of water and stop the formulation of additional ice lenses in the frost zone. So by placing a layer of gravel between the highest water table and the frost line, the capillary flow is cut off, and aside from the moisture contained in the body of the soil subject to freezing, frost heave can usually be held within reasonable limits. Nor is frost damage resulting from the use of bad soils confined solely to the action of heaving and breaking pavement surfaces. We have recorded instances where silty sand embankments, built around and over concrete structures, such as cattle-passes, have so expanded from frost as to crush the walls inwardly from both sides. Auger borings made at these structures showed the soil in the embankments to be saturated by capillarity to a height of 5 ft. or so above floor slabs which looked perfectly dry at the time of the investigations. The only remedy in these cases called for entirely new structures, and it was obvious that the embankment material at hand was not fit for use as backfill. Present day New York State specifications call for a well-compacted gravel to be placed under and around all such structures, drainage or otherwise, a precaution which should greatly decrease the chances for a recurrence of the damage just described.

It is noticeable that wherever road sections have been built up, that is, where the pavement has been carried along at an elevation of 3 ft. or more above the surrounding terrain, there are few indications of frost damage. This holds true almost invariably, regardless of whether the pavement is of a rigid or a flexible type. It would, therefore, seem that the ideal road section should have its pavement held at just such a minimum raised elevation, be carried above wide, curved ditches through cuts, have wide shoulders, and have ample clearance excavated back of the ditches to provide room for pushing snow. Road sections of this type would naturally have a higher first cost, which could be considered as insurance against future damage from frost.

THE NORWEGIAN STATE RAILWAYS' MEASURES AGAINST FROST HEAVING

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Frost heaving is a serious economic and technical problem for Norwegian roads and railways, due to severe winter cold and the extensive occurrence of fine-grained sediments and moraine deposits.

A section through frozen and strongly frost-heaving soil reveals a series of isolated and nearly horizontal ice layers that can vary in thickness from 1 to 100 mm. These ice layers are often limited in horizontal extent and are thickest through the middle section. A local accumulation of a number of such lens-shaped layers often manifests itself at the surface by marked and sharply defined "frost humps."

The formation of the ice layers is due to special physical conditions during the process of freezing, which only in recent years have been made clear. The water is furnished by capillary action in the underlying unfrozen soil, and this movement is initiated by forces of diffusion through films of water at the lower limit of the frost zone. If this limit remains unchanged for a period of time and the temperature is sufficiently low, the thickness of the ice will increase. It is the resultant surplus of water that gives the ground a nearly fluid consistency after the spring thaw.

The Norwegian State Railways was forced at an early stage to take up the battle against the evils of frost, and the following account will set forth the methods chosen to combat them.

One measure that to a certain extent reduces the harmful action of frost is the laying of an 0.5 m. thick ballast (gravel or broken stone) on a well-drained roadbed. And where the roadbed is of such a consistency that it becomes saturated in the spring thaws and thus loses its carrying capacity, reinforcements have usually been effected by the laying of stone or gravel foundations. On the most difficult stretches, especially deep ditches or covered drains have been used. Even though the ballast under the ties still gets pressed down into the roadbed in spring on a few old sections, so that the soil works its way up between the ties (Fig. 1), such occurrences are rare enough to be

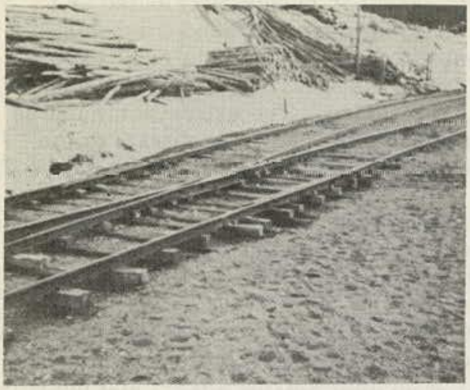

Figure 1. Fine-grained sand slightly mixed with clay has worked its way up between the ties. This happens when the ground thaws out in spring and the soil in the roadbed still contains a surplus of pore-water. A characteristic frost-phenomenon where the depth of the ballast-section is too small (gravel ballast).

Figure 2. Isolated frost humps introduce a menace to the safety of trains. The height and number of humps increase during the winter. Temporary surfacing is attained by shimming. On older lines where the disturbances from frost heaving are severe, one may find shims 6 in. thick, as shown in the figure.

considered a thing of the past.

But the main difficulty for the railways today is the uneven swelling of the ground due to frost, as any relative vertical displacement of one or both rails from approximately 10 mm. and up constitutes a menace to traffic and a hindrance to the development of speed. Frost humps grow both vertically and horizontally in the course of the winter; some develop early in the season, others late. In the December-March period an ever-watchful servicing of the line is required, and shimming in winter embraces about 7 percent (about 300 km.) of the total length of the railway network, mostly older lines.

While a frost hump still is low, the base plates over the middle of it are knocked away, and the parts of the track over the periphery are levelled out by insertion of thin wedge-shaped wooden plates under the base of the rail. As the frost humps grow in number and size through the winter, more and more shims are inserted and on stretches with especially great frost heaving are cases where up to 6-in. thick shims are used (Fig. 2). The labor involved and the considerable wear on ties caused by constant respiking are such an expense that even extensive improvements and work on foundations pay dividends in eliminating shimming.

Measures that have been taken against destructive frost heaving are drainage, lifting of rails, and soil replacement.

Attempts to drain the ground under the subgrade by means of longitudinal covered drains on one or both sides of the line have sometimes yielded good results. But very often the soils involved are so fine-grained that even 3-m.-deep drains will not suffice to adequately lower the level of ground water drawn up by capillary action. This is true of clay and clayey soils as well as silt. Experience has shown that such drainage reduces frost heaving, particularly in cracked ground and in silt, but only rarely can it eliminate shimming altogether. Drainage intended to prevent frost heaving should not be undertaken unless examination of the ground has indicated the possibility of an adequate lowering of the ground-water level.

Lifting of the line by increase of the ballast depth from 0.5 m. to, say, 1.0 m. can make possible the elimination of shims in cases where the ground conditions are favorable, especially, perhaps, in that the frost heaving becomes evenly distributed and therefore harmless. But on stretches with difficult conditions of ground frost this measure does not by any means suffice. The most effective but also the most expensive method is soil replacement. Soils susceptible to frost heaving are removed and replaced by materials that do not expand much upon freezing. The excavation must be so deep that the frost, even in the most unfavorable winters, cannot penetrate to the roadbed. The width is equal to the length of the ties plus 1.50 m. - that is, 4.0 or 4.2 m.

Soil replacement has been carried out on our lines more or less systematically since the beginning of this century. Gravel, broken stone or peat has been used as the replacement material in new lines, and on roads already in operation, cinders from the locomotive furnaces have been used with good results.

The proportions of the soil-replacement section before World War II were somewhat too rigidly fixed. Particularly in new constructions a so-called normal section had evolved, in which the depth of the excavation was 1.0 m. below ground level and the filling material stone. The bottom and sides of the trough were lined with peat (Fig. 3). This lining of peat, which originally was 0.2-0.3 m. thick and which was intended to prevent the surrounding fine-grained materials from penetrating into the layer of stones, is of special interest. It was discovered that such a replacement section eliminated the need for shimming on certain stretches, while it failed to prevent destructive frost heaving on other stretches which were not particularly cold. Investigations showed that the layer of peat at the bottom sometimes was displaced and in patches entirely lacking, probably because of careless dumping of stone, and at such places troublesome frost humps occurred even where the stones were not mixed with soil. On the other hand, there was direct evidence that any layer of peat at the bottom of the trough, even as thin as 0.05 m., effects some insulation against frost.

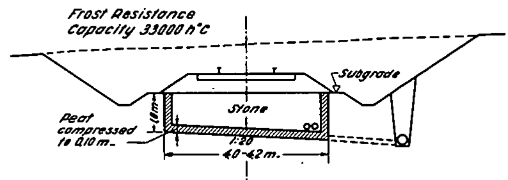

Figure 3.

The frost problem is a many-sided and difficult one, which can be solved only by systematic studies of soils, ground water, and temperature conditions, to mention only a few of the factors involved. Even though a better understanding of the nature of frost in the ground had been achieved before the last war, a method of handling the problem on a large scale was still lacking. Recent studies of the freezing and expansion of soil have, however, yielded a rich and comprehensive literature, and Scandinavia is far ahead in this field (1).

About 1940 the Norwegian Institute of Technology published pioneering investigations, and for the first time methods were indicated for computing the penetration of frost into various soils (2). These investigations and computations explain, according to the laws of physics, a number of phenomena which have long been known in practice. It has commonly been observed, for example, that frost penetrates but little into a marsh, but probably few people realize that this is due primarily to the great water content of the peat, and not so much to its poor conductivity of heat. As a matter of fact, it has been specifically demonstrated that frost penetrates deeper into dry peat than into wet (3), and the explanation of this according to physics is that the larger the quantity of water to be frozen, the larger the quantity of heat to be reduced. The depth of the frost depends on two dominant factors, namely the amount of local frost and the thermostatic constants in the ground. The amount of frost F is defined as the product of time and degrees temperature, from the time in the autumn when the accumulation of cold begins, to a point of time in late winter, when the accumulation ceases. Subtractions are made for mild periods, and the amount of frost F then becomes a collective figure for that part of the winter cold which increases the depth of frost in the ground. In practice, the amount of frost is computed on the basis of average temperatures for given periods of time (f. ex. pentads or months) within the period of accumulation of

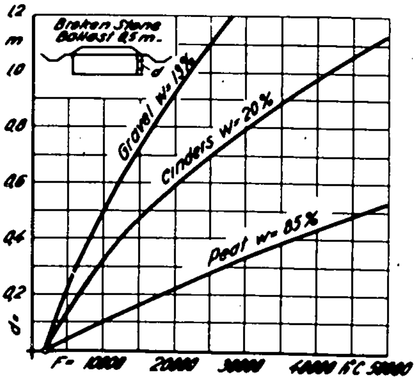

Figure 4.

cold, and the formula we use is Hours x Degrees Centigrade. Practical charts have been worked out for all of Norway (5), with curves showing normal as well as maximum amounts of frost.

Another important set of factors in determining the depth of frost is the ability of the soil to conduct heat and to accumulate cold. Since both of these factors are strongly dependent on the water content, much work has been put into determining the amount of water the different soils or replacement materials have in their proper locations along the line. A great quantity of water stores up a great quantity of cold when transformed into ice and thus impedes further penetration of frost. On the other hand, the conductivity of heat increases in direct proportion to the amount of water, and this tends to aid the penetration of frost. The problem therefore is to select replacement materials or combinations of these deposited in a succession adapted to the needs of each particular situation.

The resistance to frost Ω in a layer deposited at a given depth under other materials is determined by the following equation:

$$\Omega = q \frac{d^2}{2} \left[\frac{1}{\lambda} + \frac{2}{d} \left(\frac{1}{\alpha} + \sum \frac{d_o}{\lambda} \right) \right] \text{ Denomination h deg. C}$$

The total resistance to frost $\Sigma\Omega$ of the combined layers that lie upon each other and freeze completely through in the course of the winter is equal to the amount of frost F. The symbols of the equations have the following meanings:

- d thickness of layer in meters
- q cold-storing capacity of material in Cal. per cu. m.
- λ heat conductivity of material in Cal. per m. h °C
- α heat transmission constant between surface and air in Cal per sq. m h °C
- $\sum \frac{d_o}{\lambda_o}$ resistance to penetration of heat in top layer in sq. m h °C per Cal.

(The term Cal. refers to large or kilogram-calories.)

In the following computations a number of approximations have been reached by ignoring the resistance to transmission of heat between surface and air; 0.06 m. of hard-packed snow has been assumed to cover the ballast after the latter has been frozen through.

In Table 1 below, heat constants for the most commonly used materials are given, based on measured water content along the line in the course of the winter.

TABLE 1

Substance	V Percent water by volume	Cal^q per cu. m.	Cal per m h °C
Hard-packed snow	50		0.5
Ballast stone	8	7800	0.57
Ballast gravel	13	12300	0.80
Cinders (incl. ash)	20	17400	0.40
Peat	85	70700	1.05

Figure 4 shows the necessary depth of replacement d for different materials, depending on the amount of frost F. This presupposes an 0.5-m.-deep ballast section of stone which, after freezing through, is assumed to be covered by a layer of hard snow averaging 0. 06 m. in thickness. While stone and gravel alone are inferior replacement materials, cinders and above all peat are excellent. Those replacement materials which have the greatest water content on the line are the best, as their ability to store up cold is of the greatest significance. For the ballast materials on top, on the other hand, the ability to conduct heat is more important, and it is desirable to have the ballast material as dry as possible.

Figure 5 shows the necessary depth of replacement d when there are 0. 20 m. of pressed peat at the bottom of the trough and gravel, stone, or cinders above. The combination gravel or stone on peat is economical in new constructions. If the peat is unpressed, it should be deposited to a depth of at least 0. 40 m. , and care should be taken that it is not displaced.

To achieve the greatest possible combined resistance to frost in soil layers placed upon each other, the rule is top layer (ballast) as dry as possible and bottom layer as wet as possible. The idea that the bottom layer should have the greatest possible water content may disturb many who will feel that it conflicts with the common experience that drying of the foundation reduces frost heaving. Attention is called, however, to the fact that the drainage ditches usually have been dug in foundations where in influx of water from below or from the side has caused formation of ice layers and consequently great frost heaving, while it is a requirement of any replacement material that it should not form ice layers and should not expand considerably even if its pores are saturated with water. It is a further requirement that the replacement layer should be so thick that the frost, even in the severest winters, cannot penetrate farther than to the bottom of it.

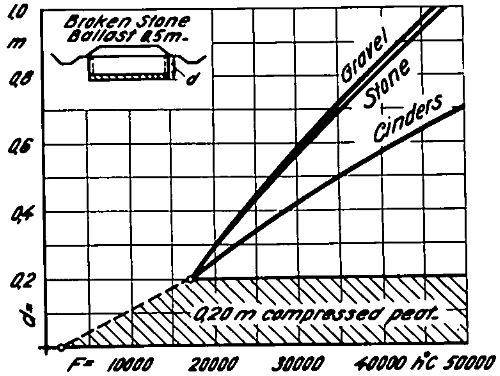

Figure 5.

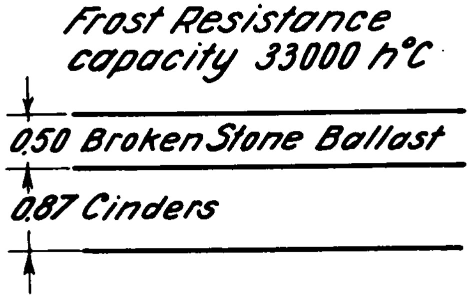

Figure 6.

Let us examine the standard section for new constructions before the war (Fig. 3) and evaluate it critically. The layer of peat at the bottom of the stone-filled, 1. 0-m. -deep trough is usually after a short time pressed down to 0. 10 m. According to the formula, then, this section has a resistance to frost of 33,000 h deg. C. , adequate for a moderately cold district in Norway, but inadequate for the cold inland and mountain regions. If the peat layer is reduced to 24,500 h deg. C. , and if it is entirely removed, the resistance in the stone-filled trough is only 16,000 h deg. C. The peat layer, which has been deposited to insulate against infiltration of soil into the layer of stones, consequently has great significance in combatting frost, and it can be assumed that the varying effectivity of the normal section is due to varying thicknesses of the peat layer. In the future, a thicker peat lining will be used in the stone-peat combination, and care will be taken to prevent the peat from getting displaced when the stone is dumped. It should be expected that loosely placed peat will be compressed to half the original thickness.

On lines already in operation, which so far have had a good supply of waste materials from the locomotive furnaces (cinders, unburnt coal, and ashes), this mixture, hereafter referred to simply as cinders, has been used with good results as replacement material. For a moderately cold district, take for the sake of comparison the same amount of frost (33,000 h deg. C) as eariler, the computed thickness of the layer of cinders is 0. 87 m. as shown in Figure 6, that is, a slightly shallower excavation than in Figure 3. Loosely deposited cinders lose about 20-percent depth when packed down and are therefore given a corresponding surplus depth. A considerable part of this compression is effected already with the passing of the first train. As all grades of the cinders are evenly distributed through the mixture, it does not become adulterated by the surrounding soil.

As early as the beginning of the century, peat was laid down as a replacement material on a couple of sections, one of which was 600 m. long. This peat (sphagnum) was placed in the trough in the form of half-dry clumps. Examination of the almost 50-year old experimental stretches, where the line still is shim-free, has shown that the originally loose peat has been pressed down to half thickness and is now covered by a correspondingly thicker layer of ballast gravel. In spite of drainage from the trough, the peat is saturated with water, and since the peat has retained its fibrous nautre, it apparently has not undergone any decay in the line. It is still sharply defined in relation to the adjacent soil.

Figure 7 shows the necessary depth of the peat layer for the same moderately cold district (33,000 h deg. C). Of all known replacement materials, peat that is compressed and soaked through requires the smallest depth of excavation.

Since 1930, pressed peat blocks have been used as replacement materials on operating lines. The blocks contain dried and torn peat (sphagnum) and are baled with two wooden frames and steel wire. They are of standard length (1. 00 m.) and breadth (0. 50 m.), while their thickness may be 0. 30, 0. 40 or 0. 50 m., depending on the local amount of frost; 50 to 90 kg. in weight, they are easily-handled units, and their form allows for temporary stacking along the line - an important consideration for example in narrow cuts. As shown in Figures 8 and 9, eight blocks are laid per meter of line (8000 per km.). The blocks are laid from the sides and in towards the center line, and the trough is dug so narrow (4. 15 to 4. 20 m.) that the two middle blocks have to be forced down. The peat fill formerly was tapered towards the ends of the trough, but now it is ended abruptly, and no practical difficulties have resulted.

On the first rainy autumn, the peat layer becomes entirely saturated with water. A large number of measurements has shown that whether the peat has lain in the line one year or fifty, the volume is very nearly the same for fibrous peat. Summer and winter alike, the peat contains in round numbers, by volume, 10 percent peat, 85 percent water and 5 percent air. The density of the layer, which can be expressed in terms of volume percent peat, appears to differ but little from the original form before it was laid into the line. Light, undecayed peat has a compactness or density of about 8, and somewhat decayed, moderately dark peat about 10. It has been established that the first blocks, which were supplied to the ordinary market as standard agricultural equipment, were too loosely pressed, as they were quickly reduced by 20 percent in the line. Even though this settling is no greater than that encountered with cinders, it is more troublesome because it makes itself felt materially and necessitates more frequent adjustments of the rails through the year. Attempts are now made to eliminate this evil by the use of more firmly pressed peat blocks, which are required to have the same compactness, 8 to 10, as a peat-layer that has been several years in the line (6).

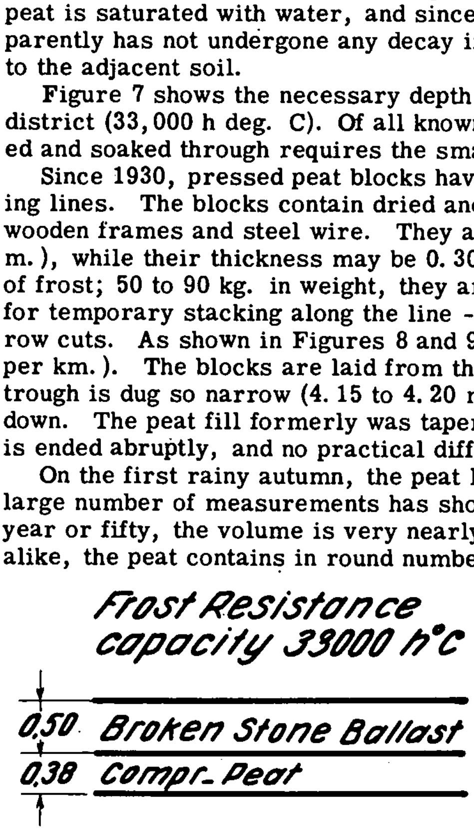

Figure 7.

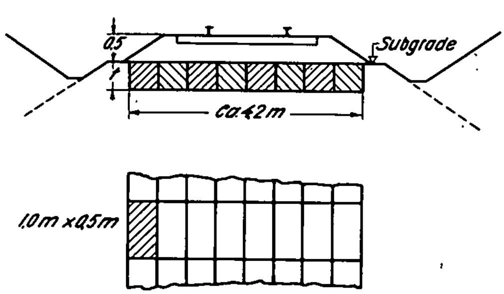

Figure 8.

Recent Developments

During the winter of 1945-46, observations were made of frost penetration into the gravel ballast and the underlying peat layer on five different sections of the railway network, and the results for one of these sections are shown in Figure 10 along with the frost limits. At the top, the local amount of frost is shown for all seasons, based on the mean air temperature for every 5th day. This figure represents a moderately cold winter. The frost limit that has been given has been determined on the basis of the water (ice) content of the ballast at all times, and it will be seen that this water content W increases steadily from 10. 5 to 18. 9 percent by volume through the winter. In the peat lining, the water content remains constant at about 86 percent by volume, summer and winter alike. The correspondence between observed and computed frost limit is very good, in fact the difference is no greater than 0. 05 m.

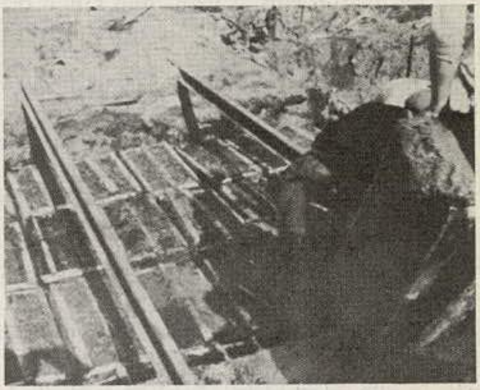

Figure 9. The peatblocks are laid in a narrow trench as closely as possible and without removing the wrapping. The length of the trench that can be excavated in one operation may vary between 4 and 12 meters, depending upon the intervals between the trains.

It can be seen that the frost has slightly penetrated the roadbed, despite the fact that the winter represented is only moderately cold, and it seems strange that this same peat lining succeeded in preventing harmful frost swelling and the need for shimming in the severe winters 1940-41, 1941-42 and 1942-43. But it is now clear that the ballast layer in really cold winters, with few mild periods, is substantially drier than in moderately cold winters; and the drier ballast gravel considerably increases the frost resistance of the underlying peat layer. The bottom of the figure shows that the frost heaving in this ballast layer of gravel has been about 2 mm. and in the completely frozen through peat, 15 mm. With 86 percent by volume water in an 0. 40 m. peat layer, the expansion in freezing should theoretically cause a 30 mm. upward swelling, and the somewhat smaller amount measured in actual practice is probably due to compression of the unfrozen peat by the frozen layer above. An even swelling of say, 30 mm. is completely harmless on an open line.

Of all the five sections under observation, there was close correspondence between computed and actual movement of frost down through the layers. The greatest difference between computed and observed frost limit in the peat lining was 0. 07 m. , in most cases less (7).

The Norwegian State Railways has not laid down 0. 3 to 0. 5-m. -thick pressed peat mats on scattered stretches totalling 19 km. Objections have been made to such a thick layer of peat under the ordinary 0. 5 mile thick ballast layer, on the grounds that the resiliency of the peat would result in a low ballast coefficient. 1/ The answer to this is that upwards of 18-years' experience has failed to reveal any tendency toward an increase in breakage or displacement of rails or in wear of the superstructure. An undeniable drawback is the increased labor of surfacing in the first years, but this drawback should be eliminated by the use of firmer peat blocks and by avoidance of short replacement stretches.

There have been divided opinions on the justification of necessity for draining the bottom of the trough. Cross-drains were formerly used, leading from the bottom of

1/ The ballast coefficient is the pressure per unit of area in kg. per sq. cm. required to depress a tie 1 cm.

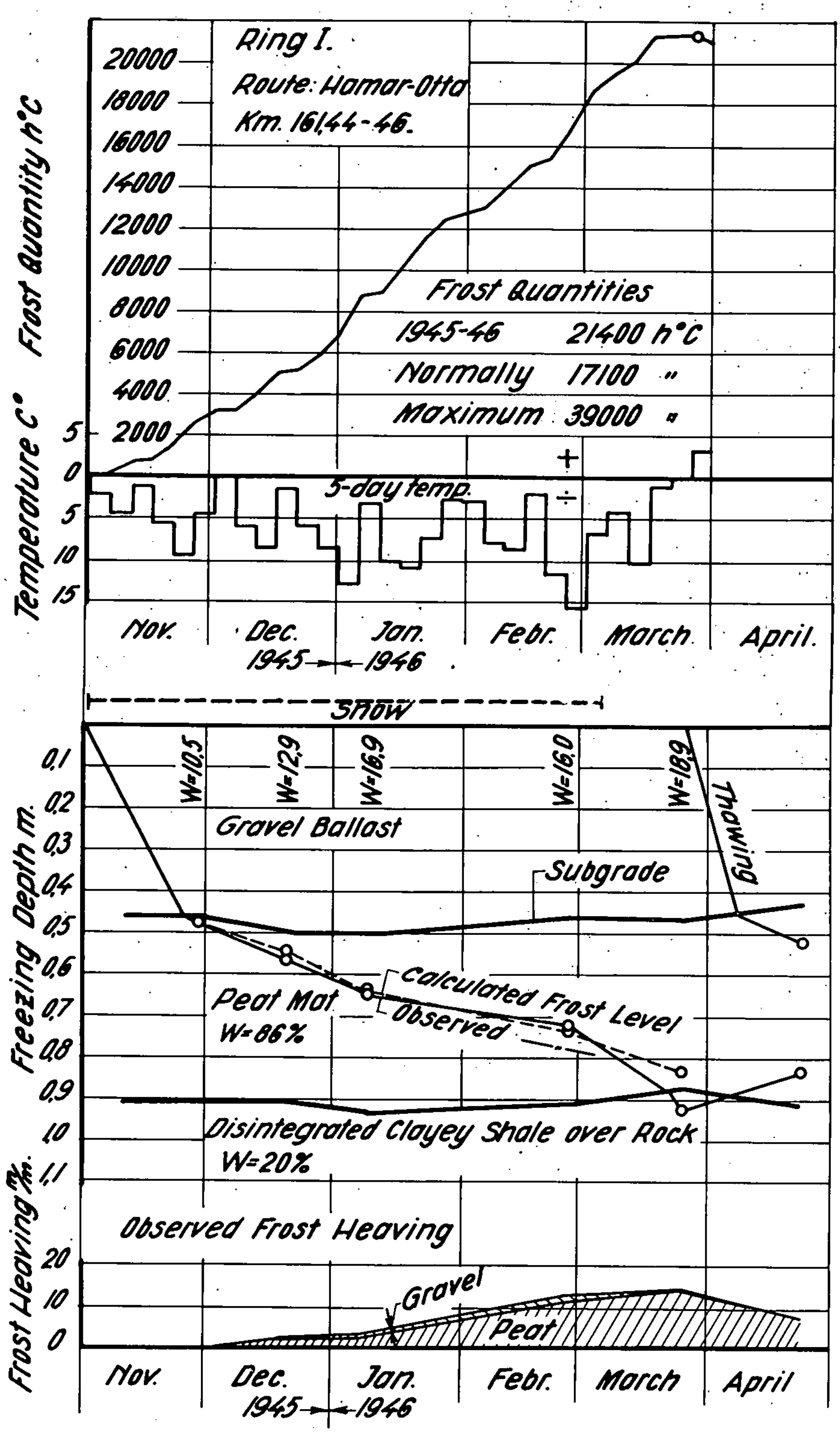
Ring I.
Route: Hamar-Otta
Km. 161,44-46.
Frost Quantity h°C
20000
18000
16000
14000
12000
10000
8000
6000
4000
2000
Frost Quantities
1945-46 21400 h°C
Normally 17100 "
Maximum 39000 "
Temperature C°
5
0
5
10
15
+
÷
5-day temp.
Nov.
Dec.
Jan.
Febr.
March
April.
1945 1946
Snow
Freezing Depth m.
0,1
0,2
0,3
0,4
0,5
0,6
0,7
0,8
0,9
1,0
1,1
W=10,5
W=12,9
W=16,9
W=16,0
W=18,9
Gravel Ballast
Subgrade
Thawing
Calculated Frost Level
Observed
Peat Mat
W=86%
Disintegrated Clayey Shale over Rock
W=20%
Frost Heaving %
Observed Frost Heaving
20
10
0
Gravel
Peat
Nov.
Dec.
Jan.
Febr.
March
April
1945 1946

Figure 10.

the trough to a longitudinal drain running parallel to the line: or a longitudinal conduit was placed along one side of the bottom of the trough, with an outlet at the end of the excavation. The development seems to tend toward elimination of drains when the replacement layer is designed for the severest winters and where there is no great inflow of water that may threaten the stability of the line.

The digging of the trough used to be accomplished by hand, and all work including the filling in of the replacement materials and repair of the rails involved breaking the line, preferably at times when traffic was lightest. As soon as conditions permit, pneumatic tools will be generally introduced for the digging, and there is further a great desire that new methods and special machinery may be developed.

Summary

Frost heaving is a serious economic and technical problem for the Norwegian State Railways because of the cold winter climate and the wide distribution of fine-grained soils in conjunction with an excess of water in the ground. Only in exceptional cases can draining of the roadbed or raising of the line eliminate shimming. To a great extent it has been necessary to take the drastic step of excavating the frost-forming soils under the line and substituting materials which do not expand materially upon freezing. The replacement layer is proportioned according to the local maximum quantity of frost based on computations which have been found to correspond closely to measured conditions. The trough dug for the replacement materials has a width of 4. 0 to 4. 2 m., and gravel, broken stone, cinders, and peat (sphagum) have been used for the replacement. As saturated peat is the most effective frost-resisting material, and consequently requires the least excavation, 1. 6 million pressed peat blocks will be laid down in operating lines through the coming years. Cinders from locomotive furnaces will also be used. With these measures, there is justifiable hope that harmful frost heaving will be eliminated, and thus also the work of shimming, on a total length of 300 km. of line.

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