it is obvious that one of the effects of some such salts may be to hydrate. On hydration the salt would develop a hydration structure, which in effect would immobilize the water involved in the hydration. An effect of the addition of the salt is, therefore, to tie up some water in an immobile form.

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ICE-BLOCKED DRAINAGE AS A PRINCIPAL FACTOR IN FROST HEAVE, SLUMP, AND SOLIFLUCTION

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Synopsis

Frost heave is caused by the freezing expansion of excess water accumulation either in the active zone above permafrost, or in the "vernal active zone" above the horizon of winter frozen ground. Normal gravitational drainage is blocked by an impervious ice horizon below the active zone. Water from melted snow cover, rain, and low evaporative rate in cool weather causes the soil of the active zone to become saturated; and as the excess accumulates, it increases the hydrostatic head. Expansive action of diurnal freezing in the active zone deforms the soils and permits formation of pockets, lenses, and layers which refill with free water or ice. The thicker these free-water layers become the greater becomes the expansive or frost heave force, disrupting the active soils above them. Frost heave under highways is intensified because winter freezing is abnormally deep due both to high conductivity of pavement and diurnal ("vernal active zone") activity. It is also more violent because of deep thawing due to solar heating of the pavement in daytime and unrestricted radiant cooling at night which results in rapid and deep freezing. Ice horizons may also block drainage and create water accumulation troughs. Control measures must either insulate pavement areas to neutralize these anomalies, or must provide positive drainage.

In sloping land, water accumulates at the base of the active zone, lying on the impermeable frozen layers which, of course, may also slope. Grav-

itational forces increase the hydrostatic head, and water instead of accumulating in layers and lenses tends to move laterally down the slope through the soils. The most plastic portion of the soil tends to be where the hydrostatic force is greatest just above the impermeable ice layer. Soil slump or movement of the active layer down-grade will occur when the critical moment is reached, i. e., when the force of soil weight at the gravity slope angle exceeds the soil plasticity constant, the inertia, the deformation resistance of thawed soil zone, and the surface vegetation binder resistance. Effective control measures would include positive prevention of excess water accumulation from above, which might be achieved by means of an impervious ground surface cover that would cause water from melting snow and rains to drain off the surface directly without downward penetration; by positive drainage at the critical depth to prevent complete saturation of the active zone; and possibly by vertical sumps draining downward through the frozen soil zone to an absorptive layer beneath. (Vertical perforated drain pipes, however, may be impractical in deep permafrost areas.)

This paper deals with conclusions and theories derived from personal observations in the field. In general, they are based on several assumptions:

1. That frost heave, slump, and solifluction do not generally occur or may be eliminated by corrective action whenever good subsoil drainage extends below the frost line, e. g. typical coarse gravels.
2. That frost heave, slump and solifluction do occur under the conditions represented by water-saturated soil at or above the frost line.
3. That with the exception of obvious cases of continually high water table resulting from purely topographic features or from the presence of impermeable sub-surface layers, freezing ground deformation must be attributed to a winter seasonal accumulation of water within the freezing zone especially where the drainage and run-off appears otherwise adequate during the "warm-wet" season.
4. That when gravitational force exceeds molecular attractive forces (capillarity, cohesion, and adhesion) free water will tend to migrate downward to a base level and accumulate there.
5. That soils which normally drain well become relatively impervious when frozen, and the soil interstices are also ice-filled.
6. That saturated soils are generally more plastic than dry or partially moist soils, and will tend to migrate (solifluction, etc.) under pressure or gravitational forces of sufficient magnitude, and in some areas, as is well known, such solifluction may take place due to vibrations.
7. That freeze-thaw action of free water accumulated in soil has a "jacking" or ratchet action which deforms the soil about it, and leaves voids during the thaw cycle which are replaced by free water.
8. That water accumulation can come from vertically downward gravitational action from surface moisture; horizontal migration from accumulation elsewhere, or vertically upward migration by either capillary action or by vapor deposition process.
9. That frost deformation phenomena occur most typically during the early vernal season in soils of fair drainage characteristics, but may occur at anytime during the freezing season in poorly drained soils or where a high water table exists.

From the foregoing, and based on climatic considerations discussed in a companion paper of this conference, it is visualized that frost deformation phenomena in the ground which give rise to frost heave, slump, solifluction, etc. can be explained by a simple process of ice blocked drainage.

Thermal lag, from seasonal accumulation or loss of surface heat, creates ground-temperature anomalies in a theoretical curve representing the thermal gradient between the surface temperature and the deep iso-thermal or mean annual temperature zone.

As winter sets in there is a strong positive heat anomaly representing stored summer heat a short distance beneath the surface, whereas both at the surface and at deeper levels the temperature is lower. As winter progresses this stored heat anomaly gradually dissipates itself and gives way to a descending cold condition, which in turn becomes a strong "temperature-deficit" anomaly in late spring and early summer. When frost penetrates into the ground it produces the additional characteristics of frozen ground which, until thawed, forms a part of the temperature-anomaly regime, especially after mid-winter. In areas of permafrost, of course, the summer and winter thermal anomalies are within the frozen soil zone.

As winter sets in frost penetration is inhibited by the stored-heat anomaly and a quick freeze at the surface may be melted subsequently from below even though the surface remains slightly below freezing. Also, if the soil in the anomaly zone is damp there will be a strong tendency, because of higher vapor pressure, for moisture migration upward with condensation in the cold surface ground where the vapor pressure is low. This tends to saturate the surface and give rise to muddy conditions even though precipitation may be light. Moisture may further accumulate by dew, frost, and direct absorption from the atmosphere during periods of the day when the surface temperature is below air temperature. Thus independent of precipitated moisture an accumulation of water begins to form at the surface, preparing the soil for solid freezing, and also in itself supplying a source of moisture sufficient in many types of fine-grained soils to fill voids with free water which later becomes ice.

As winter progresses and the temperature-deficit zone reaches its maximum intensity, and the frozen zone reaches it maximum depth, the warming cycle begins to create an active freeze-thaw layer which we may call the vernal active zone. Beneath the vernal active zone is a frozen zone which, after mid-winter, is colder than the surface. The returning sun daily becomes more intense in its heating ability, and on clear days or during warm spells thawing may be deep; but at night refreezing is equally intense, for the water layer is not only chilled by atmospheric causes but it is also dissipating its heat into the cold and frozen soil immediately beneath it.

It is reasonable to assume that freeze-thaw action tends to keep soil particles sufficiently disturbed so that free water accumulated at the surface is able to migrate downward.

Initially, during the heat of the day, any downward migrating water aids in deeper thawing of the frozen soil, but as freezing conditions set in again at the surface the melt water zone may be arrested and freeze in position and become an accretion of the frozen layer. Many variations can be expected depending upon depth of the thaw and the duration and intensity of atmospheric freezing conditions. In some cases the whole vernal active layer may freeze while in others the melt water remians liquid and ready to continue its thawing journey downward. It has been observed that water on top of lake ice but protected by snow insulation can remain unfrozen for days at a time even when the air temperature was recorded as low as -50 F.

Thus we are picturing a migrating layer of water in saturated soil with free-water accumulation gradually working downward on the upper surface of a frozen zone of soil. The frozen layer remains impervious, for even if it were fissured, water seeping in under hydrolitic pressure would soon freeze and cement the leak. However, there appears to be little reason to suspect that the downward migration of the thaw layer is uniformly level, even if the upper surface of the ground is essentially flat. Pockets will form of varying size and shape producing "inter-soil puddles" at various levels. Some soil horizons undoubtedly thaw more readily than others, and isolated blocks of sections of layers of frozen ground become isolated as enclaves or occlusions. Lateral progress may be faster in one zone than another, so in advanced stages we may picture a somewhat chaotic melting pattern. Such a pattern, or lack of pattern, would be expected on level land, whereas on slopes the migration of water is more likely to concentrate and flow down through the soil on the surface of an especially thaw resistant layer. This surmise is based upon the fact that gravity will continue to pull the water down this hypothetical inter-soil slope formed by frozen and impervious soil, somewhat parallel to the surface, rather than form inter-soil puddles as postulated for flat-land cases.

If we now postulate a period of deep freezing while the thawing action is well advanced, we recognize that the zones of water accumulation will constitute potential areas of abnormal expansion and the source of frost heave deformation upon freezing.

Although other factors which produce impermeability can likewise contribute to water accumulation and consequent frost heave, it appears most likely that ice formations blocking spring drainage are the most wide-spread cause of frost heave phenomena. It is further postulated that the foregoing conception explains the formation of ice lenses of certain types described in permafrost investigations. Frost heave development is probably self aggravating. That is, heave action is strongest over inter-soil-puddle-type water accumulations. Deformation tends to make more area for water accumulation and in turn bigger and better heaves. When ice lenses thaw out from time to time the weight of material above undoubtedly creates sufficient hydrostatic pressure to force the water upward to the surface. This, in turn, suggests the origin of ice dykes, sills, polygon patterns, slumps, etc.

On sloping land of the southfacing type, so typical of solifluction action in the north country, we find again by the above reasoning a fairly simple explanation of solifluction and downhill slump. Permafrost investigations have shown that the permanently frozen ground is deepest beneath hills and shallowest in valleys. Thus if we picture a vernal thaw zone percolating its waters downward to the upper frozen horizon, we can see that the ice-blocked impermeable layer may be steeper than the surface configuration of the hill would indicate. This should hold true whether the frozen ground below is only a winter feature or not. The melt water layer should further gain in magnitude by migratory accumulation as the water moves downhill, thus creating in turn greater melting potential and further tending to steepen the sloped surface of the upper ice horizon. If we can agree that gràvitational accumulation of water increases at the impermeable, ice-blocked sub-surface, it is but one step more to recognize that saturation will weaken the strength of the soil as well as lubricate the surface of the impermeable layer. When the weight of the mass above overcomes inertia and plastic resistance of the soil, the whole surface of the hill side may slump downward.

Two common evidences are offered in support of this concept of solifluction. First, slump more often than not begins part-way down from the hill crest. This is believed to be due to the better drainage higher up on the hill. That is, there is less available surface moisture and vector drainage, or water migration is not supported from further up slope as is the case farther down hill. The second evidence is the frequent occurence of spring-like out-flows of water from beneath solifluction slumps after movement has taken place not only immediately afterwards but on subsequent years.

If the theory of ice-blocked drainage here discussed can be substantiated by further field study, the control can be improved. For example, a highway over flat country affected by frost heave may prove to be creating a subsurface trough in spring which is accumulating migratory water down ice-blocked, inter-soil slopes created by the presence of the highway. That is, the road surface is such that in most cases it favors intensive freeze-thaw beneath it. The surface is exposed to the sky and open sweep of the wind and generally consists of higher thermal conductive materials than the surrounding surface. The surface heats fast in daytime and cools fast at night. Although it is fair to assume without supporting evidence that winter freezing beneath roads is deeper than on the shoulders, especially where snow is cleared for traffic, it can also be assumed that melting under the highway will progress more rapidly in spring. We may assume that thawing will let drainage accumulate in the thawed zone beneath the road where capacity for receiving it is increased over that of the vertical ice-blocked drainage beneath the shoulders. The presence of the migrating water further activates melting and deepening of the "trough" and presents a sizable quantity of water to support frost heaving. Thus it is suggested that restudy of the problem is required to determine methods of lessening the tendency of trough formation.

In respect to solifluction and slumping, it appears that surface moisture accumulation is an important point to be controlled, for it feeds the water drainage accumulation above the ice-blocked, inter-soil surface. In certain critical areas slumping tendency may be minimized by producing an impervious run-off surface.