SPECIAL REPORT 95-24

CRREL

# Soil Freeze–Thaw Effects on Bank Erodibility and Stability

Lawrence W. Gatto

September 1995

***Abstract***

When air temperature is below ground temperature, a thermal gradient is established in the soil that causes the soil to lose heat to the atmosphere. When the soil has lost sufficient heat for soil water to freeze, the newly formed ice changes soil structure by disaggregating, separating, and reorienting soil particles. The suction set up within the freezing soil draws water to the freezing zone through the film of unfrozen water surrounding soil particles, supplying additional water for freezing, so the volume of ice increases. When appropriate thermal and water supply conditions are in place, disseminated ice lenses can form in the soil. As the ice lenses grow, the soil surface is heaved in the direction of heat flow from the soil. Soil particles can be displaced down a bank face when surface ice in heaved soil melts. The amount of ice in a frozen soil by the end of winter can be higher than its water content when unfrozen. Thus, upon thawing, the previously frozen soil temporarily has an excess of soil water and a disrupted soil structure, which significantly reduces internal friction and cohesion and reduces the soil's shear strength. In this weakened state, thawed bank soils are usually more easily eroded by raindrop impacts, overland flows, river and lake ice forces, currents and waves, and are highly susceptible to mass failures. In some instances newly thawed soils are weaker than at any other time of the year. Some studies show that processes related to bank soil freezing and thawing cause more bank recession annually than other processes in areas where seasonal frost forms. However, with time, the strength of the thawed soil returns as excess water drains from the soil, and soil particle packing and interlocking increase. Thus, frost-induced reductions in soil strength and soil particle displacements must be included in bank migration and bank erosion models to be applied in regions with seasonal soil frost.


For conversion of SI units to non-SI units of measurement consult ASTM Standard E380-93, *Standard Practice for Use of the International System of Units,* published by the American Society for Testing and Materials, 1916 Race St., Philadelphia, Pa. 19103.


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# Special Report 95-24

US Army Corps of Engineers
Cold Regions Research & Engineering Laboratory

# Soil Freeze–Thaw Effects on Bank Erodibility and Stability

Lawrence W. Gatto

September 1995



Prepared for
OFFICE OF THE CHIEF OF ENGINEERS

## PREFACE

This report was prepared by Lawrence W. Gatto, Geologist, Geological Sciences Division, Research and Engineering Directorate, U.S. Army Cold Regions Research and Engineering Laboratory, Hanover, New Hampshire.

The author thanks James Wuebben and Edwin Chamberlain for their many useful comments on this manuscript; Sam Powell (CECW-EH-D) for providing Corps of Engineers Civil Works Guidance Update Program funds under Project H013; and Mike Trawle (CEWES-HW-R) for providing Flood Control Channel Research Program funds under Project 32550.

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# Soil Freeze–Thaw Effects on Bank Erodibility and Stability

LAWRENCE W. GATTO

## INTRODUCTION

The effects of soil freezing and thawing on the erodibility (i.e., susceptibility of in-situ soil particles to be detached by flowing water) and stability (i.e., ability of soil particles to resist movement by gravitational forces) of bank soils along rivers, lakes and reservoirs have been observed by numerous investigators. Lawson (1985) and Lawler (1989, 1993) summarized the results of some of these studies. In this report I summarize research on how soil freeze–thaw disrupts soil structure, displaces soil particles, and temporarily reduces soil strength, and I systematically assess the seasonal variations in bank soil strength likely to result from these freeze–thaw actions and relate those variations to observed bank soil erosion and failures. Lawson (1983) and Gatto (1984) have summarized the effects of permafrost on bank erosion and stability; herein I address only the effects of seasonal frost, although the processes described in this report are active in permafrost areas as well.

Many studies have emphasized the importance of hydraulic tractive force in detaching bank sediments, which leads to bank erosion and instability. In fact, the hydraulic aspects of detachment and sediment transport have generally received more attention than the bank soil resistance (erodibility/stability) aspects in bank erosion and river migration prediction models. And yet, in some instances, bank erosion results not from excessive hydraulic forces primarily but from very weak soils.

Bank soils can be highly erodible and unstable during spring thaw due to excessive pore water and disrupted soil structure. Concurrently, spring snowmelt and rain on snow often produce maximum annual water levels and flow velocities. These flows and the moving ice often associated with them can easily detach and transport this highly weakened soil. Thus, the amount of bank soil lost in the spring can be the maximum for the year if spring high water occurs when bank soil is still weakened after thaw (Slavin 1977, Wolman 1959).

Thus, soil strength variabilities must be included in bank erosion and recession models because soil frost and its subsequent thawing so drastically change soil strength. Bank erodibility factors should not be lumped as a single value for the entire year, especially in regions with seasonal soil frost. Lawler (1993) clearly stated that more research into changes in bank erodibility is needed and emphasizes the need to address soil frost effects in that research.

## BANK SOIL ERODIBILITY AND STABILITY

Many geotechnical, hydraulic and climatic processes and conditions (Fig. 1) interact to reshape soil banks through erosion and mass failures. The patterns of these interactions change with time and location and produce complex effects and feedbacks on surface and within subsurface bank soils (Table 1), resulting in highly variable rates and scales of bank erosion and failure within the same and amongst different locales (Gatto 1987, Lawson 1985).

These interrelationships are illustrated in Table 1 as follows: if one selects the first process or condition in column A (excessive soil pore water), there are at least five causes (column B) for that condition. The excessive pore water reduces granular interlocking and soil cohesion, lowering soil strength and stability in bank surface and subsurface soils (① in columns C and D, respectively). This reduction can make the surface soils more susceptible to soil water piping (2), ice abrasion (5), ice push (6), wave actions (9), water cur-

## Table 1. Interactions of bank erosion and failure processes and conditions.

| (A) Process or condition | (B) Causes of a process/condition | * Effects on bank soils (C) Surface soils | * Effects on bank soils (D) Subsurface soils | Climatic zones (E) Permafrost | Climatic zones (F) Seasonal frost | Climatic zones (G) No frost |
|---|---|---|---|---|---|---|
| Excessive soil pore water (1) | Heavy and/or prolonged precipitation<br>Snowmelt<br>Rapid river/lake level drop<br>Irrigation<br>Ground ice melt | 1 → 2, 5, 6, 9, 10, 14–18 | 1 → 14 | X | X | X |
| Soil water piping (2) | Water flow through coarse-grained, permeable soil strata discharging along bank face | 2 → 14 | 1 → 14 | X | X | X |
| Soil freeze-thaw (3) | Ground temperatures fluctuating below and above 32°F cause soil pore water to freeze and thaw, and soil mass to swell and shrink | 1 → 2, 5, 6, 9–11, 14, 18<br>2 → 14 | 1 → 14 | X | X | |
| Growth of ground ice (4) | Ground temperatures below 32°F and suction of soil water to freezing soil zone | 1 → 2, 5, 6, 9–11, 14, 18<br>2 → 14 | 2 → 14 | X | X | |
| River/lake ice scour/abrasion (5) | Ice moving along a bank | 1 → 9–11, 15–17 2 | no effect | X | X | |
| River/lake ice push (6) | Ice moving into or onto a bank due to thermal expansion, wind or currents | 1 → 9–11, 15–17 2 3 | 1 → 14 | X | X | |
| River/lake ice rafting (7) | Previously grounded ice with incorporated sediment breaks free and flows away | 2 3 | no effect | X | X | |
| Changes in soil grain mineralogy and physical condition (8) | Normal chemical and physical weathering actions and reactions | 1 → 2, 5–7, 9–11, 13–18 | 1 → 6, 14 | X | X | X |
| Water wave actions (9) | Wind<br>Boat passage<br>Landslides | 1 → 14–17 2 3 | 1 → 14 | X | X | X |
| Water current detachment and transport (10) | Gravity<br>Thermal<br>Wind | 2 3 | no effect | X | X | X |
| Wind detachment and transport (11) | Wind blowing over transportable soil | 2 3 | no effect | X | X | X |
| Toppled trees (12) | Loss of soil support below root zone | 2 | 2 | X | X | X |
| Man and animal actions (13) | Burrowing, trampling (compacting), excavating and disrupting the surface of bank soils | 1 → 5–7, 9–11, 14–18 2 3 | 2 3 | X | X | X |
| Soil failures (14) | Excessive soil water<br>Seismic action<br>Loss of bank toe support | 2 | 2 | X | X | X |
| Raindrop detachment (15) | Rain drop impacts on unvegetated bank soils | 2 | no effect | X | X | X |
| Overland sheet flow (16) | Infiltration capacity of soil is exceeded, resulting in flows on the soil surface | 2 3 | no effect | X | X | X |
| Rill/gully flow (17) | Flow on a sloped soil surface becomes concentrated in surface depressions often where vegetative cover is sparse | 2 3 | no effect | X | X | X |
| Snow sliding (18) | Binding forces between bank face sediments and snow become insufficient to hold snow mass in place | 2 | no effect | X | X | |
| Ground ice melting/ sublimation (19) | Exposure to solar radiation, water and air temperatures above 32°F | 1 → 2, 5–7, 9–11, 14–18 2 | 1 → 14 | X | X | |

*Effects on bank soils:

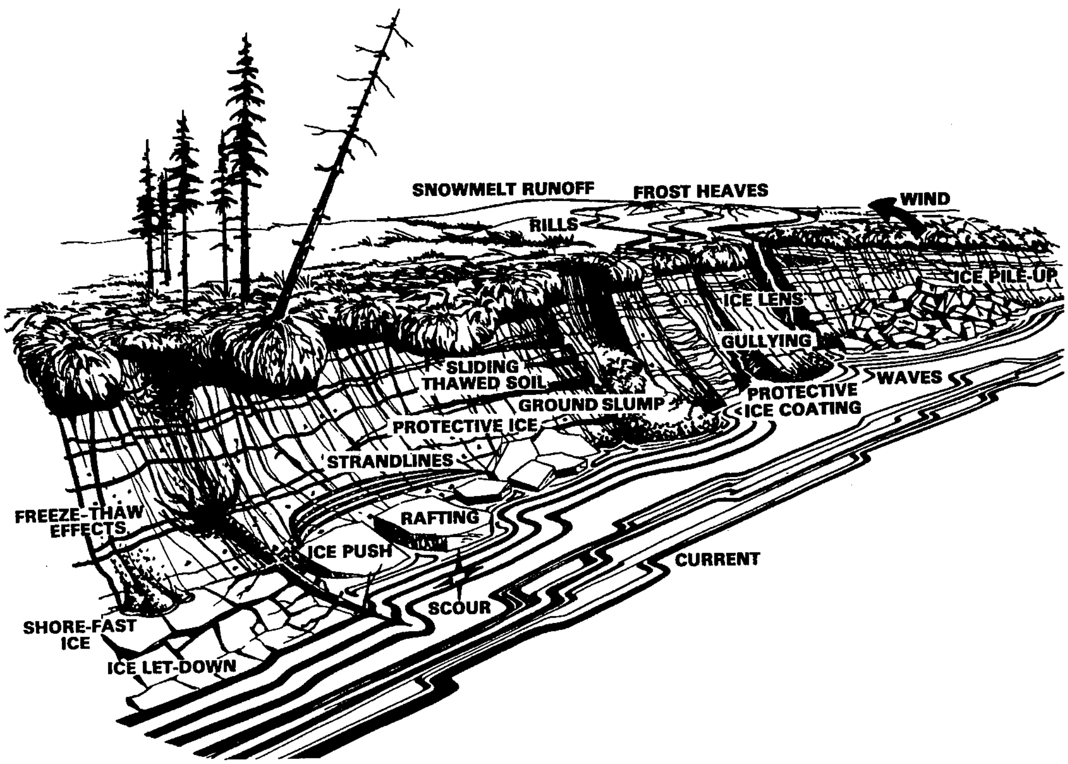
1 – Reduction in granular interlocking and/or soil cohesion with associated loss of soil strength and stability

2 – Removal of soil particles from in-situ position

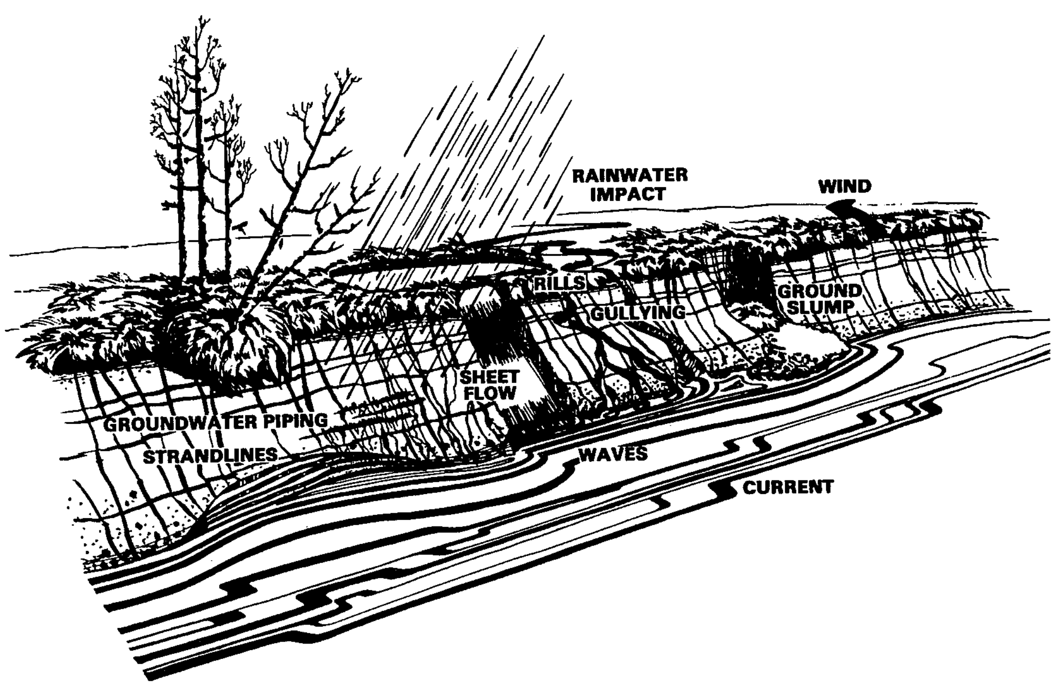
3 – Removal of soil particles from site

1 → 3, 8–10 Effect could increase the susceptibility of bank soils to other processes or condition in column A with their associated effects in columns C and D and so on.

Note: This table may not include all factors.




*a. Seasonally frozen areas.*




*b. Areas without seasonal frost.*

*Figure 1. Processes and conditions that contribute to bank erodibility and failure.*

rent detachment and transport (10), soil failures (14), raindrop detachment (15), overland sheet flow (16), rill and gully flow (17), and snow sliding (18). Subsurface soils would be more susceptible to soil failures (14) as a result of the reduced soil strength.

Looking across the remaining columns (E–G) in the table, one sees that this type of cause and effect interrelationship between excess pore water and other processes and conditions can occur in all climatic zones. The rest of Table 1 illustrates the numerous additional interactions between processes and conditions and their effects.

In the context of this report, a bank is "stable" when its soils have sufficient strength to resist many of the forces applied by the reshaping processes and conditions (column A) listed in Table 1. However, even stable banks change shape as some of their soils are displaced or removed, albeit slowly, resulting in the gradual, almost unnoticeable, landward movement (recession) of the bank crest. We are concerned herein with banks that lose sediment sufficiently fast that bank recession is noticeable each year.

## SEASONAL CONDITIONS AND PROCESSES

Such factors as soil structure, water content and bulk density, grain size distribution, shape and mineralogy, the degrees of soil–grain interlocking, grain cementation and chemical weathering, the particle-bonding mechanisms in clay soils, and the presence of vegetation determine soil strength (Gatto 1988). Consequently, processes that affect these soil characteristics may reduce soil strength (Ogata et al. 1985) and make soils geotechnically unstable or more susceptible to removal by water or wind forces. Soil freeze–thaw cycles (FTC) usually change soil structure, water content and bulk density, and degree of grain interlocking, thereby reducing soil strength, at least temporarily.

Reid (1984, 1985) reports that thaw failures resulting from a loss of soil strength when frozen soils thawed constituted up to nearly 90% of the total sediment lost from banks along Orwell Reservoir in Minnesota. Slab slide failures and mudflows that occur during spring thaw account for up to 90% of the soil lost from bluffs along Wisconsin's Great Lakes shorelines, while sheetwash and rill erosion cause up to 50% of the soil lost per year (Sterrett 1980). Gardiner (1983) observed that more than 90% of the total erosion on the River Lagan in Northern Ireland occurred during the winter due to needle ice formation and soil heaving, and that after needle ice on a bank face melts, a readily erodible skin of loose sediment remains covering the bank.

Andersland and Anderson (1978) detailed the complex thermodynamic processes involved in soil freezing and thawing. I am unaware, however, of research that addresses these processes specifically in banks. Therefore, the following descriptions of the sequence of soil freezing and thawing in bank soils (Table 2) are drawn from research on 1) the processes of freezing and thawing and resulting soil instabilities in soils below pavements and roads, under and around structures, and in man-made embankments, and on 2) the erodibility of soils in agricultural fields.

The reader should bear in mind the following additional complexities in the soil freezing and thawing processes of river and lake bank soils: 1) the effects of water level fluctuations, which often cause the soil to be alternately exposed and inundated, 2) the presence of unfrozen soils below the water line, 3) the more efficient heat loss from bank soils in contact with moving water, and 4) the heat gained by frozen soils when they are inundated during high water periods.

### Fall

*Soil freeze–thaw cycles*

As the air temperature fluctuates below and above 32°F in the early fall, some portion of the bank surface soils cycle between being frozen and unfrozen. The soil freezes from its surface to some depth, which is determined by the amount of heat lost from the soil during the last freezing period, and which in turn depends on the severity of the weather, i.e., air temperature, wind speed, solar insolation. When soil heat loss has progressed sufficiently, the void or adsorbed soil water will freeze and expand in volume by 9% (Jumikis 1962).

The ice can displace soil particles and separate soil aggregates, often disrupting the interlocking of soil grains and changing the soil structure, void ratio, density, soil fabric, saturated water-holding capacity, and hydraulic conductivity, resulting in decreased soil cohesion and mechanical strength (Aoyama et al. 1985, Benoit and Voorhees 1990, Chamberlain and Gow 1979, Frydman et al. 1979, Gifford 1984, Kim and Daniel 1992, Mostaghimi et al. 1988, Thorne 1982).

**Table 2. Hypothesized and generalized sequence of bank soil freeze–thaw with associated effects.**

| *Fall* | *Winter* | *Spring* |
|---|---|---|
| – In early fall, bank surface soils cycle between unfrozen and frozen as air temperature fluctuates above and below 32°F. | – The zone of frozen soil deepens as the average air temperature drops; soil water migrates to the thickening frozen zone. | – Strength of bank soils is significantly reduced upon thaw because of excessive soil water from melted ground ice. |
| – Later in the fall, as the daily average air temperature decreases, the lower part of the frozen surface soils remains frozen when the upper part thaws during the day when the air temperature rises above 32°F. | – Ground ice forms in the frozen zone if sufficient soil water is available. | – Thawed soils fail *en masse.* |
| | – Ground ice can sublimate at a bank face, resulting in sloughing of surface soil particles. | – High river and lake water during spring removes weakened or failed bank soils. |
| – Soil strength is reduced in the freezing and thawing zone due to the soil structure being disrupted by ice formation and swelling and shrinking of the soil mass. | – Continued ground ice growth can heave the bank soil surface and displace soil grains downslope. | – Bank soil slowly recovers its strength but is more susceptible to removal or failure during recovery. |
| * Intermediate | * Minimum | * Maximum |

* Comparative state of soil erodibility and instability resulting from freezing and thawing.

The freeze periods are usually not sufficiently long or intense in the fall to cause frost to penetrate very deeply into the soil; however, needle ice or near-surface ice lenses are very likely to grow. Conversely, solar input and the air temperatures are usually sufficiently high for most of the frozen soil to thaw during subsequent thaw periods. Even if segregated ice lenses or needles do not form, the ice that forms in soil pores during freezing and melts during thaw often causes the soil to swell and shrink, which changes soil structure and particle bonding (Anderson et al. 1978).

As the average daily air temperature drops and solar insolation lessens later in the fall, bank soils lose enough heat during the daily freezing period for the frozen layer to get sufficiently thick that its lower portion remains frozen even after its upper part thaws during the daily thaw period. More interstitial ice may form now during freezing than earlier in the fall because the intensity of the freezing has increased sufficiently for more of the soil moisture to freeze and for additional soil water to migrate to the freezing front and freeze.

*Soil weakening and failures*

Van Klaveren (1987) and Kok and McCool (1990) show that the critical shear strength of a soil subjected to FTC is less than that of the same soil that has not been frozen. However, the magnitude and types of the soil changes caused by FTC are dependent on initial soil conditions, i.e., soil type (Chamberlain, 1989), aggregate size and bulk density (Benoit and Voorhees 1990), on soil and weather conditions during the FTC, and on the number of FTC. Thus, investigators have found that a variety of complex effects result from the intensity and number of FTC and that the degree of soil weakening varies with site-specific soils.

Aoyama and others (1985) found a reduction in soil cohesion that increased as freezing temperatures dropped but found little change in the soil friction angle after the FTC. Although Ogata and others (1985) observed large differences on the strengths of undisturbed alluvial soil and consolidated kaolin, they found in both soils that FTC reduced cohesion and increased the angle of internal friction. Othman and Benson (1993) observed a network of cracks formed by ice lensing and soil shrinkage that increased the hydraulic conductivity in clay soil after one FTC, and found that new lenses and cracks formed with additional FTC. However, they determined that after three cycles new lenses are negligible and a further increase in the hydraulic conductivity ceased.

Yong and others (1985) observed that significant changes in the liquid limit and the undrained shear strength of a clay from Matagami, Quebec, occur after one FTC (Fig. 2) and that additional

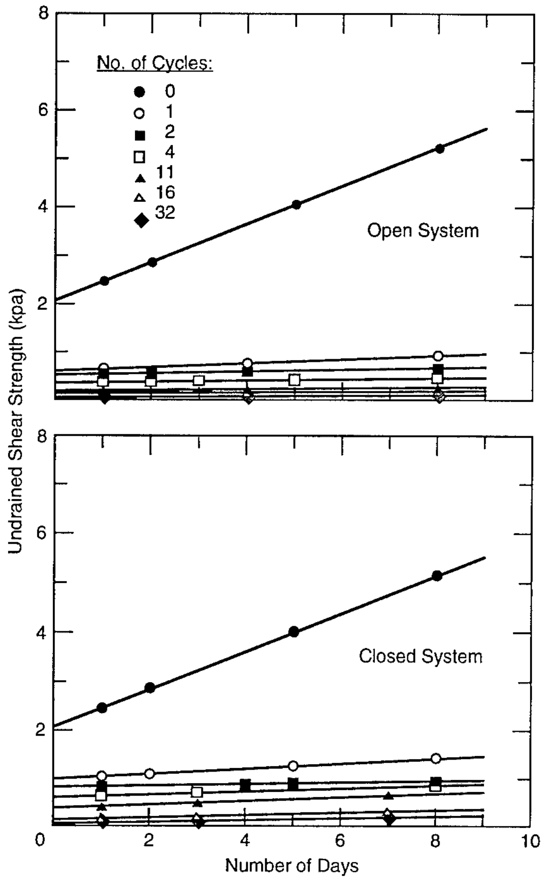



*Figure 2. Change in undrained shear strength and the thixotropic strength regain in a natural, sensitive clay exposed to FTC (Yong et al. 1985).*

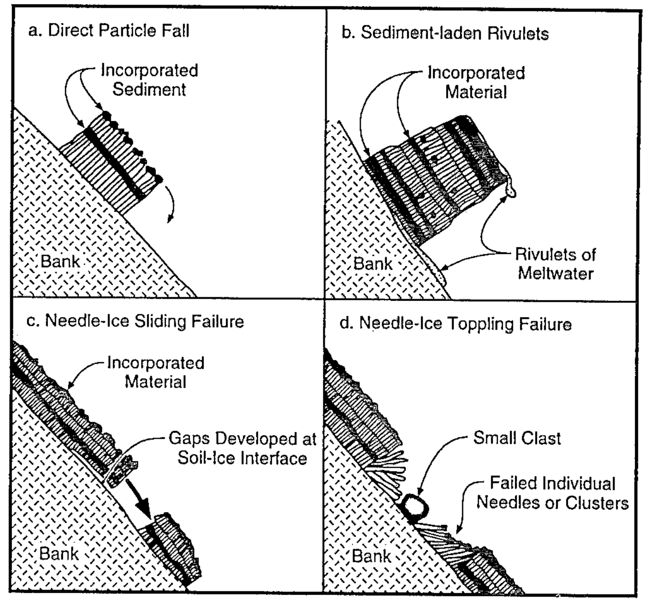



*Figure 3. Bank sediment displacement by needle ice (Lawler 1993).*

cycles did not reduce the shear strength as much as occurred after the first cycle. Chamberlain (1973, 1981) also concluded that the rate of strength reduction in clay soils decreases as the number of freeze–thaw cycles increases. Yong and others (1985) also showed that the rate of strength recovery of the clay soil was less when subjected to more FTC (Fig. 2), noted that the rate of recovery was higher in the closed system (no water drainage after thaw), and surmised that soil particle bonding may be retained more in the closed system because of dissolved ions in the pore water enhancing those bonds.

At first, this seems contradictory to me in that I would have suspected quicker recovery in the situation where excess soil water could drain away more rapidly than where it could not. However, their finding illustrates the importance that pore water quality plays in soil cohesion and strength, as has been shown by others, and further illustrates the complexity of the interplay of conditions and processes that affect soil strength.

Formanek et al. (1984) concluded that the maximum reduction in soil shear strength may result after only a single FTC, and Benoit and Voorhees (1990) report the greatest change in the ratios of the final to initial bulk densities, water contents, hydraulic conductivities and surface strengths occurred after one freeze–thaw cycle, with lesser changes in the ratios after additional cycles. Van Klaveren (1987) showed that a soil's critical shear strength may be reduced to half of its normal value after a single cycle.

Thorne (1978) measured about 0.4 in. of river bank retreat due to a single frost event and concluded that when frost events recur frequently they would contribute substantially to overall retreat. Lawler (1993) observed the growth of needle ice along a river bank in South Wales, U.K. Needle ice often forms in late fall or early winter. The needles are usually less than 0.01 sq. in. in cross section and up to 3–4 in. long and form at the soil surface. They lift soil particles on the bank surface as they grow. The particles often tumble off the top of the lifted soil and down the bank face or are displaced down the face when the needle ice melts during the day. Lawler measured the resultant displacement of bank face sediment by the needles (Fig. 3) and determined that up to 0.82 lbs. of sediment were lifted from a square foot of bank face by growing needle ice. He used erosion pins to measure that 32–43% of the actual bank retreat rate of 0.21 ft/yr. at his study site was caused by bank sediment incorporation and transfer downslope by needle ice processes.

Usually air temperatures are not cold enough for sufficiently long periods during the fall to cause substantial soil water migration to the freezing soil to form significant ground ice. Thus, the amount of ground ice that thaws in the fall during diurnal thaw periods would be much less than that which thaws in the spring after an entire winter. I conclude that the amount of bank soil loss or instability that results from FTC in the fall would be less than that which occurs due to spring thaw (Table 2).

### Winter

*Thickening of frozen soil*

Once the average daily air temperature falls below 32°F and solar insolation is sufficiently low, the soil continues to lose heat to the atmosphere, most soil thawing stops, and the zone of frozen soil thickens (Table 2). A special condition exists along an eroding bank (which is usually unvegetated) versus a stable, vegetated bank. Vegetation insulates soil and reduces heat loss to the air, thereby reducing frost depth (McRoberts 1978) in a stable bank, while an eroding bank is likely to have greater heat loss and deeper frost. The deeper frost makes more of the surface soil susceptible to erosion and instability than would be in a vegetated bank.

Heat loss from soils at the crest of an eroding bank may even be greater than occurs from lower parts of a bank because heat is lost through the upland land surface near the bank crest and through the upper bank (Fig. 4). Reid's (1985) measurements showed that the frozen zone of the upland land surface landward of the crest of an eroding bank was thicker near the bank face along Orwell Reservoir in Minnesota, and thinned landward away from the bank.

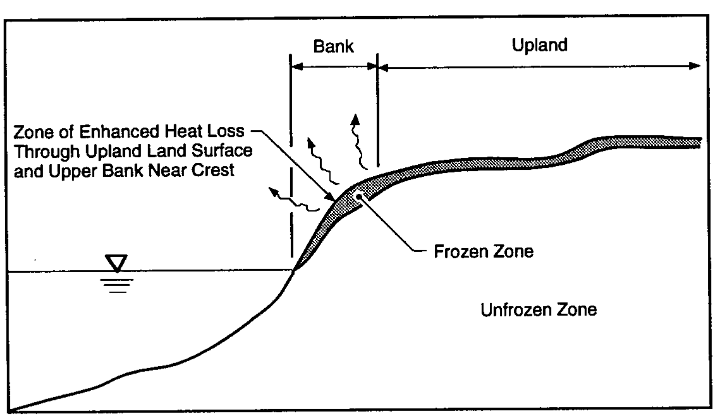



*Figure 4. Bank crest zone with thickest frozen zone along a bank profile.*

The crest of a bank may also be snow-free more often than the lower parts of the bank (Fig. 5), depending on wind conditions, which would enhance heat loss at the crest as well. Snow insulates soil and thus inhibits frost penetration and retards soil thaw in the spring (Harlan and Nixon 1978), and its insulating effect is influenced by snow type, thickness, and density.

Reid (1985) found a difference in the frost depth along north- and south-facing banks, as well: frost was thicker in north-facing banks. Harlan and Nixon (1978) concluded that south-facing banks receive more insolation and thus do not freeze as frequently, deeply, or completely as north-facing banks. Wuebben* points out that more diurnal FTC may occur in south-facing banks during that portion of the season when north-facing banks may remain frozen.

*Ground ice growth and frost heaving*

Three conditions must exist for ground ice to grow and become a substantial component of a soil mass: a soil-moisture supply, sufficiently cold air temperatures to cause soil heat loss and subsequent freezing, and a frost-susceptible soil, which is usually a silty soil (Anderson et al. 1978). (Needle ice, however, will form in almost any type soil.†) Silty soils absorb moisture rapidly because they have particles small enough to provide comparatively high capillary rise and large enough to furnish voids of adequate size to allow quick flow of moisture through the silt, which leads to rapid saturation of the voids of the soil (Jumikis 1962). Coarse- and fine-grained soils do not absorb moisture rapidly.

In addition to soil texture, soil frost susceptibility depends on, and varies with, vegetative cover and depth, thickness and density of snow cover, initial soil temperature, air temperature regime, exposure to sun, the temperature gradient within the soil, the rate of heat removal, the mobility of soil water, the depth to the water table, overburden stress, and soil density (Chamberlain 1981, Jumikis 1962).

* Personal communication with James L. Wuebben, Research Hydraulic Engineer, Ice Engineering Research Division, CRREL, 1994.

† Personal communication with Edwin J. Chamberlain, Jr., Research Civil Engineer, Applied Research Division, CRREL, 1995.

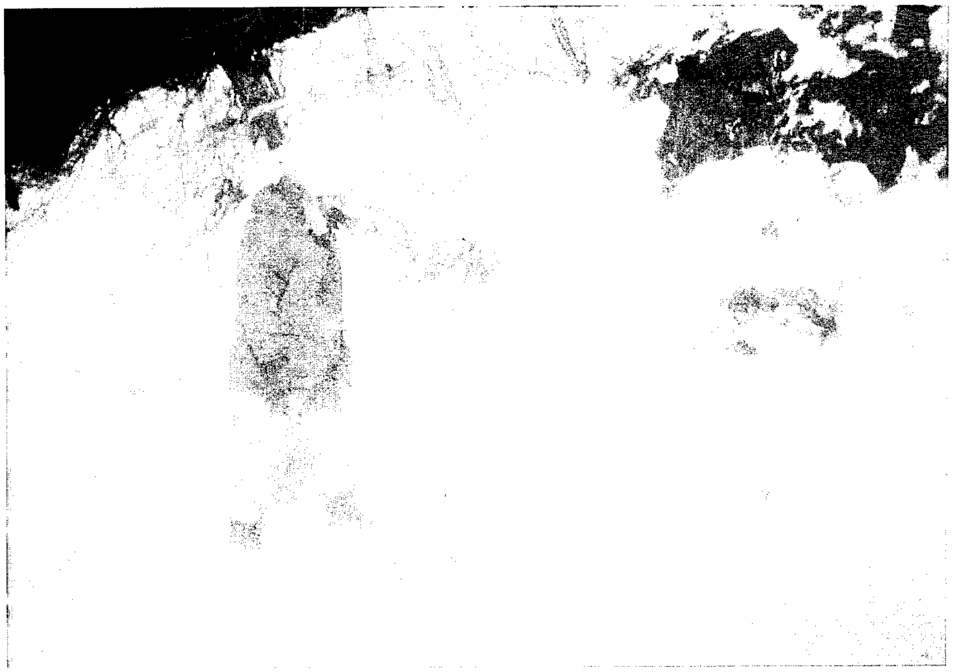


*Figure 5. Snow-covered bank, Surry Mountain Reservoir, New Hampshire.*

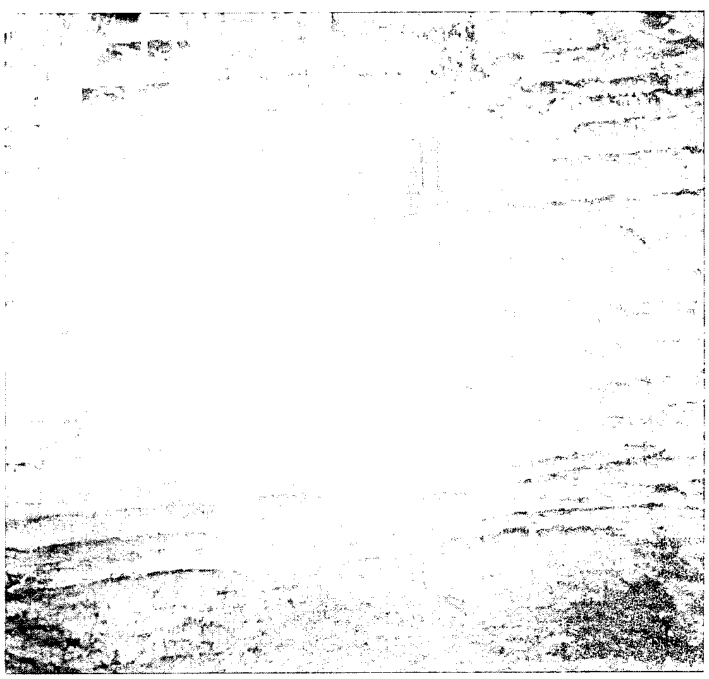


*Figure 6. Segregated ice layers in glacial varves, west bank of Waterbury Reservoir, Vermont.*

Soil moisture moves to the freezing zone from sources below due to a suction set up in the soil, and the amount of ground ice can increase, thereby increasing the soil moisture in the freezing zone (Jumikis 1962). Ice can continue to form and grow within the existing voids of a soil (Linell and Kaplar 1966), although it often grows in distinct, segregated ice lenses. As the number of these lenses increases the volume of the soil expands and can heave the soil upward more than the thickness of the ice lenses (Anderson et al. 1978).

Frost heaving is always in the direction of heat flow, which is normal to the ground surface (Anderson et al. 1978), and the segregated ice lenses can be in visible layers (Fig. 6) up to 4 in. thick. Although frost heave is usually thought of

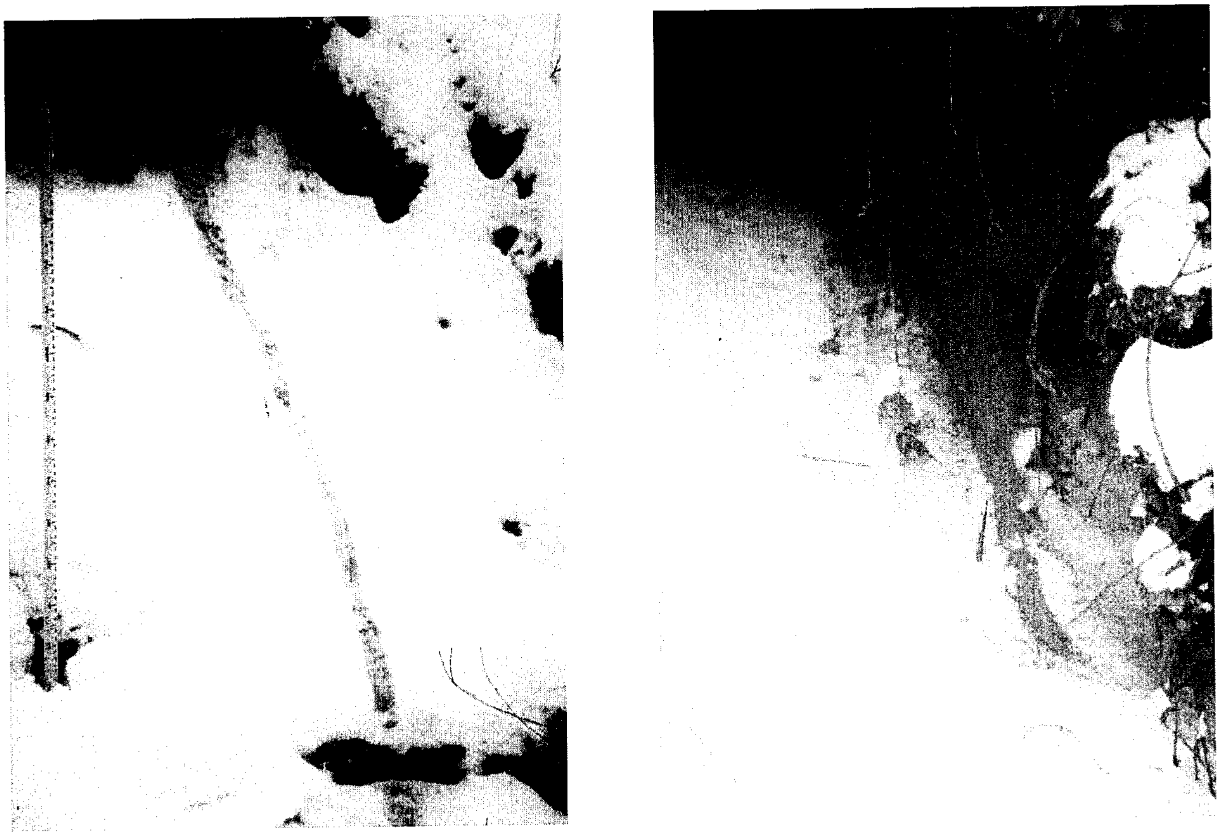


*Figure 7. Sediment sloughed off a bank due to ground ice sublimation or melting, Wilder Lake, Connecticut River, Vermont.*

as a vertical displacement, it also causes soil movement in any direction (Burdick et al. 1978).

The mechanisms of frost heave differ depending on the temperature gradient and water supply. A high temperature gradient at the beginning of freezing favors needle-ice growth while a lower gradient and good water supply lead to ice lenses (Coutard et al. 1988). Such frost heaving along exposed bank soils could be exacerbated by the presence of numerous open cracks and fissures in the soil or root channels, which can increase the average permeability of soil and conduct water readily to the freezing zone (Anderson et al. 1978).

*Soil failures*

I have observed that before any major spring thaw, midwinter sloughing of bank sediment grains or aggregates occurs when interstitial ice along a frozen bank face sublimates or thaws to a shallow depth. The grains or aggregates are released and can accumulate on the bank face, or if the bank is steep enough, can move down the face and accumulate at the toe of a bank (Fig. 7). Reid and others (1988) observed that sediment failure due to sublimation (Fig. 8) is more significant along north-facing banks because freezing along north-facing banks is more intense than along south-facing banks; north-facing banks often freeze earlier and deeper than south-facing banks.

In general, frozen bank sediment is more resistant to erosion than unfrozen sediment during summer months (Reid 1985), and I conclude that the soil loss and the volume of unstable soil would be minimal during the winter (Table 2).

## Spring

*Soil thaw–freeze cycles*

In the spring, significant thawing and limited refreezing of the surface soil begins as daily air temperatures rise and solar insolation increases (Table 2). Even when ground ice has not been segregated into lenses and a soil has not been heaved during the winter, soil structure will likely have been disrupted to some degree by ice in the soil voids, so that a weakened soil mass results upon thaw (Anderson and others 1978).

Figure 8. Sediment sloughed off a bank due to ground ice sublimation, Orwell Reservoir, Minnesota (Reid 1985).

Generally, soils thaw more quickly from the ground surface down than up from the bottom of the frozen zone (Jumikis 1962), thereby creating a layer of nearly impermeable frozen soil under thawed soil. Bank surface soils that contained ground ice will often have an amount of melt-water upon thawing that considerably exceeds the pre-frozen water content of those soils (Nixon and Ladanyi 1978); the excessive water can neither be reabsorbed into available soil voids (Chamberlain 1981) nor be adequately drained into the soil below, prolonging the time for the thawed soil to regain its pre-frozen strength through drainage.

Intergrain friction and cohesion that were reduced when ice disrupted grain interlocking and packing remain low until the soil particles have reoriented (recompacted) to a pre-frozen condition, which usually cannot occur until after drainage of the excess water. Even under drained conditions, the voids and weakened planes left in the soil after the ground ice melts often cause the soil to depress and collapse under its own weight (Burdick et al. 1978; Gifford 1984; Nixon and Ladanyi 1978).

Bredyuk and Mikhaylov (1970) reported that the resistance of thawed soil to shear, as measured with a shear vane, was 1.2 to 7 times less than the resistance of the unfrozen soil layer below the frost line, and that the maximum strength reduction occurred in a soil that heaved the most during freezing. They also concluded that the maximum thaw weakening occurred along embankment shoulders and slopes.

Although these weakened, thawed soils usually regain their pre-frozen soil strength (Chamberlain 1981), the time it takes varies with site conditions. This timing may be reflected in the pattern of change of the resilient modulus (Fig. 9). This modulus, the ratio of total stress to recoverable strain, is a measure of the dynamic modulus of elasticity, but it does not have a one-to-one linear relationship with soil strength. However, a low-strength soil usually has a low resilient modulus.

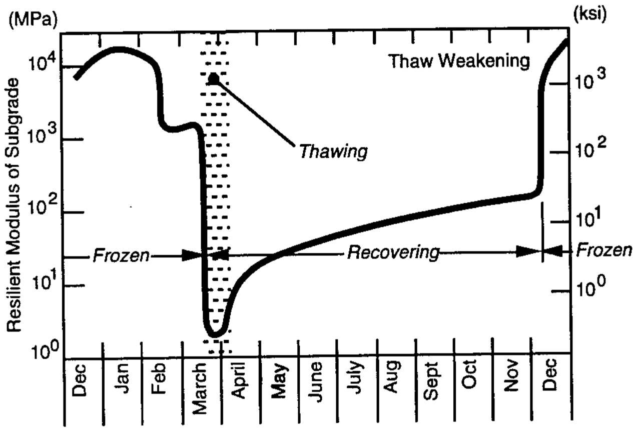



*Figure 9. Change in the resilient modulus of a low plasticity silt (Johnson et al. 1978).*

Annual soil strength drops substantially to its lowest annual quantity during and after thaw and recovers as excess soil water drains out and soil friction and cohesion return. Bredyuk and Mikhaylov (1970) reported that thawed soil regained shear strength in 15 to 45 days, depending on soil water draining rates and the thickness of the thawed zone. Usually a thicker zone has a slower draining rate.

While in this weakened state, thawed surface soil can easily fail by shear along the surface of frozen soils below. This is especially likely due to the increased unit weight of the thawed soil resulting from its excess water content. In addition, as the water draining from the thawed soils encounters the surface of the still-frozen sublayer, the water will be directed downslope along this surface (Fig. 10), and will increase seepage pressures, possibly causing piping along the unfrozen and frozen soil interface if it intersects the bank face. Such a condition could occur where snow piled along a bank has insulated the lower bank face and the soil beneath that snow is still frozen, while above the snow, the bank face has thawed.

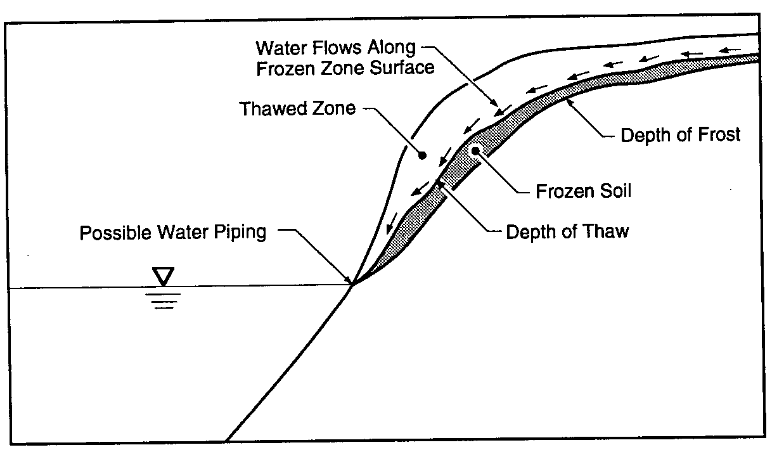



*Figure 10. Reduced subsurface soil water drainage due to frozen subsoil.*

*Soil failures*

Numerous investigations show that bank sediments weakened by freeze–thaw can fail as slabs, blocks (Fig. 11) or slides; can creep or slough down the bank face as grains or aggregates (Harrison 1970); or, if lubricated with sufficient moisture, can flow down the bank. McRoberts (1978) described the various forms of soil mass failure resulting from slope instability in cold regions where spring thaw causes a saturated layer of soil on a slope, and Reid (1984) reported that slides, flows and slumps result from thaw-induced slope instability (Fig. 12).

Even if the thaw-weakened sediments don't move down a bank, they are more erodible than before they were frozen and can be easily detached by raindrop impacts, overland flows, and waves and currents if river or lake water levels rise sufficiently due to snowmelt or spring rains. Lawler (1992) calls this "freeze–thaw preconditioning." Consequently, snowmelt floods in the spring often erode significantly more bank soils than floods of equal magnitude later in the year, after the soils have regained their strength. Slavin (1977) and Wolman (1959) concluded that most bank erosion occurs in the spring. In addition, Leopold (1973) reported that small rises in river flow that are separated by freeze–thaw periods can cause channel migrations because the rises can effectively erode bank sediments that have been loosened by the ground freezing processes.

Hill (1973), Reid (1985), Sterrett (1980), and Thorne and Lewin (1979) report that twenty to ninety percent of the erosion along river and lake banks in various regions where seasonal frost occurs was due to freeze–thaw and ground/ice processes and to freeze–thaw failures in the winter and spring. Twenty to thirty percent of the bank recession along Lake Sakakawea in North Dakota is due to frost rupture and thaw failure along the bank face and along cracks landward of the bank face (Reid et al. 1988, Reid and Dorough 1989, Reid 1992). Freeze–thaw action and thaw

*Figure 11. Soil blocks failed during spring thaw, Wilder Lake, Connecticut River, Vermont.*

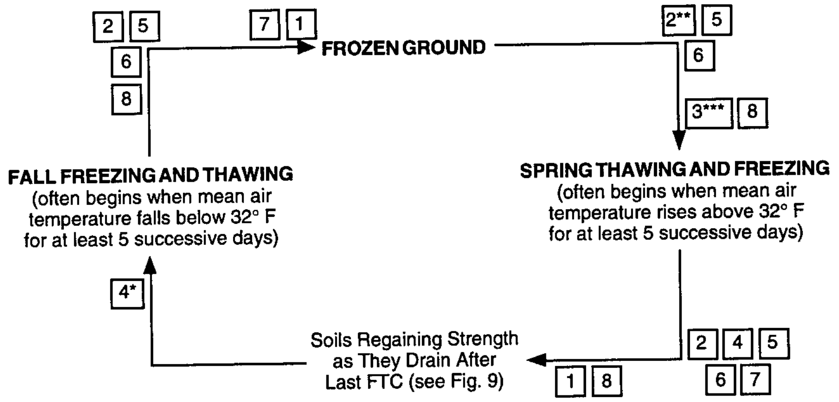
failures are two of the main processes of bluff erosion, causing an average soil loss of 2 ft/yr along some bluff faces along Lake Michigan (Vallejo 1977, 1990). Freeze–thaw and frost–thaw processes are important causes of the long-term bank erosion along Lake Winnibigoshish and Big Sandy Lake in northern Minnesota.* I conclude that maximum soil erodibility and instability usually recurs in the spring in regions with soil frost (Table 2).

*Figure 12. Spring sediment flows onto snow at the bank toe; top) Orwell Reservoir, Minnesota (Reid 1985), bottom) Wilder Lake, Connecticut River, Vermont.*

## DOCUMENTING THE EFFECTS OF SOIL FREEZE–THAW

All soils can freeze if they lose sufficient heat to the atmosphere and can be weakened during the process as previously discussed. However, most disruption of soil structure occurs when ground ice forms within frost susceptible soils. Jumikis (1962) reported that silty soils are more susceptible to ground ice formation than coarser-grained soils, and that frost penetrates deeper in granular than in fine-grained soils. Alestalo and Haikio (1979) generalize that frost depth is usually shallow in steep sand banks (dry ground), in peat banks and under deep snow, but is often deep in gently sloping silt or till banks saturated with water and in banks with little or no snow cover.

* Personal communication with Gregg Struss, Resource Manager, Gull Lake Dam, U.S. Army Corps of Engineers, 1992.




1 FTC measured with buried thermistors and resistivity gages (Atkins 1979, 1989, 1990)

2 Observations of bank soil failures; estimates of volumes of failed soil; measurements of the thickness of low-strength, surface soils

3 Frost depth estimated with Berggren equation or measured with frost tubes (Rickard and Brown 1972) or buried thermistors/resistivity gages

4 Soil moisture measured with Hydra Probe (Vitel, Inc. 1994) to correlate with penetrometer and vane shear measurements

5 Penetrometer measurements to define unconfined compressive strength of soils (strength decreases with increasing soil moisture)

6 Vane shear measurements to define undrained shear strength of soils (shear strengths decrease with increasing soil moisture)

7 River/lake stage

8 Bank shape measurements made by erosion pins or bank profile surveys (Gatto 1988)

* High antecedent soil moisture condition going into the fall can result in unusually low soil shear strengths after thaw due to high ground ice buildup, thus soils could be more unstable and erodible than under pre-fall soil moisture conditions.

** Maximum frost heave does not necessarily occur when frost depth is at a maximum (Jumikis 1962).

*** Maximum frost depth usually occurs later than the time of minimum air temperature; frost penetrates sooner and leaves sooner in coarse-grained, non-plastic soils than in clayey soils (Jumikis 1962).

*Figure 13. Timing for field observations and measurements.*

## Bank site inventories and surveys

One can map and inventory river and lake banks with these characteristics and thereby identify those reaches where freeze–thaw processes are likely to substantially contribute to bank erodibility and instability. Such an inventory could then be used to select the critical locations for which one can use laboratory tests (Chamberlain 1981, 1987) that include the effects of FTC in determining frost, frost heave and thaw-weakening susceptibilities. However, no method is available to predict where soil frost will form; variability in the controlling factors is too great from year to year to make such predictions meaningful.

However, once frost susceptibilities are determined for critical locations, repeated field observations and measurements can be done to identify and monitor the effects of FTC on a bank. I propose that a procedure of year-round field measurements and observations (Fig. 13) would provide the data required to determine the amount of failed or weakened, highly erodible soil due to FTC and the amount of soil lost from a particular site.

## Predictions of FTC-weakened soil thickness

Finite-element models are available to predict the depth of frozen ground at a site where ground frost exists; however, the less-complicated, modified Berggren equation given below has been used for many years for such predictions on upland terrain (Aitken and Berg 1968, Linell and Tedrow

1981). The predicted frost depth can be used as a measure of the thickness of FTC-weakened bank soils in the spring. Aitken and Berg (1968) provide the figures and tables needed to determine the values for the parameters in the equation and a computer program for the equation is available via E-mail.* However, some parameters may have to be modified to apply the equation to bank soils rather than uplands.

$$x = \lambda \sqrt{\frac{48\,K\,n\,F(\text{or } I)}{L}}$$

where $x$ = depth of frost or thaw penetration (ft)
$l$ = lambda coefficient (accounts for effect of temperature changes in soil mass)
$K$ = average thermal conductivity (Btu/ft hr °F)
$n$ = factor to convert an air index to a surface index
$F$ = air freezing (degree-days °F)
$I$ = thawing index (degree-days °F)
$L$ = volumetric latent heat of fusion (Btu/cu ft)

The equation assumes (1) an isothermal soil system at the beginning of the freezing season, (2) one-dimensional heat flow with the entire soil mass at its mean annual temperature prior to the start of the freezing season, (3) when the freezing season starts, the soil surface temperature changes suddenly from the mean annual temperature to a temperature below freezing at which it remains during the entire freezing season, (4) soil water must lose the latent heat of fusion before it turns to ice, and (5) soil freezes at 32°F. It cannot normally be used to calculate thaw depths in seasonal frost areas or frost depths in permafrost areas, and it cannot calculate frost penetration over part of a freezing season.

## REMEDIATING FOR SOIL FREEZE–THAW

As I have described, the general types of soil failures resulting from FTC-weakening of soils can vary with season. In the fall, needle-ice often displaces soil surface sediments when soil moisture is sufficiently high for needles to form, and minor slumping and sliding may occur. In the winter, once a bank is frozen, surface sediments are usually stable and not highly erodible, but some can slough off the bank face due to sublimation of ground ice within surface sediment, or due to shallow daily thawing of sediment that has been frost heaved. In the spring, when thaw predominates, soil slumps, flows and blocks slide down a bank face due to the high soil moisture and significantly reduced soil strength.

The sediment that accumulates at the base of a bank as a result of such seasonal soil failures must be removed if bank recession is to occur. Otherwise, these accumulations will build up and protect the bank toe from waves and currents. This protection maintains the position of the bank toe, which adds to the stability of the bank by allowing the slope of the upper bank to eventually decrease as gravity moves sediments downslope. Thorne (1982) describes this as basal end-point control. The slope of the entire bank would then decrease to a stable angle and the bank face would eventually revegetate. At this stage, instability of the bank soils and erosion from the bank face would be minimal and bank recession would be very slow.

Thus, methods that protect the bank toe have been employed for many years, because by protecting the toe, they effectively stabilize the bank whether the bank is unstable due to freeze–thaw processes or other geotechnical processes that move bank sediments to the bank toe. Efforts to develop low-cost and biotechnical toe protection approaches using native vegetation that is tolerant to shoreline conditions, combinations of readily available materials, biodegradable materials and vegetation, and reshaping and revegetating banks have been explored by the Waterways Experiment Station (WES). Some of these methods have proven successful and information on them can be obtained from the Environmental and Geotechnical Laboratories at WES.

Because waves and currents transport the accumulated sediment along a bank toe from a site and remove the sediment on a bank face that has been weakened by FTC, reducing maximum water level stage and duration in the spring would help to stabilize the banks at numerous sites. A combination of toe protection and water level control may be the most effective approach to bank stabilization.

Because excess soil water caused by thawing of ground ice is the primary condition that leads to

* Personal communication with Richard L. Berg, Research Civil Engineer, Civil and Geotechnical Engineering Research Division, CRREL, 1995.

soil instability along a bank due to freezing and thawing, hydrophobic substances that would keep soil water from migrating to the freezing zone could conceivably reduce FTC-induced bank erodibility and instability. However, I am not familiar with the use of such substances and can say no more about them.

## CONCLUSIONS

Numerous studies have reported the results of bank soil weakening along rivers and lakes due to FTC, and many studies have documented the effects of freezing and thawing on soil strength and stability. The frost susceptibility of bank soils and climatic and soil water conditions determine the degree to which this weakening occurs. Through this review I have proposed explanations for some of the significant effects of these FTC-induced changes on bank soils.

To be of any value in northern climes, methods to predict annual bank erosion must adequately account for the seasonal variations in soil strength due to soil freezing and thawing processes. Bank soil structure, cohesion, angle of internal friction and unit weight, all of which vary seasonally due to frost effects, are often used to derive bank soil erodibility coefficients in bank migration and erosion prediction models. However, as currently configured, these models often do not seasonally adjust these coefficients to account for soil weakening effects of ground frost.

Research that needs to be done includes

1) a comparative analysis of the amount of frost heave that occurs along a bank face to determine if more heave results near the water line where a ready source of water is available;
2) development of seasonally adjusted erodibility coefficients from field data analyses;
3) model testing of such coefficients;
4) analysis of the importance of post-thaw, bank soil failures as sources of sediment to the bank toe area, and thus as a source of sediment available for river transport;
5) evaluation of the effects of fluctuating water levels on the groundwater table in banks;
6) determination of the special effects of the bank slope and aspect on thermal conditions, which could cause bank soils to freeze late in the fall, not freeze as deeply during the winter and thaw earlier in the spring;
7) an evaluation of frost blockage of groundwater seepage from a thawed bank face.

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When air temperature is below ground temperature, a thermal gradient is established in the soil that causes the soil to lose heat to the atmosphere. When the soil has lost sufficient heat for soil water to freeze, the newly formed ice changes soil structure by disaggregating, separating, and reorienting soil particles. The suction set up within the freezing soil draws water to the freezing zone through the film of unfrozen water surrounding soil particles, supplying additional water for freezing, so the volume of ice increases. When appropriate thermal and water supply conditions are in place, disseminated ice lenses can form in the soil. As the ice lenses grow, the soil surface is heaved in the direction of heat flow from the soil. Soil particles can be displaced down a bank face when surface ice in heaved soil melts. The amount of ice in a frozen soil by the end of winter can be higher than its water content when unfrozen. Thus, upon thawing, the previously frozen soil temporarily has an excess of soil water and a disrupted soil structure, which significantly reduces internal friction and cohesion and reduces the soil's shear strength. In this weakened state, thawed bank soils are usually more easily eroded by raindrop impacts, overland flows, river and lake ice forces, currents and waves, and are highly susceptible to mass failures. In some instances newly thawed soils are weaker than at any other time of the year. Some studies show that processes related to bank soil freezing and thawing cause more bank recession annually than other processes in areas where seasonal frost forms. However, with time, the strength of the thawed soil returns as excess water drains from the soil, and soil particle packing and interlocking increase. Thus, frost-induced reductions in soil strength and soil particle displacements must be included in bank migration and bank erosion models to be applied in regions with seasonal soil frost.

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