examined for both moraine and sand.

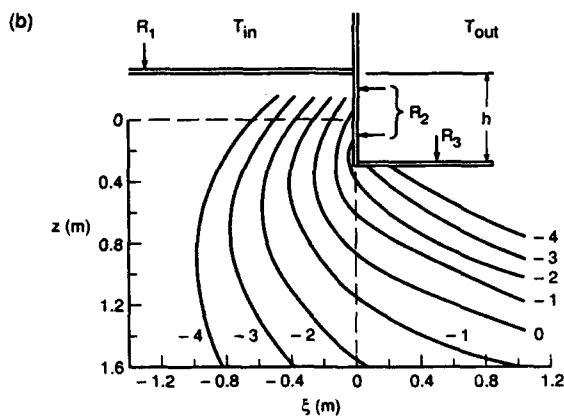
Provisional Danish results. For a foundation depth of 0.4 m and inside insulation or without insulation, the 0°C isotherm is near the outside edge of the base of the foundation. On the other hand, for the corresponding foundation with insulation on the outside,

the 0°C isotherm is forced away from the foundation. This study confirms that outside insulation is more effective than inside insulation and shows that the use of the existing standards (DS 415) concerning frost-free foundation depth is much influenced by which side of the foundation wall is protected in the case of heated buildings. (Calculations for unheated buildings are still lacking.)

Where the underlying soil is strong and stiff enough for a smaller foundation depth to be used, it would be possible to use outside insulation with the foundation. However, such a measure would be in contradiction with existing Danish practice, and Porsvig (1986) suggested that it should be done only in cases where documented calculations of both temperature and deformation condi-



a. Without ground insulation.



b. With ground insulation.

Figure 61. Effect of ground insulation on isotherms. ($R_3 = 1.08 \text{ m}^2\text{K/W}$; square building $10 \times 10 \text{ m}$; section along diagonal; $R_1 = 1.08 \text{ m}^2\text{K/W} = R_2$; pedestal height = 0.3 m ; clay soil; outside temperature = -11.0°C .) (From Adamson et al. 1973.)

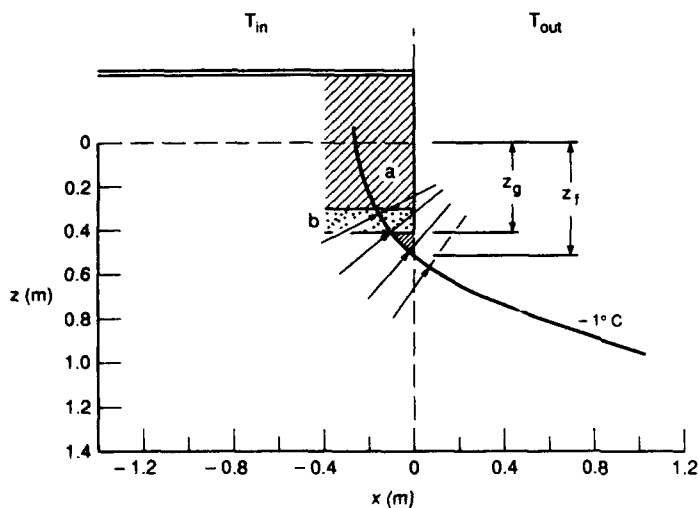


Figure 62. Freezing zone's influence on ground construction. (From Adamson et al. 1973.)

tions are available. The savings in foundation concrete can then be balanced against the expenses of extra calculations, checking and insulation material. This might be warranted where one is considering using standard foundation designs for a number of industrial buildings at a foundation depth above the recommended frost-free depth.

Foundation depth and ground insulation

Required foundation depth and ground insulation

The foundation depth is related to frost penetration, which is significantly reduced by horizontal ground insulation (e.g. Fig. 61 shows a reduction from 1.0 to 0.6 m). There must be an adequate foundation depth for protection against frost damage. The required foundation depth should account for possible heave forces that can act if frost penetrates into saturated frost-susceptible soil. Ice lenses generally follow the isotherms, and the heave forces produced are therefore mainly at right angles to the isotherms (Fig. 13), but they tend to incline towards the direction of least resistance.

Adamson et al. (1973) and the Frost I Jord project assumed the -1°C isotherm to be critical, as shown in Figures 14 and 15. Above this isotherm the soil can be considered to be fully frozen and liable to produce frost heave if it is frost susceptible.

Figure 62 shows the foundation wall or slab edge with a drainage layer below it composed of non-frost-susceptible material. This layer is considered part of the foundation depth, which thus extends a distance z_g that is nearly equal to the frost penetra-

tion depth z_f (the small hatched area in Fig. 62 being negligible). Thus, in the case represented by Figure 62, the frost heave force does not significantly affect the structural part of the foundation.

Reporting in the early 1970s, Adamson et al. stated that in Sweden remarkably few cases of damage to floor structures placed on the ground could be related to frost heave in spite of considerable frost penetration during the winters of 1966 and 1970. The most common designs using edge-stiffened floor slabs had foundation depths of 0.3–0.4 m below the ground surface, including non-frost-susceptible drainage layers. The edge of the slab was usually well reinforced with steel and could take any heave force.

Foundation depth for edge-stiffened concrete slabs

Floor slabs without edge insulation. Figure 63 shows a large frozen area, and consequently a large heave force, at a corner of a square building with a foundation depth of 0.35 m. At a distance of 0.8 m from the corner there is much less frost penetration, and the heave force is reduced considerably (Fig. 64). The corner effect may extend about a meter on either side, and to counteract it the edge should be reinforced with top and bottom steel. This would be sufficient in Swedish temperature zones III and IV, but in the colder zones I and II, special measures may be necessary.

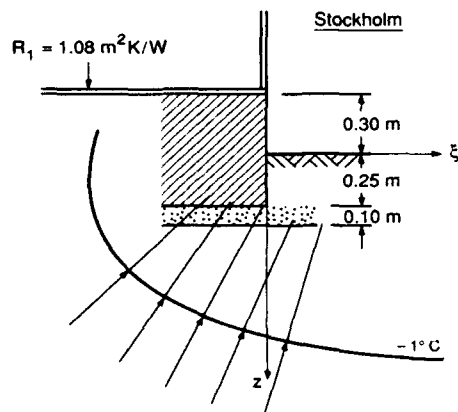


Figure 63. Frost penetration (indicated by the -1°C isotherm) at a corner of a building. (Square building 10×10 m; section along diagonal; clay soil; no foundation wall insulation; outside temperature = -9.9°C ; foundation depth = 0.35 m.) (From Adamson et al. 1973.)

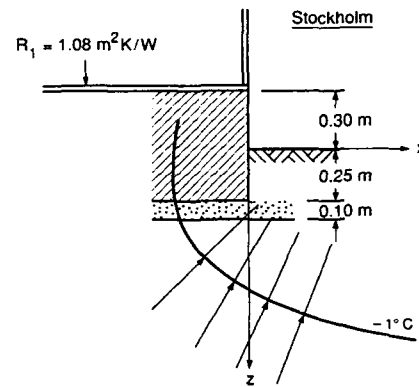


Figure 64. Frost penetration (indicated by the -1°C isotherm) 0.8 m from a corner of a building. (Square building 10×10 m; clay soil; no foundation wall insulation; outside temperature = -9.9°C ; foundation depth = 0.35 m.) (From Adamson et al. 1973.)

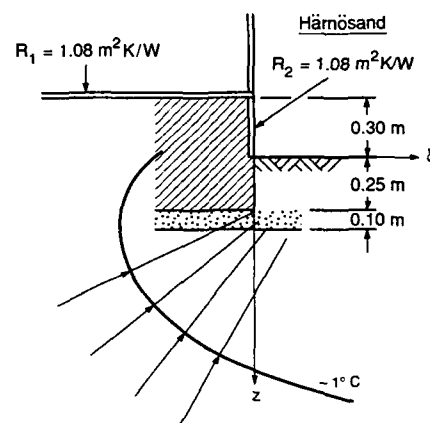


Figure 65. Frost penetration (indicated by the -1°C isotherm) at a corner of a building when foundation wall insulation is used. (Square building 10×10 m; section along diagonal; clay soil; outside temperature = -11.0°C ; foundation depth = 0.35 m.) (From Adamson et al. 1973.)

Slabs with edge insulation. Where the edge is provided with insulation of thermal resistance R_2 , there is considerable frost penetration under the foundation area at a corner, as shown in Figure 65. Again, this penetration is much less at a distance of 0.8 m from the corner (Fig. 66). If the edge insulation is extended down 0.3 m into the ground, there is significantly less penetration in either case (Fig. 67 and 68).

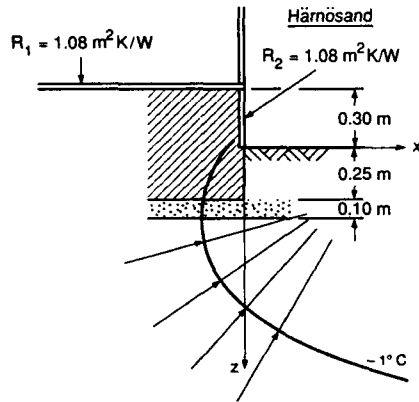


Figure 66. Frost penetration (indicated by the -1°C isotherm) 0.8 m from a corner of a building when foundation wall insulation is used. (Square building 10×10 m; clay soil; outside temperature = -11.0°C ; foundation depth = 0.35 m.) (From Adamson et al. 1973.)

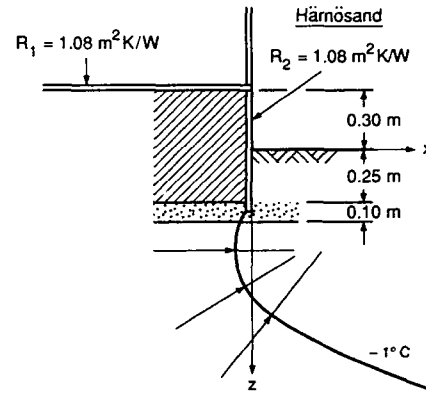


Figure 68. Frost penetration (indicated by the -1°C isotherm) 0.8 m from a corner of a building when foundation wall insulation is extended 0.3 m into the ground. (Square building 10×10 m; clay soil; outside temperature = -11.0°C ; foundation depth = 0.35 m.) (From Adamson et al. 1973.)

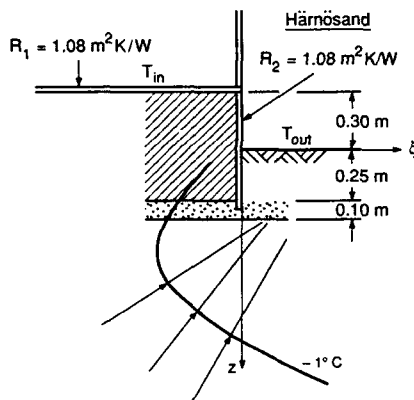


Figure 67. Frost penetration (indicated by the -1°C isotherm) at a corner of a building when foundation wall insulation is extended 0.3 m into the ground. (Square building 10×10 m; section along diagonal; clay soil; outside temperature = -11.0°C ; foundation depth = 0.35 m.) (From Adamson et al. 1973.)

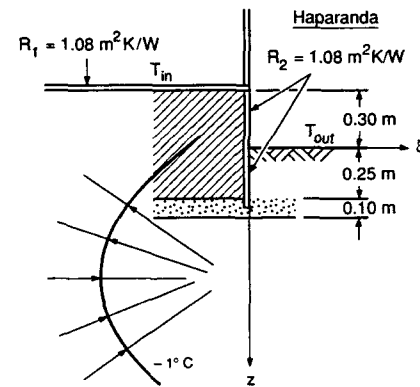


Figure 69. Oblique frost forces at a corner of a building. (Square building 10×10 m; section along diagonal; clay soil; foundation wall insulation; outside temperature = -11.4°C ; foundation depth = 0.35 m.) (From Adamson et al. 1973.)

Figures 69 and 70 show that frost forces may act obliquely up at the slab's bottom. The upward force can be eliminated or reduced by supplying heat (Fig. 71) or installing ground insulation at a corner (Fig. 72).

Adamson et al. suggested that in temperature zones I and II the edge should be insulated with insulation above the ground only, the thermal re-

sistance R_2 of this insulation being approximately $1\text{ m}^2\text{K/W}$.

Special measures at corners. SBN (1967) required special measures against frost heave at corners by providing heat from heating pipes in the building, for example. However, Adamson et al. (1973) concluded from their study that normally no such measures are necessary. They suggested neverthe-

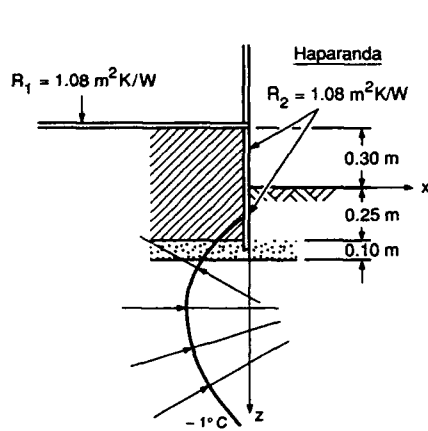


Figure 70. Oblique frost forces 0.8 m from a corner of a building. (Square building 10×10 m; clay soil; foundation wall insulation; outside temperature = -11.4 °C; foundation depth = 0.35 m.) (From Adamson et al. 1973.)

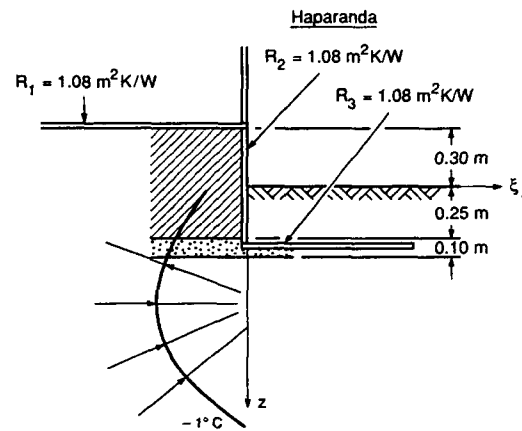


Figure 72. Frost penetration (indicated by the -1 °C isotherm) at a corner of a building when foundation wall insulation is extended 0.3 m into the ground and ground insulation is used at the corner. (Square building 10×10 m; section along diagonal; clay soil; outside temperature = -13.1 °C; foundation depth = 0.35 m.) (From Adamson et al. 1973.)

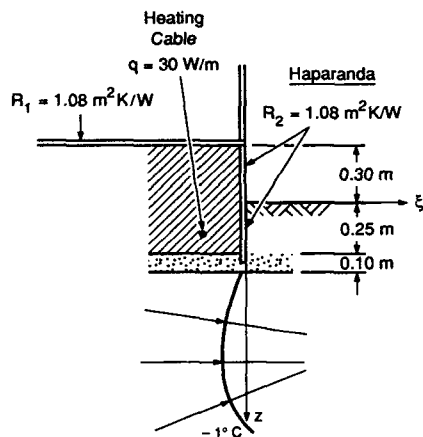


Figure 71. Frost penetration (indicated by the -1 °C isotherm) at a corner of a building when foundation wall insulation is extended 0.3 m into the ground and a heating cable is used. (Square building 10×10 m; section along diagonal; clay soil; outside temperature = -15.8 °C; foundation depth = 0.35 m.) (From Adamson et al. 1973.)

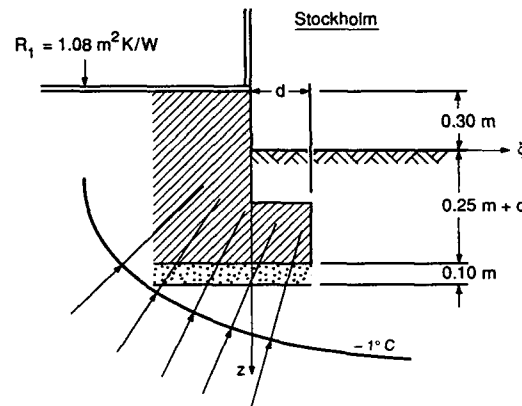


Figure 73. Frost penetration (indicated by the -1 °C isotherm) at a corner of a building when the foundation protrudes by a distance d. (Square building 10×10 m; section along diagonal; clay soil; no foundation wall insulation; outside temperature = -9.9 °C; foundation depth = 0.35 m.) (From Adamson et al 1973.)

less that edge beams (or foundation walls) should be reinforced near corners to provide cantilever action in case underlying frost-susceptible soil is displaced as a result of frost heave forces. At projecting corners in Swedish zone I particularly, the edge should be insulated along its whole height, and extra heat (from heating pipes or electrical

cables) or ground insulation may also be required. *Protruding parts of a foundation.* The results of Adamson et al. justified the requirement of SBN (1967) that, for a protruding part of a construction, the foundation depth should be increased by an amount equal to the distance that the part projects outside an outer wall. In Figure 73 the foundation

depth has been increased by the protruding distance d (giving a total foundation depth of $0.35 \text{ m} + d$) and frost conditions are more favorable than in Figure 63, where the foundation depth is only 0.35 m .

Room temperature. Adamson et al. found that the required foundation depth is not particularly sensitive to small variations in room temperature, for example, if it is reduced from 20° to 10°C . They therefore suggested that the foundation depth of 0.35 m can also be used where the room or space above a floor structure is heated to only 10°C if the total thermal resistance of the floor area next to an outer wall does not exceed $1.3 \text{ m}^2\text{K}/\text{W}$. Also, ground insulation should be provided and special measures taken to counteract frost heave along the entire outer wall. However, they considered it preferable to increase the foundation depth from 0.35 to 0.50 m if the room or space had a minimum mean monthly temperature of 10°C during a hard winter.

Standards and guidelines

Sweden. The general requirements of the Swedish building standards (SBN 1980) are that if a building is to be built on frost-susceptible soil and is to be protected against frost action, its foundation should be at least as deep as the lowest frost-free level that can be expected during the assumed life of the building. This level should be determined taking into consideration the climatic conditions, the heat contribution from the soil and from the building if it is permanently heated, and the durability of the thermal insulation. In applying these requirements it should be assumed that buildings that are not intended for permanent use (for instance, most vacation homes) may be unheated during winter months.

For a foundation slab underneath an external wall and projecting outside (or any other projecting part of a building), the specified foundation depth should be increased by the width of the slab (or extent of projection) outside the face of the wall. However, the foundation need not be deeper than $0.85 h_o$, where h_o is the frost depth in undisturbed ground. The requirement for other projecting parts of a building (e.g. external stairs) is that the specified foundation depth should be increased by the distance between the extremity of the part concerned and the external wall but need not be larger than h_o .

Particular requirements apply to slab-on-grade foundations associated with heated buildings. The floor construction is assumed to have horizontal insulation such that the total thermal resistance in

the outer edge strip is not greater than $3.3 \text{ m}^2\text{K}/\text{W}$ and there are no heat gains from heating pipes or the like cast into the construction. It is also assumed that the floor construction is situated underneath a room that has a minimum monthly mean temperature during cold winters of about 18°C as for a habitable room. With such a structure the foundation depth should be 0.35 m under the following conditions:

- The width of the building is at least 4 m .
- Edge beams or foundation walls for buildings situated in temperature zones I and II should be provided with thermal insulation having a minimum thermal resistance of $1 \text{ m}^2\text{K}/\text{W}$ above the ground surface. If the floor surface lies more than 0.3 m above the ground surface outside the building, the edge beam or foundation wall should have a thermal resistance of at least $2 \text{ m}^2\text{K}/\text{W}$ in temperature zones I and II and at least $1 \text{ m}^2\text{K}/\text{W}$ in zones III and IV. However, the floor surface should not be higher than 0.6 m above the ground surface outside the building.
- Special measures to counteract the risk of frost damage should be taken within a distance of 1 m from external corners in contact with external air. An example of such a measure could be the provision of suitable ground insulation. However, these special measures can be omitted under certain conditions, e.g. where the edge beam's thermal resistance is increased by 50% above the values given above, but with a minimum thermal resistance of $1.5 \text{ m}^2\text{K}/\text{W}$.

If the lowest monthly mean temperature of the room during winter is about 10°C , the foundation depth should be increased from 0.35 to 0.50 m .

Norway. With the change in the Norwegian building guidelines (1970), the requirement became simply that the foundations should be designed so that there would be no damage to the structure from frost action. It was no longer necessary in all cases to take the foundation down to the frost-free depth

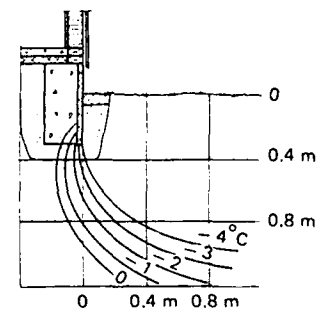
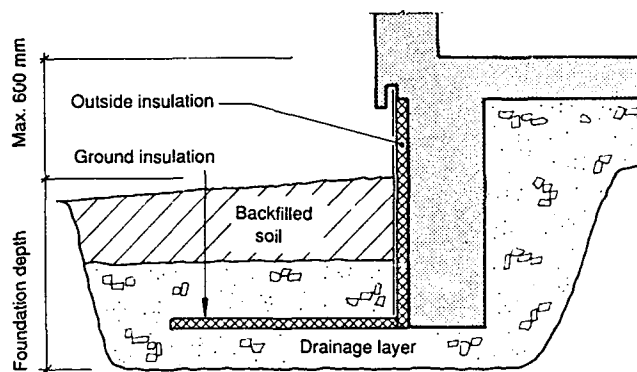


Figure 74. Example of calculated temperature distribution at a foundation. (From Torgersen 1976a.)

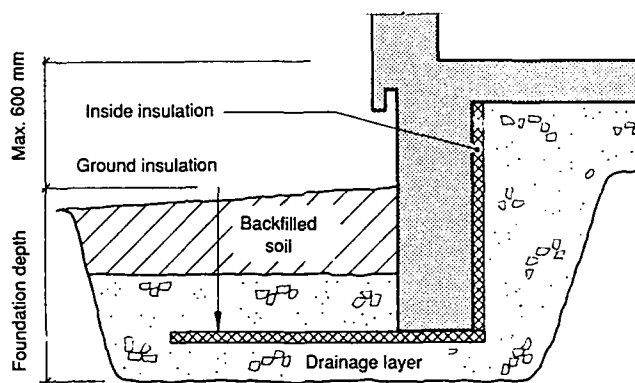
in undisturbed ground. For a typical slab-on-grade foundation, the isotherms are shown in Figure 74 at the coldest time of the year for a certain locality (Torgersen 1976a). These isotherms were produced from computer calculations that take into account the heat contribution to the foundation from the building. If the soil is frost susceptible, there is danger of frost damage unless the foundation is taken down to a sufficient depth relative to the critical isotherm or unless other special precautions are taken.

The foundation depth and requirement for ground insulation depend on the locality's maximum freezing index F_{100} . Figure 75 from *Building Details* (NBI 1986) shows the placement of ground insulation with an externally or internally insulated foundation wall. This design also applies to a masonry foundation wall. An optional drainage layer, 100 mm thick, under the foundation wall can be considered to be part of the foundation depth.

Building Details specifies that, for a freezing index up to 30,000 h°C, a foundation wall for a heated house can be 0.4 m deep measured from prepared ground, without ground insulation. If the freezing index is larger, ground insulation is necessary. Tables 11 and 12 are based on ground insulation of expanded polystyrene with a density of 30 kg/m³ and a thermal conductivity of 0.045 W/mK. For extruded polystyrene the given thicknesses should be multiplied by 0.73, and for mineral wool by 1.45. A mineral



a. Externally insulated foundation wall.



b. Internally insulated foundation wall.

Figure 75. Placement of ground insulation. For foundation depths, see Tables 6 and 7. (From NBI 1986.)

Table 11. Minimum foundation depth with ground insulation only at the corner and outside an unheated small room. If the foundation wall has inside insulation, the optional ground insulation must also be extended under the foundation wall. (From NBI 1986.)

Maximum freezing index (h°C)	Minimum foundation depth (m)		Necessary ground insulation at corner and room (mm)†
	Concrete insulated externally	Concrete insulated internally*	
≤30,000	0.40	0.40	None
35,000	0.40	0.50	50 × 500 × 100
40,000	0.50	0.60	
45,000	0.60	0.70	
50,000	0.70	0.85	50 × 500 × 1500
55,000	0.85	1.05	
60,000	1.00	1.20	

* Light aggregate blocks, 250 mm thick.

† Polystyrene 30 kg/m³; t × B × L; see Fig. 76 (t is insulation thickness).

Table 12. Necessary ground insulation with a foundation depth of 0.4 m. If the foundation wall has inside insulation, the ground insulation must also be extended under the foundation wall. (From NBI 1986.)

Maximum freezing index (h°C)	Ground insulation (mm)*	
	At corner†	Along a long wall**
≤30,000	Not necessary	Not necessary
35,000	50 × 500 × 1000	50 × 250
40,000	50 × 750 × 1000	50 × 250
45,000	50 × 750 × 1500	50 × 250
50,000	80 × 750 × 1500	50 × 500
55,000	80 × 1000 × 1500	80 × 500, 50 × 750
60,000	80 × 1000 × 2000	80 × 750

*Polystyrene; 30 kg/m³.

†t × B × L.

**t × b.

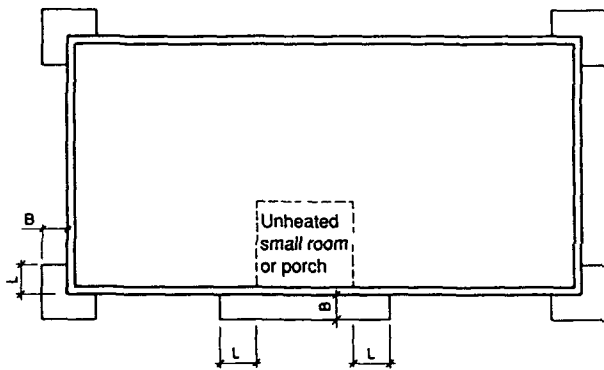


Figure 76. Ground insulation at corners and outside an unheated small room. (From NBI 1986.)

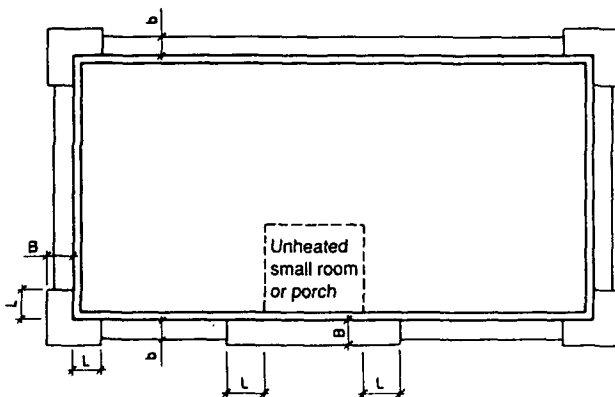


Figure 77. Ground insulation along all walls, at corners and outside an unheated small room. (From NBI 1986.)

wool board should be laid on a draining under-layer and should not be laid under the foundation wall or foundation.

- If ground insulation is used at a house corner or outside an unheated small room as shown in Figure 76, the necessary foundation depth and ground insulation dimensions can be found from Table 11.
- If the minimum foundation depth of 0.4 m is used and the freezing index is greater than 30,000 h°C, one should lay ground insulation along all walls as shown in Figure 77. The dimensions of this ground insulation are determined according to Table 12.

With an unheated room in the corner of a house or with a large unheated room, the foundation wall should be frost-protected according to the regulations for unheated buildings. The same applies to a house that is in process or is not yet heated before the cold season.

Finland. Table 13 from the Finnish guidelines (VTT 1987) gives the frost-free foundation depth in frost-susceptible soil for a heated structure with a slab-on-grade foundation. The foundation depth depends on the freezing index and the location on the foundation, i.e. at a wall border or a corner area. The floor structure's thermal resistance is taken to be 4 m²K/W, and the foundation wall is assumed to have outside insulation; no ground insulation is required.

Table 13 applies to normally present foundation fills with moisture contents of about 3–10%. Foundation depths less than those indicated in Table 13 can be used for finer-grained soils, while greater depths should be used for coarser-grained soils and moraines. With natural clays or silts the moisture content can be quite high, and it is essential to have *outside* foundation wall insulation to prevent a cold bridge from the outside air to frost-susceptible soil.

If the foundation depth to be used is less than the frost-free depth, ground insulation is required, with the thermal resistance depending on the chosen foundation depth and the local design freezing index, as shown in Figure 78. These design curves refer to a slab-on-grade foundation, with the following conditions based on the Swedish and Norwegian work:

- The inside temperature is at least 17°C.
- The building's width is at least 4 m.
- There is no snow on the ground next to the building.
- The pedestal height is not more than 0.6 m above grade.

Table 13. Heated structures (inside temperature $\geq 17^{\circ}\text{C}$) frost-free foundation depth in frost-susceptible soil for slab-on-grade foundations with insulation outside the foundation wall. It is assumed that the building's width is at least 4 m and that the ground surface by the side of the structure is snowless. Smaller foundation depths can be used for fine-grained soils and greater depths for coarse-grained soils and moraines. Intermediate values can be interpolated. (From VTT 1987.)

Thermal resistance of floor structure ($\text{m}^2\text{K}/\text{W}$)	Foundation part	Frost-free foundation depth (m)		
		$F_{50} = 35,000$	50,000	65,000 ($h^{\circ}\text{C}$)
4	wall border	1.0/1.2	1.3/1.5	1.6/1.9
4	corner	1.3/1.6	1.6/2.0	2.0/2.4
3	wall border	0.9/1.1	1.2/1.4	1.6/1.9
3	corner	1.2/1.5	1.6/2.0	2.0/2.3

- The pedestal height is not more than 0.6 m above grade.
 - The foundation wall is well insulated so as to provide a thermal resistance of at least $1 \text{ m}^2\text{K}/\text{W}$.
 - The border strip of the floor structure near the outside walls has a thermal resistance of $2.6 \text{ m}^2\text{K}/\text{W}$.
 - The width of the ground insulation is 0.8–1.0 m.
- The guidelines state that at exterior corners 40% additional insulation should be provided over a distance of 1.5 m from a corner. This can consist, for example, of 70-mm-thick insulation placed at a corner, compared to 50 mm along an outer wall. The lack of this extra insulation has resulted in many cases of frost damage in Finland due to
- Less snow cover at a corner because it is particularly exposed to wind, which blows the snow away; and

- The 0°C isotherm being lower at a corner on account of its greater exposure to the outside climate.

Comparison. The Swedish standards do not appear to give any recommendations about the design of ground insulation but leave that to the judgement of the engineer. The Norwegian and Finnish guidelines give a more detailed procedure, with recommended insulation amounts depending on the freezing index and foundation depth, but the choice of critical isotherm differs. The Finnish recommendations are based on the Frost I Jord project, and the ground insulation's thermal resistance (Fig. 78) needs conversion to a requisite thickness of insulation used, e.g. polystyrene. The Norwegian guidelines are more detailed, differentiating between a foundation wall insulated externally and one insulated internally. The minimum inside temperature assumed in the Finnish case is 17°C ,

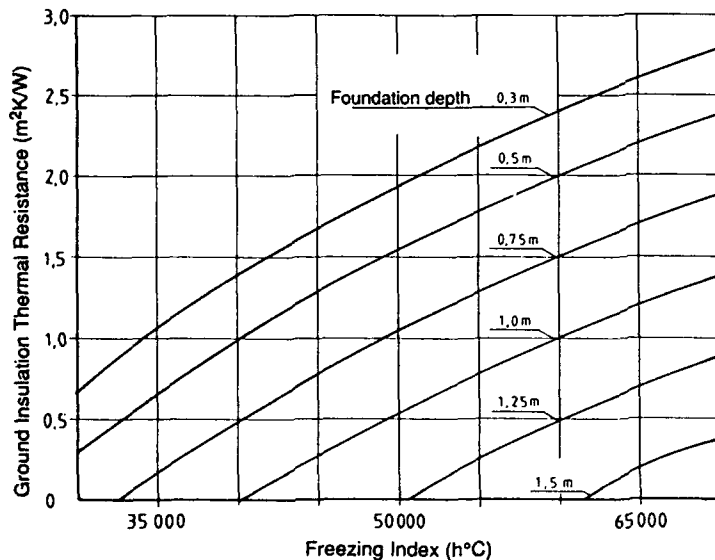


Figure 78. Thermal resistance of ground insulation according to foundation depth and local freezing index. This applies to a slab-on-grade floor structure with a thermal resistance of $2.6 \text{ m}^2\text{K}/\text{W}$. (From VTT 1987.)

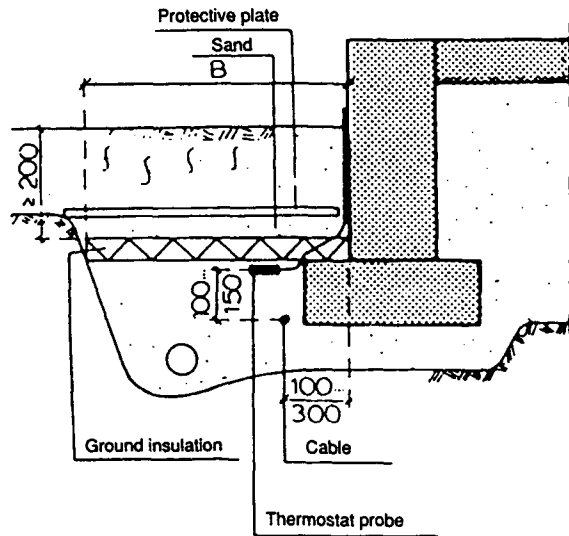


Figure 79. Location of heating cable. (From VTT 1987.)

instead of 18°C as in the codes of Norway and Sweden.

Ground insulation material and protection

According to the Norwegian *Building Details* (NBI 1986), as horizontal ground insulation outside a foundation wall one should use boards of extruded or expanded polystyrene with a density of at least 30 kg/m³ or boards of mineral wool with a density of at least 140 kg/m³. Under a loaded foundation wall one should not use boards of mineral wool. Expanded polystyrene with a density of at least 30 kg/m³ can normally be used in the construction of a small house without a basement. Extruded polystyrene has the largest compressive strength and should be used where a large load is expected.

For maximum thermal efficiency, ground insulation should be placed as near the ground surface as possible.* However, this could result in damage by inadvertent digging for gardening.

* Personal communication with S. Knutsson, 1986.

The Finnish guidelines (VTT 1987) recommend placing ground insulation on a sand bedding, and if it is near the surface, protecting it by a concrete slab 50–70 mm thick. With no such protection the ground insulation must be placed at least 0.30 m deep and protected with a plate of asbestos cement or water-resistant plywood. This cover, which should be inclined away from the foundation wall, limits possible damage to the insulation by plants and loss of insulation effect by water intake. During the construction process, care must be taken to prevent access of water to the ground insulation before protection is applied.

In Finland an alternative to insulation materials like polystyrene or mineral wool is lightweight gravel, which is placed on a sand bed that is nearly level and covered with plastic paper or coating. Over this a thin layer of sand is placed, and on top of this is placed a cover providing mechanical protection if required. If the thickness of fill that is placed on top of the lightweight gravel is less than 0.15 m, the insulating arrangement has to be protected, where damage may occur, with building panels or by stabilization with cement (VTT 1974).

Heating cable design

If a heating cable is used, it can be located as shown in Figure 79 according to the Finnish guidelines. Table 14 gives the required power for a heating cable used without ground insulation, depending on the design freezing index, the allowable frost depth and the position of foundation wall insulation. This table applies to conditions where the inside temperature is at least 5°C and where the thermal resistance of the floor structure is 2.6 m² K/W.

The heating cable is extended the full length of the foundation wall and is covered with sand free of stones. Care must be taken not to damage the cable during the filling operation. The cable is controlled with one or more thermostats, and the temperature sensor is located in an area where the depth of frost is greatest (VTT 1974).

Table 14. Necessary cable power for frost protection. (From VTT 1987.)

Foundation wall insulation	Allowable frost depth (m)	Cable power without ground insulation (W/m)		
		$F_{50} = 35,000$	50,000	65,000 ($h \cdot ^\circ\text{C}$)
Outside	0.5	10	15	20
	1.0	5	5	5
Inside or across bottom	0.5	15	20	30
	1.5	10	10	15

Protection against moisture from the ground

Problems have arisen from the transfer and accumulation of moisture, such as upward suction and condensation of moisture in the construction, with the danger of corrosion, rot and destruction of the floor covering. There is also the possibility of damage to the building due to differential movements produced by shrinkage, swelling and frost heave.

According to the Norwegian *Building Details* (NBI 1986), a floor construction should be protected against moisture from the ground by means of the following layers:

- A drainage layer under the construction consisting of at least 100 mm of crushed rock or coarse gravel.
- A capillary barrier layer that stops suction of water upward. This should consist of boards of polystyrene or stiff mineral wool. A layer of broken rock, crushed stone or coarse gravel may not act well as a capillary break if it contains dust and fine material. Because of this, it is recommended that the layer be at least 400

mm thick. It would simultaneously act as a drainage layer.

- A layer acting as a vapor barrier, which is especially important in wide buildings. Between the concrete slab and the insulation is laid a 0.2-mm-thick plastic film located above the capillary suction level. It acts as a block against water vapor from the ground. A plastic film laid under the thermal insulation can collect a considerable amount of moisture in the insulation layer during construction, in the form of precipitation and possibly casting water, in the period between the laying of the film and completing casting of the slab. If the film is placed under a concrete slab, it is very important that the slab be allowed to cure before a moisture-proof covering is put on it.
- A separation layer between underlying wet ground and the drainage layer. The separation layer should consist of specially made synthetic fiber mesh; this hinders infiltration of soil material into the overlying drainage layer.

Examples of moisture protection of slab-on-grade foundations are shown in Figure 80.

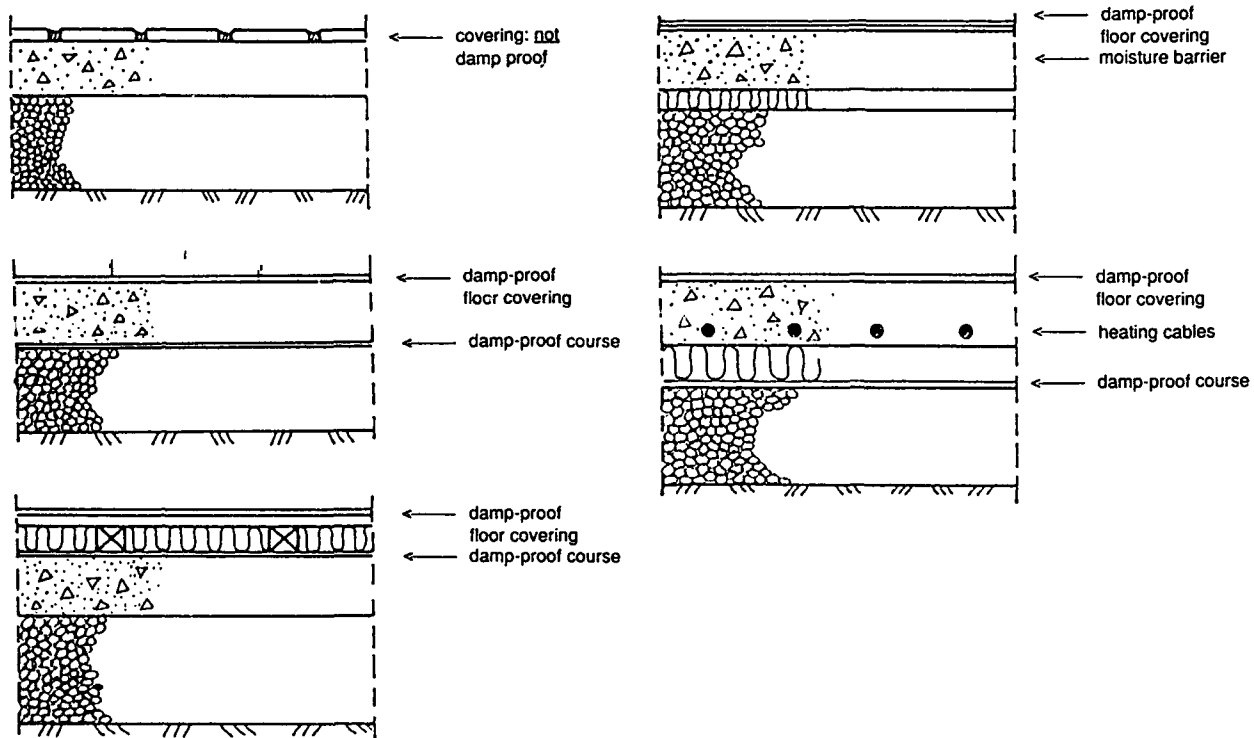


Figure 80. Position of the damp-proof course for floors with damp-proof floor coverings. When the floor covering is not damp-proof, no damp-proof course is necessary. (From Kløve and Thue 1972.)

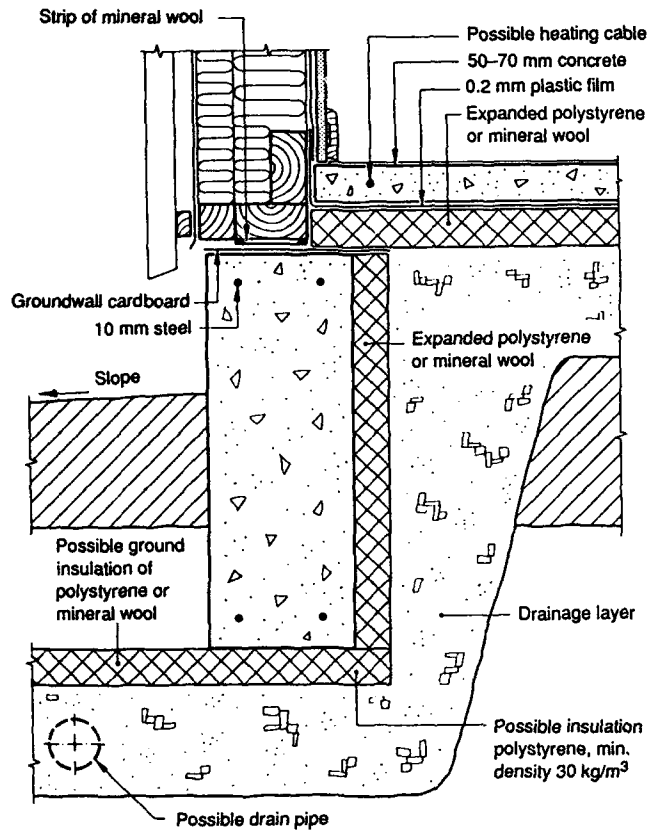


Figure 81. Concrete slab with internally insulated concrete foundation wall. (From NBI 1986.)

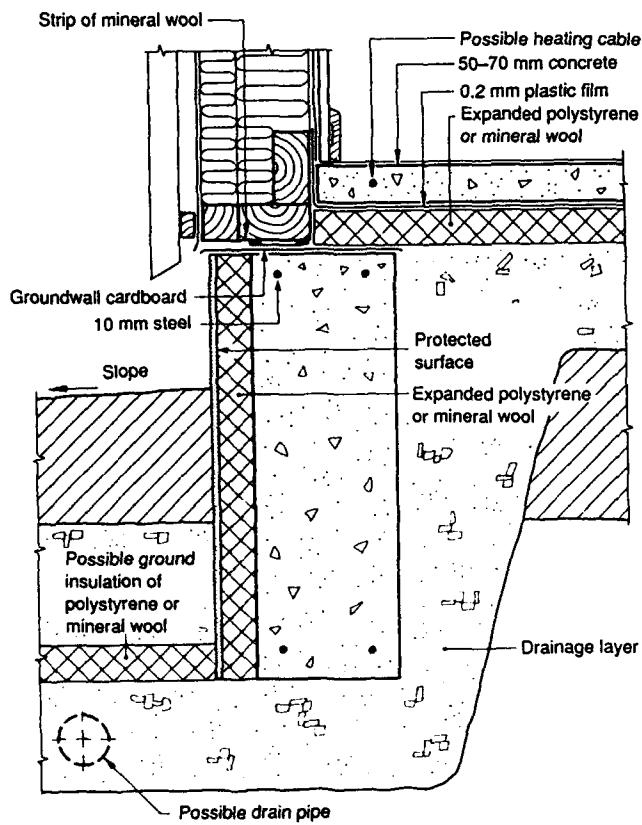


Figure 82. Concrete slab with externally insulated concrete foundation wall. (From NBI 1986.)

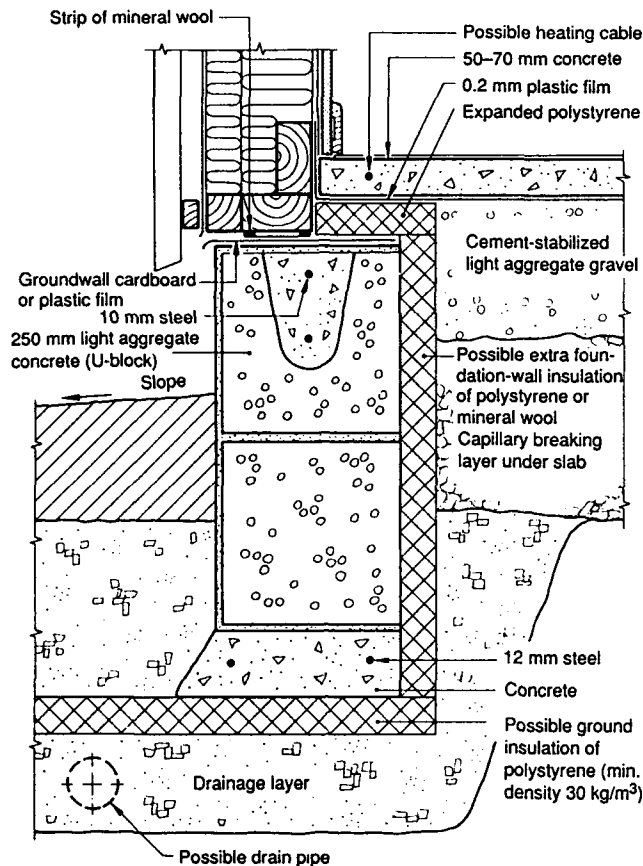


Figure 83. Concrete slab with foundation wall of light aggregate concrete. (From NBI 1986.)

Slab-on-grade construction

The following are types of slab-on-grade foundations proposed by the Norwegian *Building Details* (NBI 1986).

Concrete slab

Foundation designs using a concrete slab are illustrated in Figures 81, 82 and 83. Slab insulation of polystyrene or mineral wool acts like a capillary breaking layer, preventing upward suction of moisture to the concrete slab. Under the insulation it is therefore sufficient to have a 100-mm-thick drainage layer of material without a special requirement for it to have a capillary breaking property. Slab insulation of light clinker, however, is doubtful as a capillary breaking layer. Under such insulation, a capillary breaking layer of 250-mm crushed rock or coarse gravel is specified.

A concrete slab that carries the load from just nonbearing walls and normal household furnishings is usually cast in a thickness of 50–70 mm. A slab with a larger loading must be specially designed.

Floating floor

Figures 84 and 85 show examples of floors constructed of wooden boards on polystyrene insulation. The wood can be wood fiberboard, wood chipboard or plywood. The insulation layer is laid on a concrete slab or sand layer set out precisely to give a sufficiently level floor. At least 100 mm of drainage material is required, but there is no need for this to have capillary breaking properties.

Wood-surfaced floor

Figure 86 shows a wood-surfaced floor that is a composite of wood joists with mineral wool in between. A concrete slab, at least 50 mm thick, is cast as an underlayer and suitably reinforced. This type of floor should not be used in combination with a foundation wall that is insulated on the inside because of the danger of condensate against the plastic film closest to the outer wall. The wood-surfaced floor on sleepers can consist of 21-mm floorboard, 22-mm chipboard or 19-mm plywood. The use of a drainage and capillary breaking layer

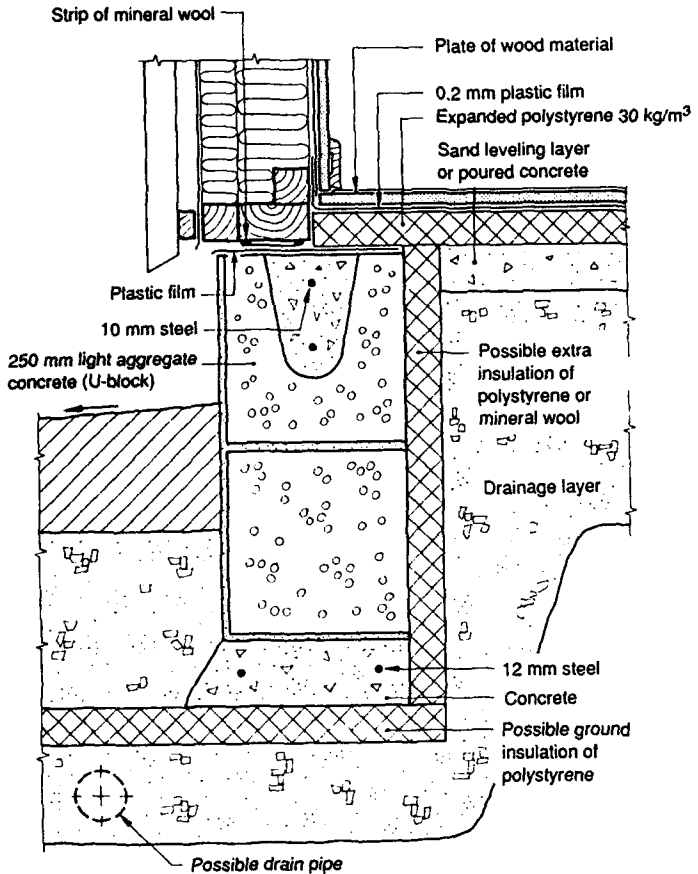


Figure 84. Light floor with foundation wall of light aggregate concrete. (From NBI 1986.)

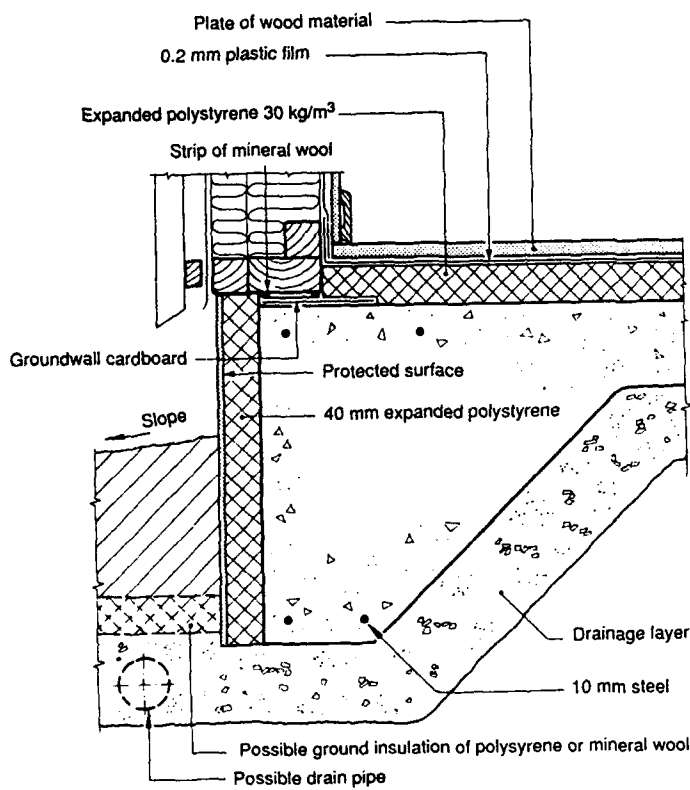


Figure 85. Light floor and concrete slab with expanded edge. (From NBI 1986.)

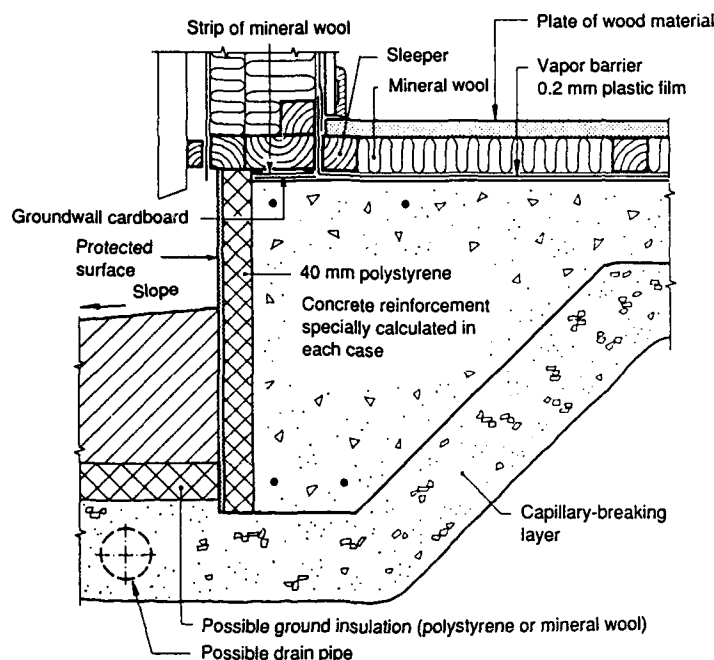


Figure 86. Wood-surfaced floor with edge-expanded concrete slab. (From NBI 1986.)

consisting of at least 150-mm crushed stone or coarse material is specified.

Thermal insulation materials

The Norwegian *Building Details* (NBI 1986) specify thermal insulation as follows.

Floor insulation

Under a concrete slab is required a sheet of polystyrene with a density of at least 20 kg/m^3 , a sheet of mineral wool with a density of at least 90 kg/m^3 or lightweight clinker that is loose, cement-stabilized or wrapped in special plastic sacks. Under a floating floor of wood fiber or chipboard, a board of polystyrene should be used with a density of at least 30 kg/m^3 .

Foundation wall insulation

This should consist of boards of polystyrene with a density of at least 20 kg/m^3 or boards of mineral wool with a density of at least 90 kg/m^3 .

FOUNDATIONS WITH A CRAWL SPACE OR BASEMENT

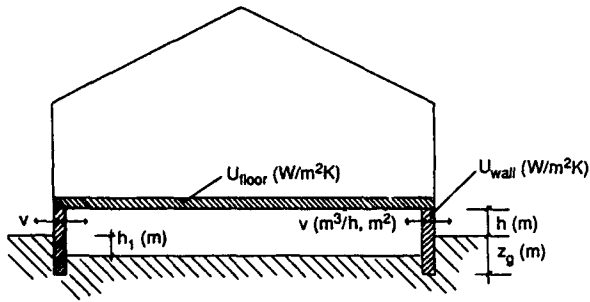
Introduction

A foundation with a crawl space (Fig. 87) is suited to the same ground conditions as a slab-on-

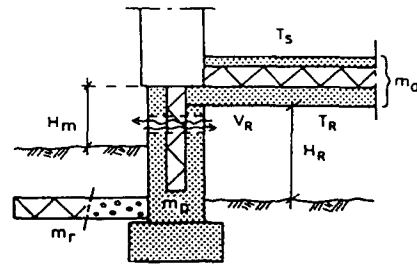
grade, but the former can be more easily adjusted to slightly hilly rocky terrain and to sloping sites. The method is relatively inexpensive and can be relatively easily adjusted for owner-builders. However, crawl spaces have given rise to a large number of problems, such as decay in the floor structure. Storage areas require level foundation ground, and the imposed loading acts as an additional load on the ground unless the ground in the crawl area is located lower than outside.

In Sweden, foundations with crawl spaces have been used from time immemorial, in the form of a free-bearing floor structure on plinths or ground walls. However, from around 1900, houses were mostly constructed with basements, and this became the dominant method by the beginning of World War II. After the war there was a renaissance in the construction of foundations without basements, until about 40% of the houses and other light buildings were being constructed in this manner.

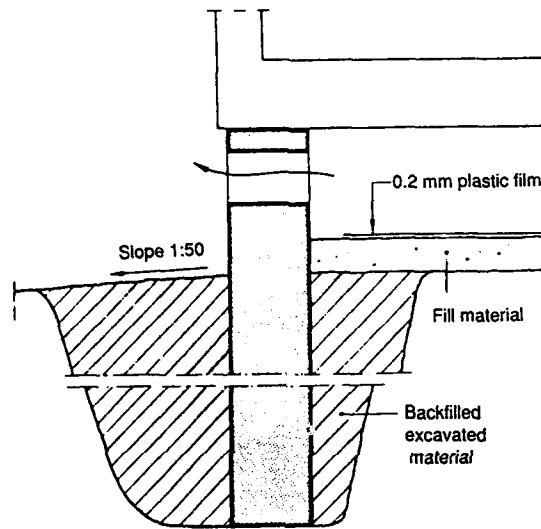
In Norway, foundations with crawl spaces were used for a long time, but building methods changed, particularly because crawl spaces were susceptible to moisture problems and rot damage. Since the war the use of crawl spaces or basement foundations, and often combinations of these, has been dominant for buildings with a small bearing pres-



a. Parameters. (From Adamson 1972.)



b. Finnish design. (From VTT 1987.)



c. Norwegian design. (From NBI 1979c.)

Figure 87. Foundation with a crawl space.

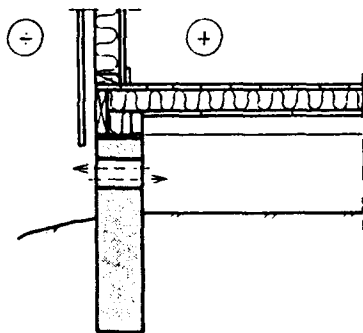


Figure 88. Cold crawl space ventilated with outside air, usually through openings in the foundation wall. (From Algaard 1976b.)

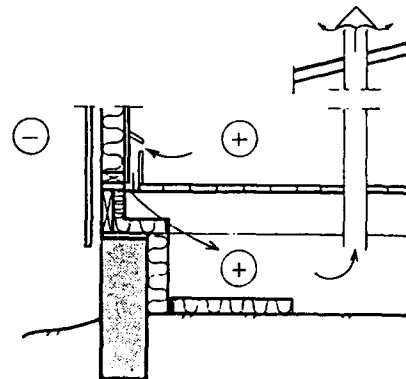


Figure 89. Warm crawl space ventilated with heated inside air. (From Algaard 1976b.)

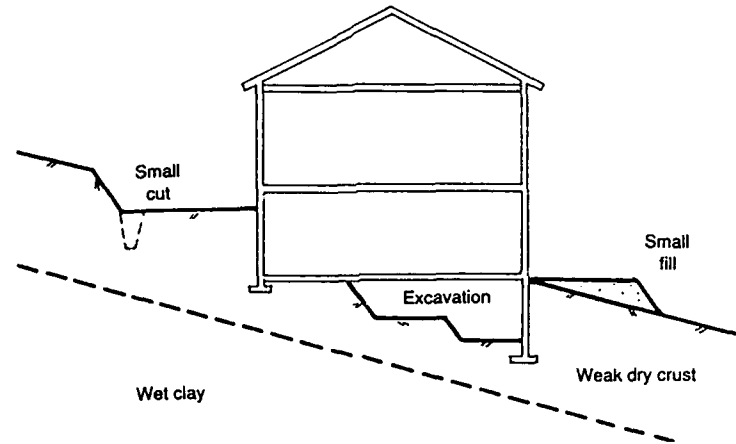


Figure 90. Combination of crawl space with basement and slab-on-grade in steep terrain. (From Algaard 1976b.)

tures. Crawl spaces have been mostly used for extensions and accessory buildings and under suspended floors of houses on sloping ground. Associated with crawl spaces, wood beams with mineral wool insulation are almost always used, with a foundation wall of concrete or light expanded clay aggregate (leca) blocks.

There are two general types of crawl space: cold and warm. The former is a crawl space that is ventilated with outside air (Fig. 88); the latter is ventilated with inside air (Fig. 89). A warm crawl space is rarely used. An unventilated crawl space should not be built.

A crawl space foundation can be adjusted to variations in the terrain and is well suited to gently undulating conditions. It is particularly well suited to non-frost-susceptible or rocky ground. It can, however, be suitable in weak ground where an excavation is in any case necessary to remove some of the soil. In such cases, constructing a basement would often be preferable to acquire additional usable inside area for the house. Where there are particularly steep slopes, a basement with slab-on-grade at the back of the house can be combined with a crawl space near the front (Fig. 90), although such a design can give problems with respect to ventilation of the crawl space area (Fig. 91).

On nearly flat sites, it is rarely an advantage to use a crawl space together with, for example, a slab-on-grade. A crawl space could involve a lower depth of foundation with increased loading, and moisture problems can frequently arise.

In wet climates there has been much moisture damage to the floor area above crawl spaces. The

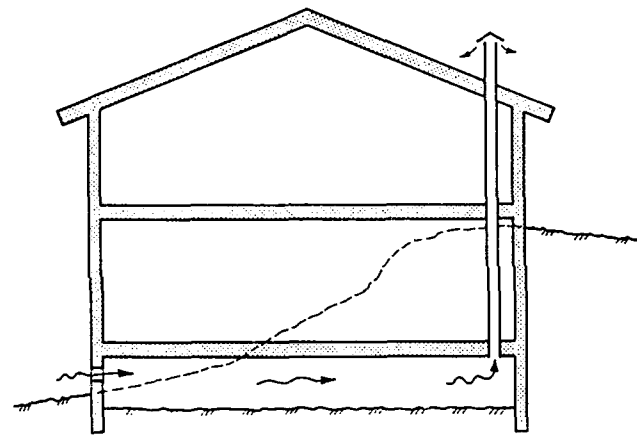


Figure 91. Ventilation of a crawl space through the ceiling. (From Algaard 1976b.)

supply of moisture can be limited by sloping the ground away from the building, draining the crawl space if it is lower than the outside ground, or covering the ground in the crawl space area with a plastic film. Figure 92 shows a design with a foundation wall cast in concrete.

There should be adequate protection against possible frost damage. The ground wall and foundation with a crawl space should be designed so that no damage occurs from frost heave, sideways frost pressure or uplift from frost sidegrip.

A comprehensive study of crawl space foundations was carried out at Lund Technical University in Sweden by Adamson and others. The results of this study (Adamson et al. 1971, Adamson 1972) formed the basis for revisions of relevant sections

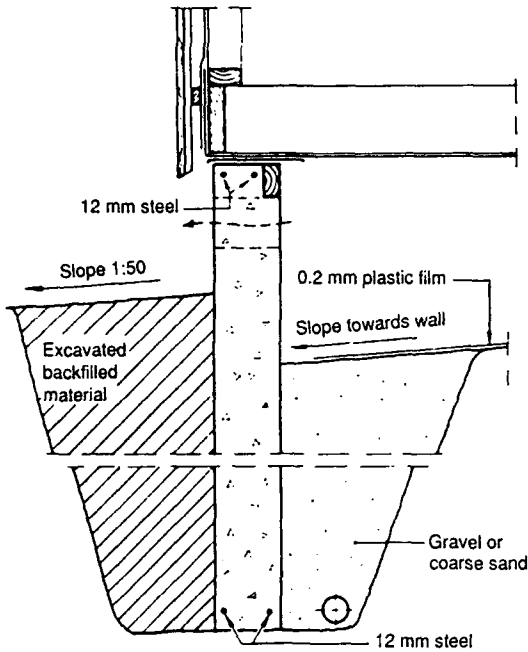


Figure 92. Foundation wall cast in concrete. (From NBI 1979c.)

of the Swedish standards (SBN 1967) to produce SBN (1980). The study also provided input to the Norwegian Frost I Jord project.

Heat flow conditions

The frost depth at a foundation wall for a cold ventilated crawl space under a heated building will be less than the frost depth in snowless undisturbed ground. Depending on the floor insulation, heat flows through the floor structure down to the crawl space and thus helps keep the crawl space temperature

higher than the outside temperature. The heat loss from the foundation wall's inner and outer side is reduced, and the frost depth decreases since heat is concentrated at the foundation bottom area.

As long as the crawl space temperature is over 0°C , heat from the crawl space flows to the freezing zone and slows frost penetration (Fig. 93). The effectiveness of this depends on the balance between heat from the floor and heat losses from the crawl space through ventilation. In cold and moderately cold regions the crawl space temperature with regular ventilation and good overlying floor insulation could fall below 0°C in critical winters. Heat flow from the crawl space to the frost front would then cease, and only soil heat would reach the foundation area. Because of the low crawl space temperature, the frost depth at a cold crawl space under a heated building will be considerably larger than in the case of a slab-on-grade foundation. On the other hand, a warm crawl space would have an associated frost penetration similar to that with a slab-on-grade.

Relevant crawl space parameters are indicated in Figure 87. They include the U -value of the floor structure and the foundation wall, the pedestal height h (the height of the floor bottom above the outside ground), the foundation depth z_g and the ventilation rate v , as well as the outside climate.

Frost penetration

Adamson et al. (1971) and Adamson (1972) charted the heat flow conditions and determined the frost penetration related to crawl spaces on the basis of extensive computer calculations for long buildings and square buildings subjected to various outside climates.

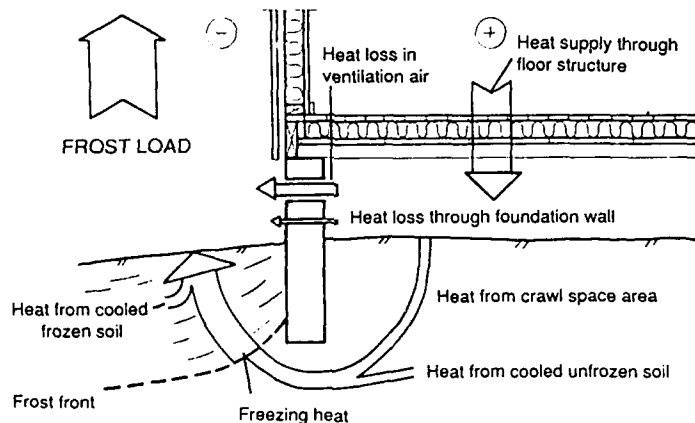


Figure 93. Heat flow through a cold crawl space under a heated building. (From Algaard 1976b.)

Figure 94. Isotherms for a long building. (10 m wide; clay soil; outside temperature = -9.0°C ; U-value of floor slab = $0.582\text{ W/m}^2\text{K}$; heat flow through foundation wall = 1.19 W/mK ; crawl space ventilation rate = $1\text{ m}^3/\text{m}^2\text{h}$; crawl space temperature = 3.2°C .) (From Adamson 1972.)

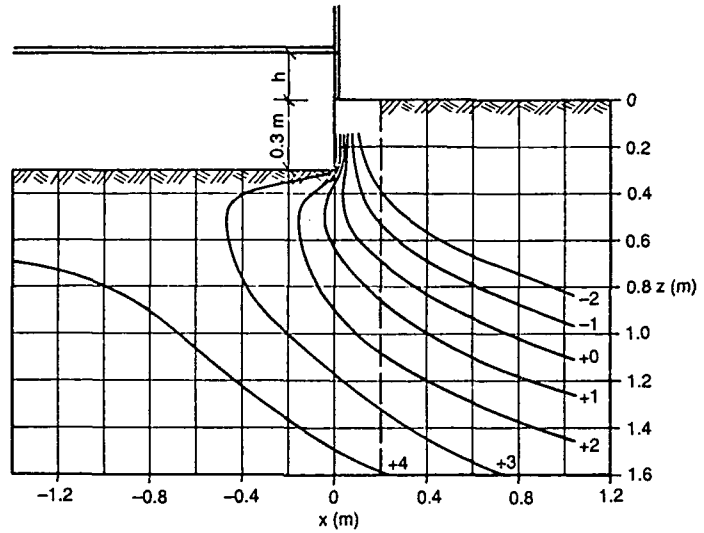
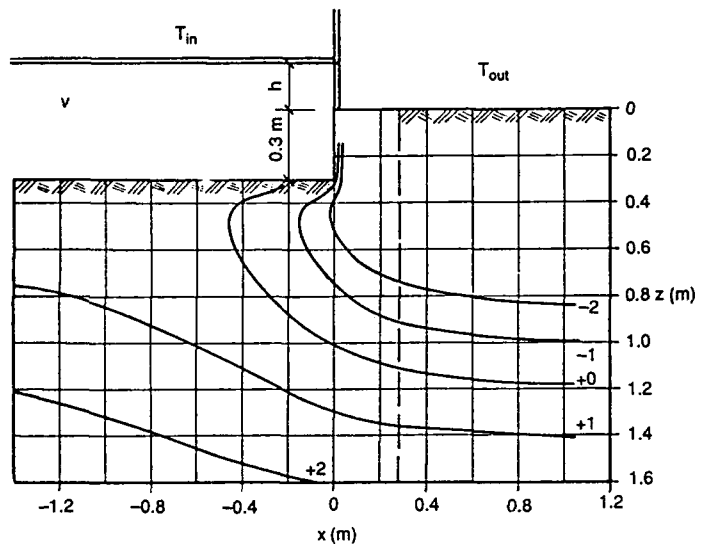


Figure 95. Isotherms for a square building. ($10\times 10\text{ m}$; clay soil; outside temperature = -9.0°C ; U-value of floor slab = $0.582\text{ W/m}^2\text{K}$; heat flow through foundation wall = 1.19 W/mK ; crawl space ventilation rate = $1\text{ m}^3/\text{m}^2\text{h}$; crawl space temperature = 0.3°C .) (From Adamson 1972.)



Geometric factors

Figure 94 shows isotherms for a long building, 10 m wide, which can be compared with those for a square building, $10\times 10\text{ m}$ (Fig. 95), at the time of maximum frost penetration with no snow cover, the same parameters being assumed in each case. The vertical broken lines in these figures represent the boundary of a 0.2-m-thick foundation wall. The intersection of this boundary with the assumed critical -1°C isotherm was taken to give the required foundation depth. This depth was about 0.9 m for the square building and 0.5 m for the long building.

For a square building, frost penetration was deeper at an outside corner (e.g. 0.9 m deep) than in the middle of an external wall (e.g. 0.7 m). This corner effect was significant only within 0.5–1 m (in a horizontal plane) from the corner.

There was less frost penetration in the middle of the facade of a long building (e.g. 0.55 m deep) compared with the penetration in the middle of a square building's external wall (e.g. 0.7 m), since heat loss through the foundation wall is greater in the latter case because of the three-dimensional effect and because of more exposure. The floor insulation, foundation wall insulation and crawl space ventilation were assumed to be equal in each case.

Other factors

As may be expected, increased insulation of the floor or increased ventilation of the crawl space reduced the temperature in the crawl space during winter and increased frost penetration. Thus, in the case of a long building, an increase in the U-value of the floor from 0.41 to $0.58\text{ W/m}^2\text{K}$ increased the

frost penetration from 0.65 to 0.7 m at a constant ventilation rate of $0.5 \text{ m}^3/\text{m}^2\text{h}$. For a long building having a floor with a U -value of $0.407 \text{ W}/\text{m}^2\text{K}$, an increase in the ventilation rate from 0.5 to $2 \text{ m}^3/\text{m}^2\text{h}$ increased the frost penetration from 0.7 to 0.95 m .

A reduction in room temperature above the crawl space from 20° to 10°C increased frost penetration from 0.45 to 0.65 m . On the other hand, the ground level in the crawl space had no influence on frost penetration and therefore on the required foundation depth.

Floor temperature and thermal insulation

With regard to thermal insulation the Norwegian building code places a limitation on the U -value of a floor structure depending on the particular climatic zone. According to Algaard (1976b) this value is rather high, as it implies too large a heat loss through the floor. It might be more appropriate to lower the U -value by using more insulation to increase the floor temperature and improve heat economy. This would lower the temperature in the crawl space and require a larger foundation depth with frost-susceptible soil.

As for a floor with slab-on-grade, the requirement should be that the lowest surface temperature on the floor over the crawl space is 17.5°C , with an indoor temperature of 21°C (Algaard 1976b). Also, the connection between the foundation wall, the outer wall and the floor structure should be made in such a way that there is no damaging cold bridge or moisture leakage, which can considerably reduce the floor temperature along the outer wall. The necessary thermal insulation for the floor structure can then be determined using these requirements and taking into consideration crawl space ventilation, the heat transfer resistance R_i between inside air and the floor surface, and estimates of the lowest crawl space temperature.

According to the Frost I Jord project, the freezing index F_{100} is used as the design frost load. Figure 96 gives the relationship between F_d (the design value) and the floor structure's necessary heat transfer coefficient (U -value) or its reciprocal, the thermal resistance R_t , to obtain a minimum of 17.5°C on the

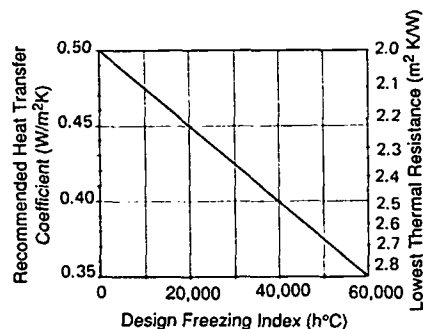


Figure 96. Recommended thermal insulation vs design freezing index for a floor structure over a cold crawl space to obtain a floor surface temperature of at least 17.5°C with an inside temperature of 21°C . The crawl space ventilation rate is $1\text{--}3 \text{ m}^3/\text{m}^2\text{h}$. (From Algaard 1976b.)

floor. This is a recommendation rather than a requirement. For crawl spaces under unheated or sporadically heated buildings, the situation is different and depends on whether they are to be used for extended occupation.

The Norwegian *Building Details* (NBI 1979c) specify the highest allowable U -values for a floor structure of 0.30 , 0.45 or $0.6 \text{ W}/\text{m}^2\text{K}$ at inside temperatures of 18°C and higher, $10\text{--}18^\circ\text{C}$ or $0\text{--}10^\circ\text{C}$, respectively. These values apply to a floor against an unheated crawl space with outside ventilation and with the total area of ventilation openings less than 0.2 m^2 over 100 m^2 of ground area. The distance from the floor structure to the ground under the house must not be less than 0.3 m .

In the Swedish standards (SBN 1980) two U -values of the floor structure are tabulated, i.e. 0.25 and $0.50 \text{ W}/\text{m}^2\text{K}$ (Table 17), with the possibility of interpolation to determine the corresponding foundation depth. The Finnish guidelines (VTT 1987) give Table 15, which specifies maximum allowable U -values of 0.22 and $0.45 \text{ W}/\text{m}^2\text{K}$ for floors in heated rooms and partly heated rooms above a crawl space, respectively. In the case of industrial buildings the values are 0.36 and $0.65 \text{ W}/\text{m}^2\text{K}$.

Table 15. Maximum allowable U -value and minimum thermal resistance for floor structure of heated and partly heated buildings with crawl space. (From VTT 1987.)

	Max. allowable U -value ($\text{W}/\text{m}^2\text{K}$)		Thermal resistance ($\text{m}^2\text{K}/\text{W}$)	
	Heated room	Partly heated room	Heated room	Partly heated room
Residences	0.22	0.45	4.55	2.2
Industrial	0.36	0.65	2.8	1.5

Foundation depth

Foundations in non-frost-susceptible ground

According to the Norwegian *Building Details* (NBI 1979c), in non-frost-susceptible ground the foundation depth may be small, the practical minimum being about 0.3 m under prepared ground (Fig. 97). For less important buildings the foundation may be set directly on sufficiently firm ground (Algaard 1976b).

Frost-free depth

For frost-susceptible soil the Norwegian *Building Details* specify that the foundation wall should be based at the particular locality's frost-free depth in undisturbed ground. The frost depth from Figure 8 for Norway is corrected depending on the local soil type, but no correction is made for water content. The correction factor is 0.85 for silt and 0.7 for clay, and the smaller depth thus obtained gives a saving in excavation work and ground wall material.

The foundation depth based on Figure 8 is deeper than necessary for heated buildings, but it is right and necessary for cold or sporadically heated buildings and for crawl spaces that are especially well ventilated (in the latter case one approaches the

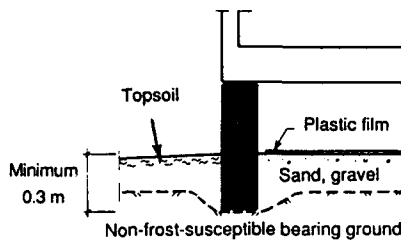


Figure 97. Crawl space foundation on non-frost-susceptible ground. Wet and weak material is removed from under the foundation, and humus-containing soil is replaced with clean and draining material. (From Algaard 1976b.)

principles for open foundations). In such a crawl space, there will also be frost penetration on the inside of the foundation wall, and then one must check both for the maximum frost depth and for uplift by sidegrip (Fig. 98). With frost penetration down both sides of the foundation wall, sidegrip can become considerable, and the resulting uplift force can be estimated on the basis of Table 16. If the total uplift force is larger than the total weight carried by the foundation wall, it must be anchored under the maximum frost depth or its surface must be coated with bitumen (at least 2 mm) or epoxy to reduce the sidegrip (Algaard 1976b).

Reduced foundation depths

A heated building provides a certain amount of heat through its floor to the foundation area, so the required foundation depth is less than the frost depth h_0 in undisturbed ground. Design procedures for reduced foundation depths are based on the work done in Sweden by Adamson et al. (1971) and on the Swedish building standards. An underlying drainage layer of gravel is considered part of the foundation. The ground around the building is assumed to have no snow cover, and the crawl space temperature is assumed to be above 0°C .

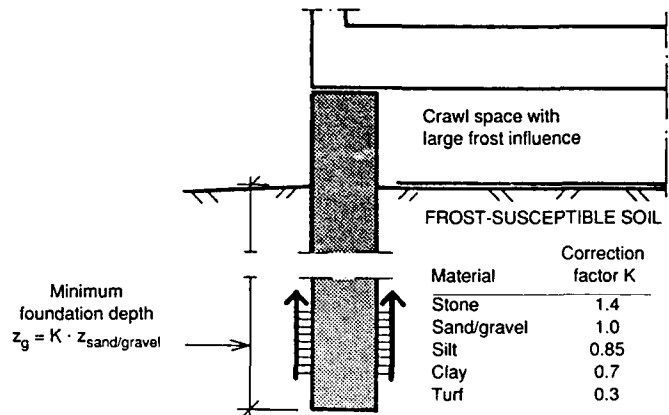


Figure 98. Foundation depth for cold or unheated buildings. (From Algaard 1976b.)

Table 16. Lifting force transmitted by sidegrip to unprotected piles or piers with diameter 200 to 350 mm in dry crust clay. The values serve as a guide. (From Torgersen 1976b.)

Material	Lifting force with sidegrip (kN)		
	$F_{100} = 10,000$	30,000	50,000 ($h^\circ\text{C}$)
Steel	50	100	140
Wood	30	50	60
Concrete	30	80	100
Concrete wall (per meter length)	25	40	50

Table 17. Reduction factor β with respect to frost penetration depth for a foundation construction below a heated building with a floor construction above an enclosed crawl space ventilated by outside air. (From SBN 1980.)

Temperature zone	U-value of floor (W/m ² K)	Reduction factor β		
		>1 m from external corners		≤ 1 m from external corners
		Long building*	Short building	
I and II	0.50	0.3	0.4	0.4
	0.25	0.5	0.6	0.6
III and IV	0.50	0.2	0.3	0.3
	0.25	0.4	0.5	0.5

* A long building is one with length more than three times its width.

Swedish building standards

According to SBN (1980) the foundation depth can be determined from h_0 by applying a reduction factor β found from Table 17.

The use of Table 17 requires the following conditions:

- The width of the building is at least 4 m.
- Rooms or premises situated above the floor, with the exception of single small spaces, regularly have a temperature of at least 18°C during the heating season.
- The layer of insulating material on the ground surface inside the ventilated crawl space has a maximum thermal resistance of 0.5 m²K/W.
- The part of the foundation wall above the external ground surface has a minimum thermal resistance of 1.1 m²K/W in temperature zones I and II, and 0.9 m²K/W in zones III and IV. However, if the underside of the floor construction is higher than 0.6 m above the ground surface outside the foundation wall, a higher thermal resistance should be selected. Its value should be such that the total quantity of heat passing through the foundation wall is not greater than the quantity of heat passing through a foundation wall 0.6 m above grade and with the thermal resistance specified above.
- The ventilation rate is 1 m³ per m² of floor area per hour. When the ventilation rate is as much as 3 m³/m²h, the tabulated values of β should be increased by 0.1. For intermediate ventilation rates, linear interpolation should be applied. [For ventilation requirements and calculation of ventilation areas, refer to section 32: 3222 of SBN (1980).]

Frost I Jord procedure

Similar assumptions were used in the Frost I Jord procedure with the following differences. In the case of room temperature it was noted that an occasional drop from the usual 17°C (instead of 18°C in Sweden) to about 10°C over a couple of weeks would not have an appreciable influence on frost penetration. Also, it is specified that the ground in the crawl space must not be thermally insulated. The minimum thermal insulation requirements for the foundation wall are also different in this case and have to be in accordance with the Norwegian building code's requirements for a basement wall against outside air. If the foundation wall is higher than 0.6 m above the outside ground, more insulation is required. With regard to ventilation, the assumption is simply "adequate ventilation."

The Frost I Jord procedure (Algaard 1976b) for calculating the minimum foundation depth is based on an outside temperature varying harmonically according to a cosine function. This gives approximately the same frost penetration as an actual temperature variation with the same freezing index. The steps in the procedure are as follows:

- 1) The local design freezing index is determined:
 $F_d = F_{100}$.
- 2) The foundation wall's U-value is checked to see that it satisfies the building code's requirement concerning a basement wall against outside air. If the foundation wall height h is greater than 0.6 m above grade, the U-value is multiplied by 0.6/h.
- 3) The floor structure's U-value is checked to see that it conforms to the building code's requirements. To obtain a satisfactory surface

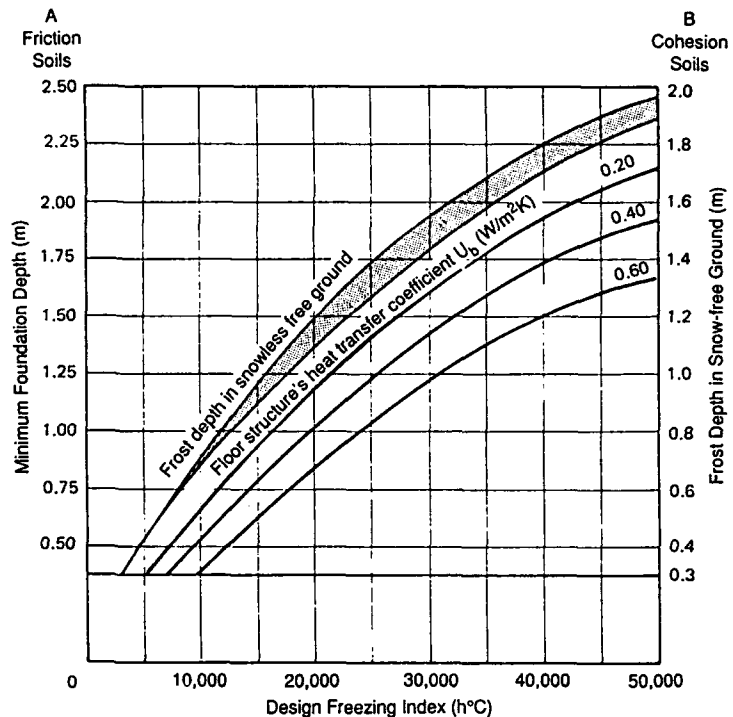


Figure 99. Minimum foundation depth for a crawl-space foundation under a continuously heated building on frost-susceptible soil. The ventilation rate is $1-3 \text{ m}^3/\text{m}^2\text{h}$. (From Algaard 1976b.)

temperature on the floor, one uses recommended values from Figure 96. The building ground is examined to see if it is frost susceptible or not. The necessary foundation depth z_g is determined:

- On frost-susceptible ground, z_g is determined depending on F_{100} , the floor structure's U -value and soil type A or B (Fig. 99). Soil A includes the finest friction soils, such as silty sand and sandy silt. Soil B includes impervious and moist cohesive soils.
- On non-frost-susceptible ground, $z_g \geq 0.3 \text{ m}$, or less in exceptional cases.

Outside ground insulation will have a large effect on frost penetration, but this is not taken into consideration in determining the necessary foundation depth according to the Swedish standards or the Frost I Jord procedure. The Finnish guidelines take the thermal resistance of ground insulation into account.

Finnish guidelines

The Finnish guidelines (VTT 1987) assume that the ground insulation is between 0.8 and 1.0 m wide, taking the 0°C isotherm as being critical; the -1°C isotherm is chosen as critical in the Swedish and Norwegian methods. Otherwise the Finnish

guidelines are based on similar assumptions to those of the Swedish standards, with the following differences:

- The inside temperature of the room above the crawl space is assumed to be at least 17°C .
- The foundation wall is assumed to be "well insulated" for at least 0.3–0.5 m below ground level, but the value of its thermal resistance is not specified.
- The ventilation rate is assumed to be not greater than $0.6L/\text{m}^2\text{s}$, which is equivalent to $2\text{m}^3/\text{m}^2\text{h}$.

Also, the thermal resistance of the floor structure is specified in the Finnish guidelines as $4.5 \text{ m}^2\text{K}/\text{W}$, whereas the Swedish standards specify the U -value of the floor structure as between 0.25 and $0.50 \text{ W}/\text{m}^2\text{K}$.

Based on the above assumptions, the Finnish guidelines enable the required foundation depth to be determined from Figure 100, depending on the local design freezing index and the thermal resistance of the ground insulation. Table 18 from the Finnish guidelines gives an alternative specification for the frost-free foundation depth in frost-susceptible soil. Where buildings are partially heated to an inside temperature between 5° and 17°C , the foundation depth found from Figure 100 is increased by 0.2–0.4 m.

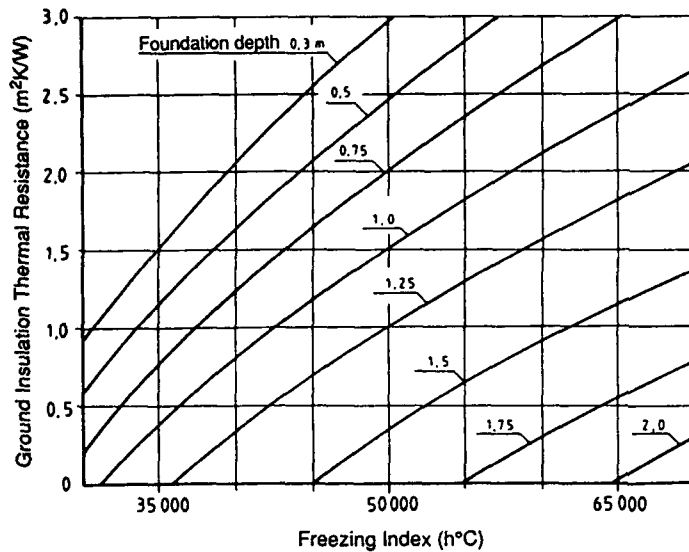


Figure 100. Design of frost protection for heated structures with crawl spaces. (Thermal resistance of floor structure = $4.5 \text{ m}^2\text{K/W}$; ventilation rate = 0.6 L/sm^2 .) (From VTT 1987.)

Table 18. Frost-free foundation depth in frost-susceptible soil for a heated structure (inside temperature $\geq 17^\circ\text{C}$) with a crawl space. The thermal resistance of the floor is $4.5 \text{ m}^2\text{K/W}$ and the ventilation rate of the crawl space is $0.6 \text{ L/m}^2\text{s}$. It is assumed that the building's width is at least 4 m and that there is no snow cover by the side of the building. (From VTT 1987.)

Foundation part	Frost-free foundation depth (m)		
	$F_{50} = 35,000$	50,000	65,000 (h°C)
Wall border	1.1/1.4	1.4/1.8	1.8/2.2
Corner	1.4/1.8	1.7/2.2	2.1/2.6

Norwegian Building Details

According to the Norwegian *Building Details* (NBI 1979c), even on frost-susceptible soil the foundation depth can be reduced to 0.3 m if insulation is laid under a foundation wall (Fig. 101). This is most practicable in relatively mild climates where moderate insulation thicknesses can be used. The necessary insulation thickness is given in Table 19, depending on the locality's freezing index F_{100} and mean annual temperature. The assumed insulation is expanded polystyrene with a density of 30 kg/m^3 .

In the case of a cold crawl space with ventilation openings not exceeding the recommendation of the Norwegian *Building Details* (0.2 m^2 per 100 m^2 of ground area), the air temperature inside the crawl space will be appreciably higher than the outside air temperature. Accordingly a design freezing index of F_2 may be used in determining the required width b of insulation extending inwards from the foundation wall. The width of insulation extending outwards, B , is still determined according to F_{100} (Dow Chemical 1987).

Foundation wall insulation

The Norwegian building code does not place a requirement on thermal insulation of the foundation wall of a crawl space. Heat loss through the foundation wall can be considerable, and in buildings for normal occupation the foundation wall should be insulated (Algaard 1976b). All estimates of the recommended thermal insulation for the floor structure (Fig. 96) and necessary foundation depth (Fig. 99) assume that the foundation wall insulation is not worse than the building code's requirement for a basement wall against outside air. By increasing the insulation of a foundation wall, the crawl space temperature will rise somewhat, and that will improve conditions with regard to the floor temperature and the frost depth at the foundation wall. Where the floor structure has a

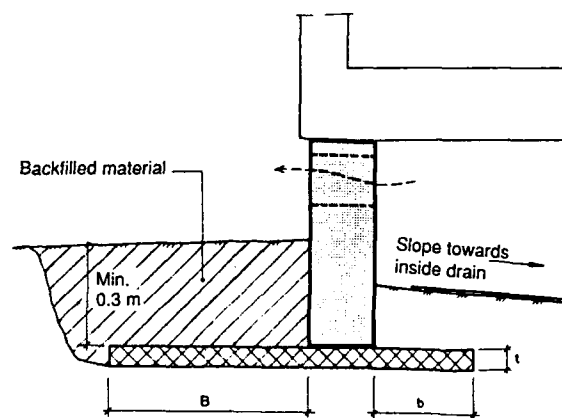


Figure 101. Placement of insulation with reduced foundation depth. (From NBI 1979c.)

Table 19. Thickness of insulation under a foundation wall associated with a crawl space. (From NBI 1979c.)

Mean annual temperature (°C)	Insulation thickness t (mm)				h (°C)
	$F_{100} = 5,000$	10,000	20,000	30,000	
3			80	120	
5	40	40	80	120	
7	40	40	60	100	
B (m)*	0.5	0.5	0.75	1.0	
b (m)*	0.5	0.5	0.5	0.75	

*See Fig. 101.

low U -value, it is particularly important to improve the insulation of the foundation wall to keep the crawl space temperature up and reduce frost and condensation problems in the crawl space.

If the foundation wall height h above the ground is greater than 0.6 m, heat loss through the wall increases beyond what is assumed in the building code's recommendation, and the greatest allowable U -value of the basement wall is multiplied by a factor of $0.6/h$ (Algaard 1976b).

The Swedish standards SBN (1980), in association with Table 17, quote minimum values for the thermal resistance of a foundation wall ranging from 0.9 to 1.1 m^2K/W , depending on the climate. The recommendation is that these values should be increased (by an unspecified amount) if the pedestal height h is more than 0.6 m. In such a case the Finnish guidelines (VTT 1987) recommend the minimum thermal resistance R of the foundation wall be obtained from the expression

$$R = R_{0.6} (h/0.6) \quad (8)$$

where $R_{0.6}$ is the thermal resistance of a wall with a pedestal height of 0.6 m.

For a foundation wall consisting of material that is not thermally insulating (e.g. concrete), the thermal insulation should be placed on the outside because that gives the best protection against frost penetration through the foundation wall.

A cold bridge should not be allowed to form, as in the top illustration of Figure 102. This cold bridge can be broken by extending the ground insulation under the foundation wall so that this insulation contacts the vertical insulation in the middle of the foundation wall, as in the lower illustration. The effect is to shift the position of the 0°C isotherm more favorably so that it does not penetrate inwards below the foundation wall. A further advantage is that only 1.2 m of ground insulation is required, instead of the former width of 1.5 m.

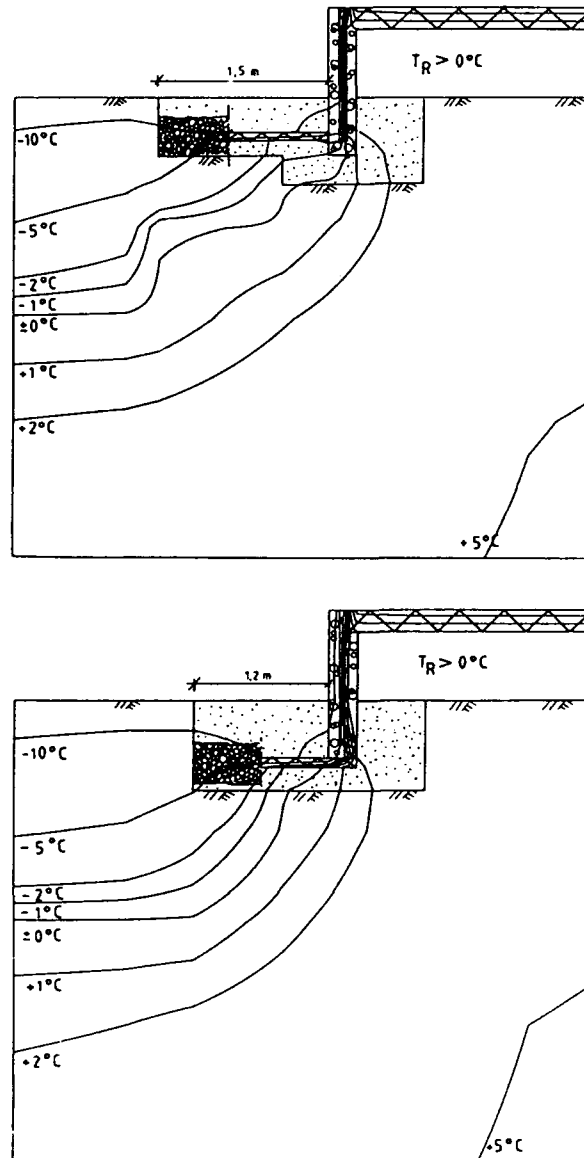


Figure 102. Effect of insulation on isotherms for a floor structure with a crawl space. (Freezing index = 37,000 $h^\circ\text{C}$; foundation depth = 0.5 m; thermal resistance of floor structure = 1.6 m^2K/W .) (From VTT 1987.)

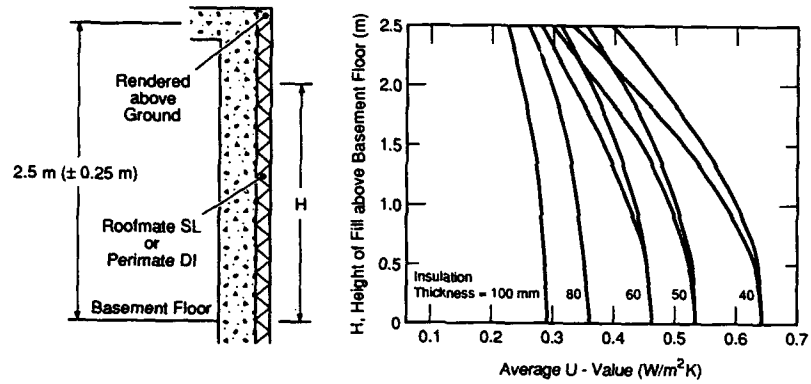


Figure 103. Design curves for the U-value of a 2.5-m-high concrete basement wall with the same thickness of Roofmate SL/Perimate DI Styrofoam above and below ground. (From Dow Chemical 1987.)

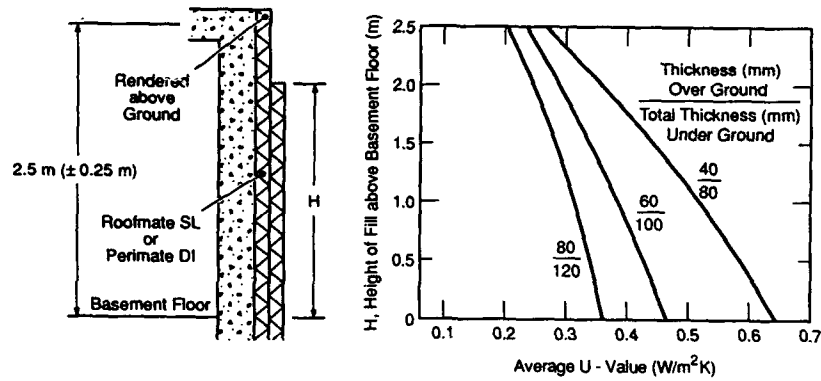


Figure 104. Design curves for the U-value of a 2.5-m-high concrete basement wall with the extra insulation thickness under the ground. (From Dow Chemical 1987.)

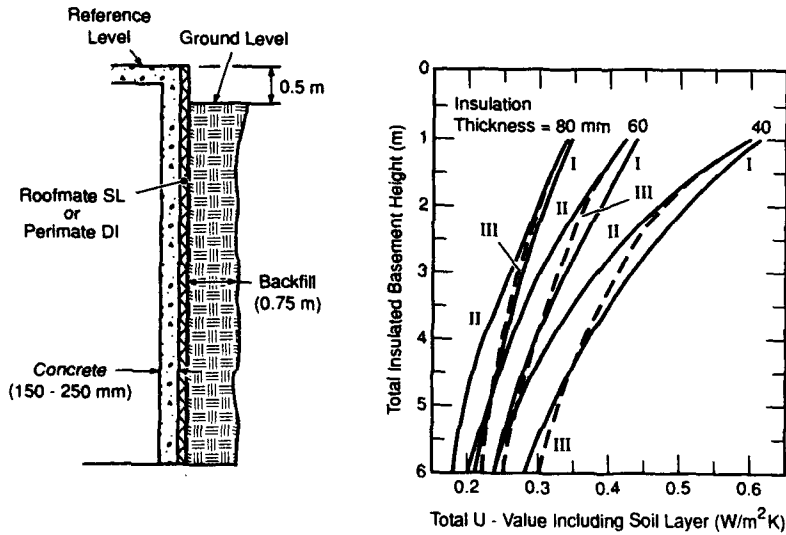


Figure 105. Design curves for the U-value of a 6-m-high insulated concrete basement wall with the top 0.5 m above the ground. (From Dow Chemical 1987.)

Table 20. Thermal resistance of the ground R_j for a basement outer wall with a fill height H (m) above the basement floor. (From NBR 1986.)

Material	R_j (m^2K/W)
Clay	$0.7 H$
Other fill	$0.5 H$
Rock	$0.35 H$

Thermal insulation of basement walls

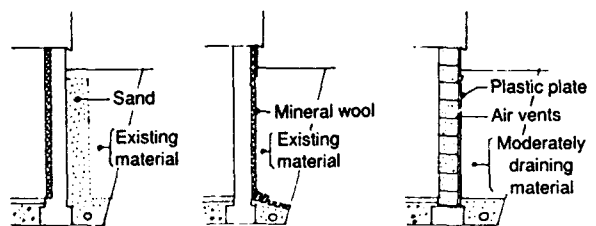
The Norwegian building code gives certain maximum allowable U -values for outer walls or basement walls, depending on the inside temperature. These U -values are 0.30, 0.60 and 0.80 W/m^2K for inside temperatures of 18°C and above, 10–18°C and 0–10°C, respectively.

As an example of how the U -value is determined, design curves are given here for a concrete basement wall externally insulated with styrofoam (an extruded polystyrene product). The average U -value depends on the height of the wall, the insulation thickness, the type of soil behind the wall and the height of this soil. Three types of ground are considered: (I) loose material, (II) clay and (III) rock. Figure 103 applies to a wall 2.5 m high with a varying soil height H . If thicker insulation is used under the ground, the U -value can be determined from Figure 104. For a basement wall up to 6 m high with a fixed top level 0.5 m above the ground, Figure 105 gives the U -value if the insulation thickness is the same above and under the ground.

For use in the thermal design of a basement, NS 3031 (NBR 1986) gives the values in Table 20 for the thermal resistance R_g of the ground, depending on the type of ground.

Drainage and thermal insulation

The usual drainage method is to use a layer of sand or gravel to replace the existing cohesive soil just behind the wall (Fig. 106). If a layer of plastic or mineral wool is used instead, it will hinder sidegrrip on the wall. With a plastic layer, however, frost-susceptible soil would lie near the wall and can still



a. Traditional method.

b. Stiff mineral wool plate that combines thermal insulation, drainage and filtering.

c. Plastic plate with projections as shaped air openings.

Figure 106. Alternate designs for basement wall drainage. (From Nordgård 1972.)

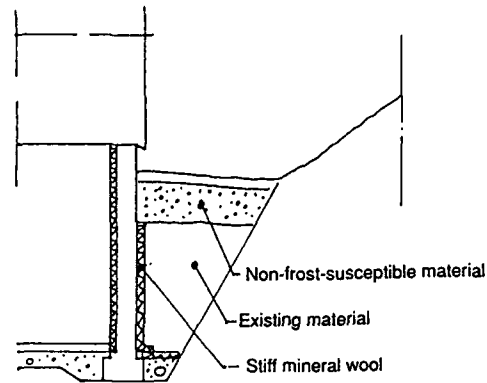


Figure 107. Replacement of steeply inclined frost-susceptible material by coarse draining material. (From Nordgård 1972.)

give horizontal pressure on the wall. The imperviousness of the plastic can lead to inadequate drainage, so the soil remains frost active.

A layer of mineral wool (for example, on the outside of a Leca wall) acts as a large addition to the thermal insulation, so that heat flow from the basement to the soil outside is considerably reduced. As a result there could be deeper frost penetration than with gravel drainage, and frost-active soil would be nearer the basement wall. Also, the mineral wool requires sufficient stiffness to take any horizontal pressure. Because of these problems one should consider removing some of the frost-susceptible soil and replacing it with non-frost-susceptible material together with some insulation (e.g. Fig. 107).

In Norway, drainage board is sometimes used as a combined basement wall drainage and thermal insulation. This board can consist of rockwool (a mineral wool) of 100- kg/m^3 density or polystyrene with an open structure or with grooves.* Other proprietary materials are used in Sweden, such as Pordrän, consisting of nearly uniform Styropor pellets of medium gravel size held together with a binder. A plate of this material is 6.5 cm thick, with a porosity of around 35%, allowing movement of water through it in liquid or vapor form. As shown in Figure 108 the Pordrän is covered with a synthetic fiber mesh called Fiberduk, which prevents access of fine soil particles. The protective combination, placed on the outside of a basement wall, has good thermal insulating properties and allows

* Personal communication with S.E. Torgersen, 1988.

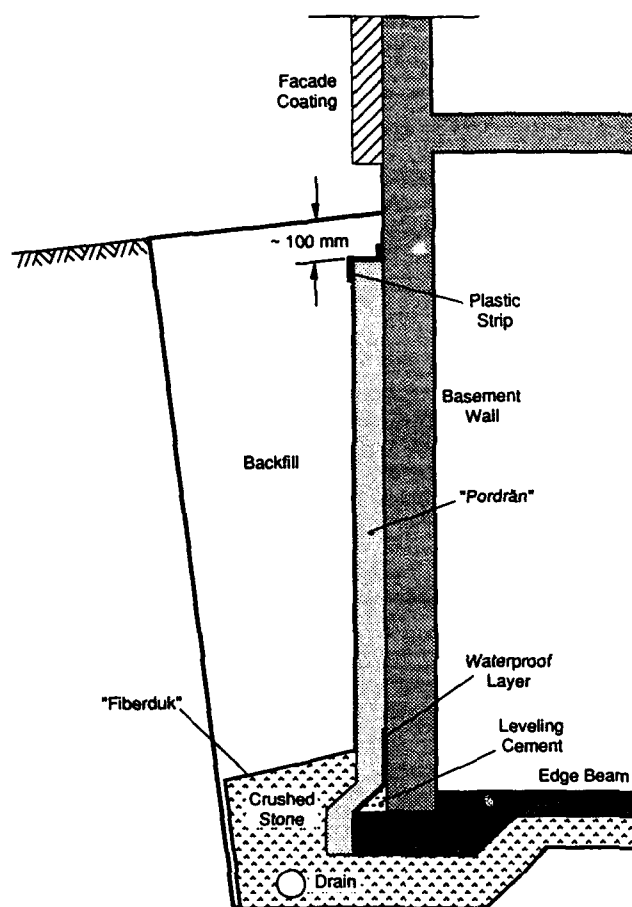


Figure 108. Protection and drainage of a basement wall. (From WIAB, n.d.)

drying of the basement wall outwards, thus preventing moisture accumulation in it due to upward suction from the ground. Adequate drainage behind the wall is also facilitated. Similarly in Finland basement walls are usually protected with an outside, thermally insulating plate and a drainage layer.

Experience shows that most of the damage from frost action occurs in the construction period during the cold season or in the first winter after construction. This is probably because the drainage system has not yet managed to drain the soil sufficiently, and as a result, there are more favorable conditions for frost action, causing larger horizontal frost pressure. Also, frost tends to penetrate deeper where soil is exposed during the construction operation, and protection measures, such as covering by a "winter material," should be considered.

Table 21. Reduction factor for uninsulated floor construction laid on the ground. (From SBN 1980.)

Lowest monthly mean temperature (°C)	Reduction factor β
~0	0.6
~10	0.3

Foundation of basements

The Swedish standards (SBN 1980) give a reduction factor β (Table 21) for determining the foundation depth for an uninsulated floor construction laid on the ground, such as a basement floor.

In Finland, foundations of basements normally reach frost-free depth, but if the basement is founded above this level, its foundations should be insulated in the normal manner.* With a cold basement, foundation conditions and designs can be similar to those for unheated structures and foundations on piers or piles. If, on the other hand, a basement is heated and insulated to provide habitable space, the construction becomes like a slab-on-grade and should be designed accordingly.

Frost problems

Frost problems with a basement construction are generally smaller than when there is no basement. The temperature in the basement is generally over 0°C, and the foundation is usually below the frost depth. The risk of frost under the foundation is negligible in practice. However, unfavorable conditions can give rise to sidegrip and horizontal frost pressure on a basement wall. Also, indoor temperatures can decrease if part of the basement is exposed to outside air.

A basement exposed to winter air is extremely vulnerable to frost. Not only is there a short distance to the foundation, but if there is soil along the whole height of an outside wall, there is danger from horizontal frost pressure if the soil freezes on account of the very cold conditions inside the basement. While care is generally taken with regard to frost protection of a basement's foundation to hinder under-freezing, there has been negligence in frost-protecting basement walls exposed to winter air. Figure 109 shows a recommended design where

* Personal communication with S. Saarelainen, 1988.

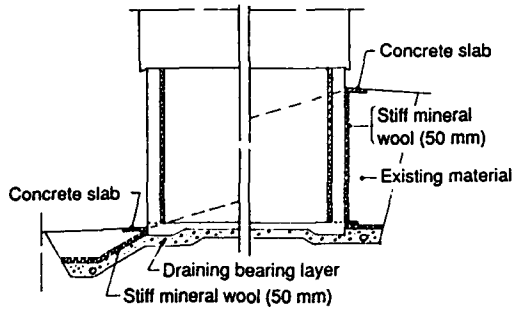


Figure 109. Recommended design of a basement foundation where one basement wall is exposed to outside air. (From Nordgård 1972.)

the floor slab bears on a drainage layer and the walls are insulated internally, with additional insulation between an outside wall and existing soil.

Sidegrip

Generally sidegrip is not a big problem with basement construction. It often happens that soil next to a basement wall shrinks, and fissures form, especially near the top of the wall. This reduces the sidegrip that the soil could exert on freezing, but water should not be allowed to percolate into the fissures since on freezing it can grip the wall.

Some damage has been observed with walls built of blocks with defective vertical joints. Sidegrip can be prevented by using a coarse-grained drainage material outside the basement wall, e.g. 0.5 m of dry gravel. This provides separation from frozen existing soil or fill so that any upward heave force is not transmitted to the wall. Alternatively a tar coating on the wall could reduce the shear between frozen soil and the wall surface.*

Horizontal frost pressure

If a basement wall is properly insulated and there is level homogeneous ground outside, the freezing front is horizontal and any heave force acts vertically upwards. If the ground is steeply sloping, there can be a significant horizontal frost force. There is no doubt that this has caused damage as basement walls were pressed inwards (Nordgård 1972). However, while damages caused by horizontal frost pressure have occurred in Norway, for example, they have not been frequent.**

If the ground on one side of a house is sloping towards the house, it is evident that the frost uplift

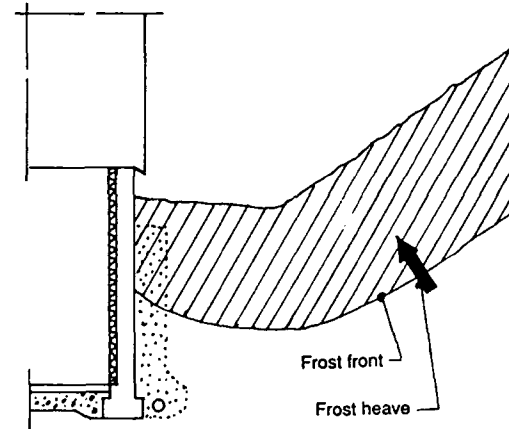


Figure 110. Horizontal component of frost heave acting on a basement wall when the soil surface is inclined. (From Nordgård 1972.)

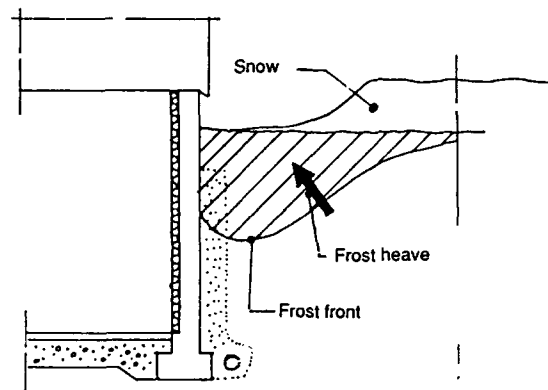


Figure 111. Inclined frost heave along a basement wall when there is a snow-free zone along the wall. (From Nordgård 1972.)

can have a horizontal component acting on the wall (Fig. 110). Even with flat ground, where snow has been shifted away from a house, it is possible to have an inclined frost force (Fig. 111). Because there is no insulating effect from snow near the house, the frost depth is lower in this region and the frost front is curved as shown. The frost force is conveyed to the wall through the frozen mass.

It is often difficult to differentiate between frost pressure and normal lateral earth pressure. The latter can be estimated, but horizontal frost pressure cannot. It would be difficult to design a wall as regards frost pressure; the best solution is to prevent frost pressure from developing. This can be

* Personal communication with S. Saarelainen, 1988.

** Personal communication S.E. Torgersen, 1988.

done by placing adequate gravel or crushed stone outside the wall. Also, the ground can be sloped downwards away from the wall or horizontal ground insulation placed outside the wall to limit frost penetration or both.*

Local uplift force

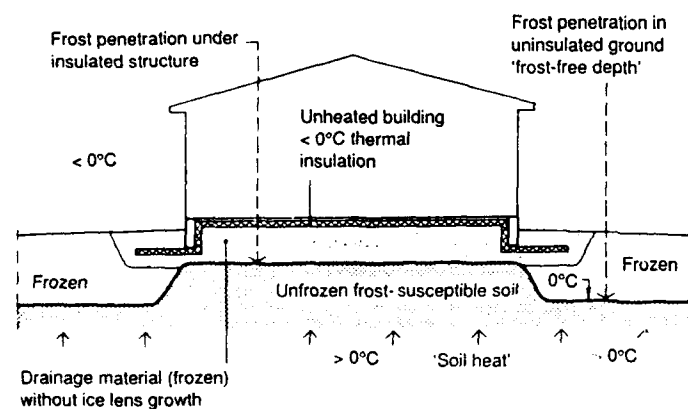
Usually a basement wall consists of internally insulated cast-in-place concrete, or it is built of blocks of expanded clay aggregate. The latter type is so weak that, if there is a local uplift force under its foundation, this could lead to a fracture in the wall. A cast wall can usually be reinforced so that a moderate uplift will not cause any damage to the wall other than some distortion. However, even a small distortion can lead to problems in the overlying house. Again, it is better to have a good design to prevent frost pressure rather than to try to solve such a problem by increasing reinforcement.

FROST PROTECTION OF UNHEATED BUILDINGS

Introduction

This section is concerned with frost protection of the foundations of unheated structures that may be associated with frost-susceptible soil. It includes frost protection of separate foundations, such as wall ("strip") and column ("point") foundations exposed to frost. The general objective is to ensure that damaging frost heave does not occur. Unlike heated buildings where heat flow from the building is utilized in foundation design, the protection of cold structures relies on the available soil heat that has been stored in the ground during summer.

* Personal communication S.E. Torgersen, 1988.



Frost protection is based on using insulation to reduce the upward loss of this soil heat, thereby preventing frost from penetrating down to the frost-susceptible ground below (Fig. 112). The protection under a building consists of a layer of insulation placed on a drainage layer. The drainage layer consists of coarse material that is not frost susceptible.

The methods described are generally based on the Frost I Jord project. They can be applied to frost protection of a slab-on-grade and, in general, to foundations for various types of unheated structures, such as industrial buildings, warehouses, garages, outhouses and shacks. These methods can also be applied to an unheated section or a large room of an otherwise heated building, to a small unheated room in a corner of a heated building or to a heated building where the floor lies higher than 0.6 m above exposed ground. Frost protection of special structures, such as exterior staircases, is included.

Frost protection of foundations can also be done in other ways:

- Placing the foundation at the traditional frost-free depth. The economics of this might have to be considered in comparison with other methods. The Swedish building standards (SBN 1980) simply state that a foundation construction below a building with a temperature not appreciably higher than that of the outside air should be taken down to the frost-free depth h_0 below the ground surface, according to Figure 10. This applies, for example, to foundations below entirely unheated buildings and below buildings with an open foundation on piers and to staircases and retaining walls outside buildings.
- Replacing frost-susceptible material down to the traditional frost-free depth. This method would normally be used only if the frost-sus-

Figure 112. Thermal insulation limiting frost penetration so that the frost-susceptible soil under the structure does not freeze. (From NBI 1978.)

ceptible material must be moved for some other reason as well.

- Using artificial heat sources such as heating cables, heat pipes or warm air. This is very energy consuming if it is not combined with insulation. It is also risky for permanent structures, because the heat supply could fail during critical periods. It should therefore not be used in permanent structures except in emergencies, although it could be feasible during winter construction.
- Casting a stiff foundation that can limit differential frost heave. The foundation then acts as a unit and is subject to a reduced amount of heave. For example, this method has been used in Norway with small unheated storage buildings (say 3x3 m). Because of the rigid foundation, the door can be closed and opened without problems. The building and foundation go up and down during the year. In spring the building tilts because thawing occurs faster on the sunny side.*

Frost load

The necessary frost protection depends on the local winter climate as expressed by the local design freezing index F_d and the mean annual temperature (MAT), which produce the frost load. The MAT is important because it can affect the extent of heaving. The freezing index at a place can have different magnitudes depending on its statistical probability of occurrence in a given period of years, i.e. F_{100} , F_{10} , F_5 and F_2 .

Norway

Values of the freezing index together with the mean annual temperature are tabulated for different districts ("kommune") in Norway. The district's maximum freezing index is in practice taken as the greatest value of F in 100 years, i.e. F_{100} . The design freezing index F_d for a particular frost-protection requirement in a particular district is chosen from among F_{100} , F_{10} , F_5 and F_2 tabulated for that district, depending on (Algaard 1976a):

- What is to be frost-protected, e.g. a foundation or floor. The consequences of possible frost heave should be assessed, and the sensitivity of the construction to heave taken into account. F_d can be different for a foundation wall and a floor of the same building (Fig. 113).

- The number of winters over which the frost protection should be effective, i.e. whether the structure is permanent or temporary. The likelihood for a certain freezing index to occur should be estimated.
- The degree of inspection by an experienced engineer. This applies particularly to the construction period.
- Whether the air temperature indoors is higher than outdoors, i.e. if the value of the freezing index inside is expected to be lower than outside. This is likely for an unheated building that is insulated and closed, particularly if it has windows giving considerable solar radiation. This is an uncertain factor but it can be important.
- Whether the surface temperature at the site and the effective frost load are significantly different from the air temperature and the air freezing index.

Radiation from an uncovered horizontal surface can increase F by 7000–8000 h°C, but snow cover reduces F , and other factors also tend to reduce F , thus usually providing an adequate safety margin. Table 22 gives guidelines for choosing the design freezing index F_d .

The tabulated values of the freezing index for a Norwegian district may require adjustment for a particular location depending on its local influencing factors, such as elevation, slope and openness. The locality may be some distance from the nearest meteorological station from which the tabulated values are derived. The local freezing index may therefore vary significantly and require a larger thickness of insulation.

At places with a low MAT (+1°C and lower) there is little effective heat content in the soil, i.e. utilizable soil heat. The demand for insulation is quite large if one does not also make use of the freezing heat by allowing part of the soil to freeze. To avoid frost heave in such cases, a sufficiently thick layer

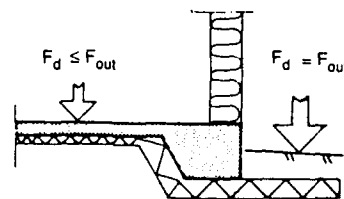


Figure 113. Different values for F_d for the foundation wall and the floor. (From Algaard 1976a.)

* Personal communication with S.E. Torgersen, 1988.

Table 22. Guidelines for choosing F_d for frost protection of construction and ground, permanently or during the building period. (From Algaard 1976a.)

Frost-protection objective	Design freezing index F_d ($h^\circ C$)		Remarks
	Foundation wall	Floor	
PERMANENT CONSTRUCTION			
Exposed to outside climate $F_d = F_{out}$	F_{10} to F_{100}	0 to F_{100}	Building construction, floor use requirement and floor type must be evaluated
Unheated, closed, insulated building $F_{in} < F_{out}$	$(F_d = F_{out})$ F_{10} to F_{100}	$(F_d < F_{out})$ 0 to F_{10}	For floor, frost load, use requirement and floor type must be evaluated
Insulated, frost-free buildings inside temperature $\geq 0^\circ C$ $F_{in} = 0$	$(F_d = F_{out})$ F_{10} to F_{100}	0	
DURING BUILDING			
Protect building to prevent frost heave		F_5 (F_2 , F_{10})	Construction's frost sensitivity and ground's frost susceptibility must be evaluated.
Protect building ground to prevent frost heave		F_2 (F_5)	Soil and risk must be evaluated.
Protect building ground to prevent thick frost crust		F_2 (F_5)	Soil, digging equipment and risk must be evaluated

of moist, protecting material (sand or gravel) is laid under the insulation, and its water content gives additional heat on freezing. The frost resistance of such a layer is proportional to its thickness and moisture content. If the MAT is $0^\circ C$ or lower (as in mountain areas and in Finnmark), one cannot use the methods for frost protection described here since permafrost conditions are approached.

The *Building Details* (NBI 1986) state that frost protection of permanent structures should normally be designed according to the local maximum freezing index, i.e. F_{100} . This would give full protection without harmful movements in the structure from the action of frost. However, if the structure can tolerate a certain amount of heave, a smaller freezing index may be used in the design, e.g. F_{10} , F_5 or F_2 . Table 23 relates to light-weight houses made of wood and gives the expected maximum frost heave (that the structure can tolerate) and its frequency of occurrence corresponding to the selected design freezing index. The values in this

table were estimated from experience and calculation. They give an idea of the maximum frost heave with soils that have high or medium frost susceptibility; differential heaves of that order of magnitude can also arise. These values, however, must be regarded as site specific, so they may not be a good guide for other circumstances. Prediction of the amount of frost heave is still at an early stage.

A floor directly on grade can be considered to tolerate some frost heave, depending on the type of construction and the functional conditions. A concrete floor designed for large loads and heavy traffic should not be exposed to frost heave. An asphalt floor can tolerate moderate deformation, while a floor of gravel or earth (for example, in a carport or open shack) can remain fit for use after normal frost heave.

If a building is to have a life of several years, the design freezing index should not be different from the usual probability value for the locality, since F_{100} can appear at any time (Algaard 1976a).

Table 23. Maximum frost heave. (From NBI 1987.)

Design freezing index ($h^\circ C$)	Maximum frost heave (mm) occurring on average one winter in a		
	100-year period	10-year period	5-year period
F_{100}	—	—	—
F_{10}	10–20	—	—
F_5	30–40	20–30	—
F_2	40–50	30–40	10–20

Cottages and other buildings that are sporadically heated will have a lower indoor freezing index, depending on the length of the heating period. However, one must be very careful before reducing F_d because a few short heating periods in the winter can, in practice, have little influence on the design requirements.

In buildings where the inside temperature in the winter half of the year is never lower than 0°C , the *Building Details* (NBI 1986) state that there is no

need for frost protection of the floor. For such buildings the foundation wall can be frost protected using F_{10} as the design value.

It is very important to note that the foundation wall and the outer walls of a building are always exposed to the outside climate, irrespective of whether or not the frost load indoors on the floor is lower than outdoors.

Finland

In Finland, F_{50} is usually chosen as the design freezing index for cold structures except in special cases. For example, F_{20} may be used where structures can withstand some differential movement due to frost heave, as in the case of buildings composed of wood or light aggregate.

For a particular locality in Finland, the value of F_{50} is determined from Figure 2, and a corresponding reduction factor obtained from Figure 114 is applied. The use of a reduced F_d is a new procedure in Finnish design for cold structures, and it allows for the insulating effect of snow cover, which is practically always present in winter. This Finnish practice is significantly different from Norwegian design, which does not take snow cover into account.

Necessary thermal insulation

Table 24, from the Frost I Jord project, can be used to determine the least thermal resistance R_0 of the insulation layer according to the design freezing index F_d and the mean annual temperature MAT (Algaard 1976a). The values can be interpolated for intermediate magnitudes of F_d and MAT. The necessary thermal resistance R_0 depends on the thickness and type of frost-protecting material placed between the insulation and the frost-susceptible soil below. A high water content in the protecting material gives a high contribution of freezing heat

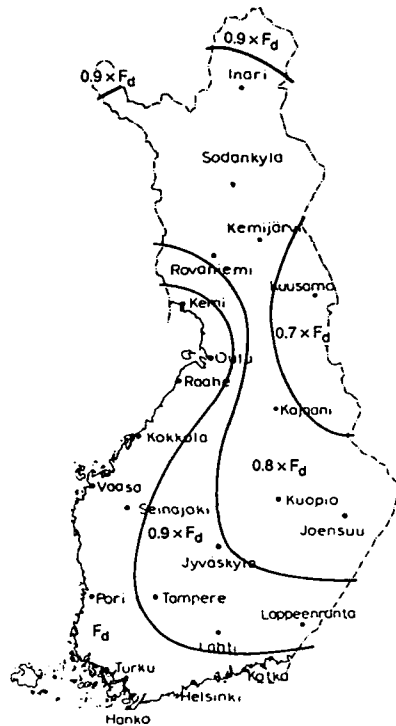


Figure 114. Reduction factors for the freezing index in Finland. (From VTT 1987.)

Table 24. Necessary thermal resistance R_0 with frost insulation to prevent frost heave under cold insulated structures. R_0 is a function of the design freezing index, mean annual temperature and type and thickness of frost-protecting layer between the insulation and frost-susceptible ground. The frost-protecting layer is gravel or coarse sand ($\rho_d = 1700 \text{ kg/m}^3$; $w = 8\%$). (From Algaard 1976a.)

F_d ($h^\circ\text{C}$):	Insulation's minimum thermal resistance R_0 ($\text{m}^2\text{K/W}$)												
	10,000	20,000			30,000				40,000			50,000	
	(all)	2	3	4-7	1	2	3	4-6	1	2	3-4	1	2
Mean annual temperature ($^\circ\text{C}$):													
Thickness of protecting layer z (m)													
0.1-0.2	0.8	1.6	1.4	1.2	3.2	2.6	2.2	2.0	4.2	3.5	2.8	(5.0)	(4.0)
0.4	0.5	1.2	1.0	0.8	2.5	2.0	1.6	1.4	3.5	2.8	2.2	(4.0)	(3.2)
0.6	0.3	0.8	0.6	0.5	1.7	1.4	1.0	0.8	2.5	2.0	1.6	3.0	2.4
0.8	0	0.6	0.4	0.3	1.4	1.1	0.8	0.7	2.1	1.6	1.3	2.5	1.9
1.0	0	0.4	0.3	0.2	1.0	0.7	0.6	0.5	1.6	1.2	1.0	1.8	1.4

Table 25. Thermal resistance of ground insulation for protection of cold structures. (From VTT 1987.)

Thickness of protecting layer z (m)	F_d (h°C): Mean annual temperature (°C):	Ground insulation's minimum thermal resistance R_0 (m²K/W)												
		20,000			30,000				40,000			50,000		≥60,000
		2	3	≥4	1	2	3	≥4	1	2	3-4	1	2	0-1
0.2		1.6	1.4	1.2	3.2	2.6	2.2	1.8	(4.2)	3.5	2.8	*	(4.6)	*
0.4		1.4	1.1	0.8	2.6	2.1	1.7	1.4	3.5	2.8	2.2	(4.6)	3.8	*
0.6		1.0	0.7	0.5	2.1	1.7	1.3	1.0	2.8	2.2	1.6	3.8	2.9	(5.0)
0.8		0.6	0.4	0.3	1.7	1.3	1.0	0.7	2.2	1.6	1.3	2.9	2.2	3.8
1.0		0.4	0.3	0.2	1.3	1.0	0.7	0.5	1.6	1.2	1.0	2.2	1.7	2.8
1.5		0	0	0	0.8	0.6	0.4	0.2	1.0	0.7	0.5	1.4	1.0	1.8

* Foundation depth should be increased.
 () In general, increase of foundation depth is more profitable.

and will delay frost penetration. In Table 24 calculations have been based on the use of a layer of sand or gravel with a moisture content of 8% by weight. A drier layer of crushed stone would give a greater thickness requirement.

The given values for R_0 will allow frost to penetrate a little into the frost-susceptible underlayer without giving rise to significant frost heave. The first line in Table 24, $z = 0.1-0.2$ m, is used if there is only a draining or capillary breaking layer of minimum thickness under the insulation. With a thicker drainage layer, the corresponding value of R_0 can be found from Table 24 according to appropriate values of F_d and MAT.

Finnish guidelines

Based on Table 24 the Finnish guidelines propose the use of Table 25, which is similar but has an additional column corresponding to a freezing index of 60,000 h°C and greater. Table 25 also has an additional row applying to the use of a 1.5-m-thick layer of non-frost-susceptible material. The mean annual temperature for a Finnish locality is obtained from Figure 7, and the design freezing index is the reduced value allowing for snow cover. The required thermal resistance R_0 of the insulation can then be determined according to the chosen thickness of the non-frost-susceptible layer to be placed under it. The idea of using this layer is to prevent the 0°C isotherm from penetrating further down into underlying frost-susceptible soil. The part of the insulation extending outside the foundation is the ground insulation with a width b .

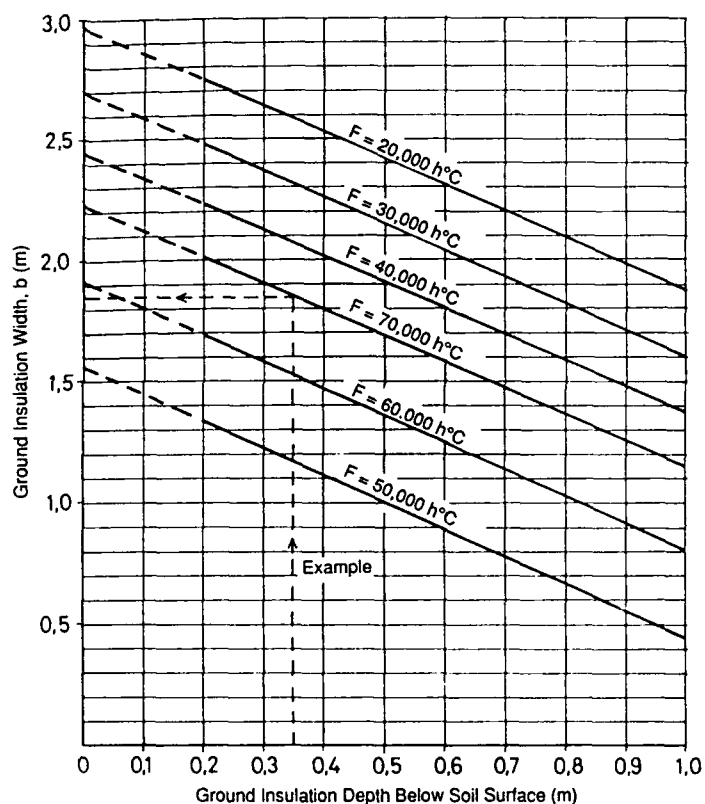


Figure 115. Width of ground insulation for cold structures. (From VTT 1987.)

From the required thermal resistance of the ground insulation (Table 25) and its thermal conductivity, its necessary thickness can be determined. The required width b of this ground insulation is then found from Figure 115, depending on the depth of the insulation below the ground surface and the design freezing index. Figure 116 shows typical examples of the positioning of ground insu-

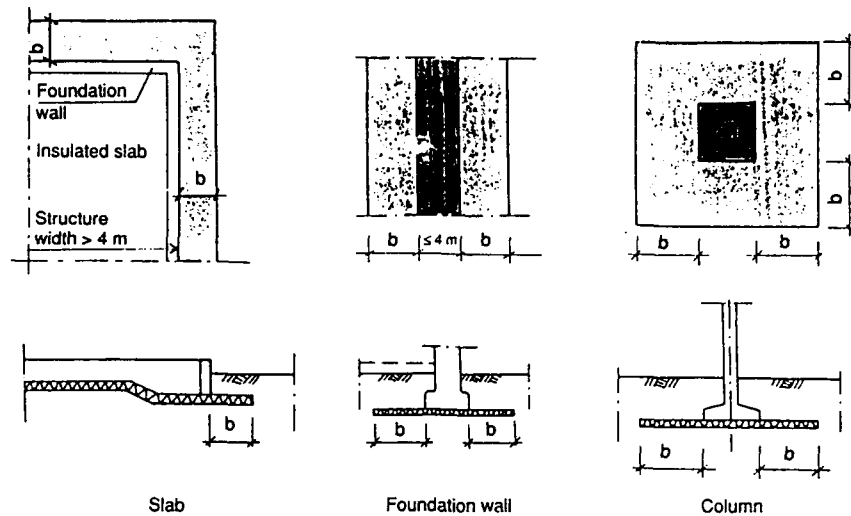


Figure 116. Typical positions of ground insulation to protect a slab, a foundation wall and a column. (From VTT 1987.)

lation, determined as above, to protect a slab, a foundation wall and a column or pier.

Ground insulation must always be located over a layer of non-frost-susceptible material with a thickness of at least 0.2 m. This drainage layer protects the overlying insulation material against capillary flow from the ground below and tends to keep the frost front in non-frost-susceptible material for a relatively long period, thus smoothing and reducing frost heave outside the foundation perimeter.*

The effect on the calculated temperature distribution of placing insulation at different locations is shown in Figure 117. In the upper illustration, 0.34 m of sand underlies the foundation wall, whereas in the lower case, insulation is placed directly below the wall with 0.2 m of sand underlying. The 0°C isotherm has a more favorable (i.e. higher) location in the latter case because of the position of the insulation. Had the foundation wall been composed of expanded clay aggregate instead of concrete, the upper case would have been satisfactory because of the higher thermal resistance of the light aggregate material.

Ground insulation as shown in Figure 117 can consist of insulation material like a board of extruded polystyrene or a light gravel layer (composed of expanded clay aggregate) thick enough to give an equivalent thermal resistance R_0 . If a polystyrene insulation board is used, it is first laid on a drainage bed and then covered with a protective layer of sand, for example. To prevent surface

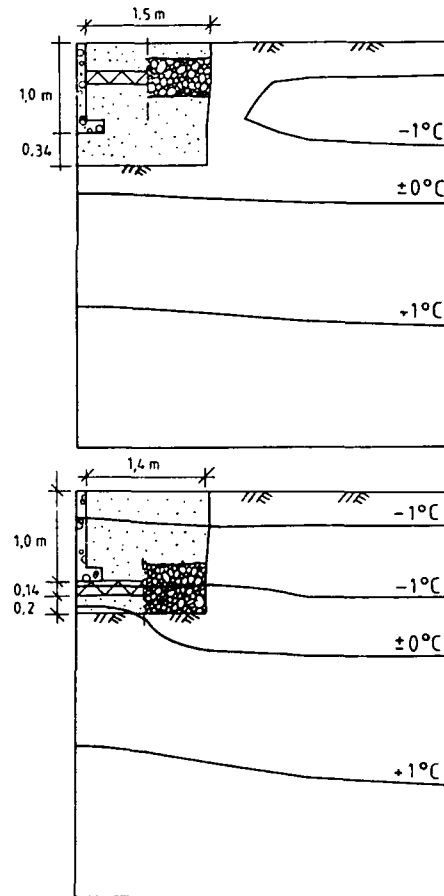


Figure 117. Effect of ground insulation positions on the isotherms for a cold structure. (Freezing index = 42,000 h $^{\circ}\text{C}$; foundation depth = 1.0 m; thermal resistance of ground insulation = 2.8 m $^2\text{K/W}$.) (From Finnish guidelines 1987.)

* Personal communication with S. Saarelainen, 1988.

Table 26. Frost protection with expanded polystyrene and underlying drainage material. For example, for a freezing index of 30,000 h°C and MAT of 5°C one can obtain frost protection with 1.8 m of drainage material, 60 mm of polystyrene and 0.4 m of drainage material, or 100 mm polystyrene. (From NBI 1987.)

Design freezing index (h°C)	Mean annual temperature (°C)	Necessary layer of drainage material (m) under expanded polystyrene insulation of the following thicknesses (mm)							
		0	40	50	60	80	100	120	150
≤3000	1	0.6	0						
	3	0.5	0						
	5	0.4	0						
5,000	7	0.4	0						
	1	0.8	0						
	3	0.7	0						
	5	0.6	0						
10,000	7	0.5	0						
	1	1.2	0.1	0					
	3	1.1	0						
	5	0.9	0						
20,000	7	0.8	0						
	1	1.9	0.8	0.6	0.5	0.3	0.1	0	
	3	1.6	0.4	0.3	0.2	0			
	5	1.4	0.3	0.2	0.1	0			
30,000	7	1.3	0.2	0.1	0				
	1	2.3	1.2	1.1	0.9	0.7	0.4	0.3	0.1
	3	1.9	0.8	0.7	0.6	0.3	0.1	0	
	5	1.8	0.7	0.6	0.4	0.2	0		
40,000	7	1.7	0.6	0.5	0.3	0.1	0		
	1	2.6	1.5	1.3	1.2	0.9	0.7	0.5	0.4
	3	2.2	1.2	1.0	0.9	0.6	0.4	0.3	0.1
50,000	5	2.1	1.1	0.9	0.8	0.5	0.3	0.2	0
	1	2.8	1.7	1.5	1.4	1.1	0.9	0.7	0.6
	3	2.6	1.5	1.3	1.2	0.9	0.7	0.5	0.4

runoff from getting to the insulation, the ground surface should be sloped away and covered with a soil layer of low permeability, such as clay fill.

Norwegian Building Details

The design process developed in the Frost I Jord project was taken a step further by the Norwegian Building Details (NBI 1987), which gives required thicknesses of expanded polystyrene insulation and underlying drainage layer (Table 26). Various combinations of thicknesses of these layers have an equivalent effect and may be used corresponding to a particular design freezing index and mean annual temperature. The specification is that frost protection can be carried out with thermal insulation, a combination of thermal insulation and an underlying layer of drainage material that is not frost susceptible, or with coarse drainage material alone. Under a floor, there must always be a drainage layer at least 100 mm thick (Fig. 118) consisting of coarse gravel or crushed stone. Such a layer should also be laid under mineral wool used as ground insulation.

Table 26 gives the interrelated thicknesses with expanded polystyrene as insulation. If another

insulation material is used, the insulation thickness from this table is multiplied by the appropriate correction factor from Table 27, which also indicates the necessary moisture protection requirements. With extruded polystyrene, such as

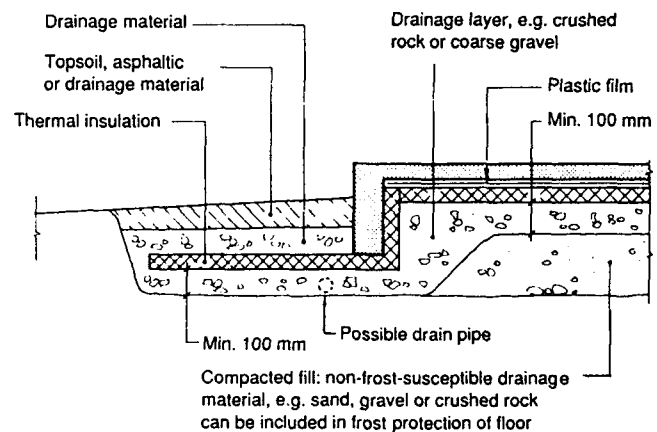


Figure 118. Drainage layer under a floor and foundation wall. If the drain pipe is laid 100 mm below the foundation wall, its distance from the foundation wall should be at least doubled, i.e. 200 mm. (From NBI 1987.)

Table 27. Correction factor for insulation thickness given in Table 26 with use of other insulation materials. The necessary moisture protection of the insulation is also shown. (From NBI 1987.)

Insulation material	Insulation thickness in Table 26 multiplied by	Moisture protection
Extruded polystyrene	0.85	None
Expanded polystyrene		
Density 20 kg/m ³	1.4	Overlying plastic film
Density 30 kg/m ³	1.0 (basis)	
Mineral wool		
Density ≥150 kg/m ³	2.0	0.1-m-thick drainage layer
Light aggregate	3.5	Wrapped in plastic bag

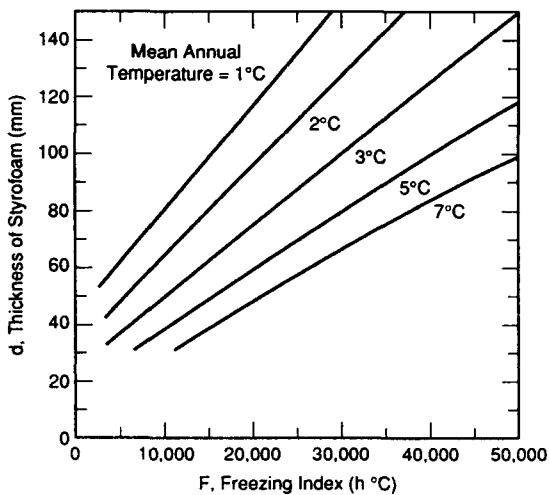


Figure 119. Necessary thickness of Styrofoam as a function of design freezing index and mean annual temperature. (From Dow Chemical n.d.)

Table 28. Necessary insulation width outside a foundation wall. (From NBI 1987.)

Maximum freezing index (h °C)	Insulation width (m)
10,000	0.50
20,000	0.75
30,000	1.00
40,000	1.25
50,000	1.50
60,000	1.50

Styrofoam, the necessary insulation thickness may also be found directly from Figure 119 as a function of the design freezing index in air and the mean annual temperature.

Under favorable snow conditions, a snow cover outside a cold building will give a thermal insulation effect. In practice, however, it would be highly uncertain what thickness of snow to use in calculations. Therefore, according to the *Building Details*, no allowance should be made for snow in designing frost protection for cold buildings.

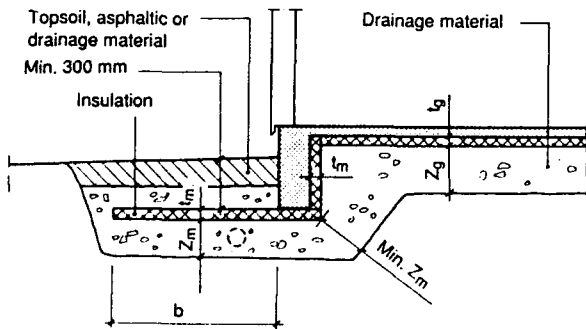


Figure 120. Frost protection of a foundation wall and slab. (From NBI 1978.)

Insulated floor and foundation wall

The floor and foundation wall in unheated buildings must be frost-protected if frost heave cannot be tolerated. Figures 120–125 give examples of frost protection consisting of thermal insulation and an underlying layer of drainage material. These must be extended over a distance b beyond the foundation wall. Table 28 gives values of b depending on the maximum freezing index F_{100} . It is very important that no frost-susceptible material be placed within the foundation wall area. At an exterior corner, extra insulation must be provided, as shown in Figure 126.

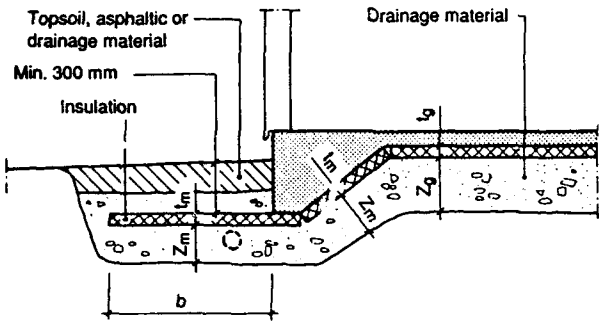


Figure 121. Frost protection of a foundation and slab cast as one unit. (From NBI 1978.)

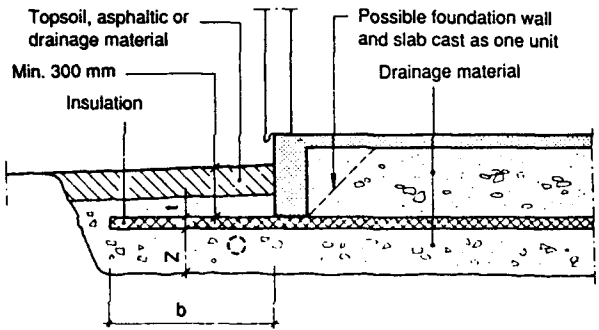


Figure 122. Frost protection of a small building such as a garage or free-standing shack. (From NBI 1978.)

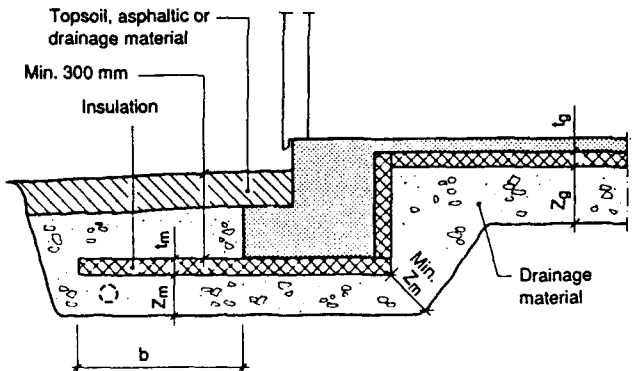


Figure 123. Frost protection of a foundation for large loading using inside formwork. (From NBI 1978.)

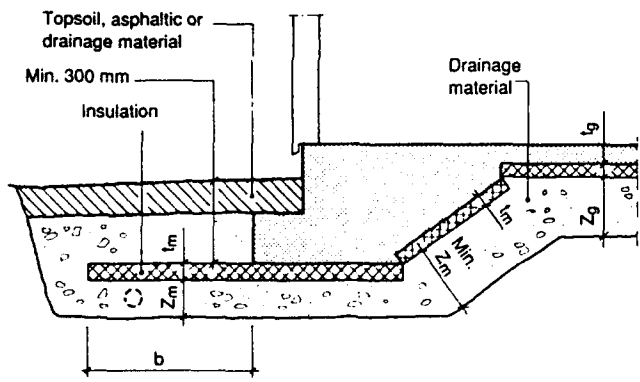
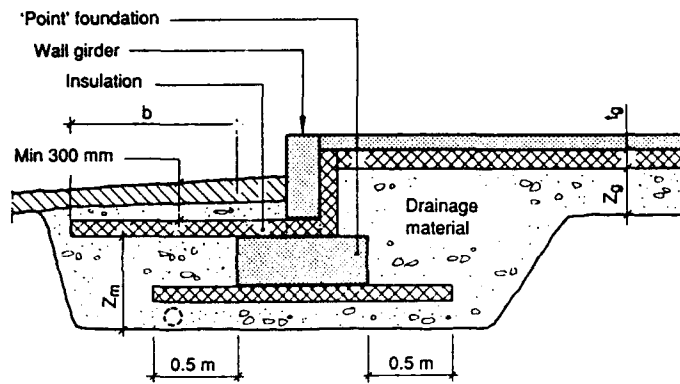


Figure 124. Frost protection of a foundation for large loading using no inside formwork. (From NBI 1978.)



Section A-A

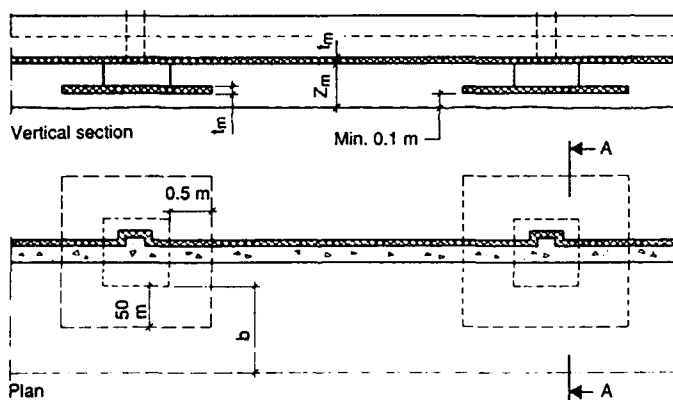


Figure 125. Frost protection of a column foundation with a wall girder. Frost protection of column foundations is only necessary when they are shallower than the usual frost-free depth in undisturbed ground. (From NBI 1978.)

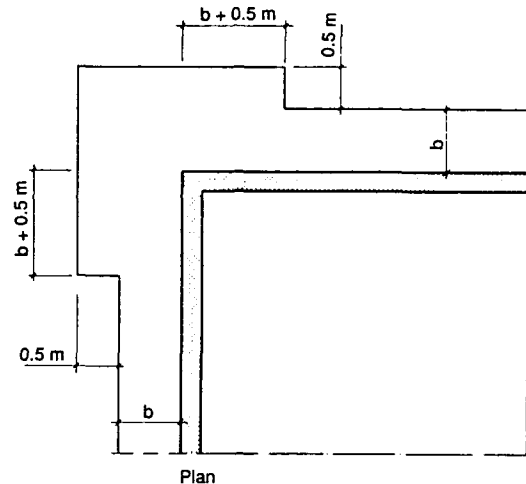


Figure 126. Extra frost protection at a corner. (From NBI 1978.)

If some frost penetration in the floor can be allowed, the foundation wall would be exposed to frost from the inside as well as from the outside. The insulation thickness calculated for the outside of the foundation wall must then also be extended a distance b in towards the floor (Algaard 1976a). If frost penetration in the floor is large, the rules given in the following section for insulation of a foundation wall should be followed because conditions would then approach those for a strip foundation.

In buildings where the inside temperature in the winter half of the year is always above 0°C , the *Building Details* allow no frost protection of the floor, as shown in Figure 127. The required width b of insulation outside the foundation wall and the extra insulation at the corner are found from Table 28. The thickness of the insulation and underlying drainage layer are designed according to Table 26 using F_{10} . To avoid condensation on the floor at the outer wall, any cold bridge effect between the floor

and the foundation wall should be broken by insulation.

Care must be taken that no cold bridges are formed, such as those illustrated in Figures 128 and 129. The insulation must form a continuous layer over or under both floor and foundation without any cold bridges that can give local frost penetration (Algaard 1976a).

There must be adequate protection for a large unheated part of an otherwise heated building or of a small unheated room in an external corner of such a building. If the inside temperature in such an unheated room can be lower than 0°C , it should be frost-protected according to Table 28 and its associated requirements, with the possibility of omitting the floor insulation as in Figure 127.

If the floor in a heated room lies higher than 0.6 m over outside ground, the foundation wall should be protected as in Figure 127, and the floor insulation should be designed as for heated buildings.

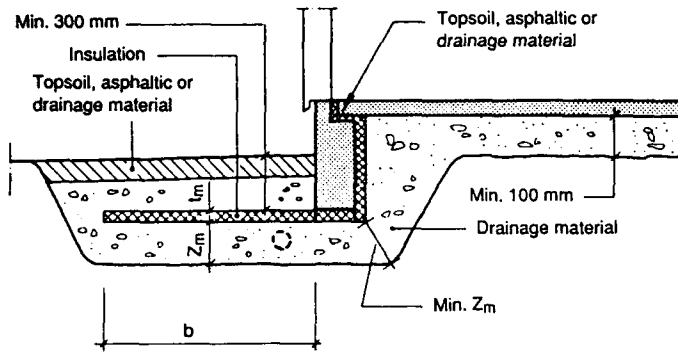


Figure 127. Omission of frost protection of the floor if the inside temperature stays above 0°C. It would be necessary to break the cold bridge between the foundation wall and the foundation. (From NBI 1978.)

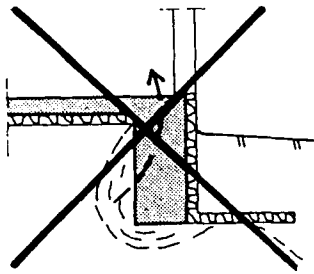


Figure 128. Dangerous design with a foundation wall. Frost can penetrate under and inside the wall. (From Algaard 1976a.)

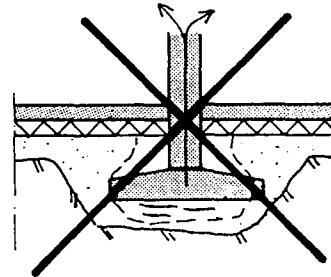


Figure 129. Dangerous design with a column foundation. The column forms a cold bridge, with frost penetration under the floor and footing. (From Algaard 1976a.)

Insulating wall foundations

In the case of foundations less than 4 m wide, there will be appreciable heat loss towards the sides as well as in the vertical direction. The necessary width of insulation is then larger and found from Table 29. At a corner the insulation width is even greater (Table 30), corresponding to the value for a column or point foundation (Algaard 1976a).

The *Building Details* specify that where a floor can accept frost heave (i.e. there is a small tolerance demand) it is sufficient to insulate the foundation

for the outer walls and for any inner walls, with no floor insulation being necessary. This can be the case in structures with a gravel floor and also in those with an asphalt floor when the ground is not particularly frost susceptible. This is also the case with foundations for "levegger" (shelter walls) and atrium walls, groundwall strips as in open foundations, foundation walls with crawl spaces for unheated buildings, foundations for small shacks or garages, etc.

Table 29. Necessary insulation width for protection of a foundation wall. The width b required on each side of the wall is shown in Figure 132. (From NBI 1987.)

Maximum freezing index (h°C)	Insulation width b (m)
10,000	0.50
20,000	0.75
30,000	1.00
40,000	1.50
50,000	2.00
60,000	2.50

Table 30. Necessary insulation width for protection of a column foundation. (From NBI 1987.)

Maximum freezing index (h°C)	Insulation width (m)
10,000	0.75
20,000	1.10
30,000	1.50
40,000	2.25
50,000	3.00
60,000	3.75

Figure 130. Building where only the foundation wall is frost protected. Frost heave of the slab beyond the insulation must then be accepted. (From NBI 1978.)

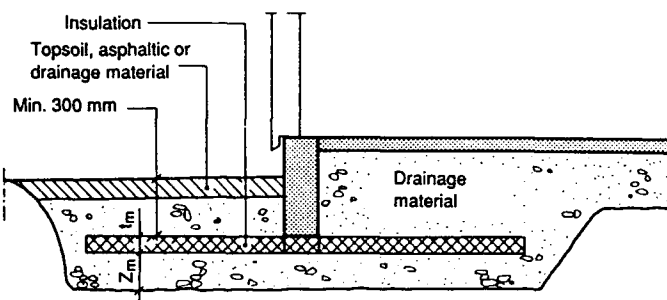


Figure 131. Frost protection of the foundation for a levegger wall, atrium wall or foundation strip. (From NBI 1978.)

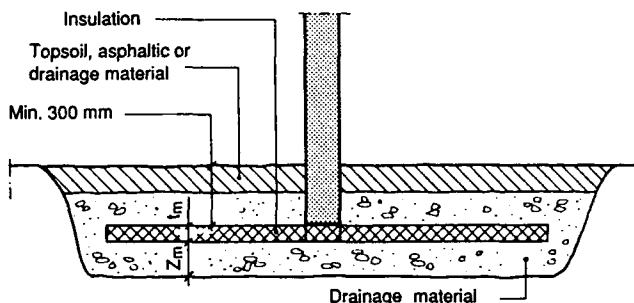
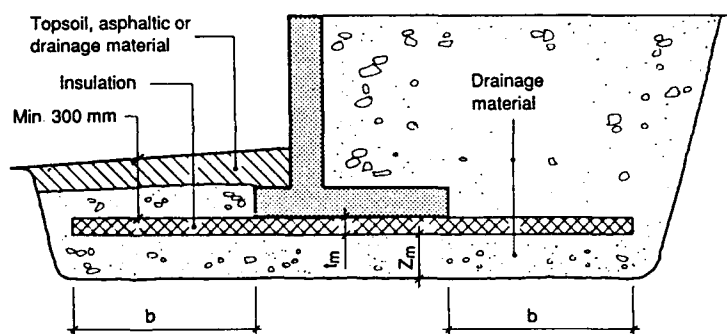


Figure 132. Frost protection of a cantilever wall. (From NBI 1978.)



Figures 130–132 show examples of frost protection of wall or strip foundations. Table 29 gives the necessary width b of insulation outside the foundation, while Figure 133 shows how a corner should be insulated. The thicknesses of insulation and drainage layer are designed according to Table 26 and its associated directions (usually using F_{100}).

This foundation method is thus appropriate when a foundation wall is to be frost-protected, leaving the floor uninsulated, or where a building has a free-bearing insulated floor on groundwall strips bearing on frost-susceptible soil. In the latter case, insulation is required between the strips and the underlying soil (Algaard 1976a).

Figure 134 shows alternative treatments of a retaining wall. Where part of the backfill material is frost susceptible, a vertical insulation layer of thick-

ness t is required behind the wall, as well as a minimum thickness of 100 mm of drainage material. The extruded polystyrene insulation (Styro-foam) under the wall need only be extended a reduced distance b beyond the inner edge of the footing such that the sum of the breadth and height from free air to the foundation is equal to the place's frost depth in sand and gravel (from Fig. 8).

Insulating point foundations

In the case of a cold building with an uninsulated floor, a point or column foundation must be specially frost-protected. The same applies to a heated or cold building with an open foundation (free-bearing floor) on piers and to small unheated structures, such as shacks, less than 4 m wide. Column foundations or piers can be frost-protected as shown

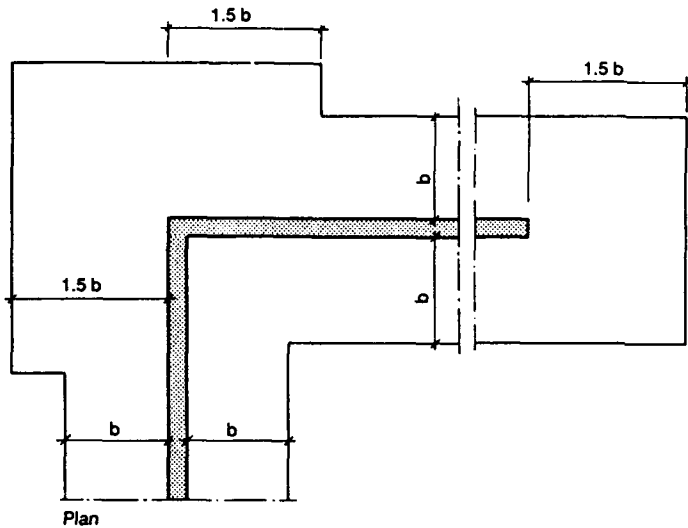
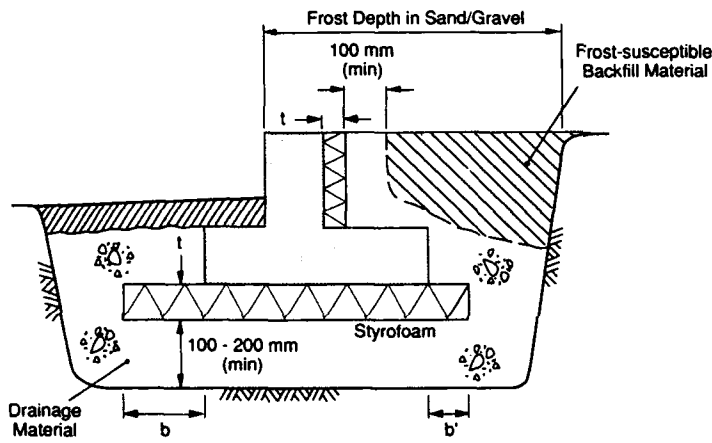
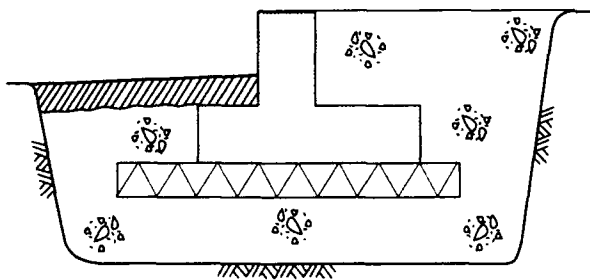


Figure 133. Frost protection at a corner and end of a foundation. (From NBI 1978.)



a. Insulated wall and footing.

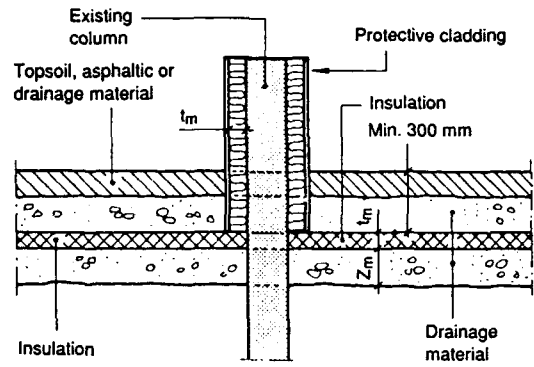


b. Uninsulated wall and insulated footing.

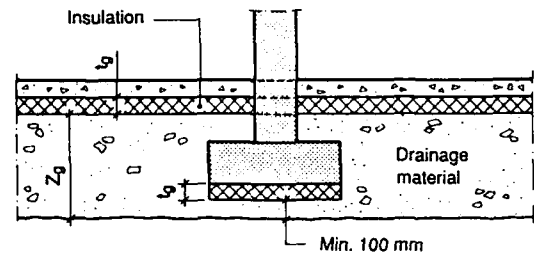
Figure 134. Alternative treatments of a retaining wall. (From Dow Chemical n.d.)

in Figures 135 and 137. The *Building Details* give Table 30, showing the distance b the insulation must be extended outside the foundation area and around it. The width and thickness of insulation and the thickness of the drainage layer are designed according to Table 26 and associated guidelines. As compared with Table 29 for strip foundations, Table 30 specifies 50% wider insulation ow-

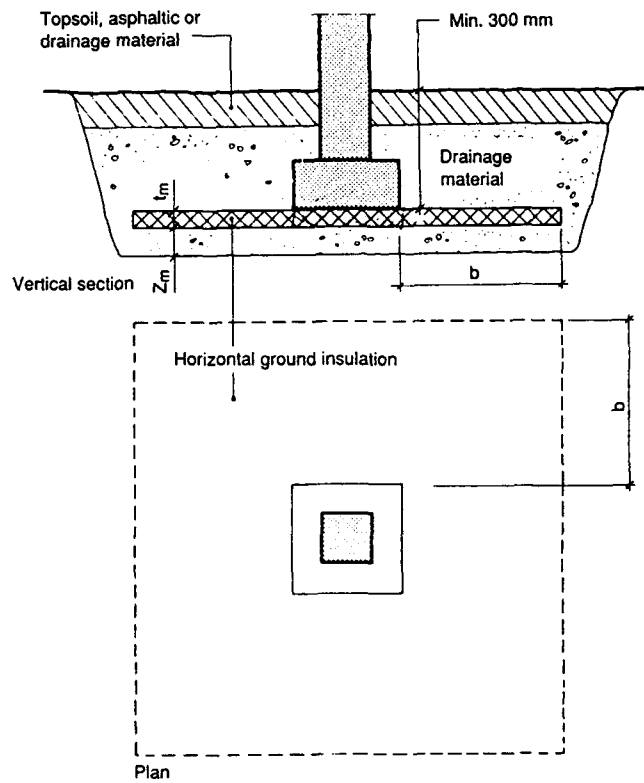
ing to the small amount of soil heat stored under the column insulation compared to the heat loss along the periphery of a column foundation. Frost protection of column foundations requires disproportionately more insulation, especially in colder regions. It often pays to frost-protect a column or row of columns with a continuous horizontal insulation area as for wall foundations.



a. Existing column exposed to frost heave.



b. Column foundation under frost-protected slab construction.



c. Column foundation over extended insulation.

Figure 135. Frost protection of columns and column foundations. (From NBI 1978.)

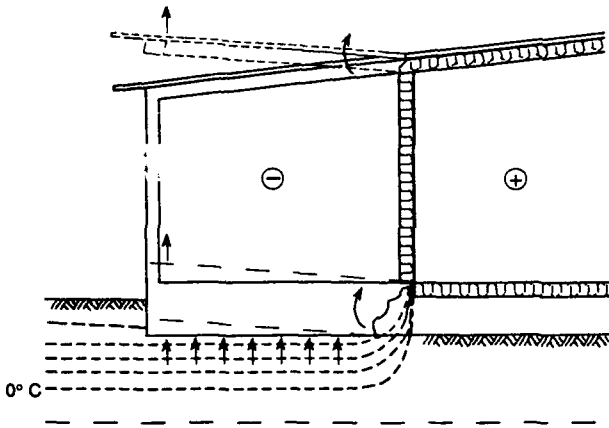


Figure 136. Differential movement between cold and heated parts of a building.

The minimum thickness of Styrofoam insulation can be found from Figure 119. F_{100} is used for permanent structures but, for less critical structures, thinner insulation can be used corresponding to a lower F_{11} .

Cold part or projection of a structure

Cold parts of, or adjuncts to, heated structures require special treatment because of their tendency for differential movement (e.g. Fig. 136). The cold part or adjunct can be allowed separate freedom of movement, or they can be frost-protected adequately.

The Swedish building standards (SBN 1980) specify that, for part of a construction outside an external wall, the foundation depth, applying to a foundation with a crawlspace or basement, should be increased by the distance between the extremity of the part concerned and the outer face of the external wall.

According to the Finnish guidelines, foundations for cold parts or projections of an otherwise heated structure can be thermally insulated as shown in Section A-A of Figure 137. This can apply to cases such as a foundation wall extension, an exterior staircase, a column supporting a balcony, a porch or an unheated garage. The design freezing index is chosen to be F_{50} , as for unheated structures in Finland.

Insulation of the following auxiliary cold constructions is described in the Norwegian *Building Details* (NBI 1987).

Exterior staircase for a basement. At an outside staircase for a basement, one should insulate under the whole staircase and up along the staircase

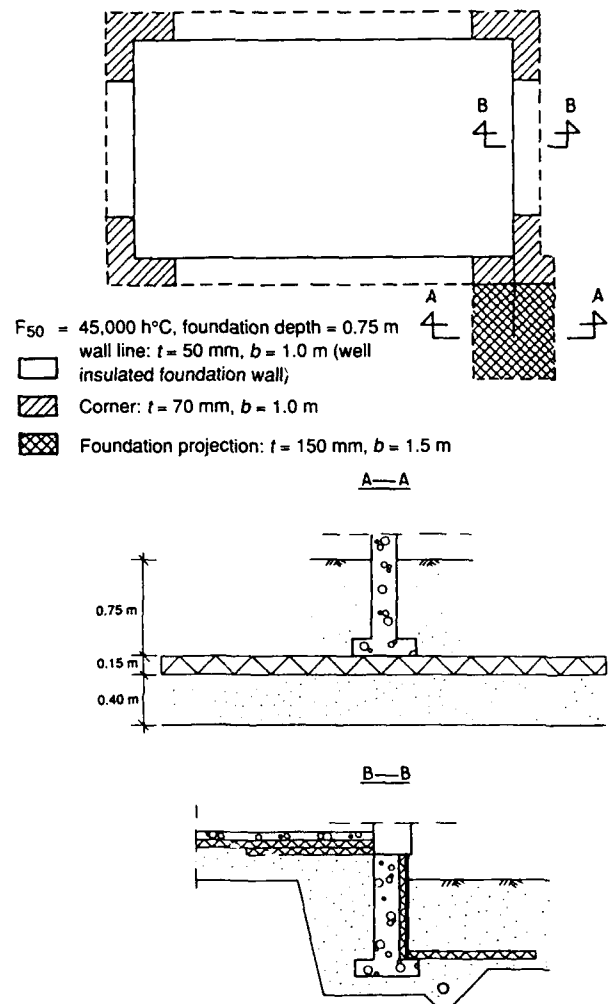


Figure 137. Examples of frost protection of heated buildings and their cold parts. (From VTT 1987.)

wall on the outside against earth fill. There can also be horizontal insulation outside the top of the staircase corner, as shown in Figure 138. The breadth b of the insulation is obtained from Table 29, and the thicknesses of the insulation and drainage layer are designed according to Table 26.

The ground slope may be used instead of a staircase wall, extending the insulation layer from under the staircase base to 1 m outside the base.

Entrance staircase. A foundation for an entrance staircase can be frost protected as shown in Figure 139, with an insulation width b as given by Table 29. The thicknesses of the insulation and drainage layer are designed with the help of Table 26. Such an unheated adjunct to a heated building must be

suitably frost-protected if the adjunct is tied to the building as in this illustration.

Closed-in entrance. Figure 140 shows frost protection of a closed-in entrance area. The width of insulation is obtained from Table 29, and the thicknesses of the insulation and drainage layer are designed using Table 26.

Garage ramp. At a garage entrance the foundation must be frost protected as shown in Figures 141. The insulation width b is given in Table 29 and is extended 1 m beyond the garage door on each side. The thicknesses of the insulation and drainage layer are designed according to Table 26. Beyond the end of the insulation, a marked swelling due to frost will appear in the ramp. This can be smoothed

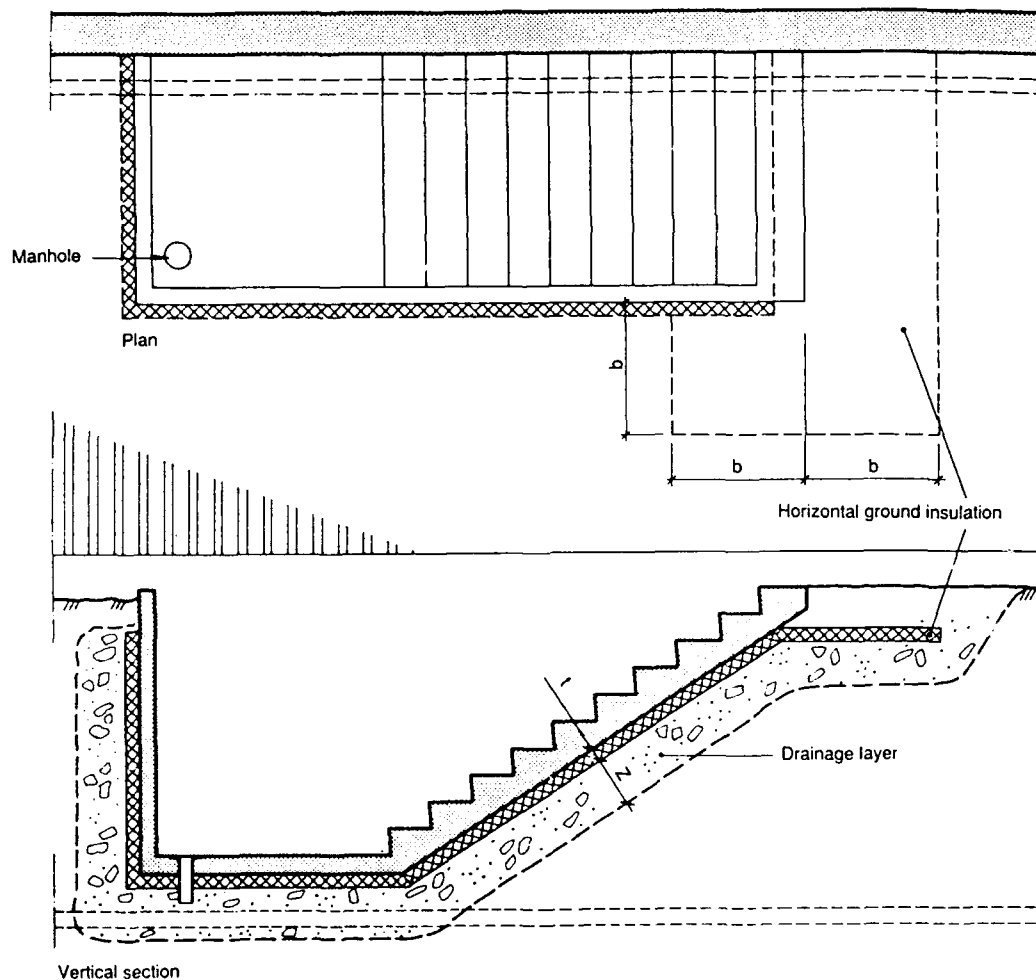


Figure 138. Frost protection of an exterior cellar staircase. (From NBI 1978.)

smoothed out by the use of, for example, a layer of loose light aggregate over a distance of a couple of meters beyond the insulation. The thickness of this layer should decrease uniformly from 200 mm, for example, to zero. Alternatively the thickness of the insulation can be reduced.

Variable heated and cold buildings

For buildings that are only sporadically heated (assembly halls, cabins, outhouses etc.) or that may later be permanently heated, the floor and foundation wall can be designed according to the requirements for floor temperature in the case of heated

buildings. The connection between the floor and foundation wall should not form a cold bridge, and vertical insulation is required on the outside or inside of a foundation wall.

Figure 142 shows design types that are suited both for heated and cold buildings, giving acceptable floor temperatures in heated buildings when the floor and foundation wall insulation are designed as described earlier. Figure 142c is satisfactory with regard to frost penetration but unsuitable for heated buildings without vertical foundation wall insulation. Heating cables may be necessary as a supplement.

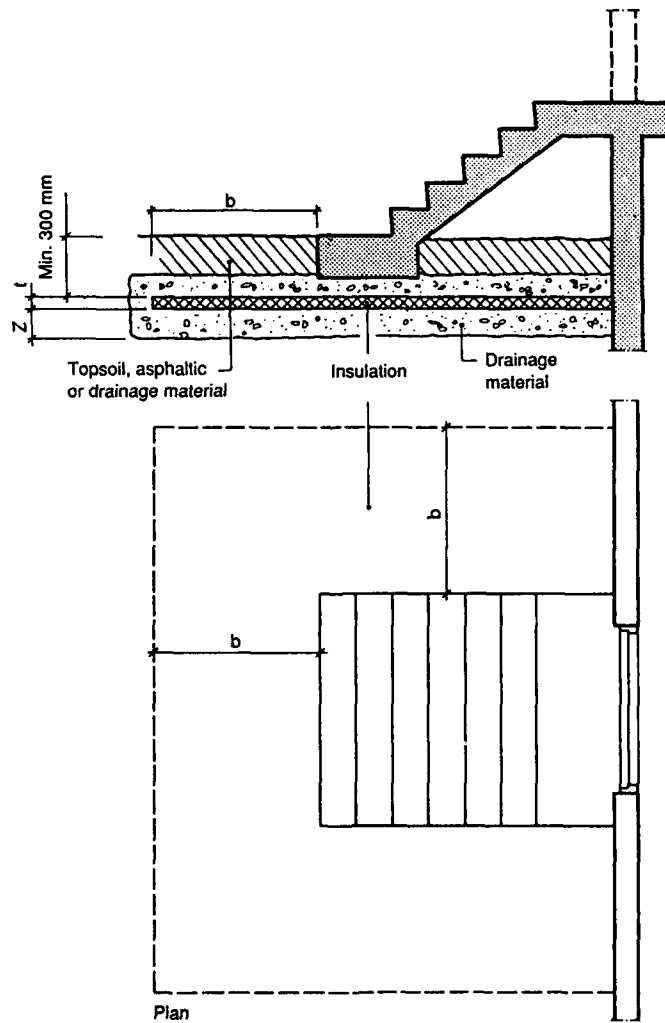


Figure 139. Frost protection of a foundation for an entrance staircase. (From NBI 1978.)

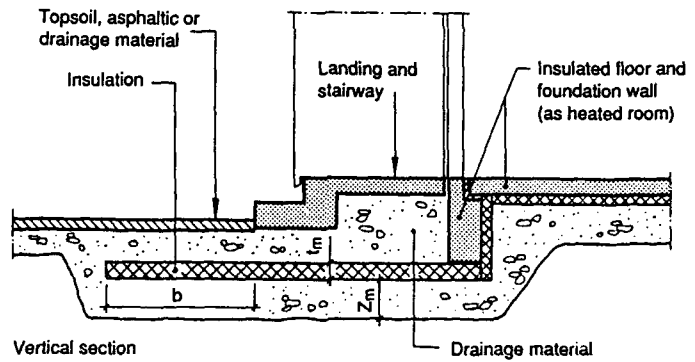
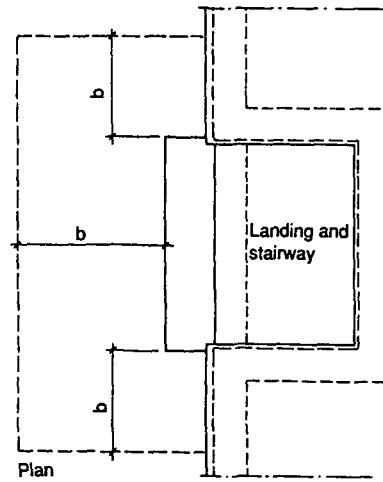


Figure 140. Frost protection of a landing and stairway with a closed-in entrance. (From NBI 1978.)

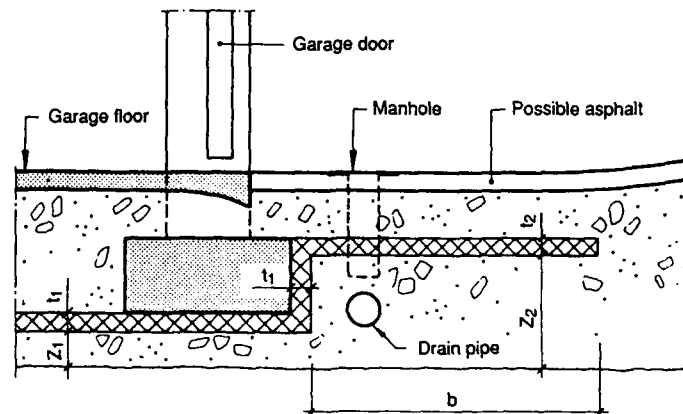
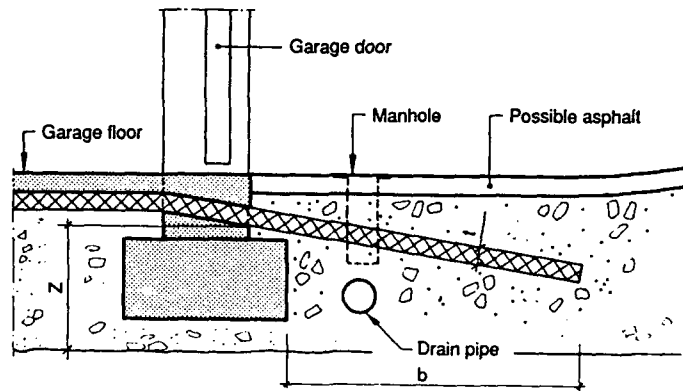


Figure 141. Frost protection of a garage entrance drive. (From NBI 1978.)

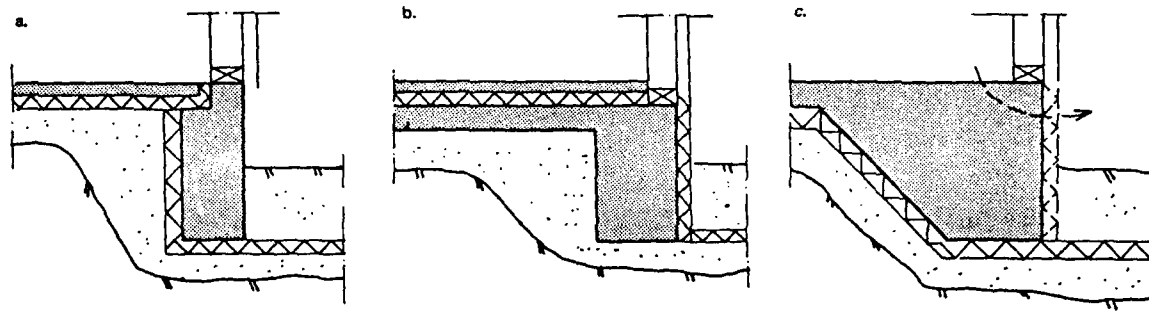


Figure 142. Designs for heated or cold buildings that are satisfactory with regard to frost penetration requirements. Design c is unsuitable for heated buildings without vertical insulation of the foundation wall. (From Algaard 1976a.)

DESIGNS WITH OPEN FOUNDATIONS

Foundations are considered open when there is free air circulation under the building. This section considers open foundation designs using ground-wall strips, piles or piers. Open foundation methods involve little interference with the existing terrain,

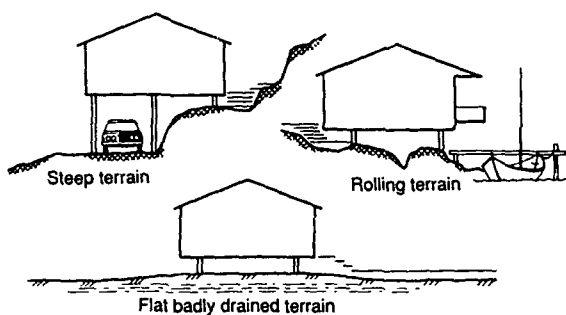


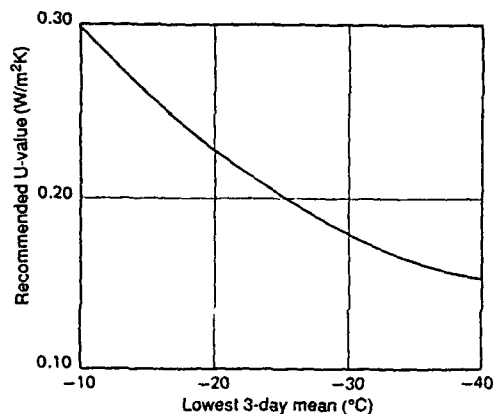
Figure 143. Houses on piers, which are especially suited to places with steep or rolling terrain or ground with bad drainage. (From NBI 1980.)

and drainage provisions are normally unnecessary. They can be used with practically all terrain and ground conditions but are especially suitable in hilly ground (Fig. 143). The free distance between the ground and the building's floor structure should be at least 300 mm. At the entrance to a building, water and sewer pipes must be frost-free (NBI 1980).

Background from Frost I Jord project (Torgersen 1976b)

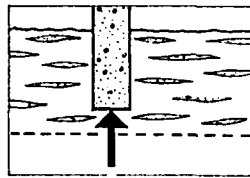
There is no special problem from moisture under the floor structure (wood frame) of a basement, but the floor should be insulated especially well. The recommended U -values for the floor structure are shown in Figure 144 to give a surface temperature of the floor equal to 17.5°C. They depend on a design outside temperature equal to the lowest average temperature in a three-day period, i.e. the lowest average temperature for three successive days found from meteorological data for a 30-year period.

The foundation should be extended to the minimum frost-free depth or to bedrock if it is not

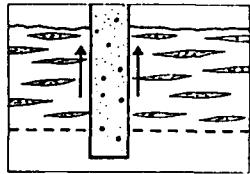


Wood floor structure, mineral wool thickness (mm)	U-value (W/m ² K)
125	0.33
150	0.28
175	0.24
200	0.22

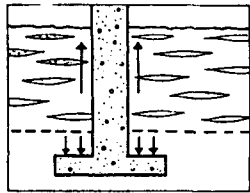
Figure 144. Recommended U -values for floor structures. (From Torgersen 1976b.)



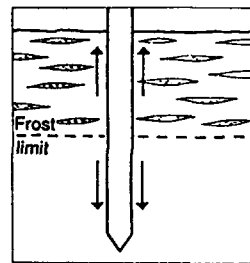
Frost under the foundation gives frost heave



Soil that freezes firmly to the foundation gives a lifting force with sidegrip



Anchoring with expanded footing under the frost zone.



Anchoring by friction between the foundation and the soil under the frost zone.

Figure 145. Frost heave and sidegrip. (From Torgersen 1976b.)

placed on insulation according to the directions given earlier. The foundation should be protected against frost uplift due to sidegrip, and the building's side stability should be checked.

Frost damage

In frost-susceptible soil there are two possible causes of frost damage with open foundations, i.e. frost under the foundation and sidegrip (Fig. 145).

Frost under the foundation. When frost penetrates under the foundation, ice lenses can form, exerting upward heave forces. As mentioned, this can be prevented by placing insulation under the foundation or by extending the foundation to the frost-free depth.

Sidegrip. Although there may be no frost under the foundation, soil can freeze firmly on the

foundation's side surface, and this sidegrip gives a lifting force. If this force is greater than the load from the building, the foundation must be anchored under the frost zone. The anchoring can be achieved by expanding the cross-sectional area of the foundation with a larger footing under the frost zone (in the case of a groundwall strip or pier, Fig. 146). It is also possible to extend the foundation under the frost zone so that friction between the foundation and the soil gives sufficient anchoring (in the case of a pile). Also, the sidegrip can in certain cases be reduced by coating the side surface in the frost zone with bitumen or epoxy.

Lifting forces from sidegrip increase with the freezing index but not proportionally. The maximum lifting force acts in the period when the outside temperature is decreasing most rapidly. The force usually increases with increasing diameter of pier and frost depth, but there is no direct proportionality. The maximum lifting force does not necessarily act when the frost depth is at its maximum.

Based on the report of Andresen (1975), Table 16 gives guidelines for the lifting force from sidegrip on piles or piers in dry crust clay. The values represent the lifting force in kilonewtons per pile or pier (or kilonewtons per meter of concrete wall) depending on the design freezing index, which in Norway is chosen as F_{100} . In a silt soil the lifting force is estimated to be about half the given values for a freezing index of 10,000 h°C and one third for a freezing index of 50,000 h°C. With a coating of bitumen (at least 2 mm) or epoxy on the pile or pier, the values in Table 16 may be reduced by 40% if there is dry material in the frost zone. For silt soils it is doubtful whether bitumen protection has some

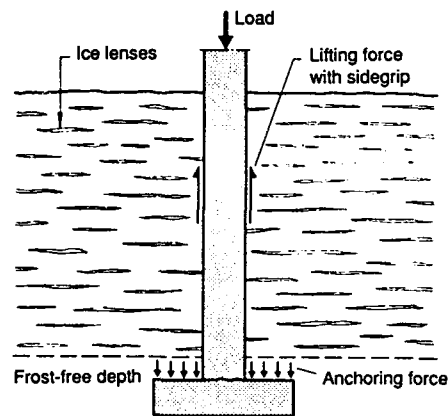
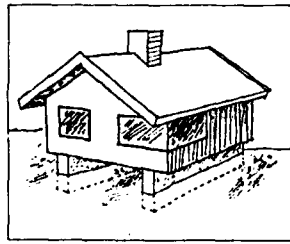
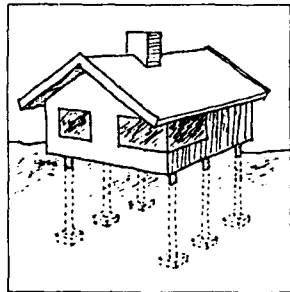


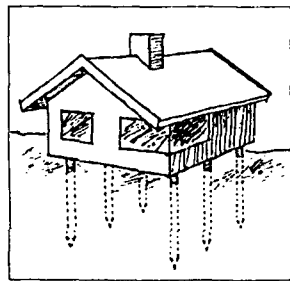
Figure 146. Pier taken down to the frost-free depth and anchored against the lifting force from ice sidegrip. (From NBI 1980.)



Foundation with groundwall strips



Foundation with piers



Foundation with piles

Figure 147. Types of open foundations. (From Torgersen 1976b.)

effect because of the large rate of heave; epoxy should be used in such a case.

Groundwall strips

Groundwall strips are well suited where the ground is not frost susceptible. A building is founded on groundwall strips under the load-bearing walls along its longer side (Fig. 147). On firm ground that is not frost susceptible, the groundwall strips are extended 0.3–0.5 m under the ground.

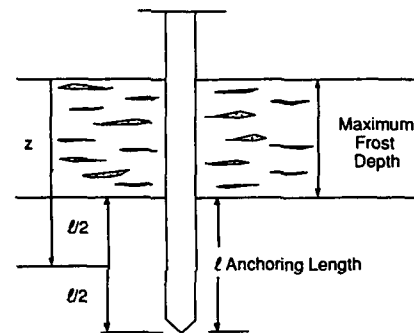
In frost-susceptible soil the strips must be placed on insulation (designed according to Tables 26 and 29) at a depth of 0.3–0.4 m or extended down to the frost-free depth (or to rock). In the latter case the foundation must be anchored against sidegrip when the lifting force is greater than the load from the building. It could then be more advantageous to use piers or piles.

Piles

Bored piles can be used instead of piers. Boring can be done quickly and cheaply with a special boring rig in cohesive soil without large stones. It is

Table 31. Friction between a pile and the under-the-frost zone. (z , shown in the sketch, is given in meters) (From Torgersen 1976b.)

Soil	Friction (kN/m ²)
Very wet clay	50–125
Wet clay	125–250
Medium stiff clay to dry crust clay	250
Silt (frost-susceptible friction material)	40 (z)



possible to bore in frozen ground in winter, and the piles can be cast in place.

Driven piles for a small house are generally costly and seldom used. However, where the depth to bearing ground is larger than 3–4 m, driven piles have been used instead of piers.

Piles must be anchored against lifting forces arising from frost sidegrip. It is usual to extend piles to such a distance below the frost-free depth that friction between the pile and the surrounding soil gives sufficient anchoring. The reduced lifting force is determined by subtracting the load carried by the pile from the lifting force. Table 31 gives values of friction in different soils for calculating the anchoring effect. The reduced lifting force divided by the friction and the pile's circumference gives the necessary anchoring length under the frost-free depth.

Piers

Each pier should carry approximately the same load from the building. A pier can be cast in place, or a prefabricated pier can be placed in an excavated hole that is later backfilled. To get a good

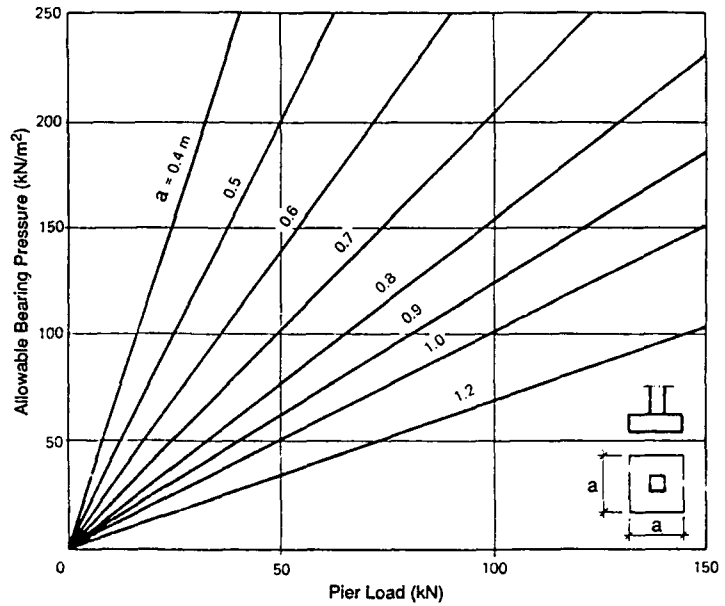


Figure 148. Necessary footing size for carrying the load of a pier. (From Torgersen 1976b.)

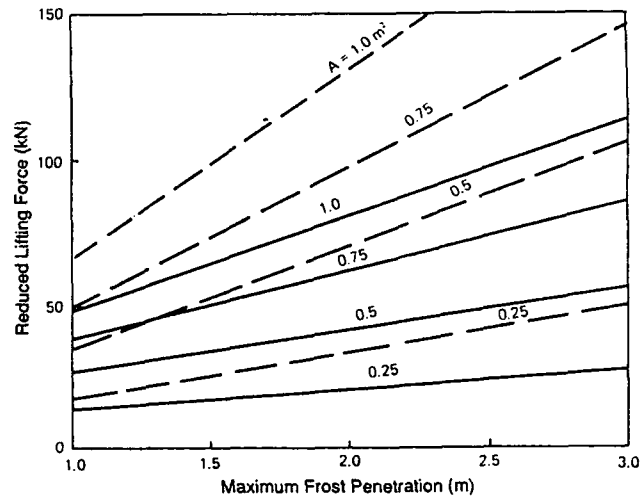
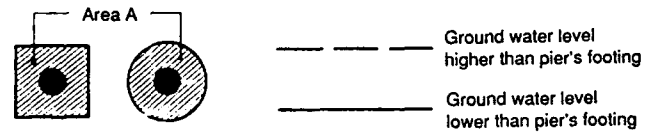


Figure 149. Necessary footing area for anchoring against sidegrip. (From Torgersen 1976b.)

anchoring effect, material that can be well compacted should be used as backfill, e.g. dry crust, sand, gravel or moraine material.

A pier's footing must be so large that its share of the load from the building can be conveyed to the underlying ground without exceeding the allowable bearing pressure. The weight of the pier should be included in the pier load. Using this and the allowable bearing pressure of the ground, the pier dimension a can be found from Figure 148.

If the ground is frost susceptible, one must then check that the pier is not lifted by sidegrip. The

appropriate value for the lifting force is obtained from Table 16, and this is reduced by the total pier load. Figure 149 can then be used to determine the necessary footing area, depending on the locality's maximum frost penetration and the reduced lifting force.

Apart from increasing the footing area, other measures that can be taken in designing against sidegrip are

- Smearing the pier with bitumen or epoxy to decrease the lifting force or
- Reducing the number of piers so that a pier's

share of the total load increases (this also requires a larger footing area).

As the pier is anchored against sidegrip, it has to withstand a tensile force equivalent to the reduced lifting force. The pier reinforcement is anchored in the footing. The latter is designed for a uniformly distributed stress equivalent to the reduced lifting force divided by the footing area (minus the pier's cross section) giving the necessary reinforcement in the footing's upper edge. Reinforcement is also necessary at the bottom edge of the footing to take the uniformly distributed bearing pressure.

Building Details guidelines for concrete piers

The Norwegian *Building Details* (NBI 1980) show mainly cast-in-place piers, but the principles also apply to prefabricated piers.

Practical details

The hole for the pier and the optional footing foundation must be dug down to rock or other ground with good bearing capacity at frost-free depth. The side stability of a pier depends on proper compaction of the backfill material around it. Where frost-susceptible soil produces sidegrip, it is particularly important that the backfill material over the pier footing be well compacted (Fig. 150). This necessitates the use of crushed rock, sand or gravel.

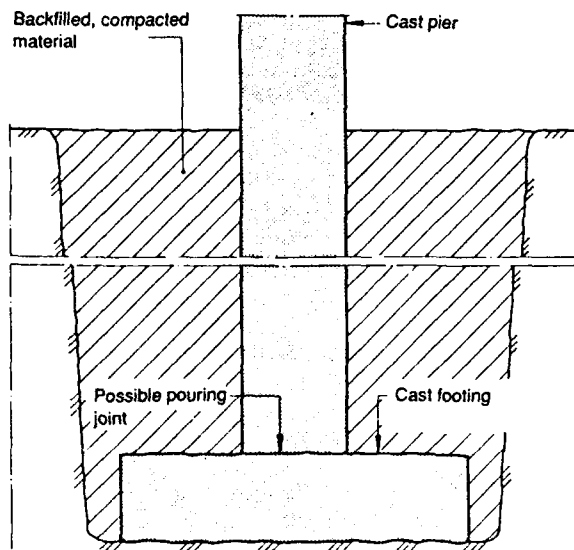


Figure 150. Section of pier with a footing. The footing can possibly be cast directly in a trench without formwork. (From NBI 1980)

In frost-susceptible soil the *Building Details* specify that a lubricating coat at least 3 mm thick should be applied on a pier's surface under the ground down to the frost-free depth. This coat can consist of bitumen with a penetration of 80-100 or of epoxy resin-paint. The latter should be used in silty soil. The long-term effect of such lubrication is not known.

On flat sites the ground under the house should be elevated in relation to the outside level, and a grade should be formed sloping away from the house to lead surface water away (Fig. 151).

Wind load on the house must be transferred to the ground. This requires the floor structure and walls to be anchored to the beams, which are in turn anchored to the piers and footings (Fig. 152).

Design

Load distribution over a pier depends on the distance between the piers, the distance between the pier rows, and whether the structure on top is

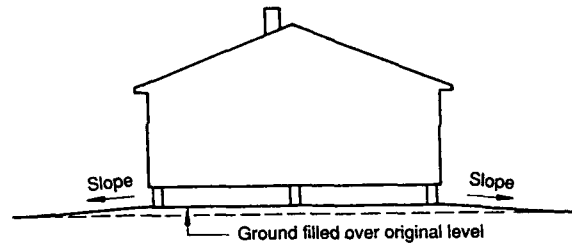


Figure 151. Elevated house to keep it dry in wet conditions. The ground should be graded outside with a slope to lead surface water away. (From NBI 1980.)

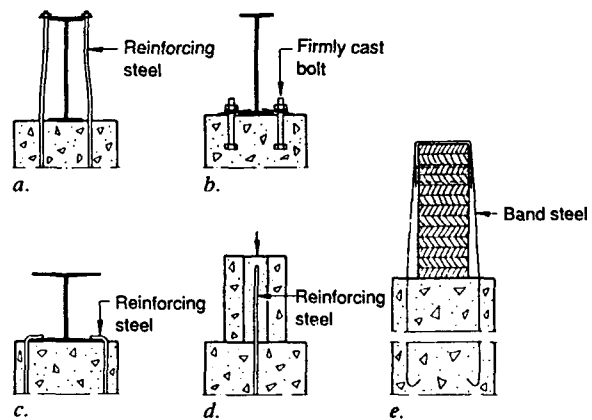


Figure 152. Anchoring of beam to columns. (From NBI 1980.)

Table 32. Necessary size of square pier footing for anchoring against frost sidegrip for various specific loads. (From NBI 1980.)

Design freezing index (h°C)	Frost-free depth (m)	Lifting force on unloaded column (kN)	Size of pier footing (m)												
			Load = 0	10	20	30	40	50	60	70	80	90kN			
10,000	1.0	30	0.85	0.70	0.55										
20,000	1.5	60	1.00	0.95	0.85	0.75	0.65	0.50							
30,000	2.0	80	1.05	1.00	0.95	0.85	0.80	0.70	0.60	0.50					
40,000	2.5	90	1.00	0.95	0.95	0.85	0.80	0.75	0.60	0.55	0.50				
50,000	3.0	100	1.00	0.95	0.90	0.85	0.80	0.75	0.70	0.60	0.55	0.45			

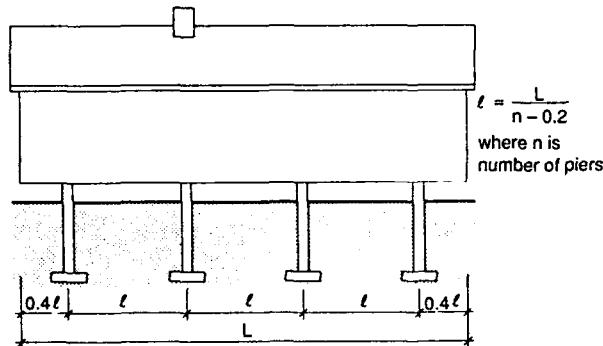


Figure 153. Pier positions to give approximately the same load on each pier under a bearing wall. (From NBI 1980.)

free-bearing or not. The distance between piers should be such that the ground pressure is less than allowable and the beam dimensions are reasonable. Placing piers under bearing walls as shown in Figure 153 gives approximately the same load on each pier. For design against sidegrip, Table 32 is proposed by the *Building Details* to obtain the necessary size of a pier footing. The design load is the specific load, i.e. the load carried by a pier including its own weight. Table 32 applies to piers with diameters of 350 mm or less. It gives the width for a square footing in meters. In addition a footing must be designed to take the net upward force that is equivalent to the difference between the upward force on the unloaded pier and the apparent specific load of the pier. The pier must also be designed for such a tensile force. If the pier is smeared with bitumen or epoxy, the values in Table 32 for the lifting force from sidegrip on the unloaded pier are divided by two.

For example, if F is 30,000 h°C and the specific load is 30 kN, Table 32 shows that the pier footing should be 0.85×0.85 m and that the lifting force on the unloaded pier would be 80 kN. The net lifting force is $80 - 30 = 50$ kN. If a lubricant is used, the lifting force from sidegrip is halved, giving 40 kN.

The net upward force then becomes $40 - 30 = 10$ kN. This equals a specific load of 70 kN without lubricant because the net upward force is $80 - 70 = 10$ kN (Table 32 applies to piers without lubricant). For a specific load of 70 kN, the footing should be 0.50×0.50 m (Table 32).

FROST PROTECTION DURING WINTER CONSTRUCTION

Introduction

For economic and other reasons, building operations cannot be limited to the summer half of the year. Construction needs to take place over the winter in spite of the considerable extra cost owing to snow clearance, the need to thaw frozen soil, frost protection of building ground and construction, heating of concrete, etc. A log book should be kept noting each working day's highest and lowest temperature, precipitation and any frost protection that has been carried out or changed (Eriksson and Magnusson 1985).

Winter construction entails the most severe problems because there is no heat contribution from the inside of a building and the construction is exposed to the climate. Most frost damage has occurred in the building period, and frost protection of foundations during this period is essential to hinder frost heave in the building ground and under the floor and foundations of a building. Structures with vertical walls (e.g. basement walls or buttressed walls) can be damaged from horizontal frost forces, and the soil directly outside these must be kept free from horizontally advancing frost (Fig. 154). It is also necessary to limit frost penetration in excavated and fill material. Fill should not be mixed with snow and ice lumps since these can melt later and lead to large settlement.

If the building ground is frost susceptible and the construction can be damaged by frost, then the ground under the construction must be kept frost

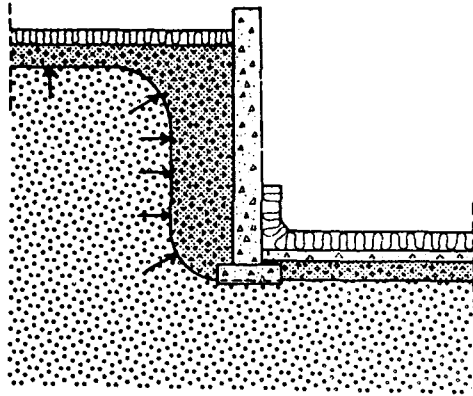


Figure 154. Horizontal heave forces on a vertical structure. (From Thue 1972.)

free to prevent damage from frost heave or from settlement after frozen soil melts. To protect against frost damage, one possible measure is to replace frost-susceptible soil with material that is not frost susceptible; this could be costly and is feasible only if there is also another motivation, such as having to backfill behind walls. The common protection measure is to reduce the frost load on the ground and the construction by covering them with insulation. This can be combined with an artificial heat supply if economically justified.

An insulated floor will often be able to prevent frost in the underlying frost-susceptible soil, especially in a relatively mild area, but in colder regions, insulation of the floor and foundation wall have to be increased. Also, depending on the climate, hori-

zontal ground insulation may have to be laid under a foundation wall and up to a certain distance outside it.

A slab-on-grade foundation that is adequately insulated with ground insulation under and outside a foundation wall and that is built before frost comes can spend the winter without other special frost protection measures; construction can continue at any time in the winter half of the year. It often requires only a relatively small increase in insulation to give frost protection during the construction period. Frost protection of a floor and foundation wall based on insulation and cover on the top side of the floor increases the cost and is not very suitable when the building is being built, i.e., if the construction is in progress (NBI 1986).

Design freezing index

One is usually concerned with frost protection for one winter season or perhaps part of a season. Construction that must be protected for more than a couple of winters requires insulation as for permanently unheated buildings.

The design freezing index F_d is less than for a permanent structure and can vary considerably depending on the protection objective and the consequences of underdesign. Generally frost protection of foundations and stiff floors requires a larger safety factor than frost protection of excavated and fill materials. For foundations and slab-on-grade, F_d is chosen as F_5 but can be increased to F_{10} if the consequences of possible frost heave are larger. Possible snow during construction can give considerable extra safety. Under exceptional condi-

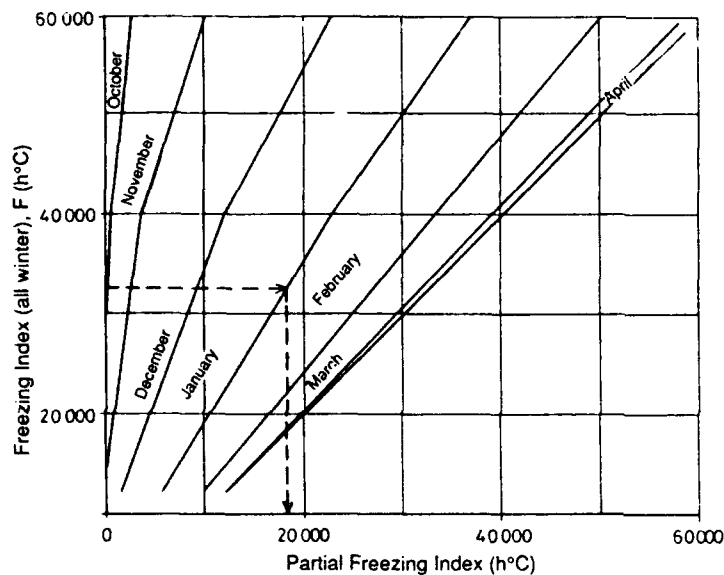


Figure 155. Estimation of a partial design freezing index. (From VTT 1987.)

tions F_2 can be used, e.g. when the consequences of frost heave are small or the soil is only a little frost susceptible. If frost protection is to take place only for part of a winter, F_d can be chosen to equal the freezing index for that actual period. This has to be estimated for a particular locality, and one should allow for a three-week uncertainty as to the beginning or end of the frost season. The partial design freezing index can be estimated from Figure 155.

Necessary thermal insulation

Foundations and groundwalls must be adequately insulated if backfilling is not carried out right away. Basement walls and other vertical boundaries against soil can also be strongly exposed to frost damage in the building period and should be frost protected.

Frost I Jord project

According to the Frost I Jord project (Algaard 1976b) the problem can be tackled in two ways:

- The construction can be covered with the necessary additional insulation no later than the beginning of the frost season; or
- The construction can be carried out with a sufficiently thick general insulation layer.

In each procedure all sections of the construction must be checked so that the thermal resistance R of the insulation is everywhere larger than the necessary thermal resistance R_0 . If the construction is provided with a built-in insulation layer (i.e. as a fixed component) placed a sufficient time before the frost season starts, R_0 can be found by the same method as for unheated buildings from Table 24, depending on F_d , MAT and the thickness of the underlying drainage layer. If this thickness varies at different sections, one must take that into account to achieve the minimum thermal resistance required.

If a construction is not adequately insulated and is to be covered with insulation when winter begins, some of the heat content in the soil would already have been lost, so the insulation requirement to hinder frost penetration becomes somewhat larger than otherwise. R_0 values are then determined from Table 33, depending on F_d , MAT and the allowable frost depth in the underlying layer.

For an insulated foundation and floor construction, the additional insulation ΔR necessary for winter cover is found by subtracting the existing thermal resistance R_e from the necessary value R_0 :

$$\Delta R = R_0 - R_e \text{ (m}^2\text{K/W)}. \quad (9)$$

One should be aware that a foundation wall and floor are often planned with different values for R_e and that R_e also can vary for different parts of the floor. The winter covering must then be adjusted such that the sum of the effective thermal resistances is always larger or equal to the necessary R_0 from Table 24 or Table 33.

In the case of a construction consisting of both insulated and uninsulated areas against frost-susceptible soil, the winter cover for its uninsulated part should as a rule be determined on the basis of the R_0 value from Table 33.

Floors and foundations for heated buildings are designed to have a certain border insulation along the foundation wall and a certain floor insulation for the outer and inner fields of the floor. The inside part of the floor can be uninsulated, but it is usually given the same insulation as the outer or inner field. In colder regions a foundation wall must also be frost protected with horizontal outside ground insulation if a reduced foundation depth is to be used. Such a slab-on-grade construction that is exposed to frost in the building period should be designed

Table 33. Necessary thermal resistance R_0 with frost insulation for winter covering of uninsulated construction and building ground. The table assumes that the insulation is placed no later than the beginning of the frost season. (From Algaard 1976a.)

Soil	F_d (h °C): Mean annual temperature (°C): Allowable frost depth (m)	Insulation's thermal resistance (m ² K/W)											
		10,000	20,000				30,000			40,000			
		(all)	1.0	2.0	3.0	4-7	1.0	2.0	3.0	4-6	1.0	2.0	3-4
Clay, silt	0.1	1.0	2.5	2.2	2.0	1.8	3.8	3.5	3.3	3.0	-	-	5.0
($\rho_d = 1500 \text{ kg/m}^3$; $w = 20\%$)	0.3	0.6	1.4	1.2	1.1	1.0	2.4	2.0	1.7	1.5	3.5	3.2	3.0
	0.5	0.3	0.9	0.7	0.6	0.5	1.4	1.2	1.1	1.0	2.0	1.8	1.6
Sand, gravel	0.1	1.5	3.9	3.2	2.8	2.5	6.0	4.8	4.3	4.0	-	-	-
($\rho_d = 1700 \text{ kg/m}^3$; $w = 8\%$)	0.3	1.0	2.8	2.3	2.0	1.8	4.5	3.6	3.0	2.8	-	4.8	4.0
	0.5	0.6	2.2	1.6	1.3	1.2	3.3	2.7	2.2	2.0	4.5	3.8	3.0

against frost penetration and frost heave during this period:

- The necessary thermal resistance R_0 is found from Table 24 for the insulated part of the floor and for the foundation wall. If large parts of the floor are uninsulated, Table 33 is used for these.
- The necessary widths of insulation outside the floor and outside the foundation wall are determined from Table 28 and Table 29, respectively.
- The difference ΔR between the necessary thermal resistance R_0 and the existing thermal resistance R_e is calculated for all sections.
- The necessary type and thickness of the additional insulation is determined according to the ΔR required.

If it is likely that the foundation and floor construction will remain unheated over the winter, it is often cheaper to design them so that winter cover becomes unnecessary. This requires that

- The insulation in the floor and with the foundation provides everywhere a thermal resistance at least equal to R_0 from Table 24.
- The insulation is continuous in the floor and over and under the foundation extending a distance b outside the outer edge of the construction (according to Table 28, 29 or 30 depending on the type of foundation).

If the second requirement is fulfilled, the thermal resistance required for the foundation wall and floor in the finished building will be sufficient to fulfill the first requirement for the greatest part of Norway. This is because, among other things, the design freezing index for frost protection in the building period (F_5 or F_{10}) is lower than for the finished building (F_{100}).

Compared with insulation under a concrete slab of a building, for example, special care is required

to protect separate insulation used as winter cover, which could otherwise be ruined. In planning construction it is important, therefore, that thought be given to conditions during winter building. It can be more economical to lay in extra insulation permanently in the structure rather than to use separate winter cover with its attendant trouble and risk.

There is often a high cost of making up "winter material" for covering floors and foundations. In Norway there is a good supply of natural insulation materials that can give reasonable frost protection, such as straw and chips, but these materials are bulky and need to be removed later. Snow cover gives an uncertain frost protection and should only be used outside the foundation and floor.

Finnish guidelines

In Finland the guidelines propose Table 34 for determining the necessary thermal resistance R_0 of ground insulation to be applied for protection during construction (VTT 1987). This insulation must be applied no later than the beginning of the frost period, and it depends on the design freezing index, the mean annual temperature and the allowable frost penetration in the particular soil type below the insulation. Table 34 is based on the Frost I Jord project (Table 33) with extra values added for Finnish conditions corresponding to a freezing index of 50,000 h°C. Another difference is that the Finnish table recommends an increase in the foundation depth where there is a cross or bracket.

Norwegian Building Details

The *Building Details* (NBI 1986) specify frost protection by thermal insulation and optionally an underlying layer of free-draining material. Under the floor there should always be a layer of draining

Table 34. Thermal resistance of insulation for protection of building ground. It is assumed that the insulation is placed no later than the start of the frost season. (From VTT 1987.)

Soil	Mean annual temperature (°C): Allowable frost depth (m)	F_d (h°C): 10,000 (all)	Insulation's thermal resistance (m^2K/W)												
			20,000				30,000				40,000		50,000		
			1	2	3	≥4	1	2	3	≥4	1	2	≥3	1	2
Clay, silt (w = 20 %)	0.1	1.0	2.5	2.2	2.0	1.8	3.8	3.5	3.3	3.0	x	x	(5.0)	x	x
	0.3	0.6	1.4	1.2	1.1	1.0	2.4	2.0	1.7	1.5	3.5	3.2	3.0	(5.0)	(4.6)
	0.5	0.3	0.9	0.7	0.6	0.5	1.4	1.2	1.1	1.0	2.0	1.8	1.6	2.9	2.7
Sand, gravel (w = 8%)	0.1	1.5	3.9	3.2	2.8	2.5	x	(4.8)	(4.3)	4.0	x	x	x	x	x
	0.3	1.0	2.8	2.3	2.0	1.8	(4.5)	3.6	3.0	2.8	x	(4.8)	4.0	x	x
	0.5	0.6	2.2	1.6	1.3	1.2	3.3	2.7	2.2	2.0	(4.5)	3.8	3.0	x	(5.0)

x Foundation depth should be increased.

() In general, increase of foundation depth is more profitable.

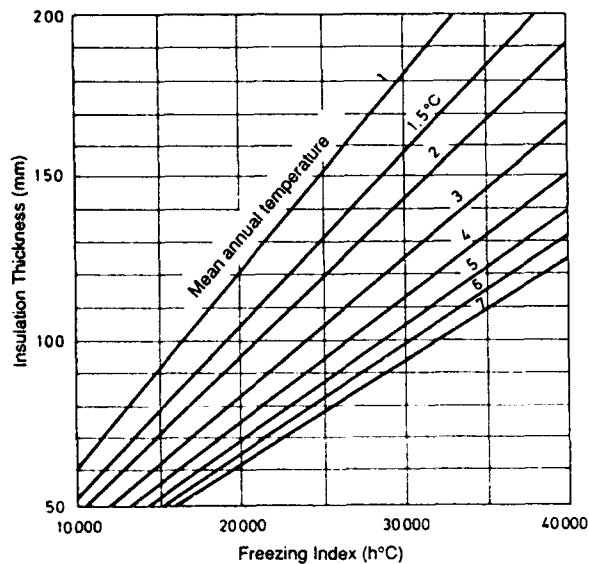


Figure 156. Necessary insulation thickness for frost protection with expanded polystyrene insulation (30 kg/m³). (From NBI 1986.)

material of at least 100 mm. In practice a considerably thicker layer is often used.

Figure 156 shows the necessary thickness if the insulation used is expanded polystyrene with a density of 30 kg/m³ and a thermal conductivity of 0.045 W/mK. This applies to a foundation such as shown in Figure 157. For extruded polystyrene the given thickness should be multiplied by 0.73 and for mineral wool by 1.45. A board of mineral wool must be laid on a permeable underlayer and must not be laid under the foundation wall or other parts of the foundation.

The insulation thickness in Figure 156 can be reduced if there is a drainage layer of sand, gravel or crushed stone under the construction. This can be considered to justify an approximate reduction of 10 mm of expanded polystyrene per 100 mm of

Table 35. Necessary insulation width *b* outside the foundation wall. (From NBI 1986.)

Design freezing index (h°C)	Necessary insulation width (m)
10,000	0.50
20,000	0.75
30,000	1.00
40,000	1.25
50,000	1.50
60,000	1.50

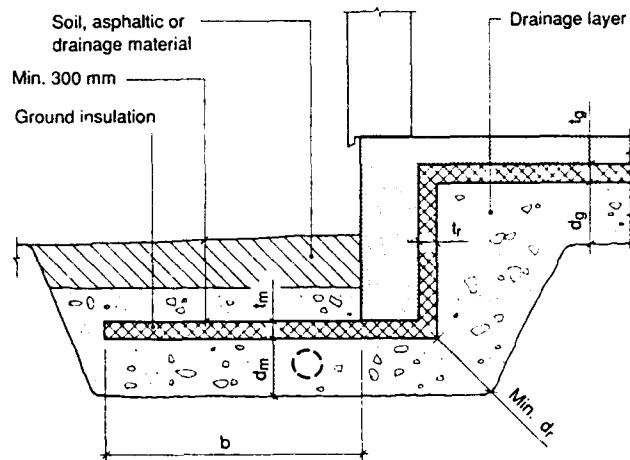


Figure 157. Thicknesses of thermal insulation and drainage material that give frost protection, together with the necessary width *b* of the ground insulation outside the foundation wall. (From NBI 1986.)

drainage layer. Figure 157 shows the interrelated thicknesses of insulation *t* and drainage layer *d* at different places in the construction. The necessary width *b* of the ground insulation outside the foundation wall, shown in Figure 157, is given in Table 35.

Some practical measures (Thue 1972)

It is generally more favorable to proceed with both digging and foundation work before the frost period and then arrange for effective covering until the construction work is taken up again. Once a basement wall has been finished, it should be protected against sidegrip, horizontal frost forces and freezing under the foundation. In general it will be necessary to insulate the basement floor either with loose, laid-on insulation or with insulation built in the floor. If one is not going to backfill outside the wall, insulation must be placed at the back of the wall.

A point that is often overlooked is that a concrete structure in soil with a high section exposed to the outside air will act as a strong cold bridge. This could lead to the formation of ice lenses (with consequent heave) locally under a basement wall, for example, in spite of the construction being otherwise well insulated. The effect of cold bridges can be eliminated by covering the wall or by bringing heat in to the critical zone. It would also be

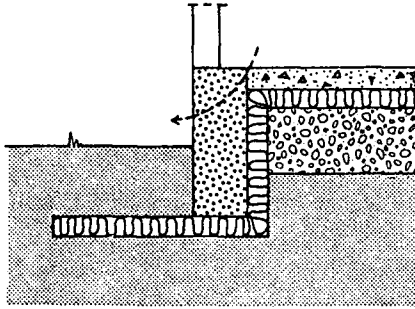


Figure 158. Foundation placed on ground insulation. (From Thue 1972.)

advantageous to draw the floor insulation some distance over the wall.

In the case of foundations at a reduced depth, the danger from sidegrip is small, but the risk from under-freezing is correspondingly large. Such constructions, especially a slab-on-grade, can be protected relatively easily by means of thermal insulation and possibly an artificial heat supply. If heating cables are used to supply extra heat, they can either be laid loosely under the insulation (and used again on another occasion) or cast near the bottom of the foundation where the heat supply is most necessary.

The slab-on-grade design shown in Figure 158 has the advantage that the insulation gives protection during the whole of the construction period and continues to be used after the house is occu-

pled. One must, of course, use insulation material that can withstand the loading from the foundation wall. The insulation must be extended outside the foundation wall and a cold bridge near the connection between the foundation wall, the floor and the outer wall must not be allowed to form.

Piers are usually taken down below the frost-free depth and built quickly, so there will seldom be problems with them in theory during the construction period if one backfills around them as quickly as possible (Fig. 159).

The materials used for covering the construction are generally mechanically weak and can be damaged by people and machines. The building site and protection measures must be managed properly, and additional protection must be supplied according to requirements to guarantee a sufficient safety factor. In particular the measures should be adjusted to the local climate and based on practical experience.

Frost protection of building ground

Frost protection of building ground is carried out by use of insulation on the ground to keep it wholly or partly frost-free until excavation or building work can be carried out. Insulation hinders the loss of soil heat and thus limits frost penetration. The allowable thickness of the frozen soil layer depends on the digging equipment. For equipment worked by hand the frozen material should not be thicker than 0.1 m, while with a digging machine the frozen layer can be 0.2–0.3 m thick.

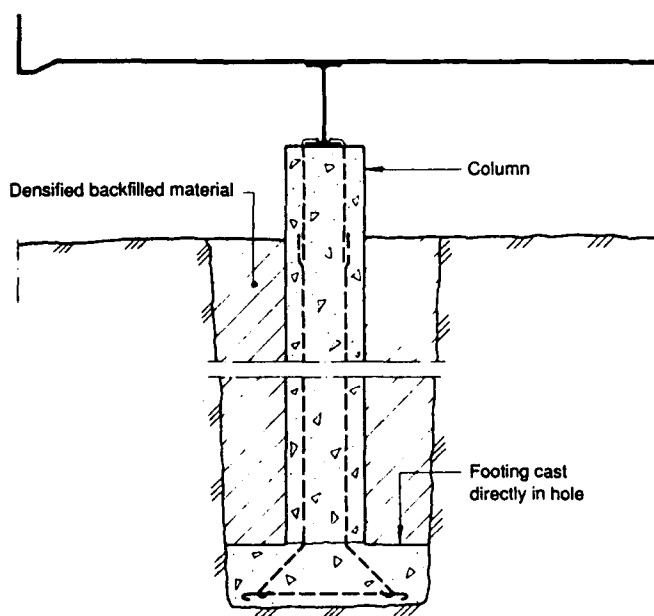


Figure 159. Example of cast-in-place pier. (From NBI 1979b.)

Figure 160. Calculations of frost penetration in undisturbed ground with no insulation. (From Thue 1972.)

Curve 20: 0°C isotherm on 20 January 1966.
 Curve 40: 0°C isotherm on 9 February 1966.
 Curve 60: 0°C isotherm on 1 March 1966.

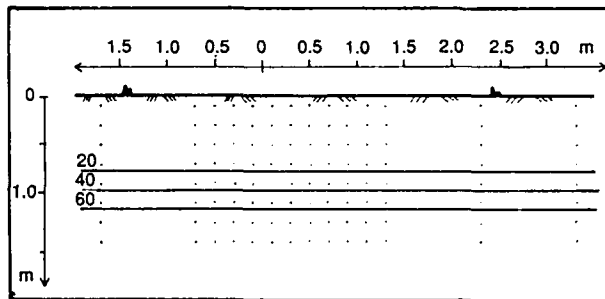


Figure 161. Calculations of frost penetration with 50-mm-thick insulation 9.20 m wide (from 0 to the right); thermal conductivity of insulation = 0.046 W/mK. The isotherms do not penetrate as deep as in Figure 160. (From Thue 1972.)

Curve 20: 0°C isotherm on 20 January 1966.
 Curve 40: 0°C isotherm on 9 February 1966.
 Curve 60: 0°C isotherm on 1 March 1966.

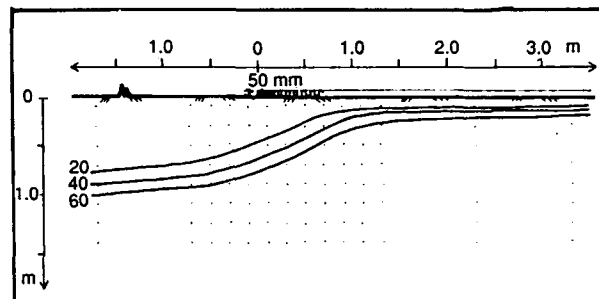
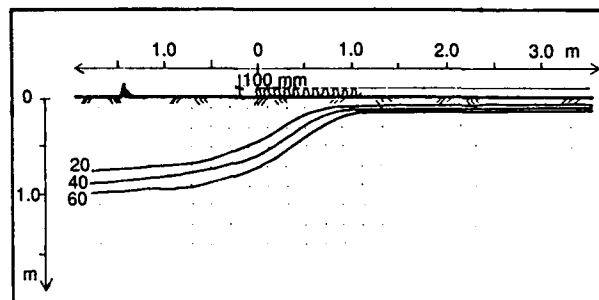


Figure 162. Calculations of frost penetration with 100-mm-thick insulation 9.20 m wide; thermal conductivity of insulation = 0.046 W/mK. (From Thue 1972.)

Curve 20: 0°C isotherm on 20 January 1966.
 Curve 40: 0°C isotherm on 9 February 1966.
 Curve 60: 0°C isotherm on 1 March 1966.



Frost I Jord project

The effect of insulation on frost penetration in the ground can be judged from the results of a computer analysis of the heat flow conditions (Thue 1972). The calculations were done for the cold Oslo winter of 1965–66, assuming a silt with a moisture content of 30%. The 0°C isotherm was computed for 20 January, 9 February and 1 March 1966. Figure 160 represents the case of undisturbed ground with no insulation on it. Figure 161 shows the considerable improvement in conditions when an insulation strip 9.20 m wide with a thickness of 50 mm and a thermal conductivity of 0.046 W/mK is placed on the surface. The result is a reduction in frost depth from about 1.0 m to about 0.3–0.4 m. The ground should be insulated about 1.0 m outside the area that is to be protected from frost.

If the insulation thickness is increased from 50 to 100 mm as in Figure 162, there is only a small additional reduction in the frost depth. The analysis also showed that it is important to maintain the protection as long as possible while the winter work is going on, because removing the insulation results in rapid frost penetration.

The necessary thermal resistance R_0 of insulation cover can be determined from Table 33 according to the design freezing index and the mean annual temperature. If the objective is to hinder frost heave, one calculates on the basis of a permitted frost penetration of about 0.1 m down into frost-susceptible soil. In this case the first line in Table 33 corresponding to clay and silt is used, the insulation lying directly on the ground. If a layer of frost-protecting material is to be placed between the

Table 36. Necessary insulation thickness with use of winter material. (From NBI 1979a)

Soil	F_d (h °C): Mean annual temp. (°C): Frozen crust thickness (m)	5,000	10,000	Necessary thickness of winter material (mm)*										
				20,000			30,000			40,000				
				4-7	3	2	1	4-6	3	2	1	3-4	2	1
Sand, gravel	0.1	20	50	80	90	100	130	120	140	-	-	-	-	-
	0.3	10	30	60	70	80	100	100	110	130	-	160	-	-
	0.5	10	20	50	50	60	80	80	80	100	130	120	150	-
Silt, silty moraine	0.1	20	50	70	80	90	110	110	130	160	-	-	-	-
	0.3	10	30	50	60	70	80	80	90	110	150	-	-	-
	0.5	10	20	40	40	50	60	60	70	80	100	100	120	170
Clay, clayey moraine	0.1	20	40	60	60	70	80	100	110	120	140	170	200	-
	0.3	10	20	40	40	50	50	60	70	80	90	100	120	130
	0.5	0	10	30	30	40	40	50	50	60	60	70	80	90

*Can consist of impregnated mineral wool encapsulated in plastic foil.

insulation and the ground underneath, R_0 can be found from the section of Table 33 corresponding to sand and gravel using the allowable frost depth as the effective layer thickness plus 0.2-0.3 m (Algaard 1976a).

If the objective is to hinder too thick a frost layer, one uses the R_0 value from Table 33 as read to the right of the frost depth that can be allowed in the actual soil. There may be large variations in the effective frost depth, and if there is a possibility of greater frost penetration than assumed, the insulation amount should be increased.

To get a frost layer that is thin enough to break with usual hand equipment (about 0.1 m), one must choose the highest line for each soil type in Table 33. If heavy digging equipment is available, the frost layer thickness can be 0.3 m and R_0 becomes less.

Norwegian Building Details

In insulating ground before carrying out foundation work, the insulation thickness should be chosen so that the ground stays frost free as much as possible (NBI 1979a). If the ground is not insulated or is very badly insulated, the frozen soil layer can become so thick that special methods must be used if digging is to be done in the winter half of the year. These include boring and blasting, ripping up, using icebreakers and using thawing procedures.

Insulation must be laid out on the ground before the frost season begins, preferably before the daily average temperature stays, on the average, lower than the local mean annual temperature. Otherwise frost would draw out a large amount of the available soil heat.

It is very important that ground operations be well planned so that the required protection is obtained. The insulated area must be closed to traffic so that the insulation is not damaged or moved. The insulation must be protected against being blown off and against cold air blowing in. This can be accomplished by loading the insulation appropriately.

Table 36 gives values for the necessary insulation thickness of "winter material" corresponding to various thicknesses of acceptable frozen crust. The winter material consists of impregnated mineral wool encapsulated in plastic foil. The foil holds the mineral wool in place and protects it against moisture, which can reduce its insulation effect. The material is normally supplied in 30- and 50-mm thicknesses.

In place of winter material, loose dry straw may be used but with a thickness two to five times as large as that required for winter material. If the straw is pressed together, the thickness should be six to ten times as large as that of winter material. If other insulation material is used, its thickness is found by multiplying the thickness for winter material by the ratio between the thermal conductivity of the used material and that of the "winter material" (0.04 W/mK).

In choosing the design freezing index, one must consider the consequences of having a thicker frozen crust under the insulation than planned if the winter is colder than assumed. The insulation and its cover should be extended 1.0-1.5 m beyond the area that is to be frost-protected, as shown in Figure 163.

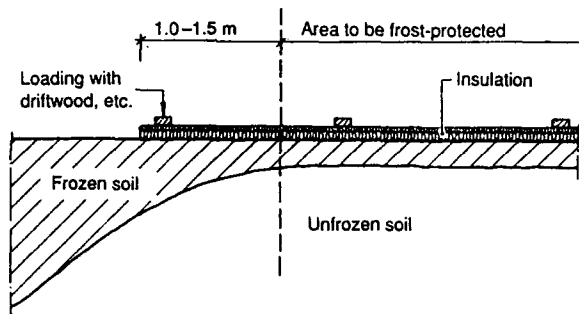


Figure 163. Insulation extended 1.0–1.5 m outside the area that should be frost-protected. (From NBI 1979a.)

When excavating in insulated soil in winter, it is very important that the insulation be removed just locally as digging continues. Otherwise there is a risk that the earth will freeze while digging is in progress. The building excavation must therefore be covered with insulating material after each digging operation. The excavated material that is to be used for backfilling later in the winter should be covered similarly.

RETAINING WALLS AND BRIDGE FOUNDATIONS

Frost forces on walls

Theoretically frost heave can produce enormous lateral forces on retaining walls, and this is confirmed by laboratory tests. However, it is difficult to simulate various factors such as characteristics

of the freezing front, variation of overburden pressure, rate of heat removal, soil consolidation and water flow (Andersland and Anderson 1978). In practice, lateral forces are usually much smaller than theory indicates.

For a given case the magnitude of the horizontal frost force on a wall is difficult to ascertain and thus to allow for in design. Also, it is often difficult to separate forces due to frost action from other forces owing to ordinary earth pressure. Figure 164 shows the results of measurements of frost forces against different types of sheet piles and a proposal for design based on these observations (Eggstad 1982). This design is based on limited data, but it applies to frost forces, whereas some other methods do not separate between frost forces and other forces from earth pressure.

The following factors influence frost forces on sheet piles (Eggstad 1982).

Stiffness of the structure—Under similar conditions of backfill material, freezing index and time lapse, a stiffer wall with internal steel reinforcement results in a significantly larger frost force. This is because the stiffer wall would provide a greater reaction against increasing thickness of ice lens formation.

Firmness of the soil—In principle the formation of an approximately vertical ice layer behind a wall changes the pressure build-up from the active condition through the “at rest” state to the passive state (as a higher limit). Therefore, a firmer soil would result in a larger force on the wall than a softer soil.

Frost susceptibility of the soil—With regard to the soil’s frost susceptibility, two factors act against

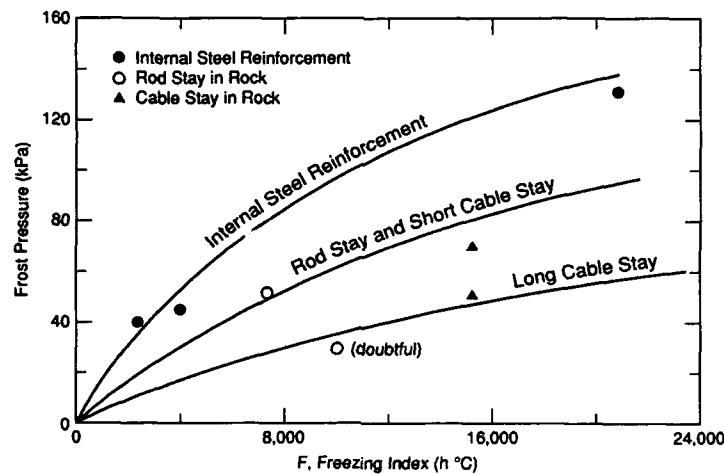
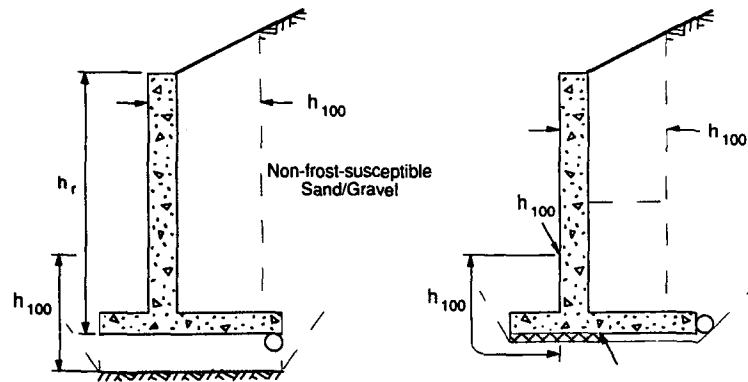
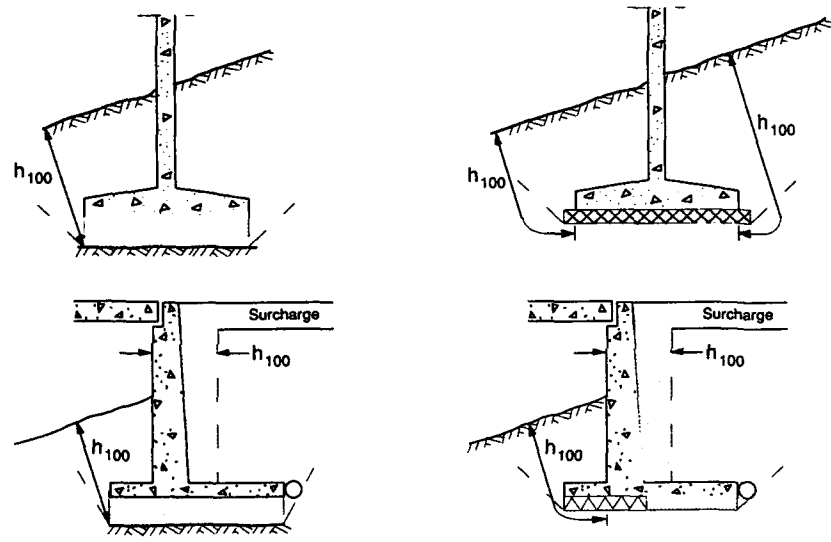


Figure 164. Proposal for design values for frost pressure, based on observations. (From Eggstad 1982.)



a. Retaining walls.



b. Bridge foundations.

Figure 165. Frost protection of retaining walls and bridge foundations. (From Statens Vegvesen 1980.)

each other. A larger grain size (e.g. silt as compared with clay) leads to a greater permeability and hence faster ice-layer formation. This should give a larger frost force in a given period. On the other hand, the maximum possible frost force is considerably less in silt than in clay. It is uncertain which effect would dominate in practice.

Magnitude of the freezing index—If the possibility of deformation can be neglected, full frost pressure would be obtained with a small freezing index. However, there will, in practice, be some deformation in the structure and in the earth mass. The frost force against the structure will therefore strongly depend on the freezing index.

Design for frost protection

As shown in Figure 165, frost protection of retaining walls and bridge foundations against horizontal and vertical forces may be carried out by using non-frost-susceptible backfill material or some insulation material such as extruded polystyrene or both. In this way the frost forces can be avoided in practice. Also, an important effect of granular fill material is to ensure good drainage and a low ground water level. The required thickness h of the frost-protecting granular layer depends on the design freezing index F_d . Thus, for a retaining wall less than 2.5 m high, the thickness h is specified as h_{10} corresponding to F_d equal to F_{10}

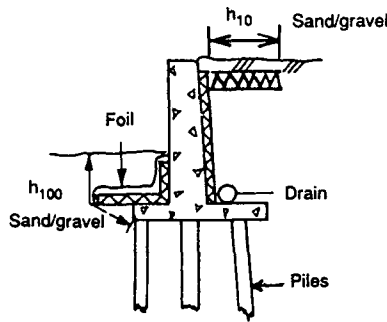


Figure 166. Insulation with a pile foundation for a retaining wall. (From Pedersen 1976.)

(Statens Vegvesen 1980). For higher retaining walls, the thickness of the frost-protecting layer is specified as h_{100} corresponding to F_{100} . Values of h_{10} and h_{100} are tabulated for every district in Norway.

Insulation may have to be used if there is not sufficient space behind a wall for the requisite thickness of non-frost-susceptible material. If a structure is to be insulated, it is often useful to attempt to sketch in the 0°C isotherm location at successive times. This should give an idea of the type and direction of the frost forces. It is, however, difficult to provide a standard recipe on frost protection of retaining wall and bridge foundations, and each case generally requires specific evaluation (Pedersen 1976).

For retaining walls the most suitable insulation is extruded polystyrene, with a minimum thickness of 45 mm where the wall height is less than 2.5 m and a thickness of 75 mm otherwise. Other possible insulation materials are foamglass and light clinker (expanded clay); these may be too uneconomic for smaller walls but they may be suitable for bridge foundations (Statens Vegvesen 1980). In the case of a pile foundation, insulation is placed over the foundation, ensuring that the shortest route of frost to the underside of the foundation is at least h_{100} (Fig. 166).

For temporary sheet pile walls, using insulation may not be the simplest or cheapest method, and local heating behind the sheet pile may be more effective. With anchored sheet piles it may be necessary to relieve the anchor stay as the frost force on the pile increases (Eggestad 1982). For especially sensitive conditions it is also a good idea to keep a check on the temperature and measure the force on a back-anchored sheet pile (Eriksson and Magnusson 1985).

INSULATION PROPERTIES AND USE

Insulation has the effect of restricting heat flow across it, causing an appreciable temperature difference from one side to the other (Fig. 167). Proper use of insulation materials with foundations is important, and this problem is still being tackled. In this connection the early work on the performance of various insulation materials, carried out by engineers concerned with Scandinavian railroads, was of great value in assessing the behavior of insulation under different conditions.

Properties and use conditions

Important properties of insulation used in frost protection are its thermal conductivity, durability under use conditions, resistance to water uptake and load-bearing capacity.

Properties of insulating materials used in Norway are given in Table 37. The required insulation thickness can be determined from Figure 168, depending on the material's thermal conductivity and the required thermal resistance in use. Thermal conductivity increases with water uptake; to prevent absorption of moisture, the material can be protected by a moisture membrane. Also, the thickness of material should not be less than a given value depending on the type of insulation and where it is used. For example, using half the thickness of extruded polystyrene makes its moisture uptake potential four times as great. To avoid uneconomic thicknesses, certain limitations should

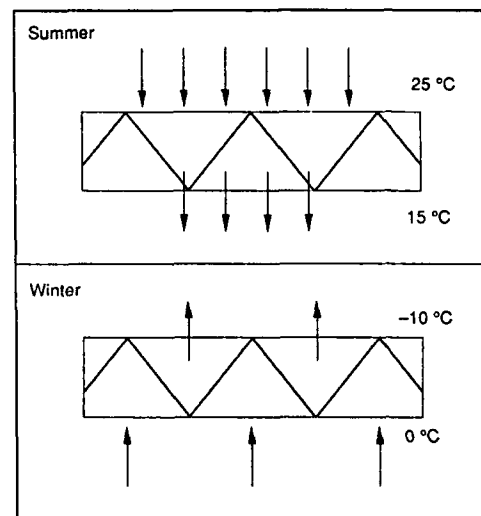


Figure 167. Temperature difference caused by insulation. (From Dow Chemical 1987.)

Table 37. Density, compressive strength and thermal conductivity of insulating materials. (From Saetersdal and Refsdal 1986.)

Material	Dry density (kg/m ²)	Compressive strength (5% deformation) (kN/m ²)	Thermal conductivity in dry material at -5°C (W/mK)
Expanded clay			
Bulk			
Embedded in plastic	400		0.12
Expanded polystyrene	20	100	
styrene	30	150	0.033
(Bead board)	40	250	
Extruded polystyrene			
Styrofoam HI	40	350	
Styrofoam RM	35	250	
Styrofoam HD 300	50-60	700	0.025
Styrodur 3000	30	300	
Styrodur 4000	40	400	
Styrodur 5000	60	800	
Polyurethane	35	250	0.02-0.03
Foamglass	125	450	
	135	600	0.047
Mineral wool	40	18-30 (10%)	0.035
	150-200		0.034-0.036

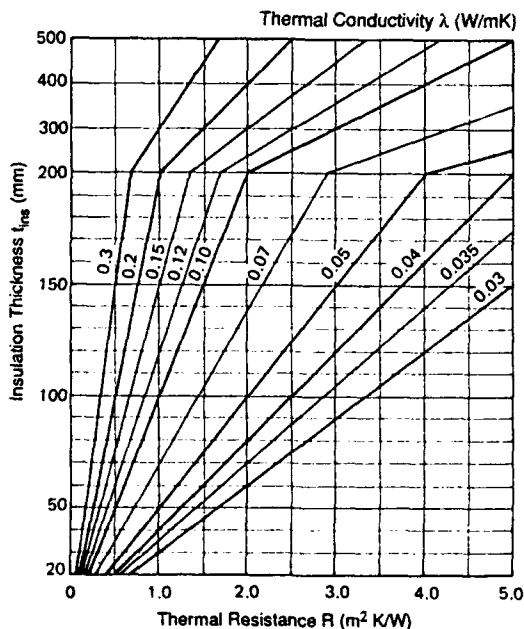


Figure 168. Necessary insulation thickness as a function of required thermal resistance and insulation's thermal conductivity. The lines are based on $t_{ins} = R\lambda$. (From Algaard 1976a.)

be placed on a material's moisture uptake in use. Under unfavorable moisture conditions most insulation materials should be protected against uptake.

Expanded polystyrene, in particular, is liable to take up moisture during use, leading to a reduction in its insulating effect. Extruded polystyrene is more reliable in this respect and is therefore often used, in spite of being three times as costly as expanded polystyrene. With expanded clay there could be a risk of convection, but it can be safely used in heated buildings.*

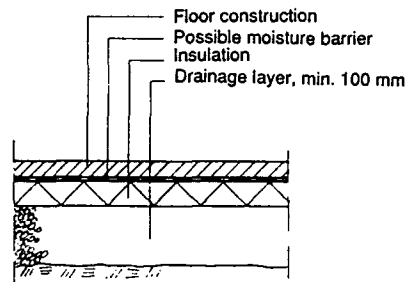
Mineral wool (e.g. Rockwool) can be expensive, and this material tends to absorb moisture, with a consequent reduction in its insulating effect. Under certain conditions, mineral wool can be easily kept dry, for example, when it is used at the wall of a heated structure where the heat flow is from the inside to the outside and remains stationary.**

Under an impervious concrete floor of a cold building, the moisture content of underlying in-

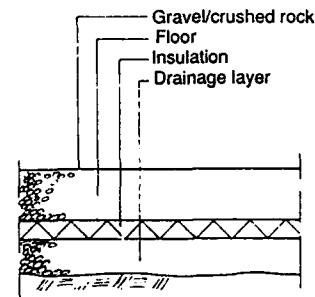
* Personal communication with S. Saarelainen, 1986.

** Personal communication with E. Algaard, Multiconsult A.S., Oslo, Norway, 1986.

a. Insulation laid directly under the slab, with strong insulation or a load-distributing concrete slab. If a moisture barrier is necessary, it should be laid between the insulation and the overlying slab. A drainage layer should always be laid on frost-susceptible ground.



b. Insulation laid lower down to reduce the stress influence from a point load. If the surface of the construction is not damp-proof and protected against precipitation, a separate moisture barrier can be omitted in many cases.



c. Floor using a wood surface with mineral wool, or load-bearing insulation (in dry conditions), in permanently or sporadically cold buildings with a small floor load. A high-grade moisture barrier must be placed under moisture-sensitive material and under the floor insulation, and a damp-proof floor cover must be used.

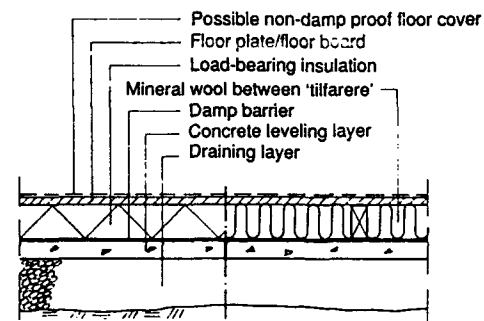


Figure 169. Possible arrangements of floor layers. (From Algaard 1976a.)

Insulation changes with the season. The conditions are similar to those under a road with an asphalt surface. On the other hand, under an open floor of crushed stone or gravel, the moisture content decreases gradually, and therefore the moisture influence on underlying insulation will be somewhat less than with an impervious floor. This implies a less stringent limitation on the insulation's moisture uptake in the case of an open floor or cover. Various possible arrangements of floor layers with insulation are shown in Figure 169.

Moisture conditions with unheated floors and foundations follow seasonal temperature and moisture variations. Conditions are different from the situation under a floor in a heated building, where heat is directed downwards the whole year. Different values for the thermal conductivity of the same insulating material apply in those different conditions.

The required service life is also an important factor. If a life of 100 years is required for extruded polystyrene used with a retaining wall, as in Norway, the minimum insulation thickness would be 75 mm (Statens Vegvesen 1980). For purposes of design, one should consider laboratory measurements of the thermal conductivity of the dry material and then estimate how this can be expected to increase under the specific conditions of field use. It is suggested that an estimate be made of the time for the dry material to pick up 20% moisture, with the resulting reduction in insulation effect.*

In Finland, 50 years is considered to be the insulation design life, and possible insulation materials are polystyrene (extruded or expanded), polyure-

* Personal communication with G. Refsdal, Directorate of Roads, Oslo, Norway, 1986.

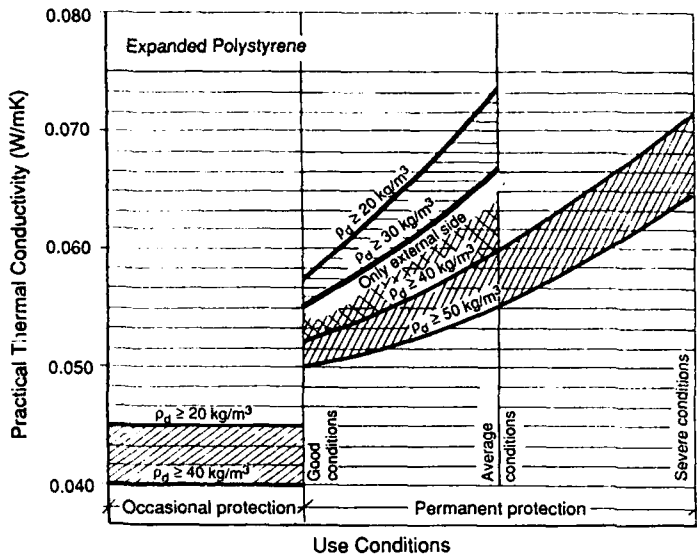


Figure 170. Design thermal conductivity of expanded polystyrene for frost protection under different use conditions. (From VTT 1987.)

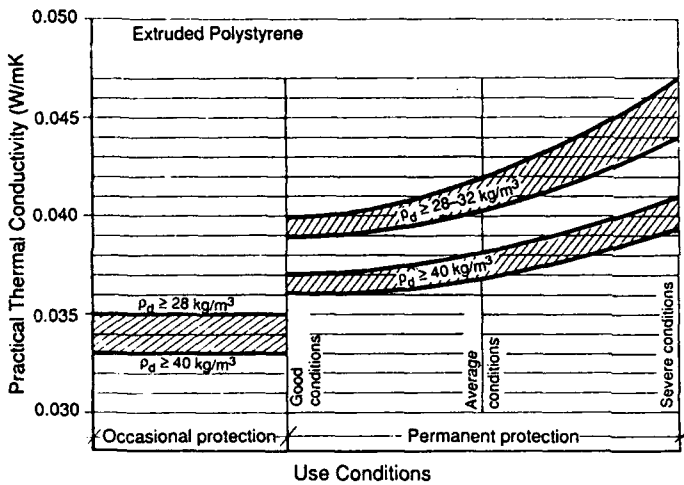


Figure 171. Design thermal conductivity of extruded polystyrene for frost protection under different use conditions. (From VTT 1987.)

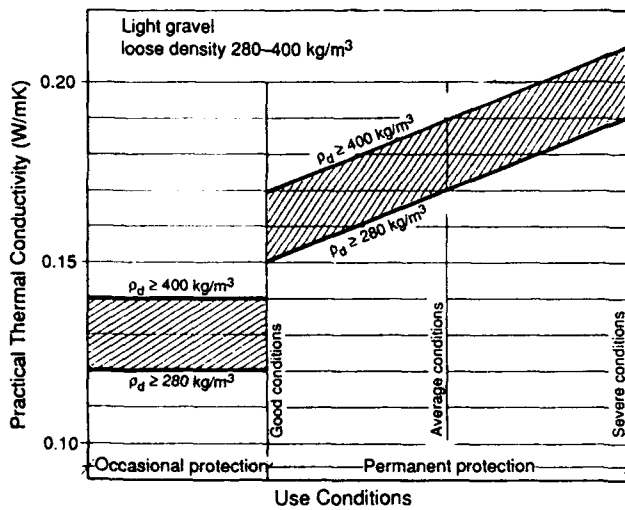
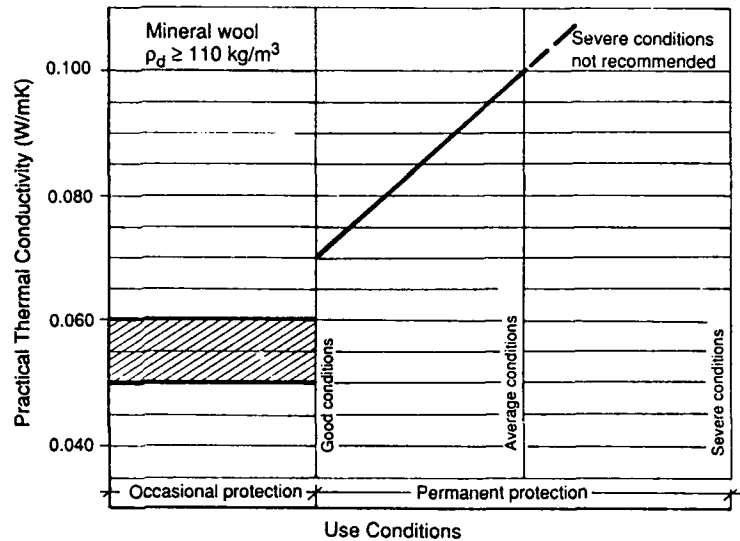


Figure 172. Design thermal conductivity of light aggregate for frost protection under different use conditions. (From VTT 1987.)

Figure 173. Design thermal conductivity of mineral wool for frost protection under different use conditions. (From VTT 1987.)



thane, polyethylene, light gravel and mineral wool. The Finnish guidelines (VTT 1987) recommend thermal conductivity design values for insulation in practical cases, depending on type and density of the insulation and use conditions (Fig. 170–173). For temporary use the thermal conductivity is lower and assumed to be constant over time. With permanent use the thermal conductivity increases and the insulating effect decreases, if the conditions of use are adverse. There are three boundary lines in each of Figures 170–173 representing “good,” “average” and “severe” conditions of use.

The relative insulating ability of other materials often used in building construction is shown in Table 38, which gives the density and thermal conductivity of these materials.

Table 38. Properties of materials used in building construction. (From Saetersdal and Refsdal 1986.)

Material	Density (kg/m ³)	Thermal conductivity at 10 °C (W/mK)
Concrete	1900–2300	1.5–2.5
Expanded concrete	400–650	
Expanded clay blocks		
above ground	650	0.20–0.24
under ground	650	0.25
Tiles	1700	0.7
Asphalt, hot mix	2100	1.0–1.5
Spruce, pine	500	0.15
Wallboard	400–600	0.12–0.14
Glass	2600	0.8
Snow: new	100	0.1
porous, dry	200	0.25
old	200–300	0.25

Ground insulation and its placement

Ground insulation should have a high resistance to vapor diffusion and, in particular, should resist rotting and attack from acids in the soil.

Care needs to be taken in installing and protecting ground insulation, as illustrated by the Finnish guidelines in Figures 174 and 175. Sand is placed in the foundation trench and can be compacted by vibration (Fig. 174, diag. 2). Proper drainage below the foundation is essential; the illustrations show a drainage pipe under the outside edge of the footing. At corners, 40% more insulation is required, as shown in Figure 174, diagram 6. This can consist, for example, of 70-mm-thick insulation placed at a corner, compared to 50 mm along an outer wall. The extra amount is applied over a distance of 1.5 m from the corner. Diagrams 7 and 8 (Fig. 174) show how sand or other non-frost-susceptible material should be placed above and below ground insulation. There should be no digging or tampering with the soil outside the finished building because this could damage ground insulation. Figure 175 shows how ground insulation can be protected in certain cases by means of a concrete slab (50–70 mm thick), a sheet of asbestos cement, water-resistant plywood or asphalt surfacing.

Examples of insulation use

The following examples are taken from Swedish practical applications as recommended by insulation manufacturers. Commonly used insulation materials are polystyrene (extruded and expanded) and mineral wool. Mineral wool can be rock fiber board or glass fiber board, but the latter is not used in contact with soil.

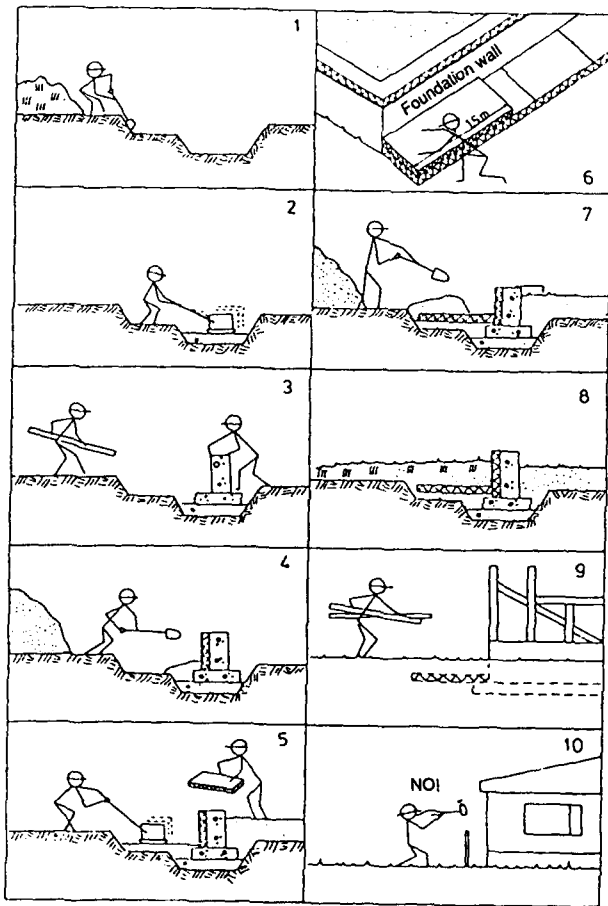


Figure 174. Method of placing insulation for frost protection as a foundation is being constructed. Similar principles apply if the insulation is placed after construction. (From VTT 1987.)

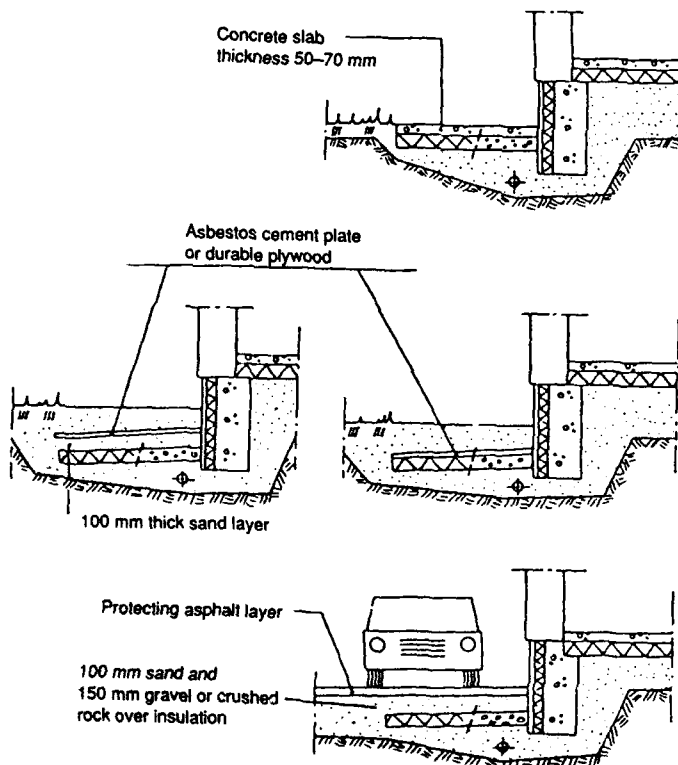


Figure 175. Examples of protection of ground insulation. (From VTT 1987.)

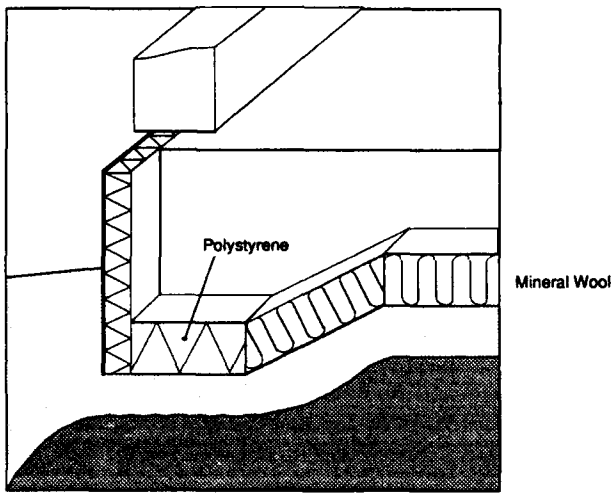
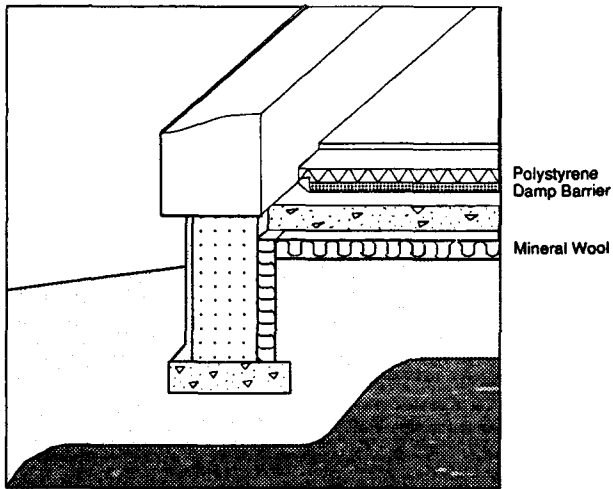
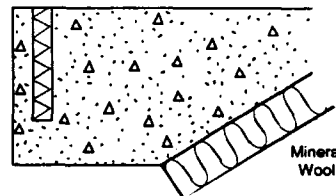


Figure 176. Types of slab-on-grade construction showing insulation. (From Gullfiber 1985.)

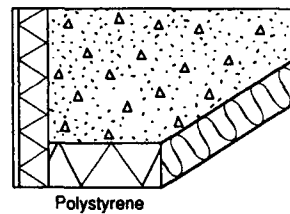
Slab-on-grade construction

Figure 176 shows the use of insulation with two types of slab-on-grade construction. Continuous insulation below and along the inside or outside of the foundation wall is essential to prevent cold bridge formation. Conventional slab insulation, as shown in Figure 177a, invites a cold bridge and is more difficult to construct than continuous insulation, as in Figure 177b. The latter also acts as a more effective moisture barrier. Mineral wool is not used where the bearing pressure is high, i.e. under an edge or foundation wall.

Figure 178 shows a concrete slab with overlying polystyrene insulation and a foundation wall of light expanded clay aggregate with ground insulation of mineral wool. Another recommended de-



a. Conventional insulation.



b. Continuous insulation.

Figure 177. Types of slab insulation. (From Gullfiber 1986.)

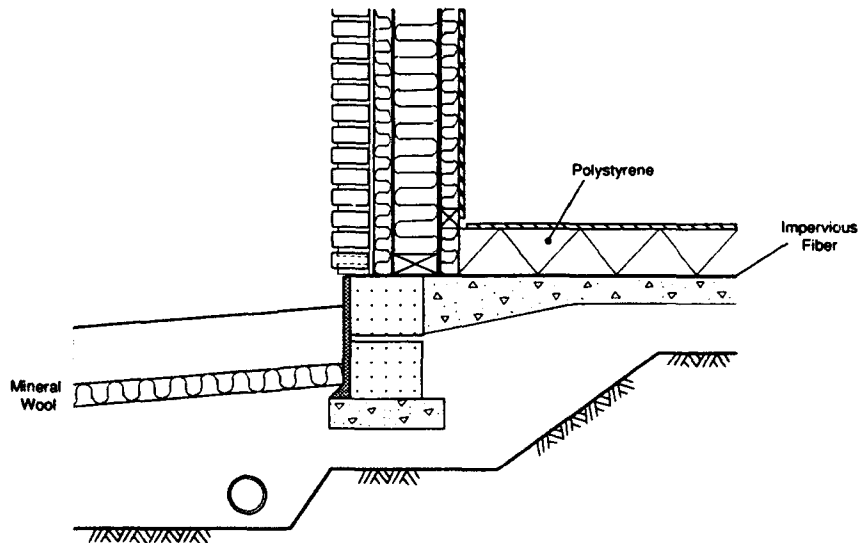


Figure 178. Leca foundation wall and ground insulation. (From Gullfiber 1986.)

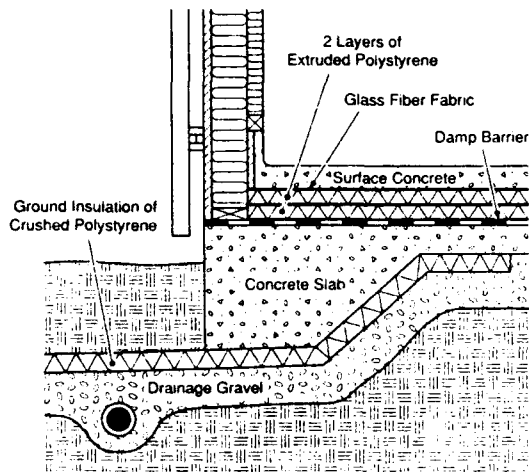


Figure 179. Foundation design using two layers of extruded polystyrene, an edge-expanded concrete slab and ground insulation of extruded polystyrene. (From Rockwool 1984.)

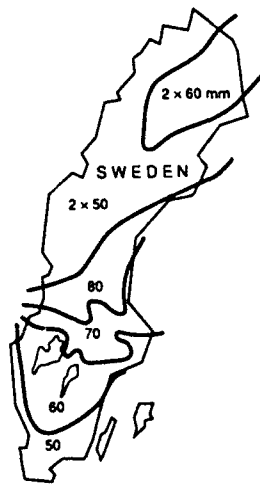


Figure 180. Recommended thickness of polystyrene ground insulation for Sweden. (From Rockwool 1984.)

sign by a different manufacturer is illustrated in Figure 179. This shows two layers of extruded polystyrene placed between a concrete floor and an edge-expanded concrete slab. Underneath the slab there is extruded polystyrene insulation that is extended externally to form ground insulation. The recommended thickness of this insulation can be determined from Figure 180, depending on the region of Sweden.

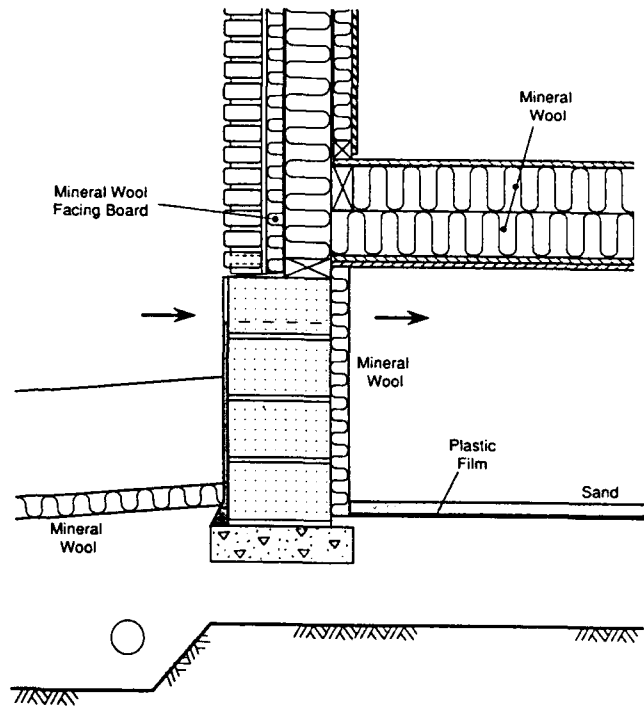


Figure 181. Foundation with crawl space and leca foundation wall. (From Gullfiber 1986.)

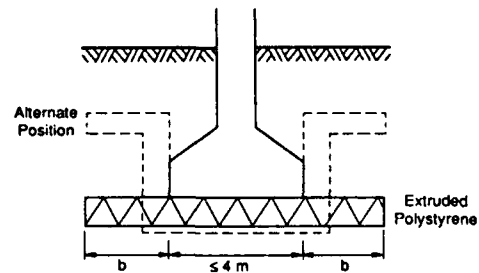


Figure 182. Alternative placement of insulation for a narrow strip foundation. (From Rockwool 1984.)

Foundations with crawl spaces

An example of insulation of a foundation with crawl space is given in Figure 181. Mineral wool is placed on the inside of the leca foundation wall. A plastic film is placed on the ground, as a moisture barrier, with a layer of sand overlying.

Foundations for unheated structures

Figure 182 shows an alternative position of ex-

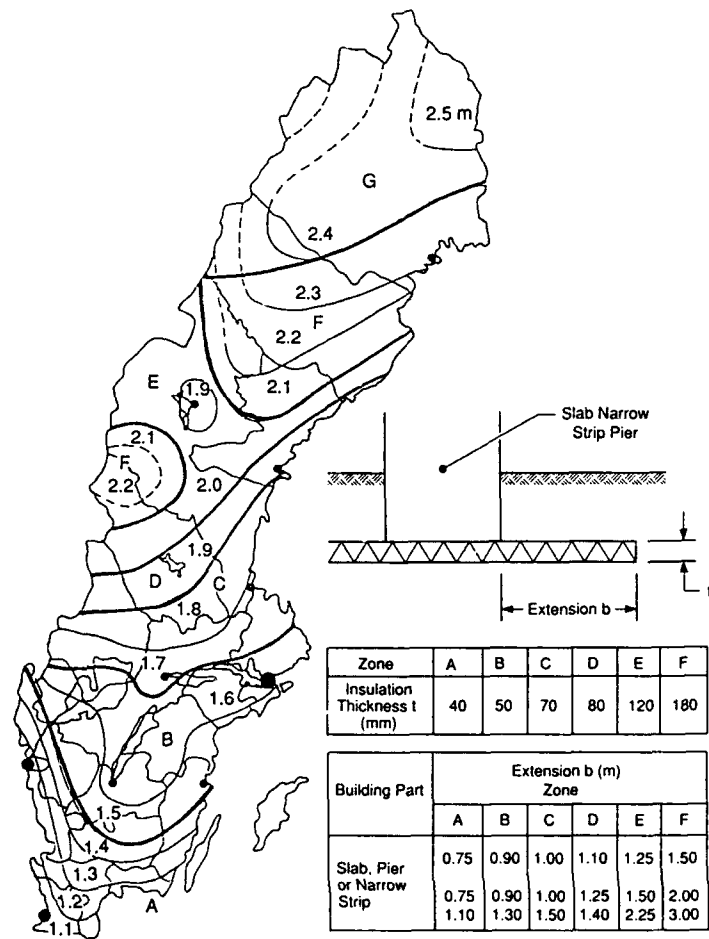


Figure 183. Dimension of insulation for foundations of cold structures in Sweden. (From Rockwool 1984.)

truded polystyrene insulation used with a narrow strip foundation.

The manufacturer's recommended values of extruded polystyrene thickness and the insulation's necessary extension width b outside a raft, a narrow strip or a pier foundation are given in Figure 183, depending on the location in Sweden and its associated frost depth h_o . For each 0.5-m lowering of the foundation depth, the insulation thickness can be decreased by 10 mm. The excavation bottom should be levelled using non-frost-susceptible material (sand, gravel or fine macadam) that is 100–200 mm thick. According to the manufacturer, this design ensures that there is no heave in the construction even if heave in the surrounding ground is appreciable.

Ground insulation

Placing ground insulation raises the 0°C isotherm (Fig. 184) and manufacturer's recommended thicknesses for use of mineral wool and extruded polystyrene are shown in Figure 185 for different regions in Sweden.

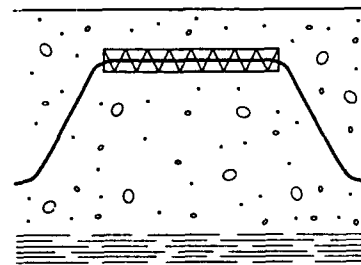


Figure 184. Effect of ground insulation on 0°C isotherm. (From Rockwool 1984.)

Retrofit of insulation

The Norwegian *Building Details* gives designs for incorporating insulation in a building after it has been in use for a period, i.e. a retrofit procedure. The purpose is to decrease the heat loss from various structural parts, which means their U -value is reduced. For example, NBI (1982) shows a procedure applying to outer walls made of concrete or built masonry. These can be fitted on their outside

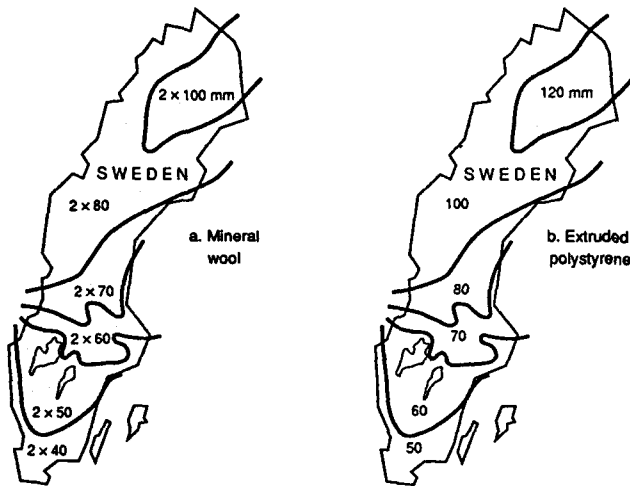


Figure 185. Recommended thicknesses of ground insulation in Sweden. (From Rockwool 1984.)

with a suitable thickness of mineral wool board to reduce the U -value to what is required. However, by reducing the foundation heat loss to the soil, foundation frost protection is reduced and frost action could occur in frost-susceptible soil.

In Denmark, retrofitting has been done to solve problems of frost heave in connection with old buildings having small foundation depths. A computer program has been used at the Danish Geotechnical Institute to calculate the associated position of the 0°C isotherm and to determine how insulation may be placed to raise this isotherm (Porsvig 1986). The Danish Geotechnical Institute has also made computer calculations related to other completed foundations where a mistake was discovered in the foundation design after use of the building. The necessary outside perimeter insulation to rectify the design was accordingly determined.

CONCLUSION

This report described how insulation is used in association with foundations of structures as part of a process of thermal engineering to produce safe and economical designs. Examples showed foundations placed at reduced depths and protected by insulation. Slab-on-grade designs based on such principles were allowed by the Swedish building standards of 1967 and the Norwegian guidelines of 1970. The implied provisos were that the designer should consider the specific factors influencing frost penetration and account for heat contributions from the building, the effect of insulation, the soil's characteristics, the ground water conditions and drainage. The comprehensive background for

these designs was provided by the Frost I Jord research project culminating in the extensive publication of 1976. This is now the basis of the most recent Norwegian guidelines (the *Building Details* of the late seventies and eighties), the 1980 Swedish building standards and the 1987 Finnish guidelines.

Accordingly, similarities can be expected in the design practices of Norway, Sweden and Finland, as borne out by the comparisons made in this report. There are some differences—for example, in the design freezing index (F_{100} in Norway, F_{50} in Sweden and Finland) and the designated critical freezing isotherm. In any case the design must ensure that the extent of this isotherm is limited with respect to the foundation depth. This involves understanding the influence of factors such as climate, floor insulation and foundation wall insulation on frost penetration.

Slab-on-grade designs are related to the freezing indexes (in Norway and Finland) or the climatic temperature zone (in Sweden). The Frost I Jord project had shown that the local freezing index is the decisive parameter with respect to the depth of frost penetration at a slab-on-grade foundation. The climatic influence can therefore be represented by a local freezing index, while the mean annual temperature plays only a small role in the case of a well-insulated slab-on-grade foundation. On the other hand, for unheated buildings, MAT should be considered as well as the local F value.

The choice of the design freezing index F_d depends on the type of structure. For example, in Norway, F_{100} is specified for permanent structures, but if the structure can tolerate a certain amount of heave, a smaller F_d may be used in the design, e.g. F_{10} , F_5 or F_2 .

The thermal design of foundations involves placing insulation at various positions at and around the foundation. Floor insulation is designed so that the room temperature is satisfactory while allowing sufficient heat to pass through the floor to reduce frost penetration. This connotes a certain U -value for a slab-on-grade construction, for example, as specified by each of the Scandinavian guidelines under various conditions. These U -values are similar, ranging from 0.25 to 0.36 W/m^2K , a maximum value being set by each code for a particular case.

Vertical foundation wall insulation is used to limit heat loss from a building and particularly to help guide heat towards the foundation base, thus reducing frost penetration. It is more effective to place the insulation on the outside of the foundation wall. Unless there is continuous insulation around and under a foundation wall, a cold bridge can be formed, leading to frost penetration under the wall. This can cause serious damage, as happened in many cases of faulty design or execution. Also, special care is required as regards the connection between the foundation wall and the floor to prevent a cold bridge effect.

Ground insulation placed horizontally (or obliquely) in the soil outside the foundation strongly reduces frost penetration by limiting the release of soil heat to the atmosphere. Such insulation is particularly necessary where F_d is large and more insulation is placed at the corners of structures because of increased exposure.

For a heated building with a cold crawl space, a reduced foundation depth can be used if the foundation wall is set on insulation, with thickness and width depending on F_d and MAT . In the case of basements, designs should also consider sidegrip on the basement wall and horizontal frost pressure. The Norwegian guidelines for designing open foundations (i.e. piers and piles) against sidegrip are the basis for designs in other Scandinavian countries.

Frost protection of unheated buildings (or unheated parts of otherwise heated buildings) is based on using insulation to reduce the upward loss of stored soil heat and thereby preventing frost from penetrating down to frost-susceptible ground below. A layer of insulation is placed under the building on a drainage layer consisting of coarse material that is not frost susceptible. The thicknesses of these two layers are designed according to F_d and MAT .

Insulation materials used in association with foundations are expanded or extruded polystyrene and mineral wool. Important properties of the insulation are its thermal conductivity, durability under

use conditions, load-bearing capacity and resistance to water uptake. The Finnish guidelines give recommended thermal conductivity design values for insulation with "good," "average" and "severe" conditions of use.

The foundation designs described in this report are adequate, provided the recommendations are followed properly. In Sweden there have been very few reports of damage to houses due to frost action.* In Norway there have also been no special problems with the designs, and no specific problems regarding frost effects and insulation are being addressed by researchers or thought necessary to be undertaken in the near future.** There are, however, minor problems concerning moisture in crawl spaces and in floor coverings associated with slab-on-grade designs. These are related to faulty execution and to deficiencies in following the guidelines. Also, there is some uncertainty about the thickness and quality of capillary-breaking layers of crushed stone under slabs on ground.†

In Finland, foundation designs based on the guidelines have been adequate in most cases. In unsuccessful cases the recommendations were generally not followed or the basic soil information was not adequate.†† Design methods are mainly based on various classifications that are applied to large areas, thus leading to overdesign or underdesign in specific cases. There is therefore a need to develop methods that provide more tailor-made solutions. A current research project is verifying frost-susceptibility criteria of soils, while another aims to verify the practical recommendations for foundation design against frost action. Further research is required on

- The soil parameters to be used in designs for Finnish soil conditions;
- The allowable values for frost heave when designing various structures;
- The long-term durability of insulation materials;
- The conversion of climatic data into a suitable form for design purposes; and
- The development of frost protection of structures, possibly by means other than insulation.

* Personal communication with J. Claesson and C.E. Hagentoft, Lund University, Lund, Sweden, 1990.

** Personal communication with S.E. Torgersen, 1990.

† Personal communication with E. Algaard, 1990.

†† Personal communication with E. Slunga, Helsinki University of Technology, Finland, 1990.

The most advanced countries in the field of foundation design against frost action are Norway and Sweden. The latter is more advanced theoretically with some research continuing along previous lines. Norway is more advanced in the practical field, having produced the comprehensive report, based on the Frost I Jord research project, that now provides practical design guidelines for all the Scandinavian countries.

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12a. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release; distribution is unlimited. Available from NTIS, Springfield, Virginia 22161		12b. DISTRIBUTION CODE		
13. ABSTRACT (Maximum 200 words) The report deals with the design of foundations against frost action in Europe, particularly as practiced in the Nordic countries. It describes how insulation is used in association with foundations of structures as part of a process of thermal engineering to produce safe and economic designs for various structures. The use of insulation enables heat management that allows shallower foundation depths and prevents damage from frost action. Results are given from the Norwegian Frost I Jord research project and the work at Lund University, Sweden, both of which provided the basis for the design guidelines of Norway, Sweden and Finland. Detailed slab-on-grade designs ensure that frost heave does not occur. Consideration is given to the design of foundations with a crawl space or basement, with their problems of sidegrip and horizontal frost pressure. Frost protection for unheated buildings is described, usually involving the use of insulation and drainage layers below the foundation with ground insulation nearby to retain soil heat. Designs with open foundations are described, as well as foundations for retaining walls and bridges. Frost protection required during winter construction is detailed.				
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