

Performance of The Squirrel Creek Slopes Steep Slopes on Discontinuous Permafrost

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Abstract

The two slopes approaching Squirrel Creek were modified during construction because natural slopes in the area of similar steepness were displaying landslides. The original design plans called for the pipe to be buried on these slopes. When drilling found discontinuous, warm permafrost along these slopes, the pipe design mode was changed to aboveground with heat pipes to maintain frozen ground. Since construction of the Trans Alaska Pipeline System (TAPS), Alyeska Pipeline Service Company (ASPC) has been monitoring instrumentation on these slopes and performing periodic maintenance. This paper will describe the history of the performance of these slopes and the maintenance activities that have been employed to address some of the issues that have developed along the slopes since construction. Documented solifluction-like movements, changes in ground thermal state, frost heave, and thaw settlement have all been monitoring and addressed with maintenance.

Introduction

The Trans Alaska Pipeline extends from the Valdez Marine Terminal on Valdez Sound at the south end to Pump Station 1 near Prudhoe Bay. Progressing north from Valdez the pipeline crosses the Chugach Mountains then enters the Copper River Basin paralleling the Richardson Highway.

The Copper River Basin is the southernmost limit of permafrost along the pipeline route. Most of the basin is underlain by discontinuous permafrost. Much of the route through basin is underlain by overconsolidated glacial clay and silt formations.

In the Copper River Basin, the pipe crosses several east-west trending drainages that direct water from the Chugach Mountains to the Copper River. At pipeline milepost 717, about 83 miles north along the pipeline from Valdez, the pipeline crosses Squirrel Creek as shown in Figure 1. Both the north and south approaches to Squirrel Creek were steep and presented concerns to the pipeline designers. Along Squirrel Creek and other similar drainages in the Copper River Basin, natural landslides were observed on some of the slopes approaching these creeks and rivers as shown in Figure 2.

Before detailed field studies began, the preliminary design for the slopes at Squirrel Creek included three different modes. A sketch depicted the three modes is given in Figure 3. At the creek crossing the pipe was to be conventionally buried. The north slope was to be moded aboveground and the south slope was to be moded special burial.

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During the first geological reconnaissance of these slopes, Alyeska engineers and geologist began to focus on mode changes that would be more appropriate for these steep slopes.

Special burial requires artificial refrigeration to maintain frozen ground to support the pipeline. Further analyses determined that the aboveground mode with thermal piles would be more appropriate in this area.

Crossing Squirrel Creek borings indicated both frozen and thawed soil profiles depending on the distance from the creek. The underlying sands and gravel were thought to be stable but there was some question as to the stability of the intermittent zones that were frozen, especially during an earthquake. For this reason this zone which was originally moded below ground was remoded above ground, again with thermal piles to decrease pile length and promote refreezing of thawed zones. The aboveground mode was originally selected for the north approach to Squirrel Creek and was not changed.

The other design issue was the steepness of the slopes approaching the creek. It was decided to flatten the slopes to no steeper than 27% in the Copper River basin formations. Thus, most of the south approach needed to be cut and a short section of the north slope had to be cut to meet this criteria. The photograph in Figure 4 shows the cut benches on the south approach to Squirrel Creek looking from the short cut section on the north side of the creek.

Because the two slopes approaching Squirrel Creek were a concern to the designers, it was recommended that these two slopes be monitored after construction to confirm that the slopes were performing as planned. Until about 1989, no significant deviations from the performance expected by the designer had been noted.

Deep Thaw

During a slope inspection in 1989, it was noted that one bent had a hanging shoe; the crossbeam had moved down enough that the shoe was no longer being supported as showed in Figure 5. This caused the initiation of a significant research effort by Alyeska. Survey data was studied and modified approaches to the acquisition and reporting of this data were established. A geotechnical drilling program was initiated to determine why the VSM's were apparently settling. The records from infrared surveys of the heat pipes were examined to determine if there had been heat pipe failures.

The research revealed the following:

- The heat pipes were functioning properly. Even in locations where the annual heat pipe surveys have indicated the heat pipes were performing inefficiently, the heat pipes were still removing heat. No VSM settlement as has been related to a heat pipe failure.
- The surveys indicated that many of the VSMs in this area were moving during the year.
 - ❖ Some were heaving
 - ❖ Some were settling
 - ❖ Some were leaning
- The borings and thermistors revealed that there was an ice lens below the depth of the VSM bottoms and that the thaw front had reached the upper part of this ice lens.

- Borings close to the VSM's indicated that there was still a frost bulb around the VSMs.

The bent settled more than one foot before, it was stabilized by adding deep, free-standing heat pipes. The settlement of this bent is inferred in the photograph in Figure 5, which shows the separation of about 0.3 m between the shoe and the crossbeam. At this location, a geotechnical investigation found an ice lens below the bottoms of the VSMs. The ground above the ice lens was thawed although there were significant freeze bulbs still in existence around the VSMs. The continued thawing of this ice lens was halted by installing free-standing heat pipes which extended through the ice zone. It was concluded that the wide zone of vegetation clearing in this area coupled with the fact that this was a south-facing slope, resulted in the development of a deep thaw bulb around the VSMs. The impact of this thawing would not have been as significant if the ice lens had not been under the VSMs. Figure 6 depicts how this thaw bulb likely progressed to the ice lens.

Heaving Thermal VSMs

Another concern developed early at Squirrel Creek. Some shoes were no longer centered on the cross beams and some VSMs were leaning. In addition, wet zones appeared during some periods of the year on the pad and mounding and voids formed around the VSMs. The initial response was to evaluate the impact of these unexpected observations on the integrity of the pipeline system. In some cases the contact between the shoe and beam was not uniform or only one skid of the shoe was touching the beam. In Figure 7, the heave process is depicted as VSM heave is beginning to initiate in mid-winter. There is a frozen bulb around the VSM and the frozen active layer has connected with the frozen bulb. The freeze front has not reached the bottom of the permeable workpad. Water is perched on the low permeability silts and clays under the workpad. It continues to flow downslope being trapped by the freeze fronts from the active layer and the frozen bulb around the VSM. The greater availability of water upslope of the VSM results in downslope, lateral heaving as the water freezes and there is more expansion at the upslope freeze fronts than at the downslope freeze fronts around the VSM. The VSM heaves and leans downslope as shown in Figure 8.

Structural analyses were initiated to determine the impact of the lost of support of a bent on the integrity of the pipe. These analyses showed that the loss of 2 or possibly more adjacent bents would not cause overstressing of the pipe. Therefore it was concluded that the complete loss of two adjacent bents, or possibly more bents, would not endanger pipeline integrity.

Since pipeline integrity was not an issue, the appearance of the VSMs and the shoe contacts were a concern from the standpoint of a deviation from the expectations of the designers. A monitoring program was established that tracked the long term movements of the VSMs and shoe movements.

Initially the VSM movements were attributed to movements of the slope since this slope had been a concern during design and construction and since this slope was designated during design as a slope to monitor throughout the life of the pipeline. Therefore, as soon as VSM movements were noted, geotechnical studies were initiated during which long term instrumentation was installed on the slope to monitor thermal changes, groundwater conditions, and slope movements. Thermistor strings,

piezometers, slope indicator casings, sondex settlement casings, and shoe movement instruments were installed. For more than 12 years this instrumentation has been continuously maintained and monitored.

The thermistor strings have shown some slight warming, but no significant areas of thermal state change. Figure 9 shows typical results from a thawed area on the south approach. Since their installation, areas that were thawed have remained thawed and areas that were frozen have remained frozen. The major changes have been in the active layer, as one would expect. The active layer freezes each fall trapping near surface groundwater flowing over the slope as shown in Figure 7. As the active layer freezes, it begins to heave the VSMs, as shown in Figure 7. The trapped water flows to the freeze front resulting in more heave as the front progresses downward. Because the heave is occurring on a slope, the VSMs lean downslope as they heave. Also, as the trapped groundwater freezes in the gravelly workpad capping the slope, it loosens this fill.

When thaw begins at the ground surface the loosen gravel fill becomes soft and wet until it has time to settle and drain. While it is wet and loose it sometimes can have near surface downslope movements similar to the solifluction movements seen in permafrost terrain such as the area shown in Figure 10. Mounds are created around the VSMs as shown in Figures 11 and 12. In some places the thawing results in springs and pipes as the frozen layer becomes thin enough to release the trapped groundwater. See Figure 13.

The inclinometers confirm that the only movement on the south side of Squirrel Creek is the solifluction of the active layer. An example of this movement as depicted by plotting the slope indicator data is presented in Figure 14. At other bents on these slopes the inclinometers have shown limited zones of downslope movements resulting from deep thawing and movements away from growing freeze bulbs.

Analyses concluded that the clearing of this south facing slope had resulted in the development of a deep thaw bulb around and eventually under the VSMs. The solution was the installation of deep heat pipes near the VSMs to prevent further thaw below the VSMs. After 10 years this solution appears to be working.

Liquefaction

The liquefaction criteria used by the designers concluded that saturated granular formations that had been recently frozen became liquefiable upon thawing. Thus, some of the area immediately adjacent to Squirrel Creek would be considered liquefiable when these areas thawed. Bent 12 located about 200 m north of Squirrel Creek falls into this classification.

During design one of the primary methods of mitigating liquefaction was to use thermal VSMs to support the pipe. The final mode selected for crossing Squirrel Creek was the use of thermal VSMs to support the aboveground pipe. The VSM logs through this area showed some locations to be frozen and others to be thawed, warm discontinuous permafrost. A boring in 1992 found loose, saturated granular soils adjacent to Bent 12, which had settled. None of the other borings in this area have identified loose granular deposits. The granular materials overly lean stiff clays. These sands and gravel deposits are thicker at the creek and feather out up the slopes. The deepest zones of these deposits is thought to be 15 to 20 m in thickness.

To stop the settlement of Bent 12, the VSMs were pushed into the ground by statically loading the bent. Steel split rings are welded to each VSM to provide support point for the crossbeam. The split rings were raised until the load of the pipe and shoe were being supported on the crossbeam. As the VSMs settled more, the split rings were adjusted again until the pipe was being supported. When the VSMs had settled about 4 to 6 ft they began to have sufficient resistance to provide support to the pipe as shown in Figure 15. Alyeska continues to monitor this bent and will adjust the split rings to maintain load on the VSMs in the future, if necessary.

Prior to these adjustments, adjacent bents did not settle significantly, but maintained the pipe support taking the increased loads which resulted from the loss of support at Bent 12. Considering this, and gravelly nature of the formation, it has been concluded that there was likely an ice pocket near Bent 12 which probably thawed and resulted in the movement at that bent. As shown in Figure 16, the other adjacent bents not moved nearly as much as Bent 12. Areas of large movement usually indicate areas of settlement or heave. Small movement zones are indicative of stable VSMs.

Although studies continue in this area, the current consensus is that there is no significant liquefaction hazard at this site because:

- The boring was performed at the time active thawing was occurring away from the thermal VSM. Since the initial thawing which was occurring at the time the boring was made, it is believed there has been some consolidation of the coarse granular soils and some increase in strength.
- It is believed that there is a year-around freeze bulb around each thermal VSM that will significantly increase its load capacity throughout the winter months, if not for the entire year.
- The settlement that has occurred is believed to be limited to a relatively small area where deep ice lenses were under the VSM bottoms.
- Squirrel Creek is a high energy stream which has not likely deposited large volumes of the fine sands and silty sands associated with liquefaction.
- Because of the free draining properties of the materials adjacent to this stream, it is expected that any adjustment during a seismic event will be not be large enough to move VSMs significantly.

Summary

The two slopes approaching Squirrel Creek were an engineering challenge during the design and construction of the Trans Alaska Pipeline. There were many concerns during design because of the limited amount of available geotechnical data and the lack of reported experience from others on the performance of steep slopes in a discontinuous permafrost environment. Since construction, much has been learned through observations and monitoring. There have been no massive slides as some had thought may occur. The granular workpad, when it becomes loose and saturated in some areas can move in the spring and summer. These movements make maintenance access more difficult for limited periods but do not appear to have more substantial impacts.

There has been some movement of VSMs from both settlement and heave. In both cases the amount of movement does not appear to have adversely impacted the integrity of the aboveground pipeline system. The slopes continue to be monitored and maintained

and much more will be learned about the performance of steep slopes in permafrost in the future by Alyeska engineers.

Acknowledgement

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Figure 1. Squirrel Creek Crossing



Figure 2. Natural Slides in Squirrel Creek Area

Aboveground

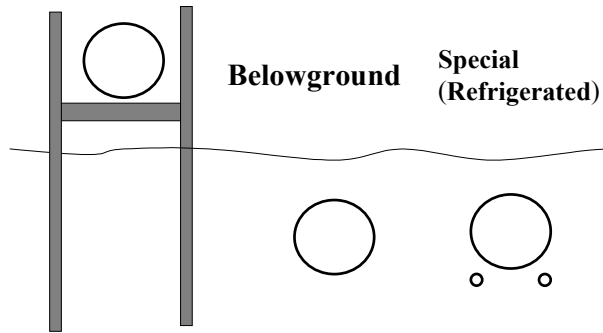


Figure 3. Initial Pipeline Modes at Squirrel Creek

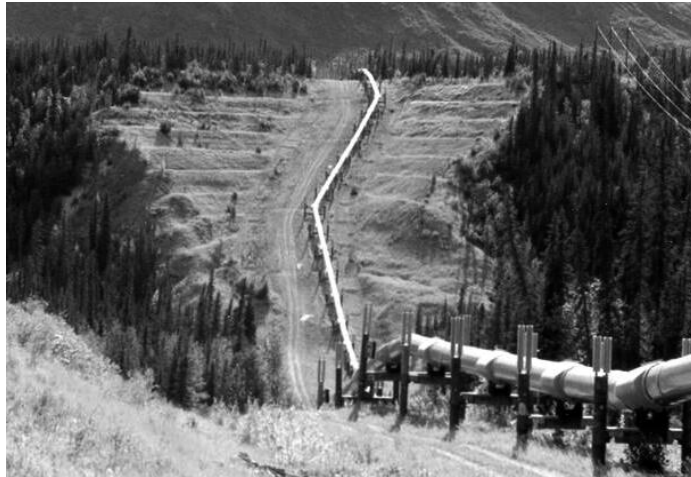


Figure 4. Benches on South Slope



Figure 5. Hanging Shoe

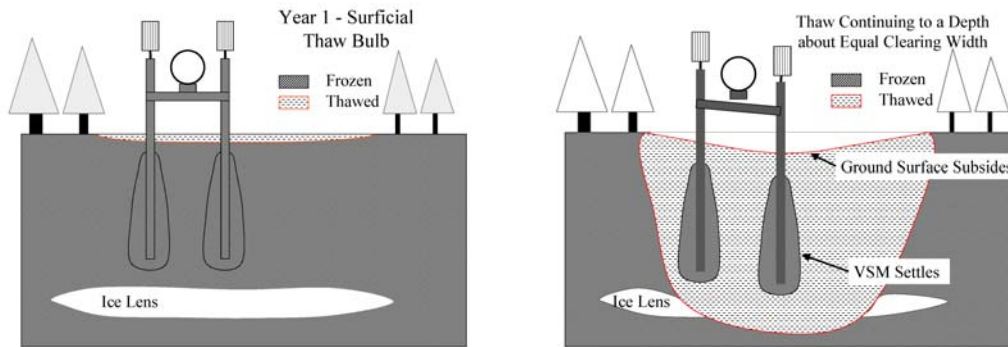


Figure 6. Thawing Around VSMs

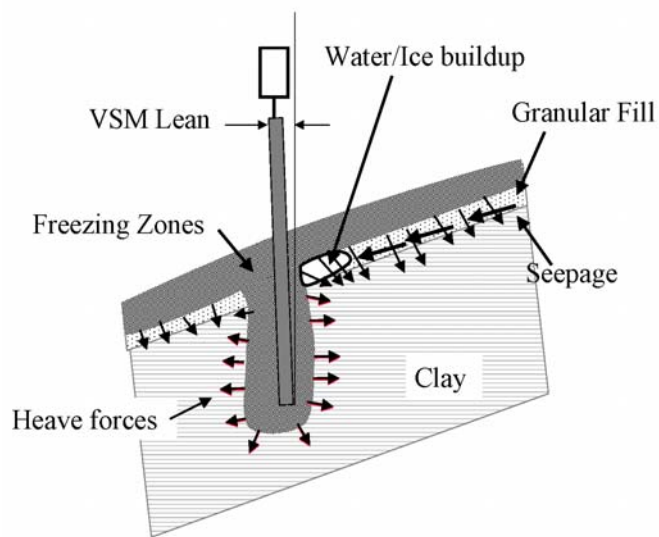


Figure 7. Heaving on a Slope



Figure 8. Leaning VSM

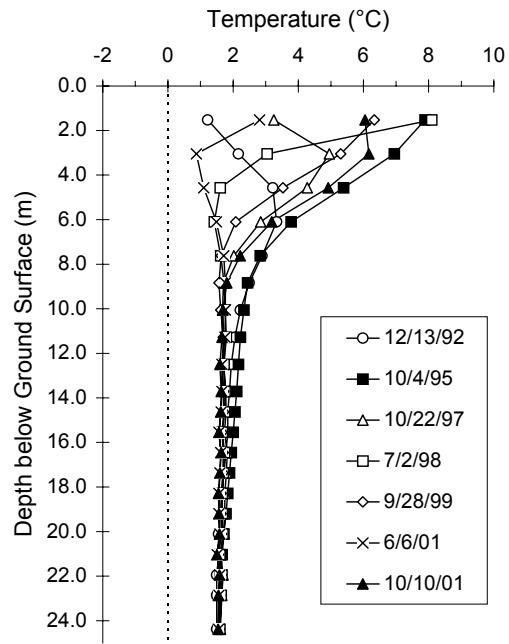


Figure 9. Long Term Temperature Results



Figure 10. Solifluction Lobes Along TAPS



Figure 11. Mounding Around VSM

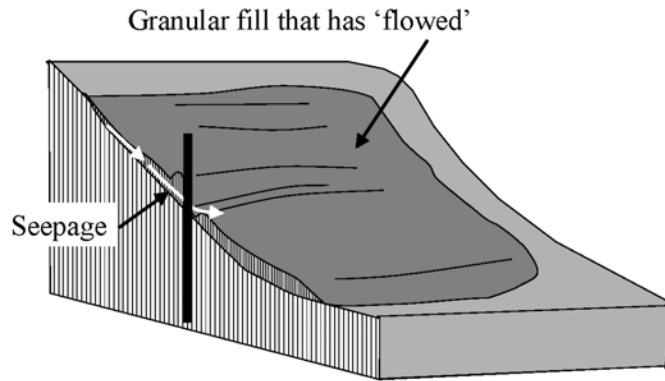


Figure 12. Skin Flow Around VSM



Figure 13. Piping Through Workpad

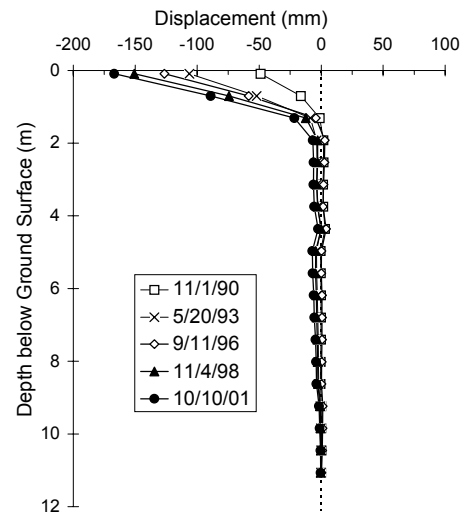


Figure 14. Skin Friction Displacements

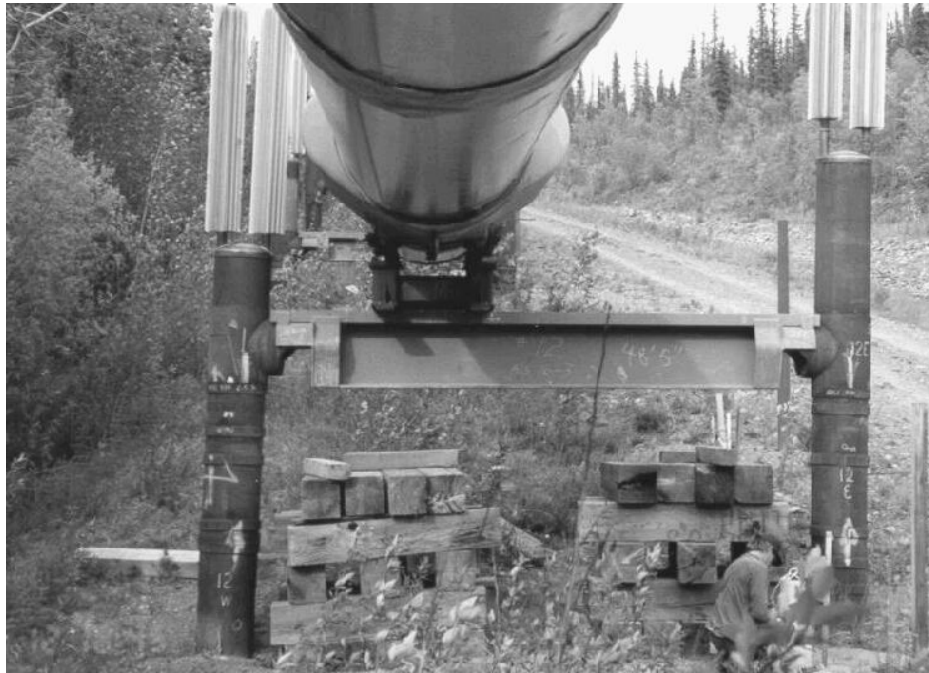


Figure 15. VSMs That Have Settled

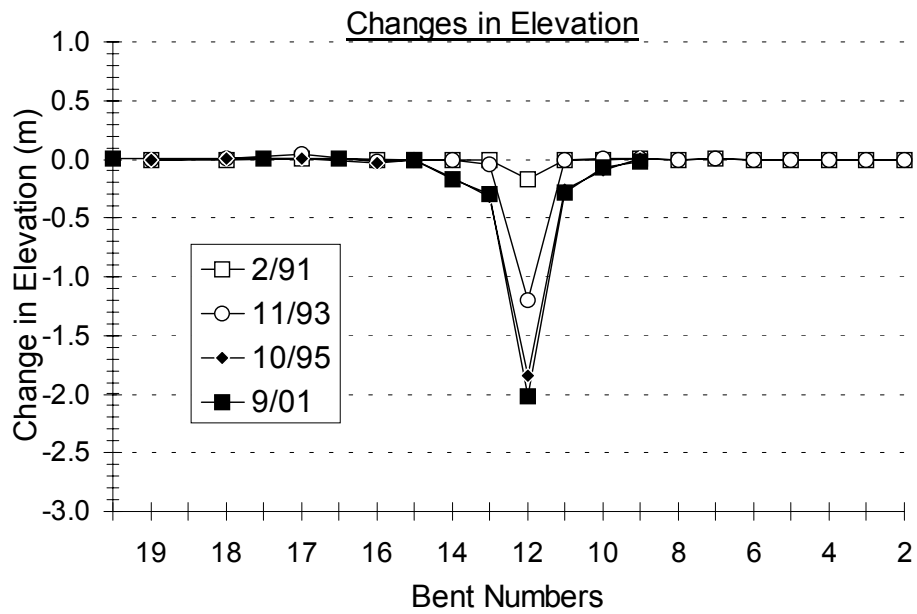


Figure 16. VSM Elevation Changes