

Erosion Control Along Transportation Routes in Northern Climates

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ABSTRACT. The widespread occurrence of permafrost in northern climates dictates the use of specialized measures to protect the terrain from adverse impacts associated with the construction of transportation facilities. Through the adoption of appropriate construction techniques and by providing proper drainage and erosion control facilities within the right-of-way, serious environmental degradation can be avoided. The most appropriate type of erosion control measure is selected according to local terrain and drainage conditions, including a Soil Erosion Code (SEC).

Erosion control begins with the provision of effective drainage across the right-of-way. Typical erosion control measures include the use of permanent linings such as granular blankets, rock riprap and gabions and temporary linings, such as plastic sheets and fiberglass rovings. Ditch checks, rock aprons, energy dissipators and siltation basins may be used to minimize erosion of exposed soils along the route and attendant siltation of streams. Cut slopes may be protected with insulation in ice-rich, fine-grained soils to ensure stability and prevent slump material from reaching the drainage system. Ultimately, long-term erosion protection along transportation corridors is provided through appropriate revegetation techniques, periodic surveillance and regular maintenance of drainage and erosion control facilities.

RÉSUMÉ. La présence étendue de pergélisol dans les régions du nord exige l'utilisation de mesures spéciales pour protéger le terrain des effets négatifs dus à l'aménagement de l'infrastructure routière. En adoptant des techniques de construction appropriées et en assurant un drainage adéquat et un contrôle sur l'érosion le long du tracé, une dégradation sérieuse de l'environnement pourrait être évitée. Le moyen le plus efficace pour contrôler l'érosion est choisi selon le terrain et les conditions du drainage de l'endroit, incluant un Code d'érosion du sol (SEC).

Le contrôle de l'érosion commence en assurant un drainage efficace le long du tracé. Les moyens typiques pour contrôler l'érosion incluent l'utilisation de revêtements permanents, tels les matériaux granuleux, les enrochements, les gabions de roches; et les revêtements temporaires, tels les feuilles plastiques et les boudins en fibre de verre. Les arrêts de caniveau, les tabliers de roche, les évacuateurs d'énergie et les bassins d'envasement peuvent être utilisés pour minimiser l'érosion des sols exposés le long de la route ainsi que l'envasement des ruisseaux qui l'accompagnent. Les ruptures de pentes pourraient être protégées par des sols à granulométrie fine, riches en glace, afin d'assurer une stabilité de la pente et empêcher les matériaux, en s'effondrant, d'atteindre le système de drainage. Enfin, la protection à long terme contre l'érosion le long des tracés est assurée par des techniques de revégétation appropriées, une surveillance périodique et la maintenance d'une infrastructure de contrôle du drainage et de l'érosion.

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INTRODUCTION

Procedures for controlling erosion are essential to the successful planning and development of transportation routes in northern climates. Construction activities such as right-of-way clearing and grading and the traversing of drainage courses have a potential for disturbances which may lead to erosion and stream siltation. Although they do not generally involve large areal disturbances, transportation corridors can have an appreciable impact on the environment because the routes are continuous and frequently extend over long distances. The economic desirability of a shorter route limits the possibilities of selecting a route which circumvents terrain that may be prone to disturbance and erosion. In northern latitudes where permafrost is present, such limitations can be highly significant. In permafrost terrain, construction-related disturbances can lead to permafrost degradation accompanied by erosion, slope instability and thaw settlement, which may impose risks to the integrity of the transportation facility as well as having adverse effects on the landscape.

Transportation routes for which a common approach to erosion control is warranted include roads, pipelines, railways and power transmission lines. Modes of transportation that are presently most in demand in the north are roads and pipelines for the transmission of natural gas and oil. Consequently, this paper is concerned primarily with these types of facilities. However, the principles of erosion control described apply to all of the facilities indicated.

Proposed pipeline, road and railroad routes in permafrost regions in North America as of 1976 are shown on Figure 1.

EROSION MECHANISMS

Erosion involves the physical and chemical weathering of rock and the transport and deposition of unconsolidated materials by water and wind action, gravity and thermal processes. A distinction is made between "geological" and "accelerated" erosion. Geological erosion is the rate

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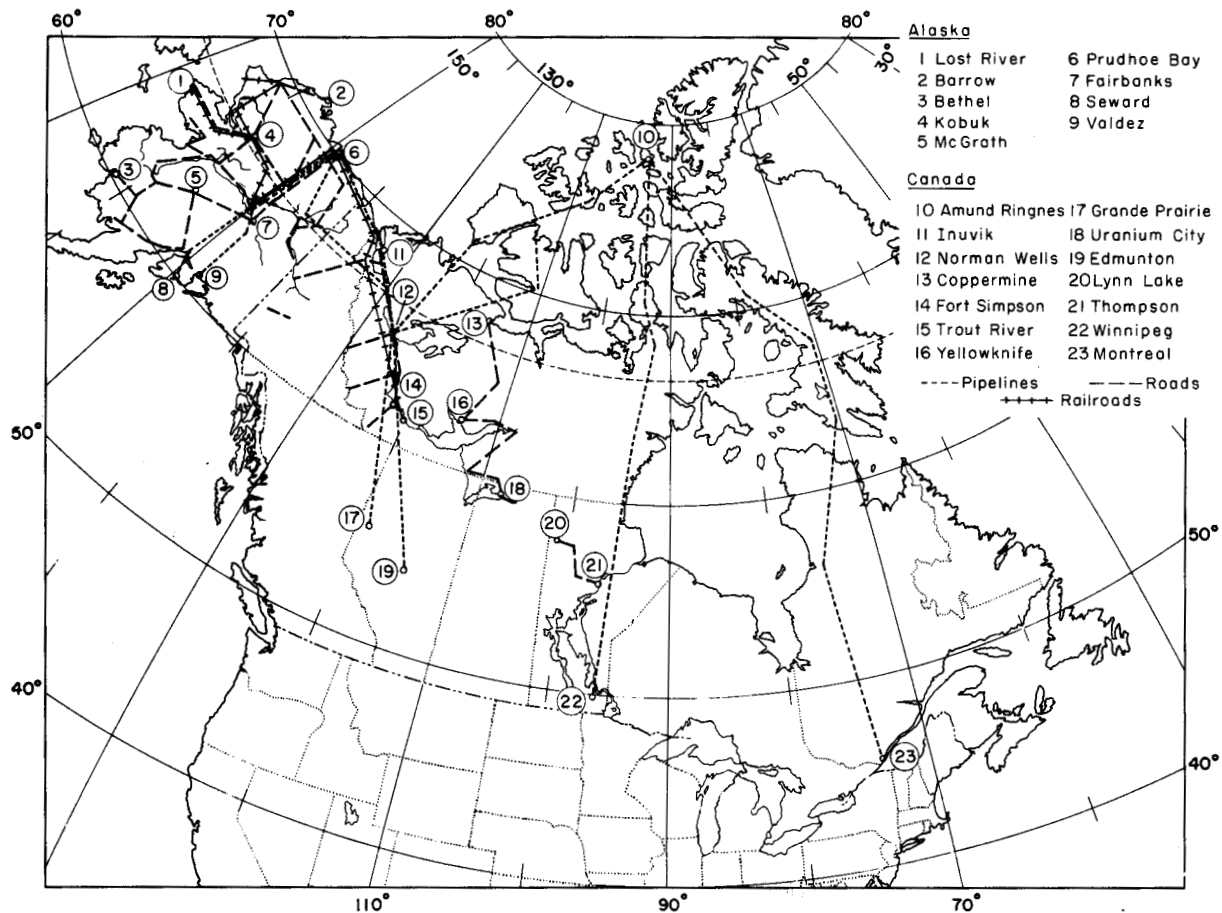


FIG. 1. Proposed transportation facilities in North American permafrost regions (Berg, 1976).

at which the land would be eroded naturally without disturbance by human activity. Accelerated erosion is the increased rate of erosion that occurs when man alters the natural system by various land use practices. Erosion associated with corridor construction activities belong to the latter category.

The erosion rate is affected by numerous variables, of which soil type, climate, vegetation and drainage basin characteristics (e.g. length and steepness of slopes, drainage density and relief) are considered to be the most important. Other construction activities such as clearing, excavation of ditches, side and through-cuts, diversion and concentration of flow, embankment construction and disposal of waste material are the primary causes of accelerated erosion. The most significant erosion occurs from hydraulic and thermal processes.

A. Hydraulic Erosion

The two principal agents of hydraulic erosion are rainfall and flowing water. The detachment and transport of soil particles results from surface runoff occurring as channelized flow or sheet flow. The susceptibility of a

disturbed site to hydraulic erosion depends primarily on the soil properties, slope, and corresponding flow velocity. Silts and fine sands that are low in cohesion are most susceptible to erosion; gravels are much less susceptible because of the large sizes of particles. Although clays are finer in grain size, they are often less susceptible to erosion than are silts and sands, owing to their structure and cohesion.

B. Thermal Erosion

Thermal erosion is generally associated with the rapid thawing of ice-rich, fine-grained soils. Thawing and erosion may result from alterations in drainage patterns, removal of the vegetation cover or excavations in permafrost soil. Thawing of fine-grained soil with high moisture content may result in ground subsidence, slope instability and siltation of streams.

Thawing, fine-grained permafrost soils are subject to mass flow, even on relatively gentle slopes. Thawing sand and gravel deposits usually remain comparatively stable. The thermal regime of an area is extremely sensitive to alteration of drainage, ponding of water and channelization of runoff.

EROSION CONTROL IN NORTHERN CLIMATES

By definition, a frozen soil is one where the temperature remains below 0°C. From the standpoint of erodibility, the significant factor distinguishing between a frozen and unfrozen soil is the presence of ice segregations in the frozen soil. If ice segregations are present and are allowed to melt, the soil may turn into a slurry and flow away. This paper is concerned with the protection of ice-rich frozen soils where ground disturbances associated with corridor construction can lead to extensive disturbance of existing drainage courses, gullying and severe siltation.

Examples of how serious erosion can accompany construction in ice-rich permafrost soil are given in Figures 2 and 3. Figure 2 is a photograph of a road cut for the Dempster Highway in the Northwest Territories. Although some five years had elapsed since the road was completed, the excavated slopes were continuing to slump and regress as ice segregations gradually thawed and silt flowed into the ditches. Unless positive measures are taken to halt the degradation process, further slumping and erosion can be anticipated. Figure 3 was taken at a



FIG. 2. Cut in ice-rich silty soil — Dempster Highway, Northwest Territories. Location — near Arctic Red River, 1978.



FIG. 3. Ditch slope slumping and regressing — Dempster Highway, near Eagle River, Yukon Territory, 1978.

similar, but less severely slumping ditch slope in the Yukon Territory.

To classify a soil for its potential to erode, the following characteristics should be recorded:

- soil gradation — coarse, fine or mixed
- whether soil is frozen or unfrozen
- ice content of frozen soil — expressed as a percentage by volume

Erodibility of soils may be expressed in the form of a Soil Erosion Code (SEC). The relationship between the SEC, type of terrain and soil type are indicated in Table 1. Soil classifications are shown according to the unified classification system (U.S. Bureau of Reclamation, 1963).

TABLE 1. Soil Erosion Code

SEC*	SOIL DESCRIPTION	GENERAL CHARACTERISTICS	EROSION POTENTIAL
FG or UG	Clean sand and gravel with little or no fines (<7% silt and clay content).	Free-draining. Medium to high density, occurs in frozen & unfrozen states, massive ice inclusions are uncommon.	Very low to nil.
FS or US	Silty sand & gravel, mixture of clay, silt, sand & gravel or cobbles & boulders. Fine-grained material <50%.	Found in frozen & unfrozen soils. Massive ice inclusions may be encountered, especially in colluvial deposits.	Low to medium depending upon thermal conditions, topography & hydrology.
FM or UM	Sandy or gravelly silt or clay. Fine-grained material >50%.	Either frozen or unfrozen. High ice content or massive ice segregation common.	Moderate to high.
FL or UL	Silt — organic & inorganic silt and clayey silt.	Occurs in frozen & unfrozen state. High ice content common in frozen silt.	High.
FC or UC	Clay or silty clay.	Varies in moisture content, in-place density and color.	Moderate to high.
FP	Peat and organic matters.	High moisture, low density.	Low to medium, depending upon silt content.
FB or UB	Bedrock, unweathered.		Non-erodible.

* Soil erosion code: 'F' indicates frozen soil and rock; 'U' denotes unfrozen materials.

Each soil type is defined under the SEC system as fine, coarse or mixed grain. Peat and bedrock are recognized as special categories. As would be expected, bedrock is classified as having the lowest SEC, or erosion potential.

Erosion control designs are based on soil erodibility criteria and the Soil Erosion Code. This approach is most useful in preparing feasibility estimates and preliminary designs for corridors, although it can also be used in the final design stage in conjunction with hydrological analysis. Erosion control designs are based on maximum permissible velocities for various soils and artificial soil linings and are aimed at minimizing changes to existing drainage patterns by directing natural flow across the transportation corridors within identified drainage courses.

CONSTRUCTION IMPACTS OF TERRAIN

Erosion and Siltation

The natural drainage pattern, soils and geology of the area and the proposed construction activities are the major factors to be considered in determining measures for prevention of erosion. The season and mode of construction, as well as the type and location of working surface, all have a significant effect on drainage. Erosion problems during and after construction can occur through failure to implement proper and timely control measures. Potential landslide areas, stream crossings and cut-and-fill sections require special measures to prevent siltation of streams and lakes. Runoff water should be essentially free of sediments before being allowed to enter a lake or stream. Preventive measures should be selected on the basis of both the effectiveness of the control device and the potential consequences of any erosion.

Erosion may be due to hydraulic or thermal processes, or a combination of both. In fine-grained, highly silty ice-rich soils, sediment may be transported by water flowing on slopes as low as 1% or less. Even where the ground is not frozen, silt is highly susceptible to hydraulic erosion and protective measures are necessary, even on relatively modest slopes. The most common form of erosion is gullying, resulting in steeply inclined, V-shaped scars.

Erosion occasionally occurs because of a diversion of flow caused by the presence of an icing, which frequently results from interception of shallow subsurface drainage. Road fill tends to compress the organic mat and the uppermost soil horizons which generally have the highest capacity to conduct groundwater flows. The lower hydraulic conductivity results in a diversion of flow to the ground surface. Flows may also be intercepted by cuts which are necessary in preparing a level right-of-way.

In permafrost, disturbance of the vegetative mat may lead to subsidence of the ground surface and the entrapment of drainage. Further settlement occurs because of the influx of heat from the ponded water. When flow

begins, the soil may not be capable of withstanding the hydraulic forces and erosion follows.

The physical removal of vegetation is a cause of erosion as it exposes the mineral soil to direct attack by flowing water. At a minimum, most transportation routes require a level graded cross section which ideally provides a balance between the volumes of cuts and fills, both of which result in the exposure of mineral soil to erosion processes.

Slope Stability

Most instability problems in ice-rich soils occur in cuts and where the ground cover has been severely disturbed. The design of a stable fill is generally straightforward and usually involves an assessment of the stability of the ground supporting the fill. Thermal analyses should be undertaken to determine whether the presence of fill will cause permafrost to thaw and if so, the rate of thaw. It may be necessary to incorporate special provisions to accelerate the release of pore pressures in thawing sloping ground to preserve stability. The fill should consist of thaw-stable material and be protected with at least a blanket of erosion-resistant material.

The design of cuts in ice-rich fine-grained soils requires the determination of the geologic origin of the deposits, the soil type, the amount and type of ice and the geometric and topographic configuration of the backslope. Cut slopes in stratified soils, or in glacio-lacustrine deposits with segregated ground ice, are the most likely to undergo flow slide activity and hence require special design considerations, described in a later section. If a cut slope in frozen ground does not perform well, the consequences in terms of instability and erosion can be severe. The slope may regress, involving slumping and transport of disturbed, thawing soils (Figs. 2 and 3).

Borrow and Disposal Operations

A major feature of the construction of a transportation facility is the movement of relatively large quantities of suitable earth materials (borrow) into the right-of-way and the removal of unsuitable materials. The development of borrow material sites and the disposal of rejects often involve activities which expose erodible fine-grained soils to moving water. Normally, disruptions can be kept to a minimum if appropriate measures are taken to divert water around borrow and disposal sites and if runoff is directed into sedimentation traps where silt loads can be removed.

From both an economic and an environmental point of view, it is advisable to select borrow sites which have a minimum of fine, erodible soils that have to be removed. Disposal sites should be selected, where possible, in topographic lows where drainage collects. Upslope sites which interrupt or contribute to drainage should be avoided. The ideal site for disposal of unsuitable materials is in the crater left over from borrow operations.

Right-of-Way Considerations

The right-of-way and facilities constructed thereon may impede or redirect flow of water, causing attendant erosion difficulties. For example, after backfilling a pipeline trench, a low berm is normally left in place to accommodate settlement of the lightly compacted fill and preclude the formation of a depression in which drainage can be trapped. A disadvantage of the berm is that it tends to intercept small (micro) drainage courses and poorly defined "sheet" flows which are difficult to recognize and for which it is often not warranted to construct separate cross drainage facilities. Closely spaced, subparallel "horsetail" drainage is characteristic of moderately sloping areas of fine-grained perennally frozen soils.

The intercepted water flows along the toe of the berm can cause erosion. This phenomenon can be severe when the facility follows a sidehill, as opposed to being routed directly downslope. Similar effects may be experienced on the margins of fills placed for roads and railways.

Drainage intercepted by a pipeline may flow into the trench and create uplift pressure due to buoyancy forces. On sloping ground, seepage may develop and cause the removal of soil fines and eventually loss of support for the pipe.

DRAINAGE PRACTICES

Most instances of severe erosion occur when drainage is uncontrolled through an area of ground disturbance. Where the ground cover has been disturbed or removed, subsidence and entrapment of water may follow, leading to ponding which can accelerate the degradation of permafrost. If water begins to flow, hydraulic erosion may follow and result in the formation of erosion gullies. Two types of drainage occur along a transportation corridor: cross drainage across the corridor, and longitudinal drainage which is parallel to the route.

In permafrost materials, longitudinal drainage paralleling potentially erodible materials such as backfill in a pipeline mound or workpad can be minimized by providing more frequent cross-drainage facilities than would otherwise be necessary, for directing identified drainage courses across the right-of-way. Ditches should not be constructed in fine-grained frozen soils and ponding should be prevented by providing for cross drainage at appropriate locations. If longitudinal ditches are necessary, protective liners should be considered.

The permanent drainage system should be adequate to accommodate the runoff expected for a particular region and watershed over a prolonged period. Current practices in pipeline construction are to design for the maximum flows anticipated during a 50-year recurrence interval. Temporary drainage controls should be designed for flows having a frequency of about five years.

Natural drainage courses should not be re-routed permanently. However, temporary re-routing and drainage

facilities are necessary during construction of a facility. Re-routed drainages should be returned to the original courses, or to other natural adjacent drainageways.

A. Cross Drainage

Drainage across a right-of-way can occur as channelized or sheet flow. The following types of cross drainage are frequently encountered:

- a) flow across right-of-way: in either relatively flat or swampy ground;
- b) flow across cut slopes and fill slopes; and
- c) flow across workpads and access roads.

The design of stable cross-drainage facilities should be based on a maximum allowable velocity for each soil type. Breaks are constructed in a pipe mound to accommodate cross drainage. The breaks are commonly 1.5 - 4.5 m wide and side slopes range from about 3:1 to 6:1, depending on the design flow calculation. The spacing between water breaks depends on a variety of factors, including drainage intensity, ground topography and the Soil Erosion Code. The length and steepness of slopes in fine-grained permafrost soils (FM, FC & FL) are the most important factors affecting the spacing between breaks. Since longitudinal ditches generally should be avoided in permafrost, breaks should be located at relatively close intervals. A typical water break design is shown in Figure 4. Breaks should be located at all defined water courses and in swampy and flat areas at locations to suit local drainage conditions and

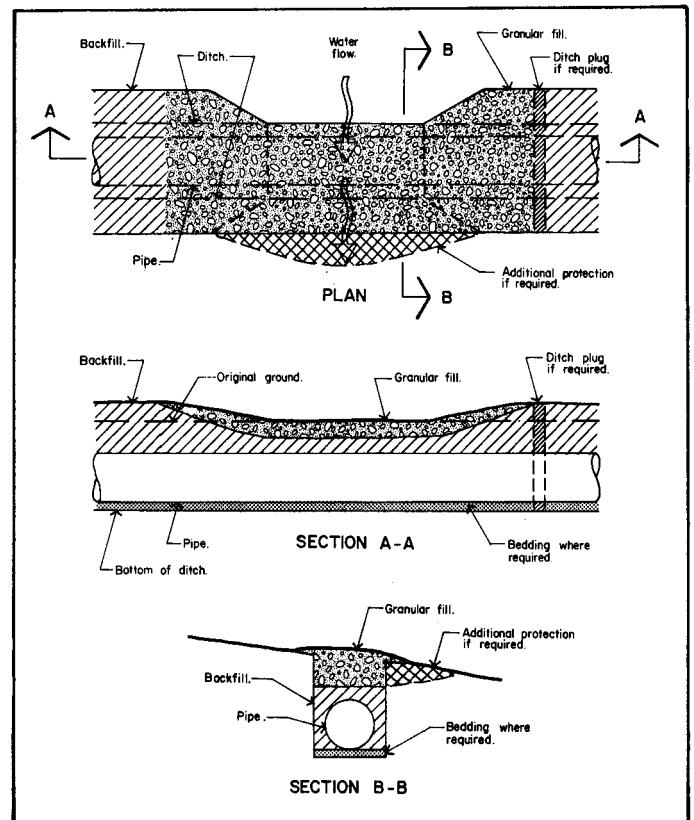


FIG. 4. Typical water break.

topography. Intermediate breaks should also be provided to prevent the accumulation of local flows that do not follow well-defined drainage courses and may not be recognized in advance of construction.

Drainage breaks should be constructed of coarse-grained materials. Well-graded gravel should be used where flow velocities are $< \sim 1.8 \text{ m sec}^{-1}$. For fish streams, protective materials should consist of clean, well-graded gravel having less than 5% fines (silt and clay) and a broad distribution of particle sizes.

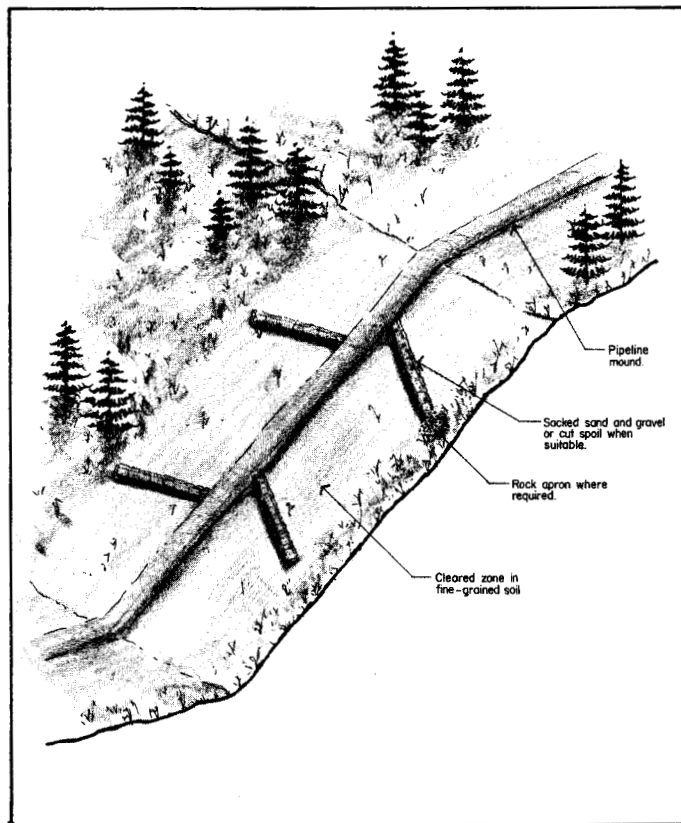


FIG. 5. Diversion dykes — herringbone type, longitudinal slope.

Where drainage descends on a slope, diversion dykes or let-down structures may be utilized to control excessive flow velocities. Diversion dykes (Fig. 5) may be used to divert sheet flow away from the slope, including the pipe mound and other disturbed portions of the right-of-way. Dykes are also effective in directing drainage into adjacent water courses outside of the areas occupied by the cuts and fills. The need for dykes in this instance depends on the height of cut slopes and the type of soil exposed. Where it is not convenient to divert the drainage, a let-down structure consisting of a lined channel (Fig. 6) may be utilized to direct the flow down the slope. A velocity control structure, such as a stilling basin or rock apron, is normally constructed at the downstream end of a let-down structure before the flow is returned to the natural water course. Figure 7 illustrates how erosion can develop in the absence of a let-down structure.

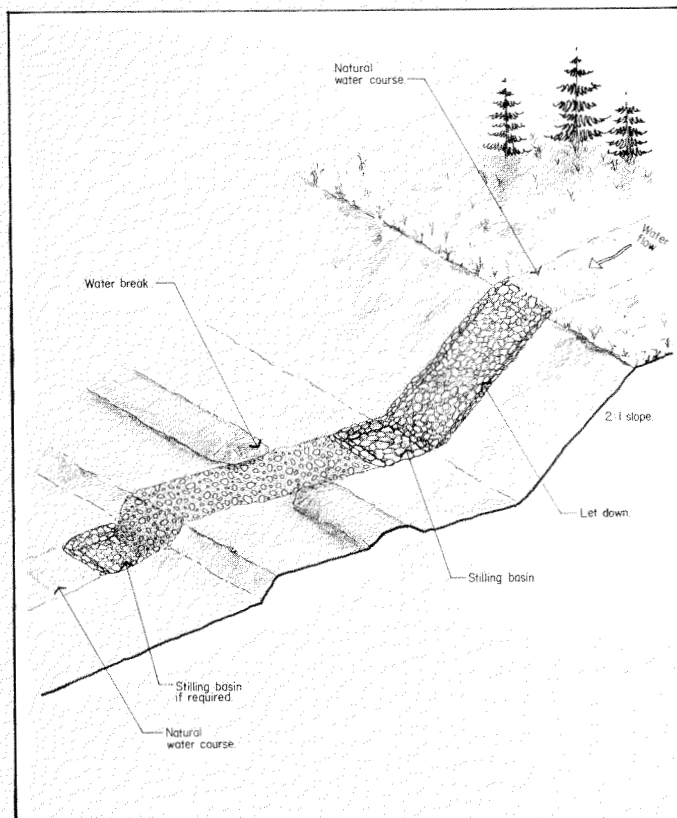


FIG. 6. Let-down structure.



FIG. 7. Erosion below outlet of road culvert due to absence of a let-down structure — Klondike Highway, Yukon Territory, 1978.

B. Icings

Icing or aufeis deposits may interrupt flow in natural drainage courses and lead to erosion. Icings fed by the active layer often cease to grow during the winter, but those formed by perennial springs or water from unfrozen zones within the permafrost will continue to grow as long as temperatures remain below freezing. Stream icings are generally formed when the water is frozen to the bottom of the stream and freezing continues into the underlying soil.

Another phenomenon that has received attention in the design of northern gas pipelines is the formation of frost

barriers and related ground heave associated with the transmission of gas at freezing temperatures. Although the effects of frost heave on erosion are not expected to be as severe as those accompanying thaw settlement, ponding and alteration of drainage courses can contribute to undesirable impacts. For example, if a stream is blocked by an icing at the time of spring runoff, there is danger that meltwater will cause flooding and the creation of new channels.

Examples of severe icing conditions along a road in northeastern British Columbia are shown in Figures 8 and 9. In Figure 9, a culvert has been completely blocked by ice. Unless the blockage has dissipated beforehand, runoff from snow melt and rain may flood the ditch on the upslope side of the road. If adjacent culverts are also blocked, water may be forced onto the road fill and wash out the road.

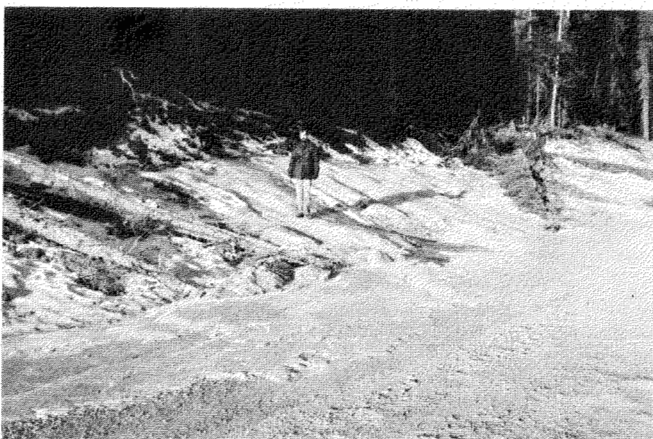


FIG. 8. Icing along road allowance, northeastern British Columbia.

When a transportation corridor is planned, it is recommended that the location, extent and sources of icings be investigated and hydrogeological causes of the icings be evaluated to allow appropriate remedial measures to be developed in advance. Measures can then be taken to prevent damage from erosion and to divert flows in a controlled manner to eliminate the icings. In addition, if aufeis-prone areas are recognized in advance, alternative routings for the corridor can be examined.

EROSION CONTROL FACILITIES

Severe erosion of exposed slopes is usually caused by concentrated flows. Diversion dykes, ditches and control structures should be constructed at appropriate locations early in the construction of the project. Benches, mulching or covering the soil with various protective materials may be required to reduce slope erosion. Facilities for cross drainage between natural drainage courses should also be installed because rain storms, snow melt and inter-



FIG. 9. Culvert blocked by ice, northeastern British Columbia.

mittent freezing can result in thaw settlement and damage to mineral soils exposed within and alongside the right-of-way.

The following types of erosion control facilities are available for protecting exposed erodible soil within the construction zone.

Granular Blankets

Exposed mineral soil which is considered to be erodible should be protected with a blanket of granular material, particularly when the transportation facility is located on a side slope and is expected to intercept extensive sheet flow. On side slopes where the right-of-way is excavated through bedrock or granular material, and in areas where a gravel or thermal pad is used, additional protection is usually unnecessary, provided that adequate provision is made for cross drainage.

Protection can be provided by spreading non-erodible granular material on the exposed soil, or by using diversion dykes upslope of the facility. If the velocity is expected to be higher than approximately 1.8 m sec⁻¹, the protective granular layer should be armoured with cobbles or riprap.

Channel Liners

To protect ditches and natural and induced drainage courses from erosion, temporary or permanent liners can be used where flow velocities exceed the allowable limits. Permanent liners should be used in erodible soils where velocities exceed $\sim 1.2 \text{ m sec}^{-1}$. Where the flow velocities are $< 1.2 \text{ m sec}^{-1}$, the channels can generally be revegetated. Temporary liners consisting of chemical stabilizers can be used to protect the channels until vegetative growth is established.

1. Temporary Liners

The following types of temporary channel liners can be used as protection for drainage ditches and channels.

- Plastic sheets:** Where flow velocities are less than $\sim 1.8 \text{ m sec}^{-1}$, plastic filter sheets can be used as a temporary liner, or as an alternative when coarse gravel is not available. The plastic sheets can be held down with pins or cobbles to prevent displacement.
- Fiberglass rovings:** Fiberglass rovings can be spread by using an applicator. To hold the fiberglass rovings in place, a soil stabilizer should be applied at the recommended rate.
- Soil stabilizing chemicals:** Polyvinyl Acetate (PVA), diluted with water, can be applied to stabilize drainage ditches having a flow velocity of $\sim 1.2 \text{ m sec}^{-1}$.

Stabilizing chemicals, particularly fiberglass rovings, should be used with discretion as they are not biodegradable and may present hazards to fish and wildlife.

2. Permanent Liners

The following materials are recommended for use as permanent liners.

- Coarse gravel:** A layer of coarse gravel (2.0-7.5 cm), having a thickness of $\sim 15\text{-}30 \text{ cm}$, should be placed where velocities are $< \sim 1.8 \text{ m sec}^{-1}$.
- Cobbles and rock:** Well-graded cobbles and rock of $\sim 7.5\text{-}20 \text{ cm}$ in size may be used as a permanent liner where velocities do not exceed $\sim 2.5 \text{ m sec}^{-1}$.
- Sacked sand and gravel and cement-soil:** Sacked sand and gravel can be used as protection where velocities are $< \sim 2.5 \text{ m sec}^{-1}$. As an alternative, a dry mixture of five bags of cement per m^3 of soil can be placed in sacks to provide protection where flow velocities are $< 3.0 \text{ m sec}^{-1}$.
- Riprap:** Riprap is a layer of large, durable rock fragments which protects the underlying surface from erosion. Riprap of different classes can be used where velocities are $2.5\text{-}4.5 \text{ m sec}^{-1}$. A sand and gravel filter layer having a minimum thickness of 15 cm should be placed on the soil beneath the riprap. Filler material may be necessary to fill the large voids in the riprap.

- Gabions:** Gabions filled with cobbles or shot rock, ranging in size from $10\text{-}20 \text{ cm}$, may be used where velocities are expected to be $\sim 3.0\text{-}4.5 \text{ m sec}^{-1}$.

Ditch Checks

Ditch checks can serve a dual purpose: to reduce flow velocity and to control the sediment load. Ditch checks are commonly installed to control erosion along drainage ditches, especially at the toes of cuts in fine-grained soils.

Ditch checks can be either temporary or permanent.

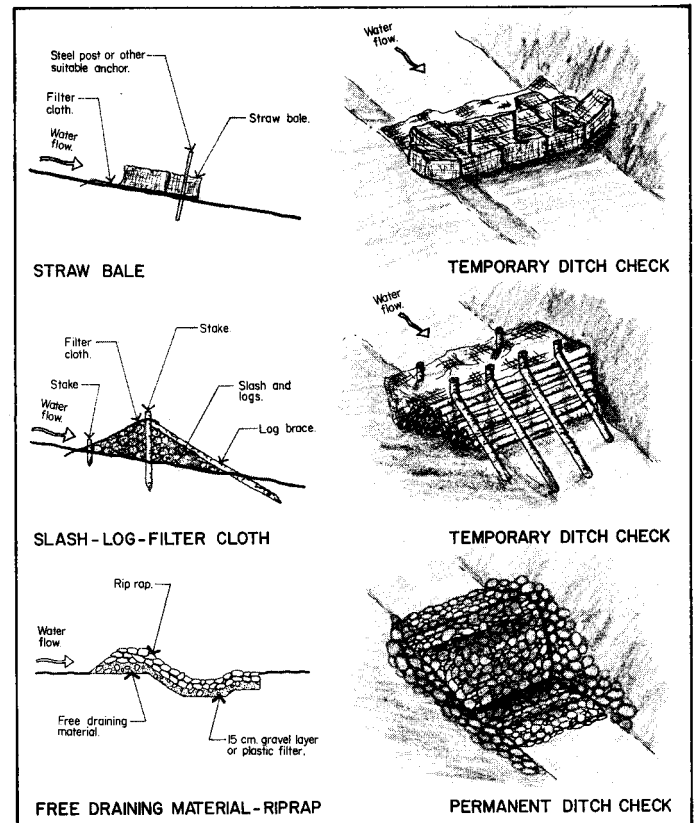


FIG. 10. Ditch checks.

Temporary structures are built either with straw bales or with wood logs and filter cloth. Permanent structures should be constructed with free-draining coarse gravel and riprap. Examples of several types of ditch checks are shown on Figure 10.

Temporary ditch checks should not be more than 0.6 m high. However, permanent structures built with coarse granular material can be constructed up to $\sim 1.2 \text{ m}$. Specific dimensions and spacings between checks should be based on flow data.

Rock Aprons and Energy Dissipators

A rock apron is commonly used to dissipate energy and spread the flow of water where outlet velocities are excessive. A rock apron should be used instead of a stilling basin in fish streams and in areas where ponding caused by other energy-dissipating structures would result in thaw settlement. Where there is no defined channel, the apron

should be placed in a fan shape to cover all areas downstream from the outlet.

Other energy dissipators, such as stilling basins, can be used at appropriate locations where the allowable velocity is exceeded and the thermal conditions allow the construction of such structures.

Siltation Basins

Siltation basins are built for temporary retention of sediments. Their purpose is to prevent the entrance of sediment-laden water from the construction zone into sensitive areas such as fish streams. Siltation basins are basically small dams and therefore are not suitable in areas of predominantly fine-grained permafrost soils. Unless specially designed for specific site conditions, their heights should not exceed ~2.5 m and the design should contain provision for an overflow spillway.

In addition to having an application in siltation control along the pipeline right-of-way, siltation basins are useful in the protection of sensitive portions of large construction areas, such as at compressor stations.

DESIGN AND PROTECTION OF CUTS IN ICE-RICH SOILS

The practice in Alaska, for roads and for the Trans-Alaska Pipeline, has been to excavate many of the cut slopes in ice-rich soils at near-vertical inclinations of about one horizontal to four vertical. Conventional slopes of 1.5:1 or 2:1 have also performed successfully in most cases, where proper protective measures were taken at an appropriate time. From the existing practices and knowledge it appears that:

- a) Near-vertical slopes (i.e. 1:4) can be successful in all ice-rich, fine-grained soils where the height of cut is $< \sim 2$ m. Near-vertical slopes in ice-rich silt and colluvium deposits may perform successfully if the height of the cuts is $< \sim 6$ m.
- b) The experience of the Trans-Alaska Pipeline in the Copper River Basin indicates that steep or near-vertical slopes in predominantly clayey soils with excessive segregated ice may not be successful, if the height of the cut is $> \sim 1.5$ m. Cuts in clayey soils require insulation, sand and gravel buttressing, riprap protection, or a combination of these types of protection.
- c) Conventional cuts have been generally successful in ice-rich sand, gravel and other soils with ice contents $< 15\%$.
- d) Revegetation is required for all cuts, except for 1:4 cuts, which require periodic surveillance and maintenance.

Cuts in ice-rich silts should be made near-vertical and allowed to self-stabilize. As the cut slope recedes, the sloughed material at the toe provides stability and the vegetative mat behind the cut face slumps over the exposed soil, thereby insulating and stabilizing the soil. To

prevent the organic mat from ripping, larger vegetation behind the cut face should be removed. A buffer zone to accommodate sloughing soils from the cut slopes, the provision of ditch checks and periodic maintenance are advisable. Where 1:4 cuts are proposed, containment structures should be installed and the behaviour of the slopes monitored in the summer so that remedial measures can be undertaken during the following winter.

Cuts in ice-rich, fine-grained soils should not be made without providing suitable insulating protection. In the case of vertical cuts, the vegetative mat will generally be restored sufficiently to insulate the cut in two to five years (Lotspeich, 1971). By comparison, sloped cuts may recede a considerable distance due to the lack of a vegetative cover. Thermal protection may be provided through application of sand and gravel, or with a layer of manufactured insulation (Fig.11). Figure 12 illustrates the successful application of a blanket of crushed rock on a section of the Dempster Highway (N.W.T.), cut in ice-rich soil, to protect it from thermal and hydraulic erosion. A blanket of crushed rock or gravel, with or without manufactured insulation, reduces the rate of thaw, facilitates drainage and thaw consolidation, but does not need to be thick enough to eliminate thawing entirely.

CONSTRUCTION PRACTICES TO MINIMIZE EROSION

Aside from the installation of physical facilities for controlling erosion, various precautions can be observed dur-

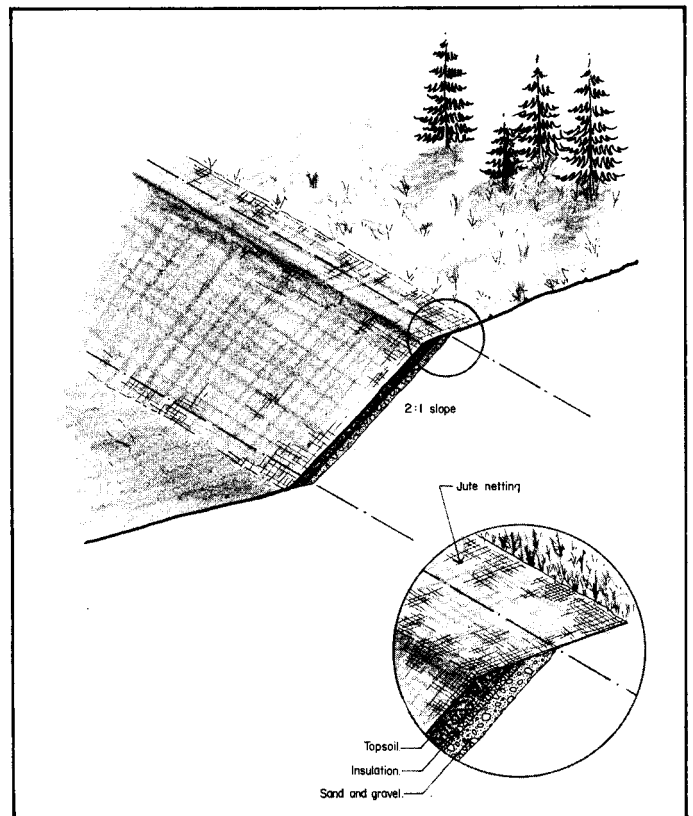


FIG. 11. Insulation protection for an ice-rich cut.



FIG. 12. Blanket of crushed rock protects a road cut from thermal and hydraulic erosion. Cut is located on Dempster Highway, Northwest Territories.

ing construction to limit terrain degradation. The impact of construction begins with clearing and site preparation operations, particularly when these activities are accompanied by grading and excavation. Once an area has been cleared and the surface soil disturbed, accelerated erosion may occur. This is especially so in permafrost soils with high ice content, where loss or damage to the organic cover can result in deeper thawing, slumping or mass flow. Where accelerated erosion has resulted from improper clearing or site preparation, restoration work is quite difficult and expensive.

Thermal erosion may occur if fine-grained, frozen soils (FL, FC and FM) with high moisture contents are exposed to thawing. The amount of grading in ice-rich, fine-grained soils should therefore be minimized by minor re-routing and by utilizing overlay snow or gravel pads on side slopes of up to ~10%.

Machine clearing should be done only where the ground surface can support clearing equipment without damage to the organic surface, or where cutting or grading is proposed. In fine-grained frozen soils, if the active layer is thawed, clearing should be carried out by hand. The optimal time for conducting clearing operations is during the winter months, when the surface soils are frozen and preferably covered by snow. This facilitates the movement of heavy equipment without damage to the ground surface.

After clearing and grading, the disposal of fine-grained, frozen material which is unsuitable for engineering purposes requires special stabilization measures due to its susceptibility to erosion. Stabilization measures may consist of placement in layers, compaction (if possible) and disposal behind containment dykes. Disposal piles should not exceed allowable heights and slopes, and should be revegetated.

Where the natural vegetation mat has been removed or destroyed in disturbed areas other than cuts, the surface should be seeded, fertilized and revegetated. Access to or

along the construction right-of-way may be provided by building a pad of compacted snow, preferably not on exposed or graded fine-grained permafrost soil. If the snow pad has to be built on graded or fine-grained permafrost, it should be removed before the spring thaw. The exposed working area should then be covered with a layer of sand and gravel 15-30 cm thick. The sand and gravel blanket should in turn be covered with topsoil, which should be seeded to protect the underlying soil from thawing. Alternatively, if sufficient material is available, access can be provided along an insulated gravel pad instead of a snow pad. Stripping or scalping of the surface organic layer under a workpad should not be permitted.

REVEGETATION AND MAINTENANCE

The primary objective of revegetation is the rapid establishment of a grass cover that is effective in controlling soil erosion. The second objective is to alter the albedo of the disturbed ground surface and thereby reduce the radiation component of heat penetration into normally frozen soil. Vegetation is also an effective deterrent to hydraulic erosion, as it protects the surface from the impact of rainfall and reduces the available run-off and flow velocities.

Where it is considered practical, the material from the surface organic layer should be removed and stored separately from other excavated material. The organic mat removed and segregated during excavation should be utilized to revegetate the disturbed areas.

Where native organic material cannot be used, revegetation should be accomplished by using procedures that include:

- a) Fertilizer application
- b) Temporary and permanent seeding (subject to timing constraints)
- c) Mulches on sloping ground
- d) Watering and sprigging

Application of mulches limits erosive processes while promoting revegetation efforts in exposed areas. Mulches can be utilized for the control of erosion from wind, rain, seepage and snow melt on cut slopes, fill slopes and within other disturbed areas. Mulches should be applied in conjunction with, or immediately following, seed application. They are commonly used on sloping ground, although they may also be beneficial in flat areas.

It is not practical to identify in advance of construction all of the hydrological and geotechnical factors contributing to erosion processes. Therefore, maintenance efforts are necessary, both to treat locations where unexpected erosion occurs and to sustain erosion control structures and facilities in their original operating condition. Advance engineering assessment is essential in determining the type of maintenance procedures to be carried out. Potential trouble spots should be identified in advance through periodic inspection to permit the selection of timely and appropriate maintenance measures. Siltation,

sloughing in of ditches, continuously degrading cuts and icing conditions constitute evidence that existing systems are inadequate and additional controls are required. However, properly designed and constructed structures will accommodate most potential siltation and erosion.

The main maintenance effort should be directed at the protection of cross-drainage breaks and culverts and stabilization of cut-and-fill slopes. Water breaks should be maintained to counter the effects of thaw-settlement, frost heave and overstressing of drainage structures during storms and spring runoff. Additional diversion structures and equalizers may be required where unexpected ponding develops. Changes in natural drainage patterns may result in concentrations of flow and an increase in velocities, causing erosion in formerly stable areas.

Clogged siltation traps have to be periodically cleaned out. Accumulation of sloughed material in a buffer zone at the toes of 1:4 ice-rich cuts is an important part of the slope stabilization process. However, sloughed material should not be allowed to restrict the flow of runoff, or cause excessive siltation.

Although structural solutions would provide immediate control against siltation, the most effective erosion control procedure is through the revegetation of disturbed areas. Seeded areas will require occasional fertilization over the years until the native plant species regenerate. Access to topsoil stockpiles and selected borrow pits should be retained for maintenance purposes.

Prolonged freezing weather with little insulating snow cover is the ideal setting for the formation of icings, which can be troublesome to drainage control. Naturally occurring icings tend to be aggravated by the construction of the facility, workpad and right-of-way grading. On roadways, icings in culverts and ditches may lead to overtopping of the road surface by an ice sheet. Methods of combatting such icings generally involve movement of the icing condition to a less sensitive location. Fire-pots, steaming and fencing procedures are commonly used by highway departments to control or remove icings.

FUTURE RESEARCH

Many of the current erosion control practices used in northern latitudes have been developed in southern climates and modified to suit the presence of permafrost. The various practices should be thoroughly researched and documented in relation to different terrain types and conditions to determine the limitations, as well as the successes, of each practice.

The most useful and significant research would be done on recently completed projects where erosional impacts are fresh. Two transportation routes that would be eminently suitable for research are the recently completed portions of the Dempster Highway and the Trans-Alaska Oil Pipeline, and the associated haul roads.

Transportation projects that are in the planning stage should budget for surveillance programs to monitor the performance of erosion control measures. The programs ideally should be in place prior to commencing the construction. The following types of information should be obtained from surveillance activities:

- a) Effect of grading practices on permafrost degradation and measured levels of stream siltation.
- b) Benefits and disadvantages of providing a compacted snow pad for access to and along a transportation facility.
- c) Effects on terrain of various clearing practices. For instance, does hand clearing have a smaller impact than machine clearing; what constraints must be applied to machine clearing methods to achieve a level of damage equivalent to, or less than, that associated with hand clearing?

Trials should be conducted to test the effectiveness of various erosion control methods in troublesome terrains. For example, the optimum angle of cutting a slope in ice-rich, fine-grained soil is not easily assessed in advance. Past excavation practices in an area are generally applied to new construction, regardless of whether they are the most suitable from the standpoint of erosion control.

It is generally agreed that the growth of a vegetative mat is the best means of assuring long-term protection against erosion. Extensive research has been conducted into the best plant species available for use in northern climates during the construction of the Trans-Alaska Oil Pipeline and in the development of plans for the Alaska Highway Gas Pipeline. This research should be continued and extended to other northern development projects.

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