Road Construction in Palsa Fields

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ABSTRACT

Palsa is an important feature of the discontinuous permafrost regions of northwestern Quebec. Because of the development of hydroelectric complexes along La Grande and Great Whale rivers, the road network will be expanded by the addition of 2000 km of road with many sections crossing palsa fields. Problems related to the design, construction, and maintenance of roads in palsa fields are identified and described. The observations are mainly based on the performance of a test embankment built 3 years ago on a large palsa and the performance of 620 km of road, paved in 1976, that cuts through several palsa fields. The topics discussed are topology, occurrence and distribution of palsa fields in northern Quebec, dating of palsa ice, description of a typical palsa field, description of the physical characteristics of a typical palsa, temperature regime in the palsa, performance of an instrumented test embankment 3 years after construction, performance and maintenance history of a 6-year-old paved road that crosses several palsa fields, and predicted versus observed rate of settlement of existing embankments. Based on the results of these investigations, recommendations are made for the design and maintenance of roads that cross palsa fields.

The development of a road network in subarctic Quebec is relatively recent. All the principal and some local roads were built after 1972. With the development of the La Grande hydroelectric complex, approximately 2000 km of roads are being added. The principal access road runs from Matagami to LG-2; it is 620 km long, and was paved between 1974 and 1976 (Figure 1).

The area under consideration is 40 000 km², extends from the 50th to the 56th north parallel, and is divided into two main topographical regions: (a) the lowlands, at an altitude under 200 m, that are composed of a silty clay plain south of the 52nd degree parallel, and a glaciomarine plateau to the north and (b) the highlands that are 150 to 250 km from the shores of James Bay and present a low rocky plateau strewn with lakes.

The area bedrock is essentially Precambrian with many outcrops in the highlands. Unconsolidated deposits are composed mainly of marine silty clay and beach deposits in the lowlands and glacial till and fluvio-glacial sands and gravels in the highlands. Almost everywhere peat deposits can be found in surface depressions.

The climate is of a subarctic continental type with maritime influence from the James Bay. The average freezing index is around 2500°C per day, and the thawing index is less than 1500°C per day; mean air temperature varies from 0 to -4°C. The in-place snow cover varies from 45 to 65 cm.

Although the area is in a discontinuous permafrost zone (1), permafrost features are scarce in the highlands except at the tops of bare hills. In the lowlands, the main permafrost feature is palsa [for definition, see Stanek (2)]. As the development of the area proceeds from south to north and from west to east, most of the roads are or will be located in the lowland area where muskeg and palsa fields are frequent.

The problem of design and maintenance of roads crossing palsa fields is dealt with. Conclusions are based on observations of the performance of an experimental embankment constructed over a palsa, on data gathered through subsurface investigations of a projected road 100 km long between LG-2 and GB-1, and on the evaluation of five settlement sites along the 620-km James Bay access road.

PALSA TOPOLOGY AND OCCURRENCE

Palsa can be defined as a discontinuous permafrost feature; it is a mound created by the formation and growth of an ice core under favorable microenvironmental conditions (2). Two main types of palsas are identified in subarctic Quebec: nonwooded palsas and wooded palsas (3). Both types occur in the lowland areas at elevations not exceeding 200 m and can be found in clusters of 3 to 10 in both dry and wet areas.

Nonwooded palsas are mainly located north of the -3°C annual isotherm in the coastal zone of Hudson Bay. They are principally of organic origin (90 percent) and have either round or irregular shapes. They can be isolated or form important palsa fields up to 5 km² in area (palsa plateau north of Great Whale). The origin of nonwooded palsas is thought to be the degradation of ancient permafrost.

Wooded palsas are found principally in the southern part of the territory where the mean annual temperature varies from -1°C to -4°C. They are normally covered with black spruce and tamarack, lichens and peat moss, forming a drunken forest at the edge of the palsa. Many palsas present signs of degradation, with cracks and water ponding at the surface. More than 400 sites of wooded palsas have been identified by Dionne (3); the first access road cuts through at least five zones (4). Each zone could have 5 to 10 palsa fields.

Palsas are generally considered relic permafrost, under tree cover, protected by microclimatic phenomena. However, a dating test by the O-16/O-18 method indicates that the palsas along the LG-2-GB-1 access road were formed during the last 40 years (5).

DESCRIPTION OF A TYPICAL PALSA FIELD

A palsa field can be defined as an assembly of individual palsas in an environment that favors palsa formation. A typical palsa field in northern Quebec is shown in Figure 2.

Palsa fields have been characterized by in situ geotechnical and geophysical surveys; by borings, soundings, and sampling; and by testing. More than 10 palsa fields were studied in 1980-1982. Borings were made either with or without B or N casing, and samples were taken with thin-wall tubes or split spoons in the disturbed and undisturbed state (4).

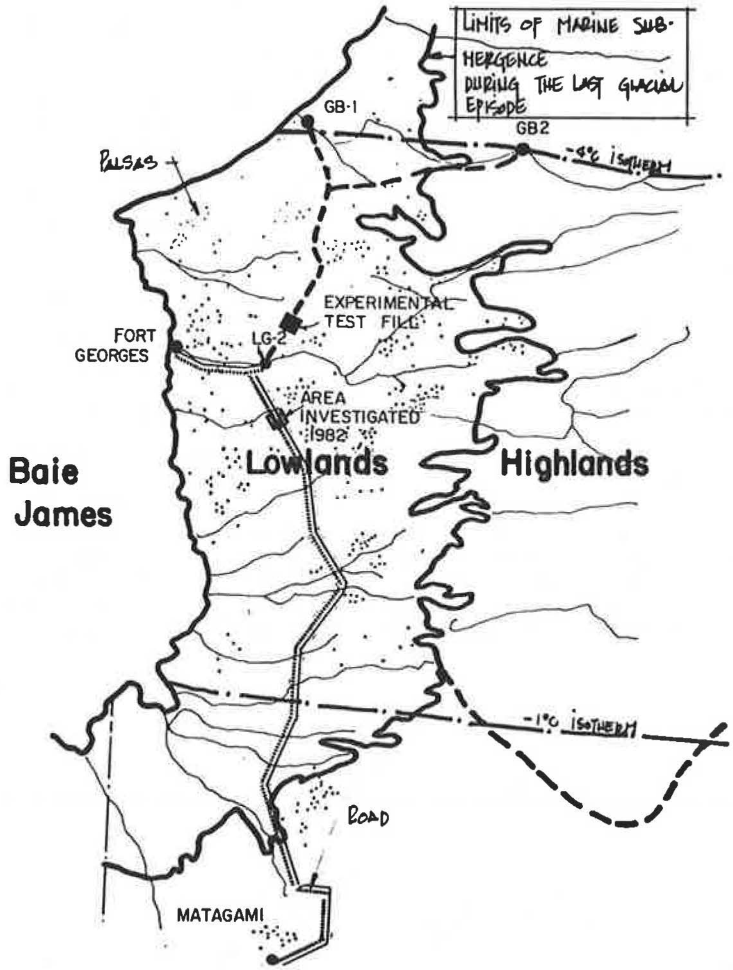

FIGURE 1 La Grande hydroelectric complex.

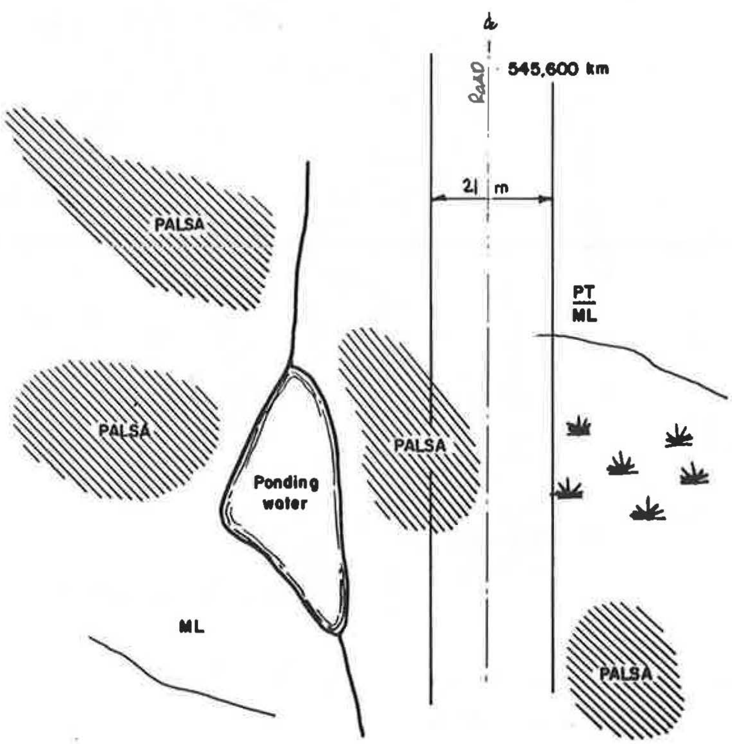

FIGURE 2 Typical palsa field.

The samples were examined in a cold room and in the field to determine the density and water and ice content. Classification tests were also made: peat was classified according to the Von Post index (6) and the frozen structure was classified according to ASTM standard procedure (7).

There could be a palsa field in every low-lying area in a particular region; but more often palsa fields are distant from each other. A palsa field generally contains 3 to 10 palsas; the distance between individual palsas is generally less than the width of the palsas.

The drainage pattern in a palsa field is not well defined and is sometimes influenced by the underlying rock. Usually the water table is close to the surface, and, most of the time, a pond can be found in the low areas of a palsa field.

DESCRIPTION OF A TYPICAL PALSA

Palsas are usually small and circular or ellipsoidal in shape; the length of a palsa generally varies from 10 to 100 m, and palsas have a thickness of 1 to 8 m with a maximum of 3 m above the surrounding terrain. The surface of a palsa is often hummocked and contains small depression zones that are at times unfrozen (see Figure 3). The peat layer at the surface of the palsa is often cracked around the boundaries and is accompanied by a slipping surface and, sometimes, exposed ice. Degradation is worst in the open areas or in old burnt surfaces; in the deep wood-covered areas, the surface is hummocky but the peat layer is not degraded. Around the palsa, underneath the pond, or in the natural peat cover, the soil is unfrozen and boundaries between frozen and unfrozen material are well defined.

All the wooded palsas investigated are composed of four typical layers: a layer of peat at the top, a silty clay layer with no excess ice, ice interstratified with silt, and the unfrozen soil. Several typical borehole sections are shown in Figure 4 and the general characteristics of each layer are given in Table 1.

The thickness of the peat layer varies from 0.60 to 2.70 m. The peat material is generally black or brown with a low fiber content and high mineral content. The Von Post index is always higher than 6. Surface cover is normally lichen or moss with an active layer varying from 20 to 50 cm. The frozen peat is generally classified as Nbn because it is well bonded with a slight excess of ice, its density

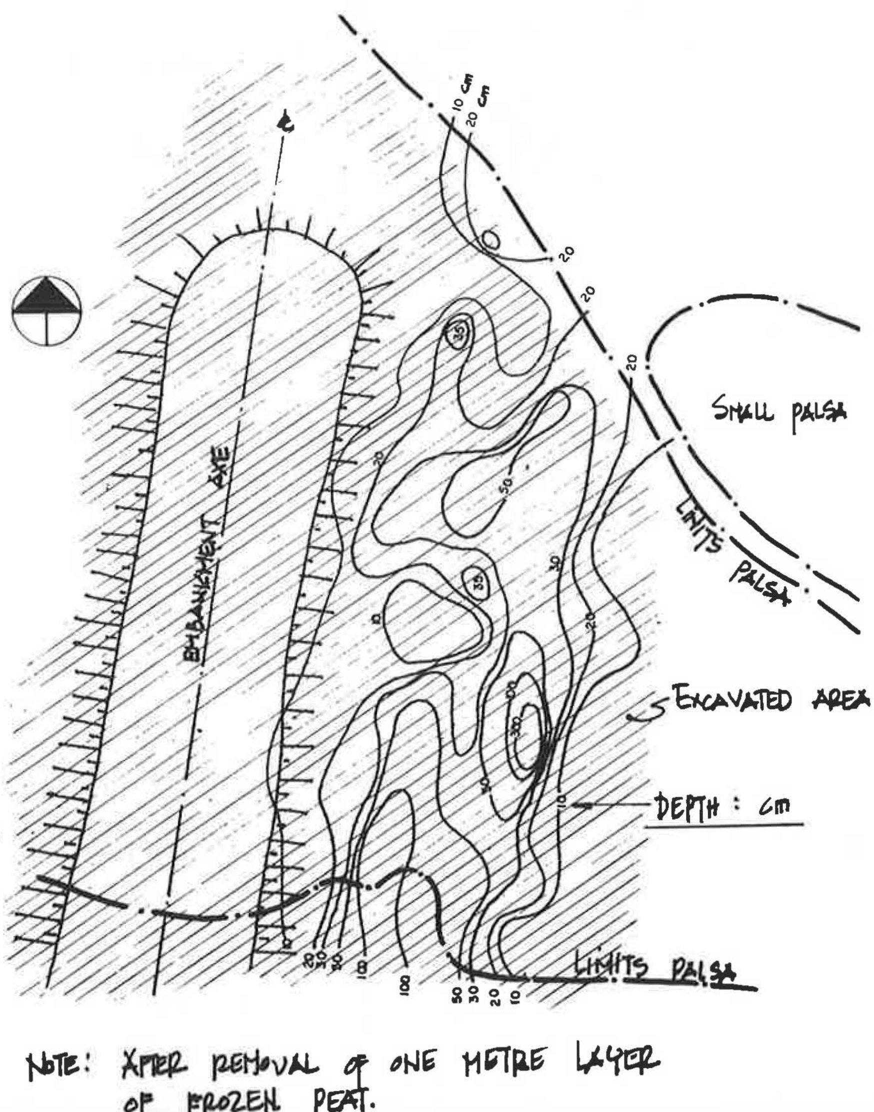

FIGURE 3 Typical unfrozen depression zones at the surface of a palsa.

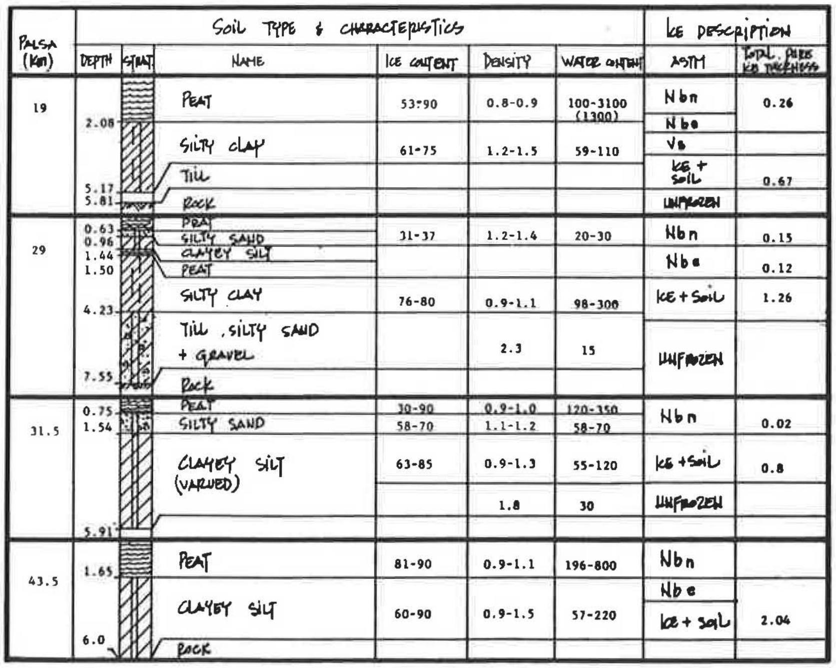

FIGURE 4 Description of typical palsa materials.

generally varies between 0.8 and 0.9 g/cm³, and in situ water content is between 250 and 2500 percent.

Between the peat layer and the icy core there is normally 0.5 to 1.0 m of well-frozen silty clay. This material, which is typically well bonded with some excess ice, is classified as Nbe. It has an in situ water content that varies between 50 and 110 percent and a frozen density that varies between 1.3 and 1.6 g/cm³.

The layer forming the icy core of the palsa is usually 1 to 3 m thick. It is composed of a highly segregated soil, formed by ice lensing the silty clay. The individual ice lenses can attain 10 to 15 cm in thickness. The frozen classification of the material varies from V_s (excess ice with ice stratification) to V_i (ice with soil inclusions) to "ice + soil." The ice is either transparent or opaque and represents up to 70 percent of the material by vol-

TABLE 1 General Characteristics of Palsa Materials

Material and layer thickness	Physical properties in frozen state			Properties in unfrozen state			Water content %		Thermal conductivity (Watt/°km^2)		
	Classification	Density g/cc	Ice content in % of volume	Description	Anticipated settlement in % of original height	Saturated shearing strength[a]	Frozen state	Unfrozen state[b]	Frozen state	Unfrozen state Unsaturated	Unfrozen state Saturated
Peat (0.6-2.7 m)	Nbn	0.8-0.9	30-50	Compressible fibered mineral peat	30-40	.1 p_o	250-2500	.6	1.7	0.5	0.6
Silty clay (0.5-1.0 m)	Nbe	1.3-1.6	30-60	Slightly consolidated fine soils	50-60	.15 p_o	50-110	.5	2.7	1.7	1.7
Icy core interstratified with silt (1.0-3.0 m)	$V_s V_i$ to (ice and soil)	1.0-1.4	80-150	Normally consolidated fine soil in suspension	60-70	.05-0.1 p_o	80-150	.5	3.0	2.0	-
Glacial till or silty clay	-		None	Over consolidated soil	< 5	.2 p_o			-	-	-

[a]Undrained shearing strength as related to effective pressures of earth in place.
[b]Unfrozen water content as a fraction of total water content.

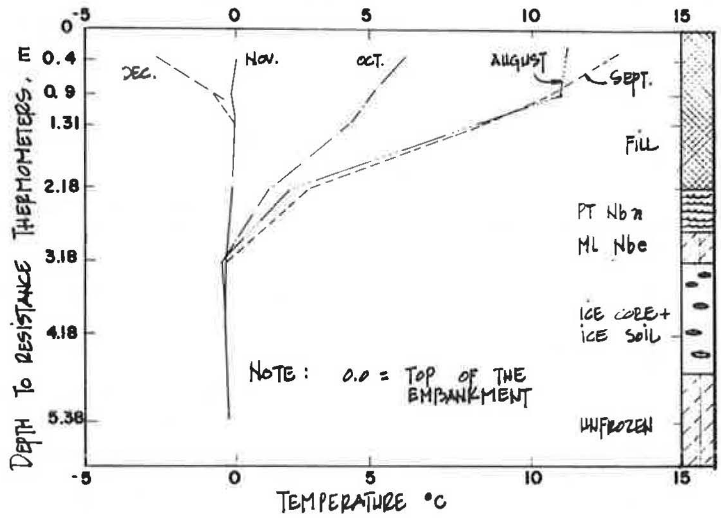

FIGURE 5 Thermal regime of a palsa: test embankment, access road to GB-1, 1981.

ume. In this zone, the soil is often dry and near freezing temperature. The water content of the material from the icy core varies between 80 percent (V_i, V_s) and 150 percent (ice + soil) and its frozen density varies from 1.0 to 1.4 g/cm³. The material underlying the ice core is generally either glacial till or silty clay, is normally completely thawed, but in some cases may be in a partly frozen state with visible ice inclusions (V_i).

The temperature profile of a typical palsa is shown in Figure 5. The profile, valid for 1981-1982, indicates that the temperature of the icy core is between -1°C and 0°C and that it has varied within a range of 0.3°C within the year.

PERFORMANCE OF AN EXPERIMENTAL EMBANKMENT OVER PALSA

An experimental embankment was built by Hydro-Quebec in 1981 over a palsa along the proposed access road to the Great Whale hydroelectric complex. The purpose of the test was to evaluate the rate of settlement and to identify problems associated with settlement prediction and embankment performance. As shown in Figure 6, the embankment was built on a typical small wooded palsa, 20 x 45 m, protruding 1.2 m above the surrounding muskeg. The stratigraphy of the palsa is typical: a layer of peat at the top followed by a layer of silty clay and an icy core. Before the construction of the embankment the protruding surface of the palsa was leveled leaving frozen peat at the surface.

Figure 7 shows the layout of test sections and the location of the instruments. The embankment was divided into three sections according to the treatment of the leveled ground (frozen peat): In one section a geotextile was placed between the peat and the fill; in the second section the peat was covered with 15 cm of sand and 10 cm of polystyrene insulation; and in the third section the frozen peat was left bare.

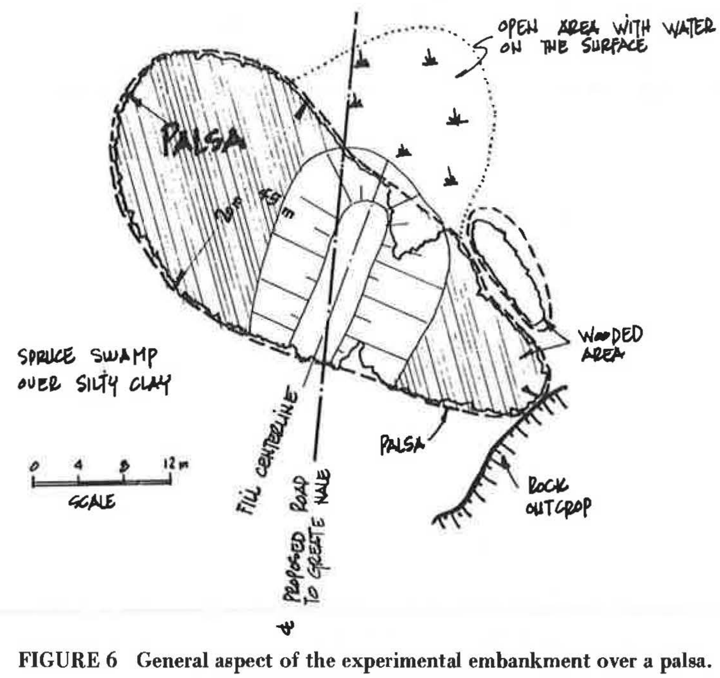

FIGURE 6 General aspect of the experimental embankment over a palsa.

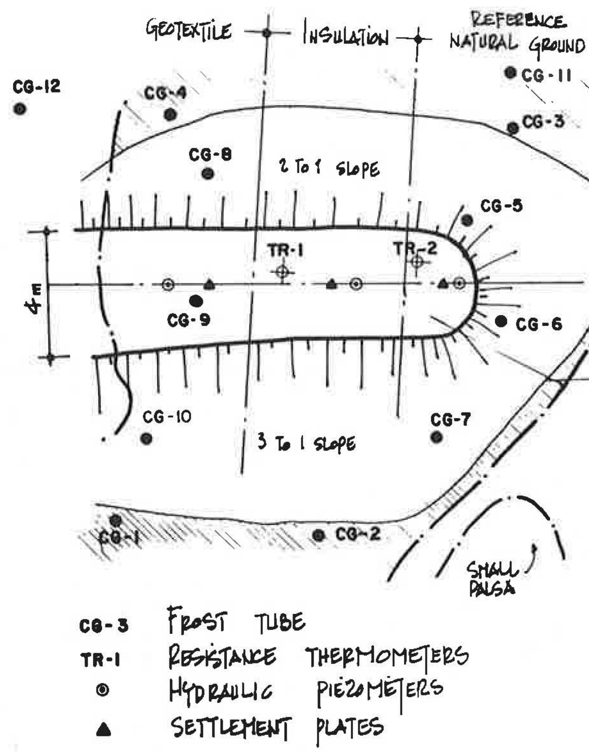

FIGURE 7 Characteristics of the experimental embankment and location of instruments.

The 2.3-m embankment was built with uniform sand containing little gravel. The slope of the fill was 2 to 1 in the western direction and 3 to 1 in the eastern direction. As shown in Figure 7, the embankment was instrumented with 12 frost tubes, 2 x 5 resistance thermometers, 3 x 2 hydraulic piezometers, and 3 settlement plates.

Because on-site testing facilities were limited, prediction of long-term settlement was based on simple tests. Thawing was predicted by thermal calculation using the modified Berggren formula (8), and settlement was evaluated using frozen soils classification, ice content, and frozen density (9,10). The prediction of the most probable long-term settlement was based on average in situ frozen soil properties, available air temperature data on a monthly basis, and instrument readings made since August 1981. The results of observations to date (December 1982) indicate the following:

1. As illustrated in Figure 8, predicted settlement is rapid at first as the peat material thaws, then becomes slower as thawing penetrates the ice core of the palsa. A rough estimate indicates that the coefficient of variation of predicted settlement can be as high as 20 percent due to the imprecision of initial input data and the natural variation in the properties of the palsa material.
2. Settlement of the fill without maintenance (no snow removal in winter and no leveling in summer) is in the lower range of prediction: about 25 cm in the insulated section and close to 50 cm elsewhere, of which 15 to 20 cm occurred during the first 4 months.
3. Settlement differential is highly correlated with the depth of the thaw front; this depth varied from 40 to 90 cm with a maximum thaw occurring under the slope of the embankment. Measured relative settlement is from 20 to 50 percent of the thawed

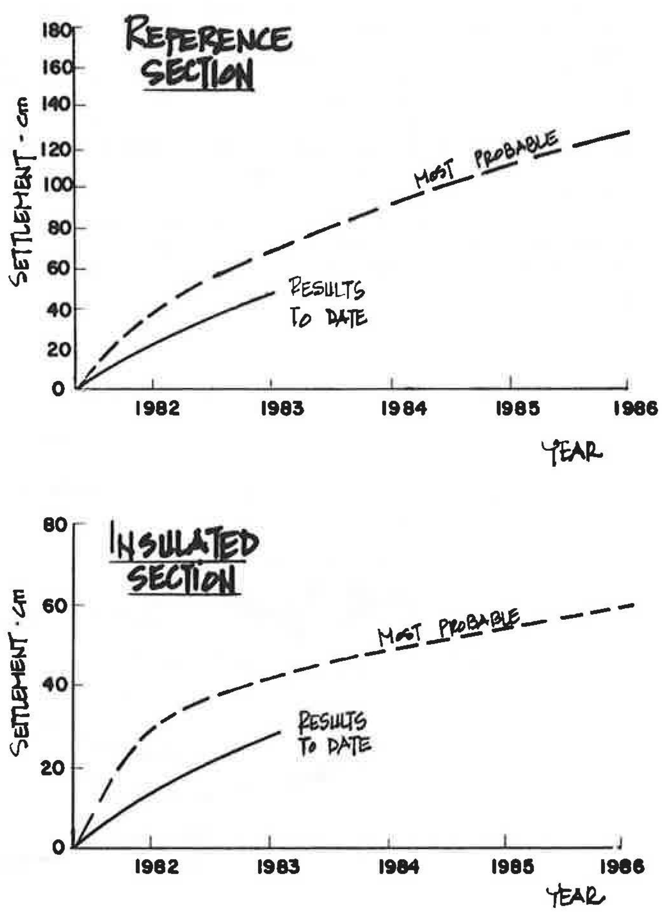

FIGURE 8 Predicted and actual settlement of the test embankment.

depth, which varies with exposure and lateral variation in the natural ice content of the material.

4. Settlement begins in the summer as soon as the fill is thawed, and continues until early winter (December) as the material underneath continues to thaw while the embankment above is again freezing.

5. Maximum thickness of the frozen ground after 2 years decreased from 2.5 m originally to less than 1.5 m, and some areas under and around the embankment thaw completely.

6. Thickness of frozen ground under the fill varies seasonally as the thaw proceeds from both the surface and the bottom. Figure 9 shows typical progress of the thaw line underneath the embankment.

7. Cracks appeared in the slopes and near the edges of the surface soon after construction and continued to develop during the thaw season. Cracking occurs because the thaw is deeper alongside the embankment.

8. Protection of the natural state of peat cover around the embankment is of the utmost importance. As shown in Figure 10, the disturbance of peat by tracked vehicles on the west side of the embankment changed the thermal regime sufficiently to cause complete melting of the palsa and the formation of cracks in the embankment. In contrast, on the east side, where the surface of the palsa has not been disturbed, the active layer is less than 20 cm thick with no degradation of the palsa.

PERFORMANCE OF ROADS THROUGH PALSA FIELD

Description of the Road

The Matagami-LG-2 road is the first paved road ever built in subarctic Quebec. This road, 620 km long, extends north to the 53rd parallel. The pavement is 8 m wide and the shoulders are unpaved. The pavement is composed of 8 cm of high-quality bituminous surfacing, 20 cm of crushed stone base, and 45 to 95 cm of granular subbase. On muskeg, the pavement profile is normally kept 1 to 2 m above the surrounding terrain.

At the time of construction, it was found that frost penetration varied within a range of 3 to 5 m under the pavement and that frost did not disappear until late September in the northern part of the road. Although massive ice was encountered locally during ditch excavations, the existence of palsa was yet unknown at that time.

Evaluation of the Road

The pavement has been subjected to periodic evaluations since the road was opened. Dynaflect deflections were measured once in the summer of 1978 at a rate of four measurements per kilometer. Road roughness has been evaluated eight times since opening of the road to traffic--twice in the winter to measure the effect of winter. The degradation of the surface was identified and quantified in terms of extent and severity in 1978, 1980, and 1982.

In general, the pavement has performed satisfactorily to date, except in settlement zones where periodic leveling and reloading have been required.

Road Settlement

Severe settlement zones where the pavement is badly deteriorated represent around 0.8 percent (or 5 km) of the road length; in known degrading palsa fields settlement zones represent up to 15 percent of the total length (15 km). Figure 11 shows the variation in the lengths of the settlement zones: The average length is about 90 m and the range extends from less than 10 m to more than 300 m.

It is believed that most if not all the major settlements are due to the presence of palsas. Indeed, an extensive investigation conducted in five settlement zones (11) revealed that

1. Major settlements occur mainly in palsa fields;

2. Settlement far exceeds that which is predictable by geotechnical calculation; the level of the soil-embankment contact varied from 1.5 to 2.5 m below the natural ground level whereas 20 to 30 cm could have been anticipated from soil consolidation;

3. Palsas are still in existence and cause degrading even 10 years after construction of the embankment (1972-1973 ; in one location, where no palsa was visible along the road, an icy core about

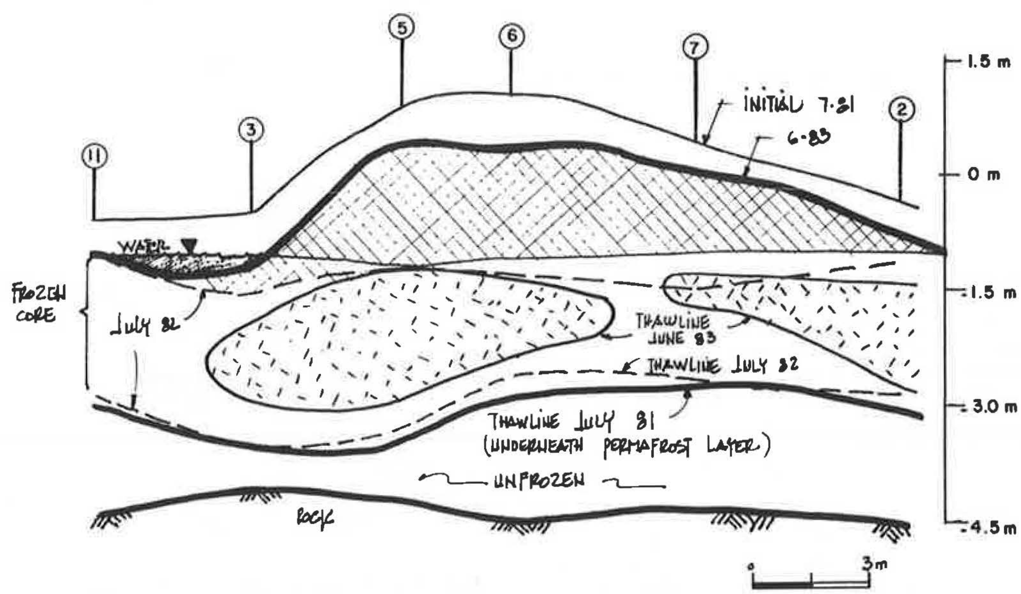

FIGURE 9 Progress of thaw line underneath test embankment (1981-1983).

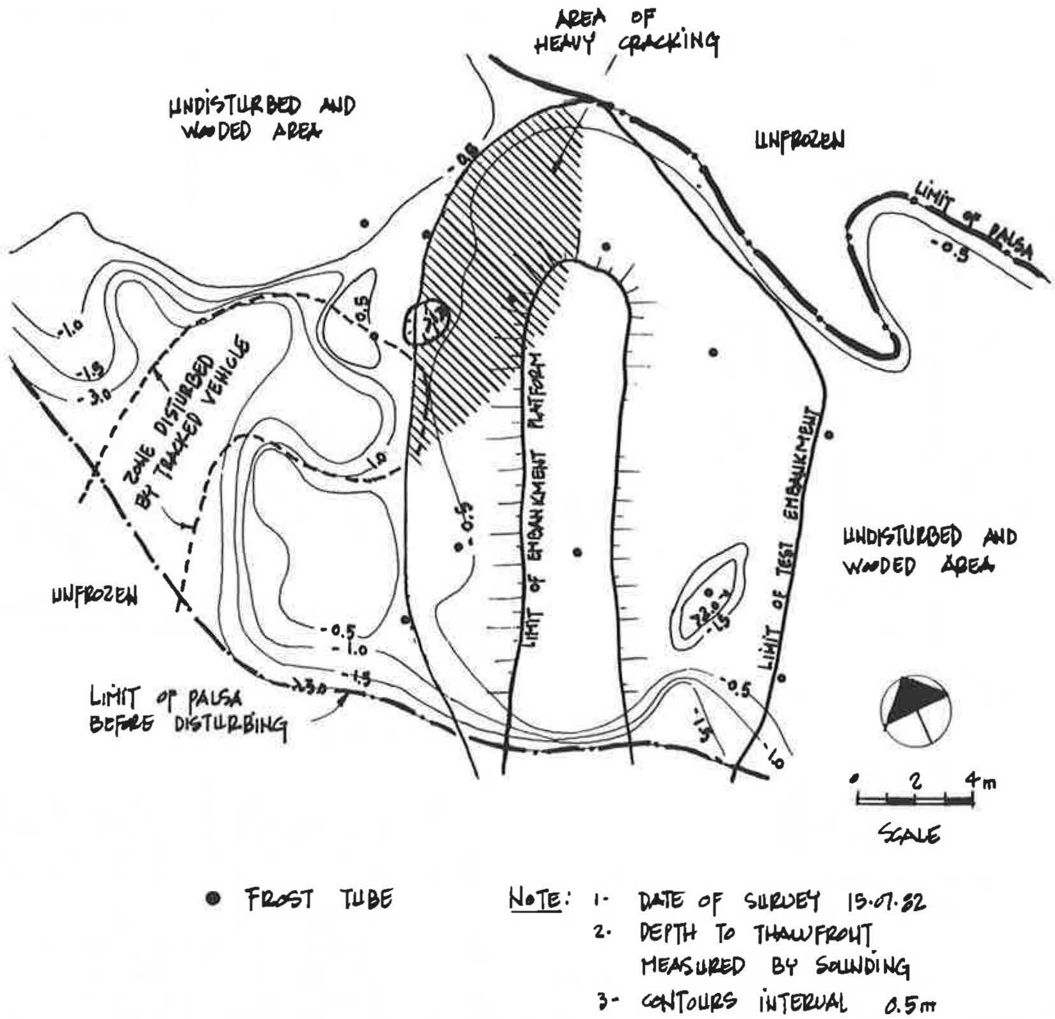

FIGURE 10 Melting of palsa and cracking caused by the disturbance of peat by tracked vehicles around test embankment.

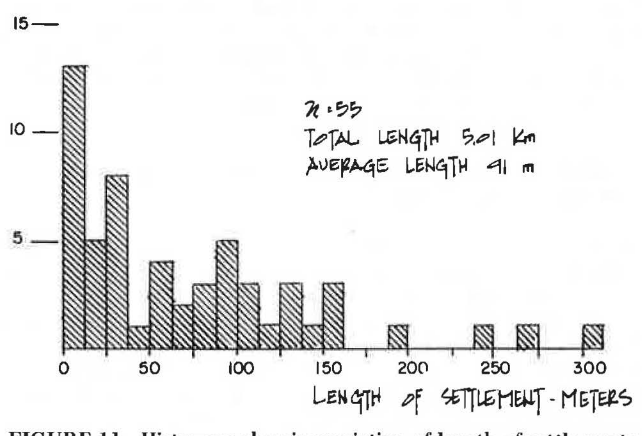

FIGURE 11 Histogram showing variation of length of settlements.

10 m in diameter and 1 m thick (Figure 12) was found 4.2 m from the surface of the road; the temperature of the ice was about 0°C; and

4. Settlements generally appear either in late fall or in early summer and are highly differential; they are rapid at first (10 to 20 cm in a very short period) and slower during each following thaw season (5 to 10 cm or more).

To evaluate past and future settlements, several test pits and borings have been made. The results, described hereafter, are shown in Figure 13. Note that

- Palsas under settlement sections have completely disappeared except under the settlement area detected in 1981 and described earlier;
- Total settlement varies between 1.0 and 1.3 m;
- Maximum annual rate of settlement varies between 20 and 30 cm; and
- Settlements observed on the road compare well with those of the experimental embankment.

The small palsa found in 1981 settled 8 cm in early summer, became unstable in fall, and suddenly settled 20 cm in the spring of 1982.

Road Stability

The stability of the palsa embankment system depends to a great extent on how the road covers the palsa. (Figure 14).

1. When the road cuts through the palsa and the palsa is large compared with the width of the embankment (as is the case of the experimental embankment), the performance of the road will be as shown

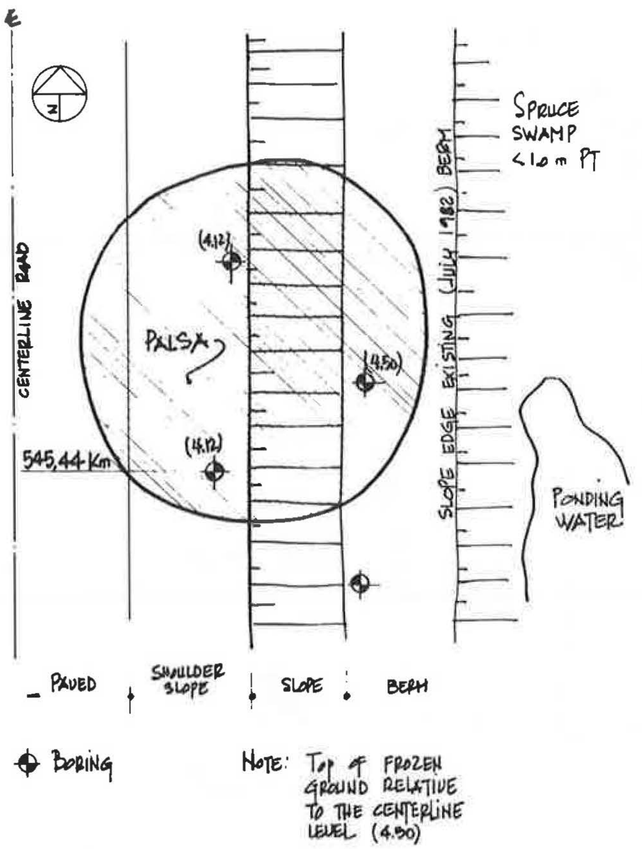

FIGURE 12 Degradation caused by a small palsa found 8 years after construction underneath 4.2 m of fill.

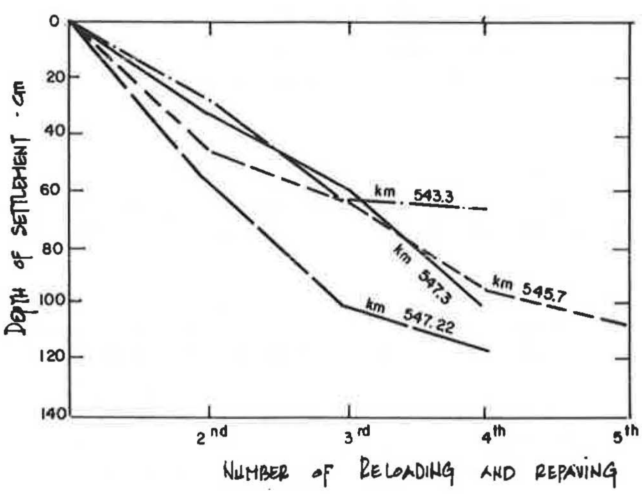

FIGURE 13 Progressive subsidence of five settlement areas over palsa field.

in Figure 15; the differential evolution of the thaw front underneath and along the sides of the embankment will create local instability under and at the edges of the embankment.

2. When the palsa is smaller than the width of the embankment, thawing of palsa will create a locally unstable area where depressions will eventually occur.

3. When the road embankment cuts through the edge of a palsa and covers it only partly (most cases), differential settlements will result between

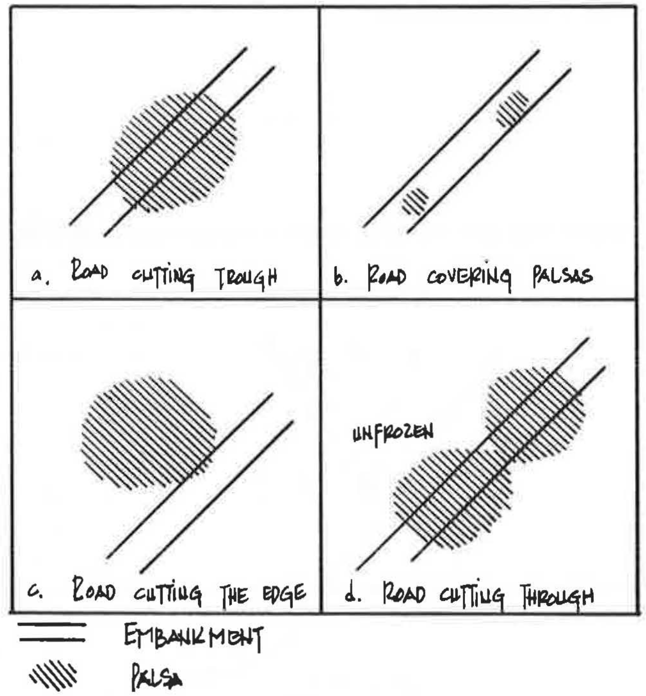

FIGURE 14 Typical palsa crossing.

the unfrozen zone, which will settle rapidly, and the frozen zone where the settlement rate will depend on the progress of the thaw front. Furthermore, instability will result laterally toward the frozen zone as the palsa thaws.

4. When the embankment cuts through several palsas separated by nonfrozen zones, local instability and differential settlement are concentrated at the transition zones, but, because the drainage distance is small, the pore water pressure is low and consequently the stability problem is attenuated.

Note that stability can be greatly affected by the quality of the embankment material; for instance, it was found that where the material is too fine and uniform it will not respond well to dynamic or pluvial compaction and will stay loose beneath the water table and above the thawed soil.

RECOMMENDATIONS FOR DESIGN AND MAINTENANCE OF EMBANKMENT OVER PALSA

Because palsa is a relatively high-temperature permafrost feature, any disturbance of the thermal regime by road or other types of construction may or will initiate thawing. Because palsa has a high ice content, its melting may lead to serious stability problems. Based on all field investigations and laboratory test results, a design approach is suggested. The main steps are shown in Figure 16 and briefly described.

1. Locate palsa field; this can best be done by interpretation of aerial photographs;

2. Select alignments to avoid palsa fields; if this is impossible follow step 3;

3. Determine the exact location of palsas and their geometric and geotechnical properties: the problem of detecting palsas has been discussed elsewhere (12,13); however, based on work in subarctic Quebec where the overburden is relatively thin, more

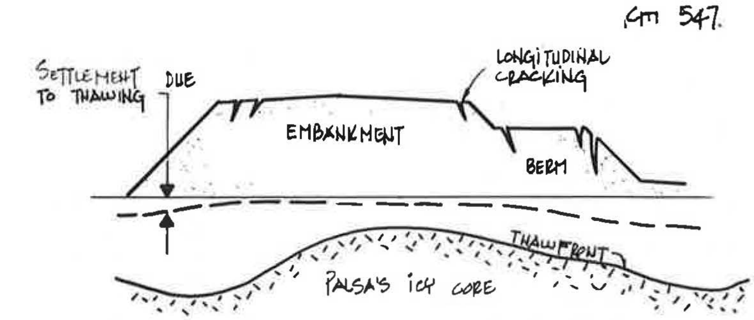

FIGURE 15 Typical thaw-front profile underneath embankment over palsa and related distress.

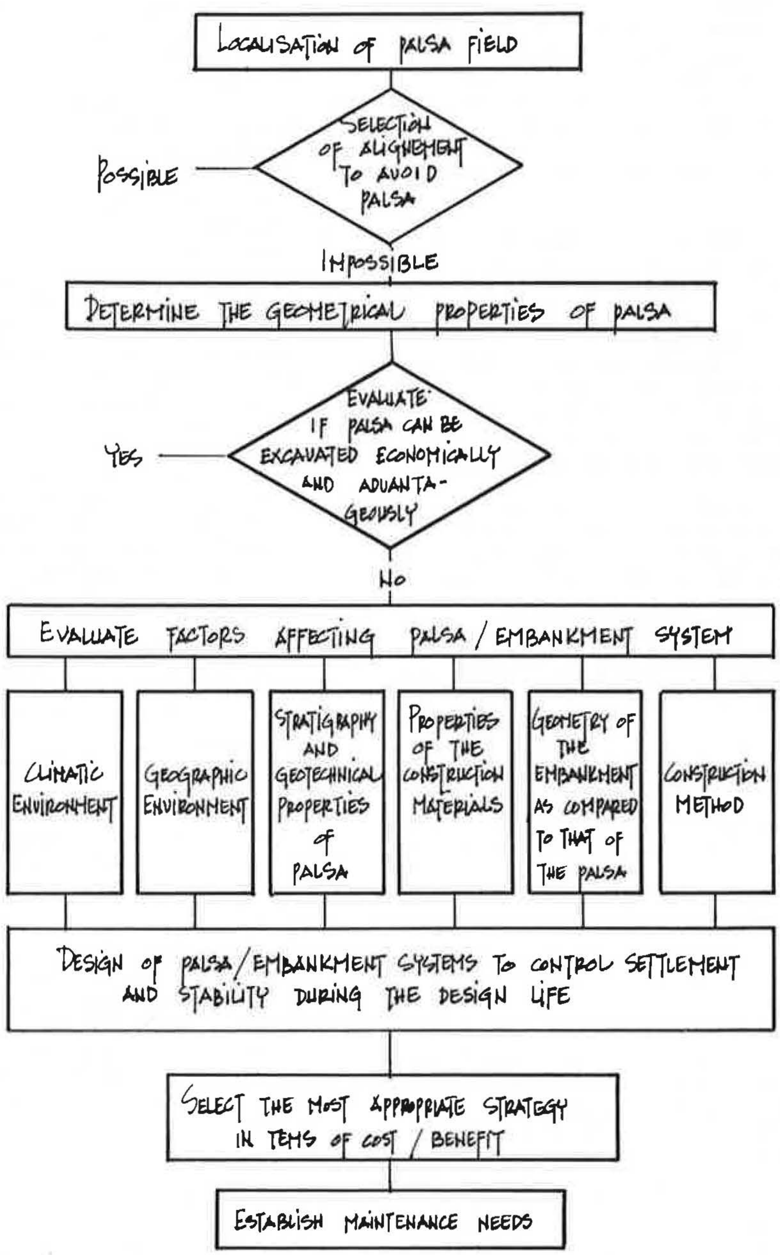

FIGURE 16 Steps involved in the design of embankment over palsa.

research is needed to develop reliable detection methods (14,15);

4. Evaluate if the palsa can be excavated advantageously; this is usually the case when the palsa is small (Figure 14b) or when the proposed embankment cuts through the edge of the palsa (Figure 14c);

5. Define parameters influencing the design of palsa embankment system; the main parameters are (a) the climatic environment of the palsa: temperature, snow and rain precipitation, wind speed, duration of sunlight, freeze-thaw frequency; (b) the geographical environment: profile of palsa above surrounding ground, drainage condition, condition of peat and vegetation, existence of degraded zones and water ponding; (c) the stratigraphy and geotechnical properties of palsa materials such as those given in Table 1; (d) the geometry of the embankment compared with that of the palsa: height, width, and lateral slope of the embankment, relative position of the embankment over the palsa, exposure of the embankment to wind, sun, and snow; (e) the properties of embankment materials: type, permeability, capillarity, filtration capability, saturated and unsaturated thermal conductivity, and mechanical stability when saturated; and (f) the construction method: water level and thaw profile during construction and degradation of the natural environment during construction.

6. Design the palsa embankment system to control settlement and stability.

The designer should bear in mind that, considering the nature and the thermal regime of palsas described in this paper, complete frost protection is uneconomical and impossible even with artificial insulation. Therefore, any design will eventually result in a progressive degradation and disappearance of the palsa. The object of the design is to assure stability and to either accelerate the settlement rate or lengthen the settlement period in relation to the proposed uses and anticipated life of the road.

Note that different approaches can be used in the design: The rate of settlement can be controlled by the thickness of the embankment that, when dry, acts as an insulating layer; the total amount of settlement can be diminished by partial excavation of the palsa's icy core; and the stability of the system can be assured by a proper selection of embankment material and appropriate construction control to assure the preservation of the environment surrounding the palsa.

In any case, when the thawed material under the fill is saturated peat or silty clay of very low bearing capacity or both, the system must be stabilized; it might be advantageous to use geotextiles either as an anticontaminant or as a reinforcing material. If high instability is suspected, berms can be designed for the embankment in the same way as is done for embankments over unstable muskeg (16).

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