# SOIL INSTABILITY ON SLOPES IN REGIONS OF PERENNIALLY-FROZEN GROUND

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Synopsis

Road construction in many parts of Alaska north of the Alaska Range and elsewhere in northern latitudes must contend with problems resulting from intensive frost action and the presence of perennially-frozen ground. Because of poor drainage, wet soils, disturbances caused by repeated cycles of freezing and thawing, and the presence of a glide plane at the surface of the perennially-frozen ground, slopes subject to rapid creep are much more common than in more temperate regions. In tundra areas the soil is covered by a mat of shallow-rooted vegetation which modifies but does not prevent the characteristic soil movements on slopes. Special precautions must be taken to cope with these conditions during highway construction and maintenance.

Soil movements on slopes produce a set of characteristic micro-relief features including soil terraces (solifluction terraces, altiplanation terraces), soil lobes (solifluction lobes, zunge), peat-mound stripes, peat rings, tussock-birch-heath stripes, rock stripes, and swales. Many construction problems on Seward Peninsula can be anticipated by identification of these features along proposed routes. Recognition of their significance permits the field worker to estimate the character and degree of instability of the soil, the drainage conditions, and the danger of subsidence upon thaw in areas in which these features are found. In many localities, study of the microrelief features would assist in selecting the best of several routes.

Frost action in soil of arctic regions creates unusual problems in the construction and maintenance of roads. Roads built on perennially-frozen silt or peat are subject to considerable subsidence if the silt or peat is allowed to thaw. Flood plains and perennial springs are sites of winter "icings" (Muller, 1945, p. 76) that cover roads and make them impassable. Movement of soil on gentle slopes causes difficulty in maintaining road cuts and grades on hillsides. Despite such movement, in the tundra regions 1/ of Alaska the slopes afford the best location for road construction.

Instability of soil on slopes in arctic regions manifests itself in such microrelief features as soil terraces, lobate terraces, soil lobes, tundra mudflows, and stone stripes. Most of the field studies on which this report is based were confined to the Seward Peninsula within the coastal tundra zone. The principles presented here, however, are believed to apply to tundra regions elsewhere.

Seward Peninsula, which is between the Arctic Ocean and the Bering Sea in west-central Alaska, has a rigorous continental climate, with wet cool summers and cold winters. Frequent periods of alternating freeze and thaw occur in early summer and fall. Peaty soils from 1 to 30 ft. thick cover the floors of most valleys, lower slopes, and summits of low hills. Sandy soils mantle lower slopes of hills composed of schist, marble, and slate and cover the surface of older lava flows present at several localities. Large areas underlain with peaty silt or muck are present in the valley bottoms, on lower slopes of dissected uplands, and on coastal plains. Nearly all soils, except pure sand, are wet as compared with soils of temperate regions. Even on hill summits silty soils are wet, plastic, and difficult, if not impossible, to drain.

Most of Seward Peninsula is beyond the Arctic timber line; the vegetation consists of mosses, sedges, dwarf willows, and small birch and heath shrubs. Spruce grows in the southeastern part, where small amounts of it are cut for rough timber.

1/ Tundra is defined here as those areas in high latitudes in which timber is lacking and the ground bears a partial or complete cover of sedges, willows, dwarf birches, mosses, and lichens.

During the summers of 1947-1950, the writers studied processes of intensive frost action and related phenomena on Seward Peninsula. This project was part of the permafrost program of the U. S. Geological Survey financed in part by the Corps of Engineers, United States Army. The present report is a by-product of that study.
Sincere appreciation is expressed to L. L. Ray and F. C. Whitmore, Jr., for their helpful criticism during the preparation of this report.

## Highway Construction Methods

In 1949 Seward Peninsula had 350 miles of road and tramway (Mr. J. D. Hudert,

Figure 1. Road Construction in Area of Perennially Frozen Peat and Silt Near Council, Alaska. Gravel is Laid on Tundra without Disturbing Surface Vegetation.

District Engineer, Alaska Road Commission, personal communication). The road net consists of a group of connected roads serving mining areas near Nome and several short, isolated roads extending inland from other coastal towns. Traffic is light, and consequently roads are constructed as cheaply as possible; none are paved. No attempt is made to keep the roads cleared of snow during winter except in the city of Nome.

Areas mantled with muck and silt are avoided in highway construction, because the surfaces are poorly drained and subject to subsidence if the perennially frozen peat and silt are allowed to thaw. A 4-ft. layer of gravel was put on a road north of Nome in 1941, according to Mr. Hudert; by 1950, because of subsidence, the surface was level with the surrounding terrain. Where these areas must be crossed, roads are constructed by placing gravel upon the undisturbed vegetation in order to minimize subsidence from deep thawing (Fig. 1). Part of a road across deep, frozen silt was constructed by removing 1 to 3 ft. of the surface soil along the right-of-way and using it for a subgrade. The remainder of the road had no subgrade preparation prior to spreading gravel on the surface. The part that had subgrade preparation has required the more maintenance, as severe subsidence and erosion have formed ditches as much as 20 ft. deep along the sides of the road.

Most valley bottoms and lowland areas are underlain by perennially frozen silt and peat from 6 to 50 ft. thick. Bare gravel is exposed adjacent to the channels of many streams, however, and is one of the best sources of road material. On slopes bedrock is commonly near the surface, mantled by only a few feet of soil and weathered rock.

Roads have been constructed on gravel bars along some small, swift streams. The bars are cleared and graded with bulldozers. Fords are required at close intervals in order to take advantage of bars on alternate sides of the stream. Such roads are not satisfactory in areas of heavy traffic, however, because they are impassable during high-water stages in summer. Flood-plain icings along most streams render parts of the roads impassable during winter. According to Mr. Hudert, an icing more than 8 ft. thick formed across a road in the winter of 1949-50. Because of threats from these sources, it is commonly desirable to avoid the valley bottoms and lowlands, and to build roads on the valley slopes. Construction on slopes, however, present problems unique to the Arctic.

## Instability on Slopes

Creep resulting from frost action is a primary factor in moving masses of surficial material downslope in tundra regions. Soils also are transported by slow and rapid viscous flow. Running water, one of the most important agents of erosion in temperate regions, is of minor importance. The relative intensity of creep and viscous flow determines the form of the resulting microrelief features.

Differential movement of rock fragments in fine-grained soil forms garlands and stripes of stones. These features have been described by Sharp (1942). They commonly occur in the higher and steeper parts of the slopes, upslope from the terrace forms and mudflows. Fragments are broken from bedrock by congelifraction or frost riving (Bryan, 1946, p. 627) and moved individually downslope by creep. Continued congelifraction reduces them until the deposit is predominantly silt. The deposits of silt, then, are moved farther downslope by creep and viscous flow and eventually form soil terraces, lobate terraces, soil lobes, and mudflows. Ideally rubble, stone stripes, and garlands extend downslope to soil lobes, soil lobes down to lobate terraces, and lobate terraces down to soil terraces. Tundra mudflows occur in areas of soil lobes and lobate terraces but are more common on steeper slopes. The zone between the terrace forms and the rubble forms is marked by a conspicuous break in slope. Terrace forms develop on slopes locally as steep as 25 deg., usually less than 20 deg.

## Creep

"Creep" is defined by Sharpe (1938, p. 21) as "the slow downslope movement of superficial soil or rock debris, usually imperceptible except to observations of long duration." It results chiefly from expansion of the soil normal to the slope during heating or freezing followed by vertical subsidence upon cooling or thawing. Downslope movements that result from wedging of the soil by plant roots and from burrowing by animals contribute to creep. Sharpe regards viscous flow as a component of creep; we regard creep and viscous flow as two distinct processes between which, however, there is a complete gradation.

Soil involved in creep moves primarily during the autumn freezing cycle. Wet soils are distended upon freezing, owing to the segregation of lenses of clear ice. Individual crystals of ice within the lenses grow by elongation of their axes, which are oriented normal to the cooling surface. (Taber, 1943, p. 1456)

No part of the substratum can be termed a "glide plane" during the progress of creep. Soil movement downslope is greater in the surface layer than at the base of the seasonally thawed layer because the surface, on freezing, is distended more, and thus moves farther horizontally from its original position. Vertical subsidence upon thawing consequently moves the surface material farther downslope than the underlying layers. This horizontal-vertical step process is illustrated in Figure 2A.

The rate of downslope creep is not constant over the entire slope. When the rate of

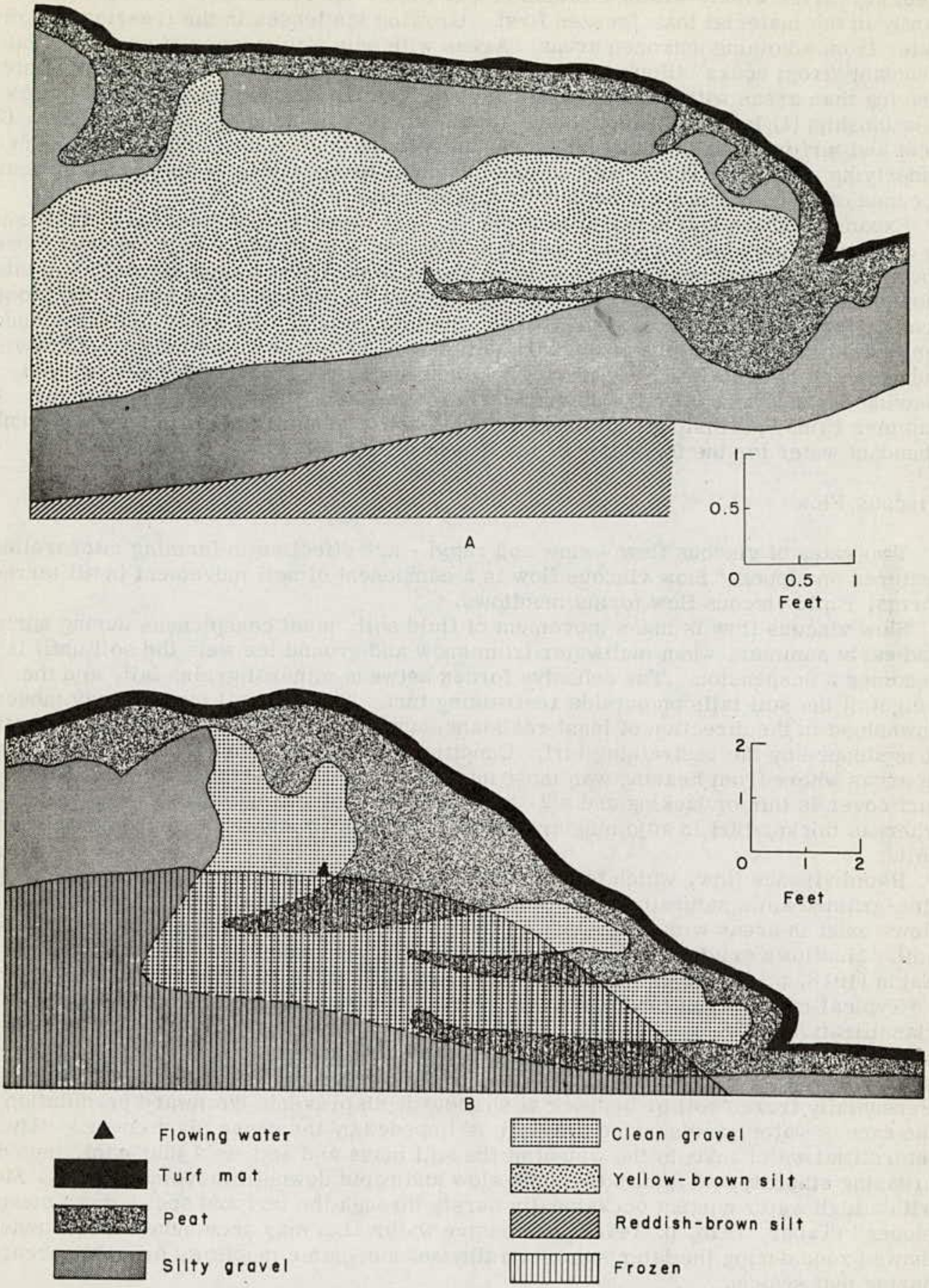


Figure 2. Diagrammatic Illustration of Creep Mechanism and Terrace Formation. (A) Theoretical mechanism of creep. Wide black bars represent theoretical columns of soil whose distension upon freezing is shown by thin lines parallel to slope. Upon thawing, columns bend downslope, owing to vertical subsidence of soil. (B) Illustration of terrace formation by creep, horizontal thrusting, and viscous flow. Soil moves downslope farther than vertical subsidence would carry it, as it is pushed by frost thrusting, and it flows.

freezing varies widely within a radius of a few feet, ice lenses are formed most abundantly in the material that freezes first. Growing ice lenses in the freezing soil draw water from adjoining unfrozen areas. Areas with only a thin cover of peat or areas of abundant "frost scars" (Hopkins and Sigafoos, 1951, p. 66) are subject to more intense heaving than areas with a thick mantle of peat. Several factors are involved in this relationship: (1) Ice lenses form more abundantly in silty soil than in turf or peat. (2) Peat and turf form an insulating blanket that retards the freezing and thawing of the underlying soil. (3) Thick mats of roots, stems, and peat resist disruption by heaving because of their greater strength over thinner mats of turf.

Expansion of the soil below breaks the thin turf cover and permits bare frost scars to develop. Continued expansion enlarges the frost scars and the soil involved moves downslope. Heaving normal to the slope, vertical subsidence upon thawing, and lateral movement by thrusting move the soil over the turf on the downslope side of the frost scar or force the turf into a small ridge. Simultaneously, soil moves out from under the turf on the upslope side of the bare soil area. This type of downslope soil movement, which is illustrated in Figure 1B, constitutes creep. The intensity of frost heaving depends also upon the amount of water available during autumn freezing. Late summer rains, persistent snowbanks, ground-water seeps, and swampy areas furnish abundant water for the formation of ice lenses in late autumn.

## Viscous Flow

Two rates of viscous flow - slow and rapid - are effective in forming microrelief features on slopes. Slow viscous flow is a component of soil movement in all terrace forms; rapid viscous flow forms mudflows.

Slow viscous flow is mass movement of fluid soil, most conspicuous during spring and early summer, when meltwater from snow and ground ice wets the soil until it becomes a suspension. The cohesive forces between mineral grains fail, and the weight of the soil falls on outside restraining turf. The wet soil mass slowly moves downslope in the direction of least resistance until the soil is no longer fluid or until it is stopped by the restraining turf. Conditions are most favorable for viscous flow in areas where frost heaving was most intense during the previous autumn. Here, turf cover is thin or lacking and a 2- to 6-inch layer of soil has thawed and is fluid whereas thicker turf in adjoining areas is still frozen firmly to the underlying frozen soil.

Rapid viscous flow, which forms mudflows, consists of sudden fluid movement of fine-grained soils saturated with water. Exceptionally favorable conditions for mudflows exist in areas with a perennially frozen substratum on steep slopes mantled with soil. Mudflows originating under these conditions are described and illustrated by Eakin (1918, p. 50 and pl. 8), Capps (1940, pp. 167-168), and Taber (1943 and pl. 13).

Typical mudflows of tundra regions represent a type not included in Sharpe's classification (1938, pp. 58-61). Mudflows occur on sloping surfaces mantled with silt-rich soil covered with a turf mat that is locally underlain by fibrous peat. During spring, surface layers of soil are saturated with water set free by seasonal thawing. Perennially frozen soil or bedrock at shallow depth prevents downward percolation of the excess water, and surface drainage is impeded by the dense plant cover. "The interstitial water adds to the weight of the soil mass and acts as a lubricant, thus decreasing stability and facilitating both slow and rapid downhill movement. . . . Mud with a high water content occasionally bursts through the turf and spews down steep slopes" (Taber, 1943, p. 1458). Excessive water also may accumulate in the annually thawed zone during the later summer rainy season; some mudflows probably occur during that season.

Mudflows in areas of shallow annual thaw are limited to that zone; thus they commonly involve only a thin layer of soil. Commonly the slopes are indented 3 to 6 ft. at the heads of flows; one flow illustrated by Taber (1943, pl. 13B), however, left a scarp 10 ft. high at its head. Eakin (1918, p. 50) described a mudflow that started on a 10 deg. slope and stopped on an 8 deg. slope.

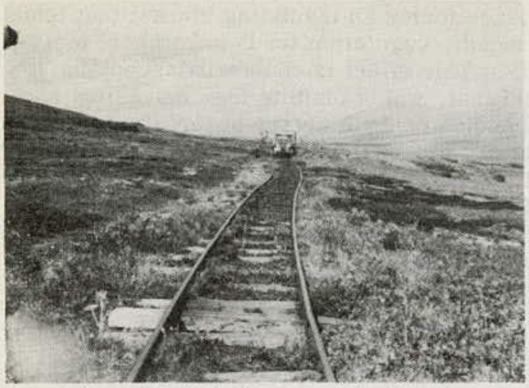

Figure 3. Roadbed of Seward Peninsula Tramway Displaced by Movement of Active Lobate Terrace.

Slope Movements as Seen in the Field

Creep and viscous flow rarely occur separately, but one process or the other generally predominates in the movement of given bodies of soil. A complete gradation exists between the two processes. Soil heaved by freezing flows slightly during subsidence. Soil moved predominantly by viscous flow is heaved normal to the slope when it freezes. During autumn, when the soil is relatively dry, creep may predominate because freezing is progressing and little water is available for viscous flow. In the spring, when the soil is wet and plastic, it moves predominantly by viscous flow because excess water is present. Part of a microrelief feature may be formed by viscous flow, another part by creep, the processes responding to varying drainage conditions or varying insulating properties of the plant cover, respectively.

These processes combine to produce net downslope movements perceptible to observations continued over periods as short as one year. Roadside and placer ditches on Seward Peninsula are being filled slowly by sod-covered soil encroaching from upslope. T. L. Péwé (personal communication) reports similar phenomena along ditches where spruce-birch forest was removed at altitudes of approximately 1,200 feet near Fairbanks, Alaska. A ditch 15 feet wide, cut through unconsolidated material on Seward Peninsula, has been completely obliterated in places in the 40 years since the ditch was abandoned. The Seward Peninsula tramway has been displaced as much as a foot within the last decade where the tracks cross active lobate terraces (Fig. 3).

Climate ultimately determines the areal distribution of conditions favorable for creep and viscous flow. Local microclimatic variations in the number and intensity of annual freeze-thaw cycles are reflected by variations in the relative intensity of the two processes. Shallow movements, involving less than 6 inches of the surface soil, result from short-period cycles of freezing and thawing due to diurnal and air-mass temperature fluctuations. Frequent, intense, short-period cycles promote severe movements in the upper 3 to 6 inches of the soil but have little effect on the deeper layers, which are affected only by long-period, seasonal temperature fluctuations. The optimum climatic conditions for soil creep and flow are found in climates with large fluctuations between winter and summer temperatures and in climates with frequent summer frosts and winter thaws.

The intensity of movement varies with the character of the soil, if the angle of slope and moisture conditions remain constant. Rubbly soils lacking a silt or fine sand matrix undergo little perceptible movement. Grain size and shape are more important than the chemical composition of the soil. The grain size of arctic soils, however, is largely a function of the type of parent rock (Hopkins and Sigafoos). Soils with a high proportion of silt are most unstable and are subject to detectable movement on the gentlest slopes.

Figure 4. Front of Active Soil Terrace, North Central Seward Peninsula. Note Concentration of Boulders in Re-Entrant in Scarp at Center.

Slope movements due to creep and viscous flow are modified by the plant cover. A tight mat of roots, stems, and peat at the surface forms an insulating blanket that tends to maintain a high frost table. By retarding runoff, vegetation tends to promote moisture conditions favorable for slope movements. This effect is counterbalanced, in part, by the stabilizing effect of an elastic turf mat, which inhibits free movement of underlying soil. Creep and viscous flow proceeding beneath layers of turf produce a set of characteristic microrelief features that are discussed below. These features are best developed in areas of tundra vegetation, but they have been observed also at altitudinal timber line in Alaska. Activity of soil at timber line is indicated by bent tree trunks, split trunk bases, and irregular sequences of suppression rings within individual trees growing on the unstable ground.

## Microrelief Features

Soil terraces, lobate terraces, soil lobes, and mudflows are members of a continuous, gradational series of convex slope features that play an important part in the building and maintenance of roads on slopes. Soil terraces are formed chiefly by creep. Creep is the chief process involved in the formation of lobate terraces, but viscous flow plays a minor role. Soil lobes, on the other hand, are formed chiefly by slow viscous flow, aided by creep. Mudflows are formed by rapid, viscous flow of saturated soils. Soil terraces are found on relatively well drained slopes, lobate terraces on wetter slopes, and soil lobes and mudflows on slopes that are extremely wet during at least part of the year. All are confined to slopes ranging generally from 5 deg. to 30 deg.

## Soil Terraces

Soil terraces ("solifluction terraces") are described by Obruchev (1937) and many others. They are regular steplike or benchlike physiographic features formed by soil creep on slopes ranging from 5 deg. to 15 deg. (Fig. 4). They consist of abrupt escarpments 3 to 20 feet high extending 300 to 4,000 feet along the slope nearly parallel to the contour, capped by broad, gently inclined surfaces 100 to 600 feet wide.

The escarpments slope from 30 deg. to vertical, and locally they overhang. The terrace surfaces are inclined at angles of 3 deg. to 10 deg. in the direction of major slope; the slope is gentlest near the rear edge and steepest just upslope from the escarpment.

Turf and peat 0.5 to 1.5 feet thick, supporting a sedge sod, cover most of the terrace surface, including the frontal scarp, but may be lacking near the upslope edge. In the upper part of the scarp, the surface peat is folded and involuted into the underlying soil. At the base of the scarp, a long stringer of peat, representing overridden turf, extends several feet upslope beneath a layer of mineral soil (Fig. 5). The terrace soil generally consists of coarse, unsorted sandy silt containing abundant angular rock fragments ranging from a few inches to several feet in longest dimension. The soil ranges in thickness from 1.5 to 20 feet or more. It is thinnest beneath the upper part of the terrace surface and thickest at the downslope edge. Rocks are especially abundant just beneath the turf for a distance of a few feet above and below the scarp. The frontal scarp of some terraces consists entirely of boulders containing little or no fine material in the interstices. The bedrock surface, which underlies the terraces, generally is smoothly inclined and does not reflect the relief of the terrace surface. In some older terraces, however, a low escarpment is present in the bedrock surface beneath the terrace front.

The substratum of most soil terraces is perennially frozen at depths ranging from 3 feet beneath swampy areas at the rear of the terrace to 6 feet beneath the drier frontal portions. Relief of the frost table is a subdued expression of the surface relief. The soil thaws downward as a hummocky surface; each point is more or less equidistant from the surface directly above except as it is modified by insulating peat and vegetation of various thicknesses. The substratum of some terraces near Nome is unfrozen.

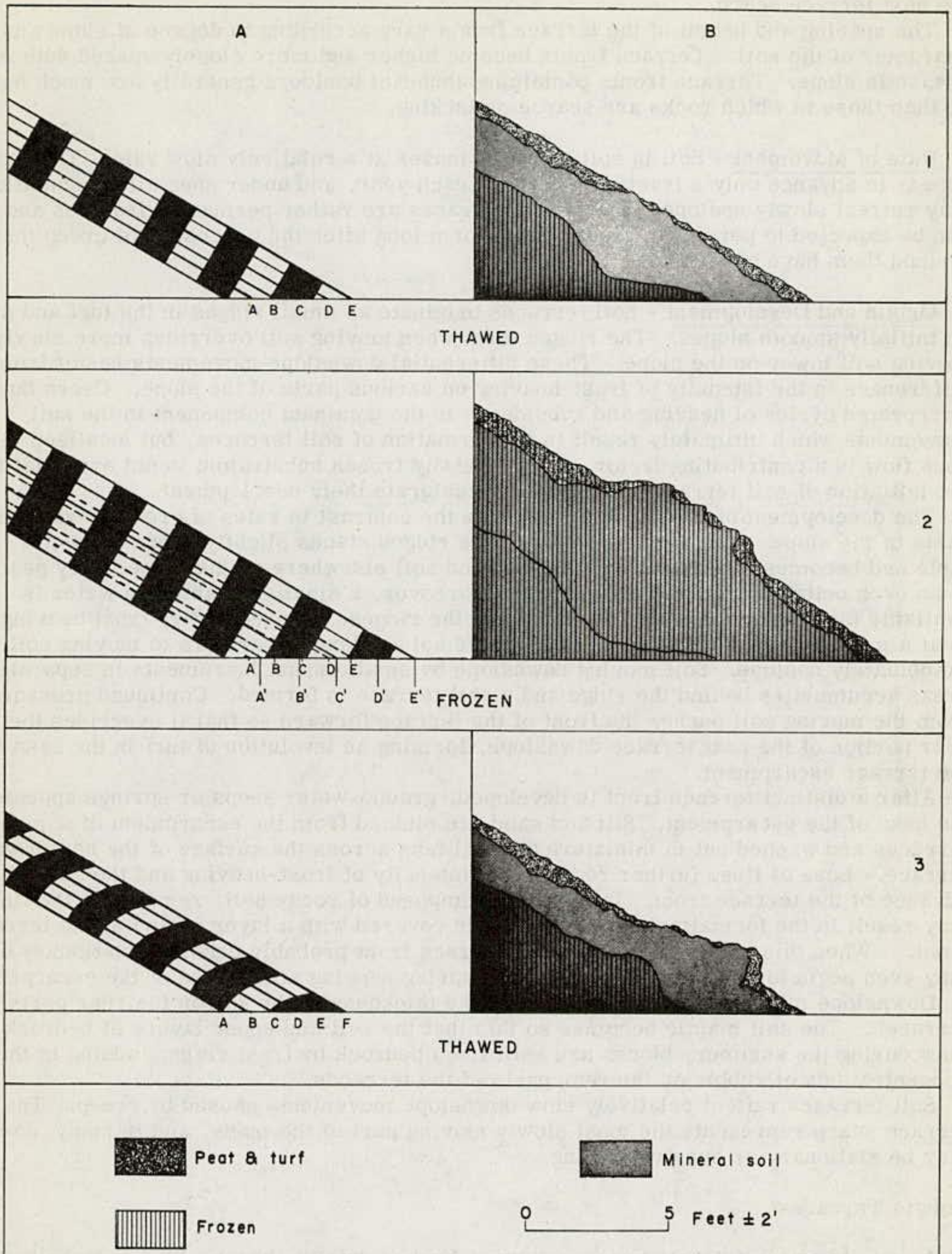


Figure 5. Cross Section Through Terrace Scarps. (A) Section Through Small Scarp. Note that scale is twice that of B. (B) Section Through Larger Scarp.

Seeps and small springs emerge at the base of frontal scarps and water runs in small rills to swampy areas at the rear of the terrace surface below. Water percolates into the soil near the middle of the terrace surface to re-emerge in seeps at the base of the next terrace scarp.

The spacing and height of the terrace fronts vary according to degree of slope and character of the soil. Terrace fronts become higher and more closely spaced with increase in slope. Terrace fronts containing abundant boulders generally are much higher than those in which rocks are scarce or lacking.

Rate of Movement - Soil in soil terraces moves at a relatively slow rate. The fronts appear to advance only a fraction of an inch each year, and under specialized conditions may retreat slowly upslope. Large soil terraces are rather permanent features and can be expected to persist in recognizable form long after the processes of creep that formed them have ceased to be active.

Origin and Development - Soil terraces originate as small ridges in the turf and soil on initially smooth slopes. The ridges form when moving soil overrides more slowly moving soil lower on the slope. These differential downslope movements result from differences in the intensity of frost-heaving on various parts of the slope. Creep due to repeated cycles of heaving and subsidence is the dominant component in the soil movements which ultimately result in the formation of soil terraces, but localized viscous flow is a contributing factor. A perennially frozen substratum is not essential for the initiation of soil terraces, but it does accelerate their development.

The development of turf ridges heightens the contrast in rates of creep on various parts of the slope. The thickened peat in the ridges stands slightly above the water table and becomes slightly drier than peat and soil elsewhere on the slope. Dry peat is an even better insulator than wet peat; moreover, a smaller quantity of water is available for the formation of ice lenses in the ridges. Consequently, frost heaving is at a minimum at these sites and the ridges act as flexible barriers to moving soil immediately upslope. Soil moving downslope by small annual increments in separated areas accumulates behind the ridge and a soil terrace is formed. Continued pressure from the moving soil pushes the front of the terrace forward so that it overrides the rear portion of the next terrace downslope, forming an involution of turf in the base of the terrace escarpment.

After a distinct terrace front is developed, ground-water seeps or springs appear at the base of the escarpment. Silt and sand are sluiced from the escarpment of some terraces and washed out in miniature alluvial fans across the surface of the next lower terrace. Loss of fines further reduces the intensity of frost-heaving and the rate of advance of the terrace front. In terraces composed of rocky soil, removal of the fines may result in the formation of an open rubble covered with a layer of turf at the terrace front. When this stage is reached, the terrace front probably becomes stationary or may even begin to retreat upslope owing to spring sapping at the base of the escarpment.

Downslope migration gradually reduces the thickness of the soil in the rear parts of terraces. The soil mantle becomes so thin that the soil and upper layers of bedrock thaw during the summer; blocks are split from bedrock by frost riving, adding to the concentrations of rubble on the rear parts of the terraces.

Soil terraces reflect relatively slow downslope movements caused by creep. The terrace scarp represents the most slowly moving part of the mass, and in many cases may be stationary or even retreating.

## Lobate Terraces

Lobate terraces ("lobate benches," "turf-banked detritus benches") are described and illustrated by Taber (1943, pp. 1460-1463, pl. 4) and many other previous authors. They are characterized by festooned escarpments, 1 to 5 feet high, on slopes ranging from 7 to 20 deg. (Fig. 6). The terrace scarps are vertical or overhanging and separate the more gently sloping terraces, which are inclined at 5 to 10 deg. Individual

Figure 6. Lobate Terraces Along Road Between Solomon and Council, Alaska.

lobes are 20 to 100 feet wide; the frontal scarps are spaced at intervals of 10 to 100 feet on the slope. Hummocks, cracks, folds in the turf, miniature lobate terraces, and lobate frost scars with fronts 0.2 to 1 feet high mark the surfaces and indicate movement of soil by frost heaving and downslope adjustment to gravity. The vegetation cover consists of grasses and low, matted woody plants.

Lobate terraces are found on slopes throughout the tundra region, and at and just above altitudinal timber line on slopes within the forested country (Sigafoos, in press). Open stands of spruce trees and alder shrubs characterize the forest margin. The trees grow on the terrace scarps and surfaces. Trees growing on lobate terraces at altitudinal timber line on Seward Peninsula are commonly bent and some have split trunk bases. Studies of annual tree rings show periods of suppressed growth that are due to disturbance of the roots by moving soil.

Most of the terrace surfaces are covered with turf and peat, 3 to 6 inches thick, but many areas of bare soil break the cover. Stringers of peat extend several feet upslope in the soil beneath the scarp. Buried layers and infolded masses of living Sphagnum moss and peat, as in soil terraces (Fig. 2B), indicate recent movement.

Lobate soil terraces are composed of unsorted, sandy silt with many angular rock fragments a few inches to 2 feet in longest dimension. The soil ranges in thickness from 1.5 to 6 feet; it is shallow at the rear of the terraces and deepest under the scarp. Rock fragments are most abundant in the frontal scarp beneath the turf. Slabby or platy fragments generally rest on edge. Lundqvist (1949) believes that their orientation indicates their direction of movement. As the terrace front advances, the stones are forced out of the soil by frost action and are rolled farther downslope. Loose soil or voids occur within the scarp on the upslope side of the boulders, offering further evidence of downslope movement.

The bedrock forms a smooth, inclined surface at depths of 3 to 6 feet below the turf. Soil beneath many active lobate terraces is not perennially frozen; frost table may lie below the bedrock, or perennially frozen ground may be lacking. Perennially frozen soil is not essential for the formation of the terraces.

Surfaces of lobate terraces are generally better drained than well-developed soil terraces during most of the summer. The driest soil in lobate terraces is immediately above the scarp; the wettest areas are at the back, for ground water emerges from the base of the next higher scarp and flows a short distance across the surface. Lobate terraces commonly are limited to the wetter parts of slopes; they are found below ground-water seeps, and below persistent snowbanks and in wide re-entrants where surface drainage is concentrated.

Lobate terraces are only temporary features of hill slopes. Once they become stabilized by changing climate, by angle of slope, or possibly by deeply rooted trees, they are soon destroyed by small-scale frost action and gullying. Most recognizable lobate terraces, therefore, are active.

Rate of Movement - The soil of lobate terraces moves downslope more rapidly than that in soil terraces. The rate may vary, however, from year to year. Tree-ring studies of spruce near Council indicate periods of stability as long as 30 years; these long periods are separated by 1- to 5-year periods during which the soil moved several inches to 1 foot. Injury of roots by moving soil retards growth and is recorded in the cross section of the trunk as annual layers of wood that are much thinner than those grown during years of soil stability. Series of eccentric rings are evidence that the tree has been tilted (Pillow and Luxford, 1937, pp. 11-13), for tilted coniferous trees grow more rapidly on the lower side of the stem.

The rate of terrace movement depends upon the frequency and areal extent of soil movement. Movement of soil probably occurs annually on the wettest slopes and may be as much as 1 to 6 inches. Washburn (1947, p. 92) reported that the center of a small terrace on Victoria Island in Arctic Canada moved 1.75 inches in 7 months, June to January. The track of the small railroad north of Nome, Alaska, constantly moves out of alignment where it crosses lobate soil terraces. The track was laid without grading and requires frequent realigning.

Origin and Development - Lobate terraces, like the larger soil terraces, originate as turf ridges. Creep is the chief mechanism of movement but viscous flow also plays a prominent role in the development of the lobate forms. Late-lasting seasonal frozen ground impedes drainage and contributes moisture to the upper layers of soil during the critical spring thaw season. Moisture from external sources such as snowbanks and ground-water seeps appears to be essential to the formation of lobate terraces.

The relative importance of the roles of viscous flow and creep in the development of lobate terraces varies widely. In some terraces movement by creep predominates; in others, movement is mostly by viscous flow. In general, lobate terraces resulting from creep are larger, more widely spaced, and more regular in outline than those formed by viscous flow; the larger ones approach the form of soil terraces. Lobate terraces formed mostly by viscous flow are smaller, lower, more closely spaced, and approach the garland form of soil lobes. Nearly 50 percent of the surfaces of lobate terraces that move chiefly by creep are barren of vegetation and are covered with frost scars, ridges, splits in the turf, and low hummocks. Surfaces of lobate terraces that move chiefly by viscous flow are covered with an unbroken turf and are relatively smooth. Lobate terraces that move chiefly by viscous flow are found in re-entrants of slopes around drainage lines, or on broad, wet slopes where well-defined drainage lines are lacking. Lobate terraces that move chiefly by creep occur on the lower slopes of the better drained spurs.

### Soil Lobes

Soil lobes are probably equivalent to the "Zunge" of various German authors. They are tonguelike microrelief features 1 to 5 feet high, 10 to 30 feet wide, and 20 to 150 feet long; they are formed chiefly by viscous flow and are found on slopes ranging from 20 to at least 25 deg. Their surfaces slopes at angles of 10 to 15 deg., or less steeply than the general slopes of the hillside. At the upslope end of the lobes, a small, steep-walled, cirquelike indentation in the hillside is generally present. The volume of the depression is approximately equal to the volume of the lobe. Most of the central part of the soil lobe is barren of vegetation or supports only a few scattered plants. Matted woody plants and grasses form a complete cover on the outer edge and scarp of the lobes.

Soil lobes are found downslope from persistent snowbanks and ground-water seeps. Bedrock forms an inclined plane at depths of 1 to 5 feet beneath the surface. The bedrock may be perennially frozen at depth.

Drainage of the lobes is poor, and during spring thaw the soil is extremely wet and nearly fluid until it has thawed to a depth of a foot or more. Soil is thawed to these depths 20 to 30 feet downslope from snowbanks. Only the well-drained soil at the upper edge of the scarp is firm; that upslope is nearly fluid. In summer the soil becomes drier, but by comparison with soils in temperate regions, it is wet.

Rate of Movement - Measurements of the rate of soil movement in soil lobes are being made by the writers near Nome. It is believed that soil lobes move faster than lobate terraces and soil terraces because movement is more frequent. Soil in the lobes moves short distances, but it moves a few inches each spring. During extremely wet years movement is greater. Because of the small size of the soil lobes, even rapid rates of movement do not result in the transport of much material downslope.

Origin and Development - Soil lobes originate in scattered areas of thin soil on steep slopes downslope from persistent snowbanks and ground-water seeps. Soil accumulates on the slope by increased frost riving and by deposition from rills of running water. Where soil accumulates to depths of 1 to 3 feet and meltwater wets the soil until it is nearly fluid, slow viscous flow occurs. Movement continues until the moisture content in the soil drops or the degree of slope lessens. Creep then becomes more effective in moving the soil. Water draining from the soil is filtered through the turf and little soil is removed from the lobes by running water; after spring snows have melted, the soil in the lobes becomes dry enough to retard viscous flow.

Soil moves downslope under the turf cover, pushing the frontal scarp forward, breaking and stretching the turf on the upslope surface of the lobe. Increased frost heaving on this surface effectively prevents the growth of plants.

### Tundra Mudflows

Tundra mudflows are characteristic features of certain undisturbed tundra areas

Figure 7. Mudflow Scar 15 Mi. North of Nome, Alaska. Note niche at left of man, hummocky topography in right foreground.

(Figs. 7, 8). They result from the sudden spewing of fluid soil down steep slopes, breaking the retaining turf. On Seward Peninsula, semicircular niches 1 to 4 feet deep and 20 to 50 feet across have been left when soil and rock suddenly moved downhill. Below the shallow scar, irregular heaps and mounds of rock, soil, and turf are formed where the flow stopped. The niches and mounds of old and recent mudflows completely cover some 20 to 30 deg. slopes underlain by weak, weathered bedrock. Isolated mudflows are common on slopes as low as 10 deg. and are locally associated with soil terraces or lobate terraces.

Recent flows can be identified by bare soil and decomposed bedrock in the floor of the depression and around the mound of moved soil; older flows can be identified by a ragged, weedy vegetation in the depression and a festoon of shrubs around the lower side of the mound of soil. Mudflows have been reported from other parts of Alaska by Capps (1940, p. 168) and Taber (1943, p. 1458) and from the Kluane Lake region of Yukon Territory, Canada, by H. M. Raup (personal communication).

Figure 8. Recent Mudflow 15 Mi. North of Nome, Alaska.

Small mudflows can be expected during spring and summer in artificial cuts in fine-grained soils (Muller, 1945, p. 74).

Origin and Development - Mudflows occur when the vegetation mat can no longer retain a semifluid mass of soil and decomposed rock on a slope. If unweathered bedrock approaches the surface or if the ground is perennially frozen, the surface water cannot percolate downward, and consequently it accumulates in the upper layers of the soil. Severe heaving in autumn is sufficient to break the turf, allowing the saturated soil to flow downslope the following spring. If the period of severe frost heaving is preceded by a period of heavy rains, mudflows are likely to occur. Mudflows are common in the spring of the year following a wet summer and an autumn with numerous periods of freezing and thawing.

## Identification, Interpretation, and Significance of Features

Microrelief features on slopes can be recognized on aerial photographs by an experienced observer. Many construction problems can be anticipated by the identification of these features along proposed routes if the worker is thoroughly familiar with them on the ground. Recognition of their significance permits the field worker to estimate the character and degree of instability of the soil, the drainage conditions, and the danger of subsidence by thaw in areas where these features are found. In many localities, study of the microrelief features can assist in selecting the best routes for roads. The following descriptions are intended to assist in clarifying the details for the worker who is familiar with the general characteristics of tundra terrain.

### Soil Terraces

Soil terraces can be recognized on aerial photographs scaled 1: 40,000 or larger. They occur on the lower parts of slopes; lines of willow shrubs fringe the scarp base and appear as lines of rounded dots composed of various shades of dark gray. The scarp fronts are arcuate, closely parallel to the contour of the hill. The surface of the terraces are gently sloping and are light gray. Darker gray patches near the back of the surface represent low heath plants growing in less well drained, peaty soil.

Areas with soil terraces are among the more favorable areas available for road construction because the slopes are gentle and these areas lie near valley bottoms. Roads can and should be built with a minimum of artificial cuts at the roadside. It is impractical to lay subgrade on bedrock in most soil-terrace areas because of the great thickness of overburden and because much of the overburden is frozen. Surface heaving and downslope creep are less intense, however, than in areas with lobate terraces, soil lobes, or mudflows. Removal of the surface mat of peat and vegetation will cause surface subsidence in some soil-terrace areas and will result in severe gullying in many areas. Drainage is difficult, especially within 100 feet downslope from terrace scarps. Small mudflows will form on faces of cuts and excavations and will clog drainage ditches.

## Lobate Terraces

Lobate terraces can be recognized on aerial photographs scaled 1: 40,000 or larger. A lobate terrace appears as a scalloped line trending parallel to the contour of slopes of 7 to 20 deg., steeper than those on which soil terraces occur. The dimension of the lobate terraces parallel to the direction of slope is greater than the width of an individual lobe. The upper edge of the scarp is lighter gray than the scarp face and the surface of the terrace. Willow shrubs grow below the scarp, forming a line of rounded dots parallel to the scarp. The surface below the scarp is light gray, contrasting with the darker willow shrubs. Lobate terraces are best developed below persistent snowbanks.

Areas with lobate terraces are considerably less favorable for road construction than areas with soil terraces because of steeper slopes, poorer drainage, and greater soil instability. Artificial faces will be necessary along much of the roadside and these will be subject to slumps and small mudflows throughout most of the thawing season. Surface heaving and downslope creep are intense, but deformation of the roadbed can be reduced by excavating overburden to bedrock and replacing with suitable fill. Subsidence due to abnormal thawing will be negligible. Wet conditions prevail throughout lobate-terrace areas, especially during spring and early summer, and good drainage will be difficult to maintain.

## Soil Lobes

Soil lobes appear as tongues extending parallel to the direction of maximum slope. They can be identified on aerial photographs scaled larger than 1: 40,000. The dimension parallel to the slope is two to four times the width of the lobes. The slope of the surface is less than the overall slope of the hillside. Isolated patches of willows grow around the margin of the lobes. Soil lobes are associated with lobate terraces on slopes; the forms are gradational from one to the other.

Areas with soil lobes are somewhat less favorable for road construction than areas with soil terraces because of steeper slopes and because of greater soil instability in local areas. They are more favorable than areas of lobate terraces because drainage is better and overburden is thinner. Artificial cuts will be necessary along most of the roadside but these will be composed largely of fractured bedrock, rather than overburden. The wetter areas will be subject to slumps and small mudflows, but these can be reduced by stripping overburden for several tens of feet upslope from the top of the cut. Surface heaving and downslope creep are locally intense, but deformation of the roadbed can be reduced by excavating overburden to bedrock in these areas and replacing with artificial fill. Subsidence due to abnormal thawing will be negligible. Extremely wet conditions prevail locally, and in these areas good drainage will be difficult to maintain.

## Tundra Mudflows

Tundra mudflows consist of semicircular depressions merging downslope into fan-like convexities. They extend several hundreds of feet parallel to the direction of slope.

TABLE 1. CHARACTERISTICS OF CERTAIN MICRORELIEF FEATURES FOUND ON SLOPES

| Feature | Topographic expression and position | Development process | Soil and Substratum | Vegetation | Water table and perennially frozen ground | Character during periods of thaw | Appearance on aerial photographs | Construction Characteristics |
|---|---|---|---|---|---|---|---|---|
| Soil Terrace | Terrace sequences spaced at intervals of 100 to 600 feet on lower hill slopes of 5 to 15°. Abrupt terrace escarpments steeper than 30°, height 3 to 20 feet, extend 300 to 4,000 feet parallel to slope contours. | Dominantly creep. | Turf and peat 0.5 to 1.5 feet thick overlying sandy silt 1.5 to 20 feet thick; abundant angular boulders, especially in escarpment. | Sedges, matted and low shrubby heaths, and mosses on terrace surface. Willows, heaths, and other shrubs fringe base of escarpment. | Perennially frozen ground generally present within 3 to 6 feet of surface; occasionally absent. Water table controlled by perennially frozen ground, but close to surface, emerging at base of escarpment. | Escarpment well drained; standing water or high water table close to surface at escarpment and at back of terrace. Seepage zone at base of escarpment. | Identifiable on photographs on a scale of 1:40,000 or larger as nearly continuous, arcuate escarpments closely parallel to slope contour. Rounded dots of various shades gray represent vegetation at escarpment border; vegetation of terrace surface shows a lighter gray. | One of the more favorable sites for roads because of wide distribution on basal slopes. Surface heaving, downslope creep less intense. Drainage less difficult. Some terrace areas subject to excessive subsidence, severe gullying upon disturbance of surface vegetation. |
| Lobate terrace | Scalloped escarpments bordering terraces spaced at intervals of 10 to 100 ft. on 7° to 20° midslopes of hills. Escarpments 1 to 5 feet high extend 100 to 500 feet parallel to slope contours. Individual lobes 20 to 100 feet wide. | Creep and viscous flow. | Turf and peat 0.25 to 0.5 foot thick overlying unsorted sandy silt 1.5 to 6.0 feet thick; abundant angular boulders. | Matted woody plants on surface. Low shrubby willows fringe base of escarpment. | Generally perennially frozen below the bedrock surface. Water table moves down with thawing of frozen ground. | Soil wet and semifluid during spring thawing season. Dry, well drained, later during dry weather; wet poorly drained during rainy weather. | Identifiable on photographs on scales of 1:40,000 or larger as scallops convex downslope but roughly parallel to slope contours. Length parallel to contour greater than width of individual lobes. Surface of scarp dark gray, scarp edge lighter | Less favorable for roads because of instability of soil, poor drainage. Shallow soils permit foundations on bedrock but surface heaving, downslope creep intense. Drainage very difficult during spring. Faces of cuts subject to small mudflows. |
| Soil lobe | Tonguelike lobes on upper hill slopes of 20° to 25°. Height 1 to 5 feet; width 10 to 30 feet; downslope length 20 to 150 feet. Lobe surface slopes 10° to 15°. Small steep-walled indentation at upslope end equal in volume to that of lobe. | Dominantly viscous flow; some creep. | Turf 0.25 to 0.5 foot thick over sandy silt 0.5 to 5 feet deep. Bare soil exposed at back of soil lobe. | "Weedy" vegetation of scattered plants at back of lobe. Matted willows, grasses, and sedges on scarp. Isolated patches of willow fringe base of scarp. | Perennially frozen below the bedrock surface. Water table moves down with thawing of frozen ground. | Soil wet, semifluid during spring thaw. Dry, well drained, and firm during remainder of summer. | Identifiable on photographs at scale larger than 1:40,000. Length parallel to slope 2 to 4 times width. Isolated patches of willow appear as rounded dots of various shades of gray around lower margin of lobe. | Somewhat less favorable for roads because of steep slopes. Shallow soils permit foundations on bedrock. Surface heaving, downslope creep locally intense. Drainage generally good but locally difficult throughout year. Faces of cuts locally subject to minor landslides and mudflows. |
| Tundra mudflow | Semicircular niches upslope from fan of hummocky soil, turf, and rock. In groups on 20° to 30° slopes or as isolated features on 10° to 20° slopes. Niche 1 to 5 feet deep, 20 to 50 feet across, and 50 to 100 feet long. Debris pile proportional in size to scar. | Sudden viscous flow. | Turf 0.25 to 0.5 foot thick over silty soil 1 to 5 feet deep; abundant angular boulders. | Matted shallow-rooted plants in area prior to flow. "Weedy" plants and fragments of original vegetation after flow. | Perennially frozen below bedrock surface or 1 to 4 feet below turf. Water table moves down with thawing of frozen ground. | Soil wet, semifluid during spring thaw, Dry, well drained, and firm during remainder of summer. | Identifiable on photographs scaled 1:40,000 or larger. Semicircular niches upslope from hummocky fan of debris. Upper end of fresh fans very light grey; lower end darker and irregularly mottled. Older flows have darker tones throughout. | Very unfavorable for roads because of extreme instability of soil. Surface heaving and downslope creep intense. Drainage generally difficult. Road may be inundated or removed by new flows. |

On the downslope edge of the depressions are deposits of soil and rubble, forming low mounds. Mudflows on Seward Peninsula can be identified on aerial photographs scaled 1: 40,000 or larger.

Areas with mudflows are very unfavorable for construction of roads and should be avoided because of the extreme instability of the soil. Artificial faces will be necessary along much of the roadside and these will be subject to large mudflows, which can obstruct or destroy sections of road. Surface heaving and downslope creep are intense. In many areas it is impracticable to lay subgrade on bedrock, because of thick overburden. In other areas bedrock is deeply weathered and does not constitute a stable foundation. Subsidence due to abnormal thawing will occur in many mudflow areas. Drainage is difficult.

## Summary and Conclusion

Roads are preferably built on hill slopes in regions of perennially frozen ground because the hill slopes are subject to less heaving and less severe subsidence than the marshy lowlands and some hill summits, and because the roads are out of reach of the winter icings that occur along stream channels.

In regions of cold climate, weathered materials are transported downslope mostly by mass movement of soil and rock through processes of frost action, viscous flow, and gravity. The rates of movement - rapid or slow - depend upon the material, slope, amount of water available, and the type and density of plant cover. Slow mass movement of silty soil mantled with shallow-rooted, dwarf vegetation forms characteristic microrelief features on gentle slopes. Perennially frozen ground, seasonally frozen ground, or bedrock at shallow depths prevents downward percolation. Tight, silty soil inhibits lateral drainage, and a dense plant cover inhibits surface runoff and erosion. Under these conditions, the surface layers of soil become nearly fluid, especially during spring thaw, and the unstable soil forms soil terraces, lobate terraces, and soil lobes. If movement is sudden and extensive, mudflows develop.

All four features described are gradational in form, in areal distribution, and in origin. Soil terraces, the largest of these features, occur on gentler slopes, and are formed mostly by frost heaving and subsidence. Lobate terraces form on steeper slopes than soil terraces, are smaller, and result from frost heaving, subsidence, and viscous flow. A perennially frozen substratum is not necessary for their formation; persistent seasonally frozen ground or sloping bedrock close to the surface, which aids in maintaining a high moisture content in the soil, is sufficient for their initiation and development. Soil in lobate terraces moves in numerous isolated areas over the surface, resulting in net downslope movement of the scarp. Soil lobes are individual tongues of soil occurring downslope from persistent snowbanks or ground-water seeps on steeper slopes - 20 to 25 deg. Movement of the soil is by viscous flow and is most rapid in the spring, when meltwater is abundant and seasonally frozen ground is close to the surface. Perennially frozen ground is not necessary for the initiation or development of lobes, but their formation requies impervious bedrock close to the surface, or wet, fluid soils when seasonally frozen ground is near the surface. Mudflows result from the sudden flow of semifluid soil and rock downslope when the turf has been broken either by frost heaving or by the weight of the saturated soil. Mudflows are most common after a wet summer and an autumn with numerous cycles of freezing and thawing.

An understanding of the significance of these slope features on the ground would aid in determining the best location of roads and other installations in tundra regions. Recognition of the features on aerial photographs would aid in mapping of hill-slope conditions.

## References

1. Bryan, Kirk, Cryopedology - The Study of Frozen Ground and Intensive Frost-Action, With Suggestions on Nomenclature, Am. Jour. Sci., Vol. 244, pp. 622-642, 1946.

2. Capps, S. R., Geology of the Alaska Railroad Region, U.S. Geol. Survey Bull. 907, pp. 1-201, 1940.

3. Eakin, H. M., The Cosna-Nowitna Region, Alaska, U.S. Geol. Survey Bull. 667, pp. 1-54, 1918.

4. Hopkins, D. M. and Sigafoos, R. S., Frost Action and Vegetation Patterns on Seward Peninsula, Alaska, U.S. Geol. Survey Bull. 974, pp. 51-100, 1951.

5. Lundqvist, C., The Orientation of the Block Material in Certain Species of Flow Earth: Geografiska Annaler (Stockholm), Hafte 1-2, pp. 336-347, 1949.

6. Muller, S. W., Permafrost or Permanently Frozen Ground and Related Engineering Problems: Strategic Engineering Study 62, MID, OCE, U.S. Army, pp. 1-231, 1945.

7. Obruchev, S. N., Solifluctional Terraces and Their Origin, Based on Studies in the Chukotsk Region: Problemy Arktiky No. 3, pp. 27-48; No. 4, pp. 57-83, 1937, English Abstract by Dr. E. Golomshtok at Engineer Library, Ft. Belvoir, Va., 1937.

8. Pillow, M. V. and Luxford, R. F., Structure, Occurrence, and Properties of Compression Wood: U. S. Dept. Agr. Tech. Bull. 546, pp. 1-32, 1937.

9. Sharp, R. P., Soil Structures in the Saint Elias Range, Yukon Territory: Jour. Geomorphology, Vol. 5, pp. 274-301, 1942.

10. Sharpe, C. F. S., Landslides and Related Phenomena: A Study of Mass Movements of Soil and Rock: Columbia Univ. Press, New York, pp. 1-137, 1938.

11. Sigafoos, R. S., Some Effects of Congeliturbation Upon the Development of Vegetation, Seward Peninsula, Alaska: Ecological Mon., (in press).

12. Taber, Stephen, Perennially Frozen Ground in Alaska, Its Origin and History, Geol. Soc. Am. Bull., Vol. 54, pp. 1433-1548, 1943.

13. Washburn, A. L., Reconnaissance Geology of Portions of Victoria Islands and Adjacent Regions, Arctic Canada: Geol. Soc. Am. Mem. 22, pp. 1-142, 1947.

## CALCULATION OF DEPTH OF THAW IN FROZEN GROUND

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### Synopsis

An investigation was started in 1945 under the general direction of the chief of engineers, Department of the Army, on the design and construction of airfields in arctic and subarctic regions. This investigation, which is still in progress, is being conducted by the St. Paul District, Corps of Engineers.

Observations of existing structures have been made at various airfields in Alaska since 1945. Additional test structures were constructed near Fairbanks in 1946 and 1947. Laboratory research has been carried on at the University of Minnesota to determine the thermal properties of soils and certain insulation materials. Library research has also been conducted to locate information pertaining to calculation of depth of thaw in frozen ground.

Equations for depth of freezing located in the library research were checked and modified to permit their use in calculating depth of thaw. A correction factor was developed for the relation between air temperatures and the temperature of various surfaces, such as concrete, asphalt, gravel, and vegetation. This correction factor is used in the equation for depth of thaw and in effect converts the basis of calculation from normal air temperatures to surface temperatures. Calculations of depth of thaw are made for different soil conditions and under various surfaces and structures. The data used in these calculations include those obtained in the field tests of soil density and moisture content, field observations of air temperatures, and laboratory tests of thermal conductivity of soils. The calculations can be