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Heave and solifluction on slopes

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ABSTRACT: The Trans Alaska Pipeline System (TAPS) traverses three major mountain ranges. The pipeline route crosses significant lengths of rolling terrain with many steep slopes interspersed in these hills. Some of the slopes are in permafrost and others are in thawed ground. In both cases shallow granular overburden, whether naturally deposited or placed as pipeline workpad, on these slopes moves producing solifluction features on the slopes. Solifluction features are sometimes very evident around the piles that support the pipeline for approximately one half of its length. The formation of these solifluction features, whether in naturally deposited materials or in man-made fills, is believed by the author to be closely related to the frost heave and the trapping of near surface groundwater by an advancing freeze front. This paper compares the solifluction-like features and frost heave found along the pipeline workpad to the formation of solifluction lobes on undisturbed natural slopes.

1 INTRODUCTION

The purpose of this paper is to present information collected over the past 15 years that suggests that solifluction movements are a result of frost heaving and subsequent thawing, and that creep is not a significant part of the process. In this paper the term solifluction is used to refer to the down-slope movement of saturated lobes of primarily granular materials, whether the movement occurs over frozen or thawed terrain. This definition of solifluction combines the meanings of solifluction and gelifluction as presented in French (1996) and van Everdingen (1998). This paper presents examples of data that have been collected that seem to support the idea that solifluction is closely related to frost heave and that creep is a negligible part of the overall movement. The following are the reasons for this hypothesis:

1. Creep of frozen ground is dependent on constant near thawing temperatures. If ground temperatures are too cold there is no creep and if they are too warm the ground thaws.
2. Surficial features such as solifluction lobes experience extreme variation in ground temperatures because they are shallow features that usually can feel all the changes in air temperature.
3. Ground temperatures have less fluctuation with depth and thus creep is more likely to occur at depth.
4. Creep is slow and continuous once it starts until there is a load change or temperature change.
5. All soils flow when adequately loosened and saturated.
6. Surficial freezing can trap groundwater perched near the surface causing pore pressures to rise.
7. A freeze front with water available to it will expand pore space in most soils making them looser by lowering their density.
8. Solifluction is usually found on slopes where bedrock or impermeable soils are found under a thin mantle of more permeable soils.
9. Many solifluction lobes consist of saturated sands and gravels.

2 VSM HEAVE ON A DISCONTINUOUS PERMAFROST SLOPE

TAPS consists of about 644 km of belowground (B/G) pipe and an equal length of aboveground (A/G) pipe. The A/G pipe is supported on 46 cm pipe piles (frequently referred to as VSMs or vertical support members), some of which are cooled by passive cooling devices called heat pipes. The A/G support system consists of two piles, a crossbeam, and a sliding shoe that is clamped to the 122 cm pipe and which slides on the crossbeam.

Along TAPS there are several slopes that have been monitored for almost 15 years. The results of the monitoring on two of these slopes are reported in Tart & Anderson (2002a, b). The monitoring has consisted of continuous and/or periodic ground and air temperature measurements, sporadic ground water level measurements, some settlement measurements, periodic VSM movement measurements, periodic inclinometer measurements, and continuous measurements of the relative position of the shoe and crossbeam on the aboveground structure. As a result of these measurements, trends of movements have been established for the slopes and the structures on the slopes.

One of the movements that have been studied in detail is the heaving of piles in areas where the ground is thawed beneath the pipes as reported in Tart & Ferrell (2002). In places where this heave occurs, surficial sliding has also occurred. These areas are typically

Figure 1. Workpad flowing around a pile.

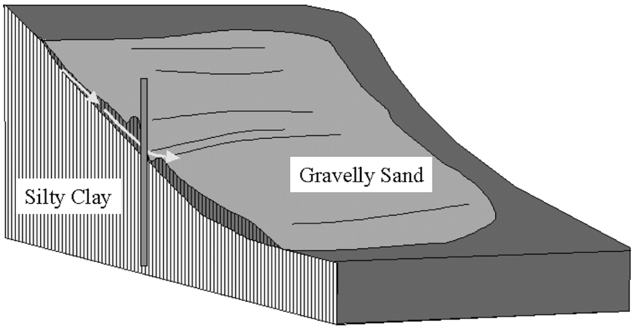

Figure 2. Conceptual sketch of flow around a pile.

underlain by thawed moderately consolidated silty clays, which were formed by an ancient glacial lake that covered this area. Most slopes are results of drainages that have cut these lake sediments leaving steep approaches to streams. The pipeline was constructed by flattening some of the steeper slopes, and then placing a sand and gravel workpad on the surface of the graded slope to provide access for construction and maintenance.

In spring and early summer, sections of the workpad can soften in some locations, resulting in flow-like downslope movements in some of these areas. Figure 1 shows a picture of the workpad materials flowing around a pile and this is conceptualized in a sketch in Figure 2. Thermistor and inclinometer data from the vicinity, in which the flowing has been observed, are presented in Figures 3 and 4. Figure 3 shows the typical high variations in surficial ground temperature in the active layer and thawed ground below the active layer at this site. Figure 4 shows near surface ground movements. Harris & Davies (2000) show similar movement data in laboratory tests they performed that simulated conditions similar to those found on this slope.

In a few areas along the pipeline route, VSMs have heaved and/or settled. When this has occurred, instrumentation has been setup to monitor these movements to make certain the movements do not impact the integrity of the A/G system. Figure 5 shows some of the instrumentation used to record continuously the relative

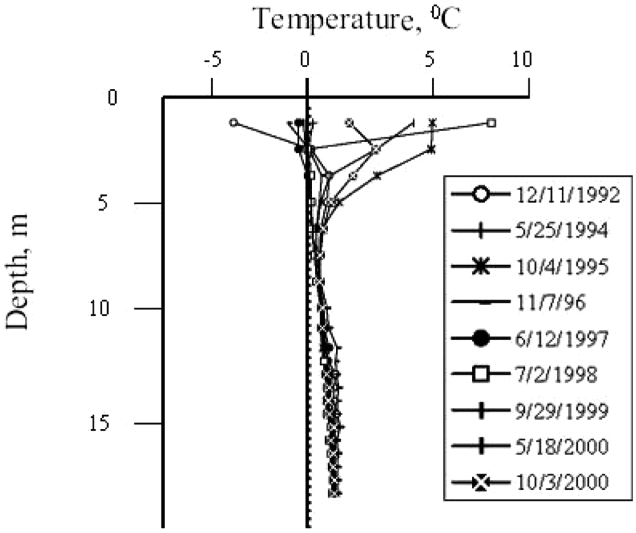

Figure 3. Ground temperatures at flowing site.

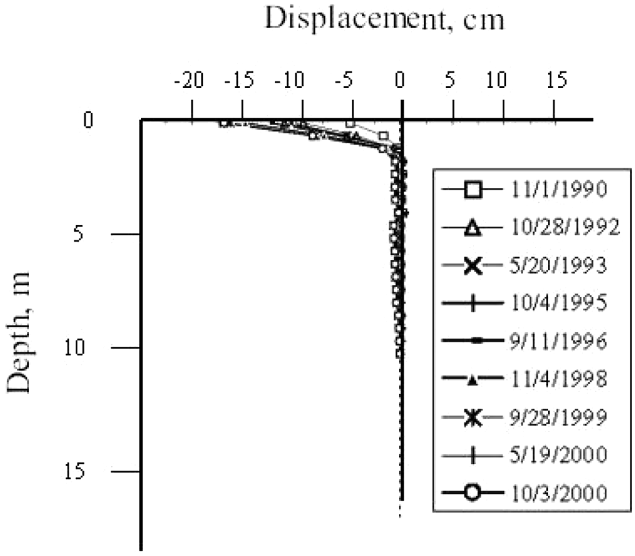

Figure 4. Ground displacement at flowing site.

Figure 5. Shoe monitoring instrumentation.

movement of a shoe along the cross beam. Figure 6 compares the record of these continuous measurements of the relative movement to a simultaneous record of the air temperature. The relative movement of the shoe

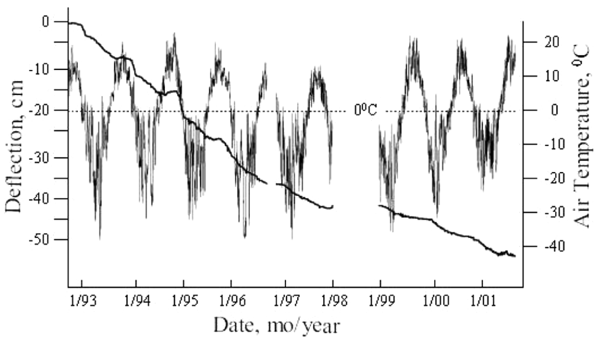

Figure 6. Continuous temperature and movement.

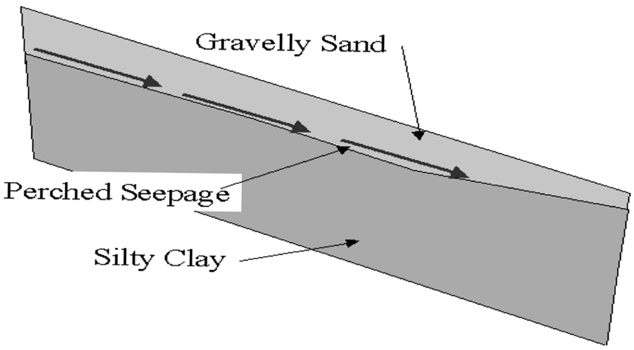

Figure 7. Perched seepage in early fall.

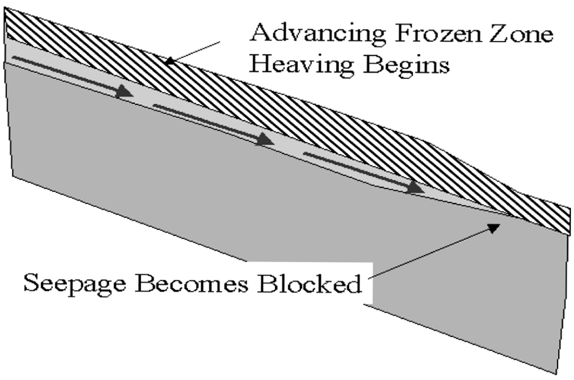

Figure 8. Frozen zone advancing in winter.

is primarily a result of the movement of the piles as they heave and settle each year. However, the pipe itself moves with changing flow rates and oil temperatures. Therefore, the primary use of these instruments was to determine the times of movement, not the magnitudes. Figure 6 shows that movements start in the fall and stop in summer when temperatures are well above freezing.

Short lengths of the workpad soften and flow in early summer on a limited number of slopes. A series of conceptual sketches are introduced in Figures 7, 8, 9 and 10 and will be used to explain the process that the author believes results in workpad flow. The fall or late summer is represented in Figure 7. At this time, the surface water and groundwater permeates the granular workpad and perches and flows on the

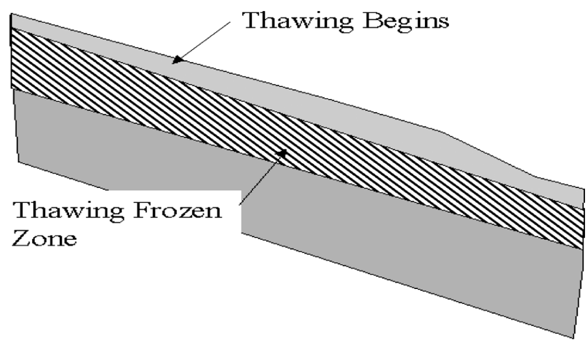

Figure 9. Thawing begins in early spring.

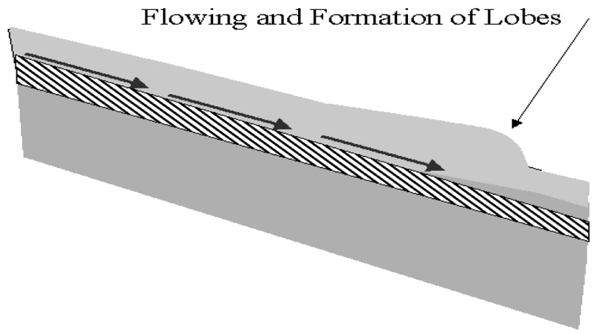

Figure 10. Workpad flow in later spring.

impermeable silty clay. Figure 8 represents late fall or winter as the active layer begins to freeze. The freezing front proceeds downwards until it meets an undulation of the clay strata that then can block the perched groundwater flow. Some pore pressure may build up in the granular workpad, but certainly water is readily available to the freezing front. This water expands as it freezes and may develop ice lenses. It causes oversaturation and heaving of the workpad. In some cases the water is forced to the surface and forms icing layers on the ground surface. As shown in Figure 9, thawing begins in spring. At that time the workpad is wet and loose, and in some places wet enough to flow until it drains adequately and stops moving. This is shown in Figure 10. The result is a solifluction lobe or mound around a pile, as shown in Figure 1.

The remainder of this paper will discuss other examples of slope movements in frozen terrain, some of which the author believes are not related to the solifluction process, and others that are.

3 CREEP ON A WARM PERMAFROST SLOPE

As stated earlier, one reason the author believes that solifluction is not influenced by creep is that creep is only significant for a very small ground temperature range. In the following example, creep on a slope has been monitored for more than 10 years. The creep occurs continuously in an ice-rich silt layer and terminates at the contact of this layer with low ice-content silty sand. The slope covers an area of about 2.5 km^2. Inclinometers, surface survey monuments, and thermistors are located throughout the area. TAPS crosses this area with an A/G section on a cleared workpad. The creep slide plane is below the pad and the bottoms of the piles so that the plane appears independent of the pipeline and its workpad. It is occurring in a zone of stable ground temperatures just below 0°C.

Figures 11 and 12 show temperature and displacement data for one of the fastest moving locations in this area. This is in a relatively undisturbed area, located about 150 m from the pipeline workpad. This site creeps because it is so ice rich and is just below a temperature of 0°C, that has remained essentially constant below a depth of about 4 m for more than ten years. The ice provides the latent heat resistance to thawing, which is responsible for keeping the temperature constant. The displacement data presented only covers two seasons because the displacements are so large that the original inclinometer casings became inaccessible and had to be replaced by those shown in the figure.

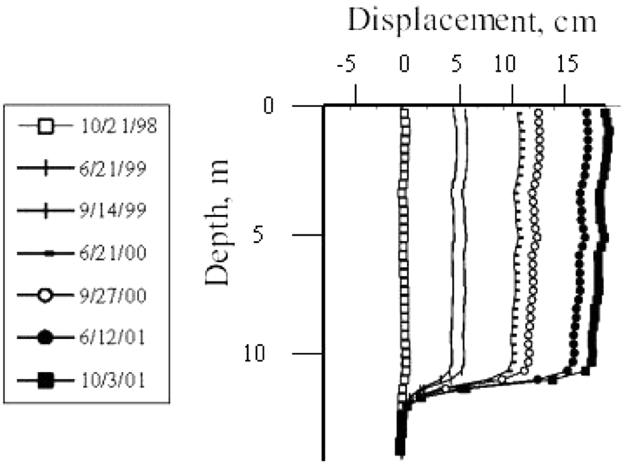

Figure 11. Ground creep displacements.

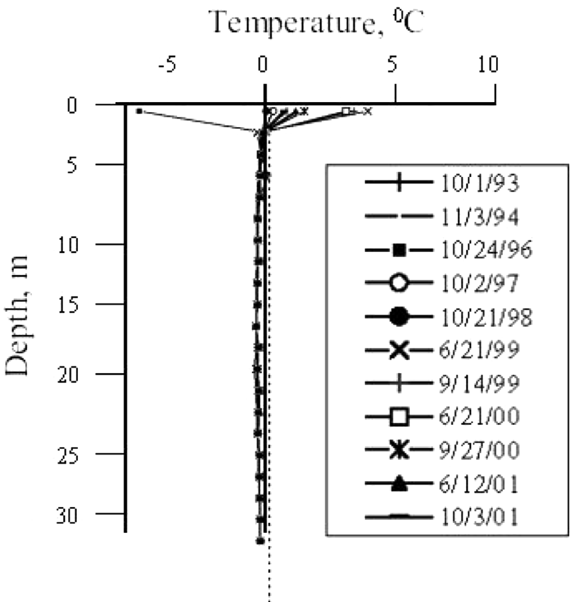

Figure 12. Ground temperatures at creeping site.

4 BULGING SPOIL PILES, NATURAL LANDSLIDES, AND DEBRIS FLOWS

Tart (1996) reports several landslide phenomena that are related to the confining of near surface groundwater by the freezing of the ground surface. Figure 13 shows natural landslides in a discontinuous permafrost area. The author believes that this is a result of the same process that results in solifluction. It is likely that there were seeps at these landslide locations. The freezing active layer confined these seeps in the fall and winter. The landslide footprint became saturated and heaved throughout the winter. In spring, the loose saturated surface materials began to slide. These "skin" slides are primarily saturated surficial materials.

At a coal mine site in Alaska, the spoils of the mining operation are fine silty sands, which resulted from the breakdown of weakly bonded sandstone that had been moved during the mining process. The extracted mineral is found between layers of this sandstone and thus huge volumes of spoil are generated as the mineral is extracted. In some locations, this spoil has been placed over slow flowing springs. The permeability of the spoil was assumed to be sufficient to allow the springs to drain. This assumption may have been correct in summer. In winter, ground freezing contains the spring water, causing bulging and significant downslope movement of the spoil. A photograph of these moving spoil piles is presented in Figure 14. The movements are so large that standard inclinometer casings can be made inaccessible in a single season. A large rock buttress has been used with success to stop some of the advancing of the spoil piles.

It is further suspected that other types of landslides, debris flows and/or rock avalanches, as shown in the

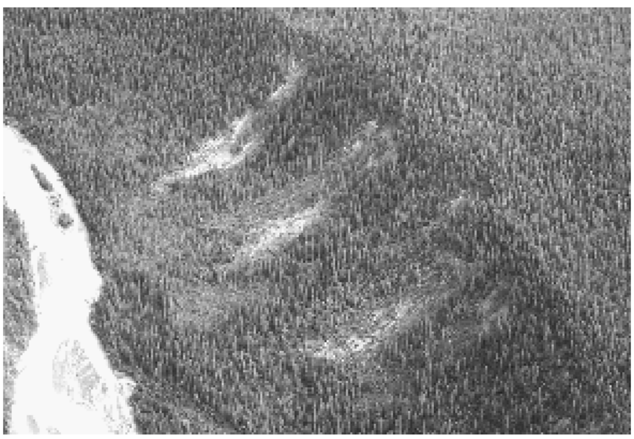

Figure 13. Natural landslides in discontinuous permafrost.

pictures in Figures 15 and 16, are results of the same mechanism. Movements are dependent on water being available for freezing, a granular upper stratum, and an impermeable under layer. These are just larger examples of the freezing mechanisms that also result in the solifluction landforms. It is the author's opinion that, in each case described, there is a relatively impermeable layer over which there are permeable granular deposits. Surface water, snowmelt, and groundwater penetrate the surface deposits and perch on the impermeable layers. These impermeable layers could be clay, bedrock, permafrost, or thawing active layers. The freezing active layer begins to trap water in these masses in fall. In spring, when the thaw is faster than the rate of drainage of these features, they flow until they drain sufficiently to become stable again. Examples of solifluction lobes in Alaska, that appear to be formed through the process discussed earlier in this paper, are presented in Figures 17 and 18.

Figure 14. Bulging, advancing spoil piles.

Figure 15. Bulging landslide near Alaska Highway in Canada.

Figure 16. Flowing landslides in Chickaloon Pass, Alaska.

Figure 17. Solifluction lobes in the Alaska Range.

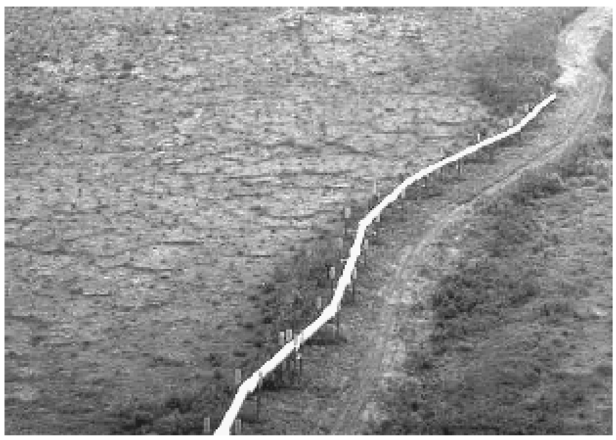

Figure 18. Solifluction along TAPS.

5 CONCLUSIONS

Based on the data reported and the observations of the author, it is his opinion that the mechanism of the formation of solifluction lobes and some of the other well-documented permafrost and cold regions landforms on slopes is essentially the same as the process observed and monitored on the TAPS slopes with the flowing workpads. Further, the process of heaving and the resulting mass density reduction is a key element in the development of flowing surficial materials that is characteristic of these cold regions landforms. The data that have been collected over the past ten years imply there is an explanation to these landforms that could be further verified with instrumentation methods similar to those used to collect the data presented in this paper.

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