A Study of Unstable Slopes in Permafrost Areas: Alaskan Case Studies Used as a Training Tool

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TABLE OF CONTENTS

1.0 INTRODUCTION

This report is the companion to the PowerPoint presentation for the project "A Study of Unstable Slopes in Permafrost: Alaskan Case Studies Used as a Training Tool." The objectives of this study are 1) to provide a comprehensive review of literature on unstable soil and/or weathered rock slopes in permafrost areas, and 2) to summarize three case studies of key historic and/or ongoing unstable soil slopes in permafrost in the Alaska Department of Transportation and Public Facilities' Northern Region.

This report closely parallels the format of the PowerPoint presentation, and slides that correspond in content are referenced accordingly. For example, this introduction corresponds to Slides 1 and 2. In what follows, the relevant slide number/s will be included as subheadings.

2.0 REVIEW OF UNSTABLE SOIL SLOPES IN PERMAFROST AREAS

<u>Slide 3:</u>

Slope movement forms a continuum from very slow to very rapid events. In frozen ground, much of the focus is on active layer processes. Because of the wealth of studies that have focused on the active layer, we limited this investigation to deep-seated movement within permafrost.

McRoberts and Morgenstern (1974a, 1974b) are attributed as being the first to classify slope failures in permafrost; they followed the classic landslide classification system established by Varnes in 1958. The figure presented in Slide 3 is a summary of their classification. A "flow" is broadly defined as a material that behaves as a viscous fluid as it flows downslope. This type of movement is commonly associated with thawing permafrost, and it can be further subdivided into solifluction, bimodal flows, skin flows, and multiple retrogressive flows. In contrast, a "slide" occurs when a rigid body of soil moves downslope as a coherent mass. The term "rotational slide" was reserved for thawed soil only. Finally, falls occur when a soil mass falls, travelling most of the way through air.

<u>Slide 4:</u>

Focusing on the "slide" type of movement, the most relevant studies are from the Northwest Territory in Canada. A study by Foriero et al. (1998) investigated deep-seated creep in glaciolacustrine soils in far northern Canada. McRoberts and Morgenstern (1974a, 1974b), along with their permafrost landslide classification, investigated several different slides in the glaciolacustrine soils within the Mackenzie River Valley. Savigny and Morgenstern (1986) also studied deep-seated creep in glaciolacustrine soils along the Great Bear River. The common thread among all of these studies is that they focused on slides occurring in frozen glaciolacustrine soil, that is, clayey soil deposited in lakes that were fed by glaciers.

<u>Slide 5:</u>

There are few documented failures of permafrost slopes in Alaska. Most deal with the thawing of ice-rich silt in road cuts, such as presented by Smith and Berg (1973, 1976), and Mageau and Rooney (1984). In 1986, Johnson documented a slide within ice-rich graphitic schist along the Parks Highway. The highway was realigned over competent schist with higher quartz content, which solved the problem. Although this presents an interesting case study, we were unable to locate any additional material on this slide. Wahrhaftig and Black (1958) investigated deep-seated landslides along the Alaska Railroad in the Nenana Canyon in the Alaska Range. They identified the landslides as rotational and occurring in glaciolacustrine soils. These authors hypothesized that the railroad had created a thermal disturbance, causing ice-rich permafrost to thaw, pore water pressure to increase, and ultimately resulting in slope failure. Like the slides documented in Canada, the slides in the Nenana Canyon also occurred in clay-rich, glaciolacustrine sediments.

Slide 6:

Through discussion with personnel with Northern Region Materials Section at the Alaska Department of Transportation and Public Facilities, we identified three problem areas within Northern Region that qualify as deep-seated movement in permafrost. These are the Nelchina slide, the slide at Rich113, and the Chitina Dump Slide. In the companion presentation, we discuss the history and soils of each site, the possible slide mechanism, and what the major concerns are for each area.

Slides 7-10:

In the companion presentation, Slide 7 contains a map of a portion of south-central Alaska. The Copper River drains this portion of the state (Slide 8). At several times during the Quaternary (or the last two million years), glaciers have advanced from the Alaska Range, the Chugach, and the Wrangell-St. Elias mountains (Slide 9). During these advances, the glaciers dammed the Copper River, creating Glacial Lake Atna (Slide 10).

Slide 11:

As a result, the soils of the Copper River Lowland are a complex sequence of glacial till and glaciolacustrine deposits (Ferrians, Jr. et al. 1983), which range from silty clay to clayey silt with sand, gravel, and scattered cobbles and boulders throughout. Some of these soils are exposed in river-cut bluffs along the Copper River and its tributaries.

Slide 12:

Lake Atna drained about 9,000 years ago, and much of the Copper River Lowland was blanketed by a layer of wind-transported silt, or loess. Permafrost exists throughout most of the lowland. In many areas, the clayey soils contain ice lenses and massive ice. Generally the permafrost is warm, which means it is just below freezing. The top of the permafrost table is typically about 5 feet below the ground surface in undisturbed areas. In areas where surface disturbance occurs, the permafrost thaws and the ice in the foundation soils melts.

Slide 13:

Our three areas are all located within previously glaciated areas and within or on the edges of the previous extent of Glacial Lake Atna.

3.0 THE NELCHINA SLIDE

Slide 14:

The first site is the Nelchina slide, which is located on the Glenn Highway at about MP 138.

Slide 15:

Because of its proximity to the Chugach Mountains to the south, this site has been glaciated in the past. Subsurface investigations in the area indicate that the site consists of a Cretaceous marine claystone, overlain by glacial till deposited during the Pleistocene (AK DOT&PF 1969).

While the soil profile does not include glaciolacustrine clay, the claystone exhibits many of the same properties when it is wet. Permafrost is present in undisturbed areas.

Slide 16:

The highway in this area was realigned in 1972 and 1973, during a project that required replacing the bridge over the Little Nelchina River. Slides began shortly after construction was complete in 1973. There were two main areas of sliding, referred to as the "West Fill Slide" and the "East Cut and Fill Slides" (AK DOT&PF 1989).

Slide 17:

Slide 17 contains a photograph that is a view of the Glenn Highway to the west, and shows the affected area west of the bridge. The photograph was taken from the vicinity of what was the "East Cut Slide". Our discussion will focus only on the east slides.

Slide 18:

A slide repair was conducted in 1977. At this time, a variety of different drains were installed, and cut slopes were flattened from 1.5:1 to 2:1. While these measures reduced sliding, the sliding continued, especially the east slides, which required cleaning out of the uphill ditch and the addition of fill to the roadway embankment to maintain grade (AK DOT&PF 1989). The causes of sliding were similar for both the west and east areas. The overall area has saline groundwater, which forms seeps and springs and flows year round. The groundwater caused excess pore pressures in the weak claystone, which was used as embankment fill. In a 1983 investigation, the permafrost table was intercepted below the embankment, which served as a lower impermeable layer to groundwater flow. Additionally, when the embankment was originally placed, the original ground surface was not stripped, and the embankment was not properly keyed into the foundation soils at its base (WCC 1983).

Slide 19:

In a 1989 design study report, the following items were recommended to repair or slow the "East Cut Slide":

1) Lay back the cut slope to 2:1 for overall stability and to unload the slide;
2) Construct a wide uphill ditch-bottom to help with cleanout efforts and to maintain extra space before complete ditch closure occurs;
3) Install a ditch-bottom subdrain to intercept and direct groundwater flow away from the embankment and the current slide area.

In the 1989 report, it was noted that these measures were not a guarantee against further sliding; instead, they were to increase the overall stability and safer maintenance operations (AK DOT&PF 1989).

Slide 20:

Slide 20 contains a portion of the 1989 Alaska DOT&PF design study report showing the extent of the slide area in 1978 and again in 1988.

Slide 21:

Slide 21 contains a portion of the 1990 plan set for the "Glenn Highway MP135 North Nelchina Slide Repairs; Grading, Drainage, and Paving" project. In this excerpt, flat ditches are indicated, as are a variety of subdrains, drainage blankets, and trenches. The focus of these was to eliminate water from the cut slope.

Slide 22:

Slide 22 contains more excerpts from the 1990 plan set, showing “Subdrain C”. For this drain, a blind drain collected into the “Subdrain C” collector pipe, which eventually was routed into a culvert extended beneath the new embankment constructed uphill of the existing embankment.

Slide 23:

During the 1991 construction, the cut slopes failed in several locations. The 1 ¾ to 2:1 cut slopes were not stable. Groundwater flow was evident at many of the failed areas. It was advised to decrease the cut slope further to a 3:1 in some locations. Further observations during construction indicated that the active slides were the reactivation of paleo-slides along the Nelchina River.

Slide 24:

During our site investigation in 2011, we identified several small surficial failures on the cut slope, which corresponds to the “East Cut Slide”.

Slide 25:

The soil in each failure and that exposed in the scarp was granular, suggesting the failures occurred in the glacial till layer. Slide 25 contains a photograph that illustrates the steep slope of the toe of the largest surficial slide.

Slide 26:

What was most noticeable about the area during the 2011 investigation was the presence of water. In the photograph on Slide 26, the morning sunlight reflects off of the water. Two surface failures are shown. A stream of water was flowing out of the slope at the toe of one of the failures, and wet areas were present at the toe of the other failure, as well as in the uphill ditch, despite the dry day.

Slide 27:

Slide 27 contains a photograph of the water in the uphill ditch; the flow of water is steady.

Slides 28 and 29:

Downhill of the slide area, a culvert crosses beneath the highway. At the culvert location, the guardrail indicates overall settlement on this portion of the highway, which is also coincident with a pavement patch. Slides 28 and 29 contain photographs of this location.

Slides 30, 31, and 32:

At the time of our investigation, the uphill ditch and the culvert inlet were dry, yet water was flowing out of the culvert outlet. These slides contain photographs of the inlet and outlet, and a short film segment from the culvert inlet, which contains the sound of running water from within the culvert despite the dry inlet. This indicates that the “Subdrain C” is still functioning.

Slides 33 and 34:

Downhill of the road, the “East Fill Slide” continues to demonstrate signs of distress with tilted trees (Slide 33), and a pronounced scarp (Slide 34).

Slide 35:

Below the scarp and within the forested area, cracks are evident, which split the trunks of some of the leaning trees.

Slide 36:

To summarize, the Nelchina site is still experiencing slope instability, despite the tried mitigation measures. Above the road, the slope failures are associated with groundwater flow. At least one of the subdrains from the 1991 construction was working in 2011; but the embankment settlement at the culvert location may indicate piping of fines from within the embankment from additional groundwater flow. Below the road, the "East Fill Slide" continues to demonstrate slope failure.

4.0 THE RICH113 SLIDE

Slide 37:

The second site is along the Richardson Highway at MP 113, about three miles south of Glennallen. It will be referred to as the Rich 113 site. Subsurface investigations indicate that the site consists of about 5 ft of loess (or windblown silt) covering ice-rich clay that often contains massive ice (Darrow et al. 2011). This clay layer is interpreted as glaciolacustrine deposits from Glacial Lake Atna. The clay continues to a depth of about 52 ft below the surface, where the soils transition into ice-poor coarser-grained clay, which may be glacial till. In 1965, the highway was realigned to the west, placing more distance between the highway and the bluff edge overlooking the Copper River.

Slide 38:

Slide 38 contains a video segment of the area known as "Simpson Hill". The new alignment required a deep cut and a high side-hill fill through this area.

Slides 39 and 40:

During construction, a portion of the embankment fill failed. Slides 39 and 40 contain photographs that show the site both during the early stages of failure and after failure was complete. A geotechnical investigation identified the cause of the failure as excessive loading of the saturated clay foundation, which caused excess pore pressure and the loss of strength (Platts 1965). The melting of massive ice exposed in the uphill cut was identified as a possible source of water.

Slide 41:

The solution to the sliding problem at Simpson Hill was to construct a soil buttress along the toe of the embankment and to install trench drains along each ditch line to direct excess water away from the fill section.

Slide 42:

While the Simpson Hill area commanded the attention of construction and maintenance crews in the area, the bluff at Rich 113 (about a third of a mile to the north) developed into another problem.

Slides 43 – 48:

Along the bluff, leaning and falling trees are a sign of general instability; however, these signs penetrate the forest in the form of large cracks and scarps. One crack, which runs parallel to the toe of the highway embankment about 50 ft away, has fractured the trunks of at least seven spruce trees. The pre-1965 alignment has experienced much distress due to ground movement, and portions of it are missing, as erosional gullies form along the bluff edge.

Slide 49:

Based on visual observations of the bluff face and the results of several drilling programs in the area, the bluff face can be divided into three zones (Darrow et al. 2011).

- Zone 1 is from the elevation of the Copper River to a "shelf" approximately 200 ft above the river. This zone appears to be covered with loose soils that have fallen from above, now resting at their angle of repose.
- Zone 2 is steeper, with an average slope angle of 55 degrees. Visual observation and drilling data indicate that these soils are stratified, frozen, and ice-poor, and are more granular, containing more sand and gravel. The top of Zone 2 is roughly 52 feet below the ground surface.
- Zone 3 is the zone of erosional gullies. The gullies typically flatten out at about 20 to 30 feet below the ground surface. Drilling data indicates that Zone 3 consists of frozen, ice-rich clayey soils, and the permafrost table ranges between 18 to 25 feet below the surface along the bluff edge.

Slide 50:

Water is regularly observed to be seeping out of the gully bottom nearest the highway.

Slide 51:

Slides 50 and 51 contain photographs taken in November, in which the seepage is very clear as it freezes when it exits the soil.

Slide 52:

Based on analysis of geotechnical data, the soils in Zone 3 are experiencing creep along the natural slope of the bluff. As the ice-rich soils move horizontally towards the bluff face, they carry the soil column above with them (Darrow et al. 2011). This results in cracking and back-tilted blocks at the surface. Groundwater perched above the permafrost table and flowing through the coarser soils may create excess pore pressures, facilitating rapid retreat of the bluff edge through the formation of gullies.

5.0 THE CHITINA DUMP SLIDE

Slide 53:

The third site is about half a mile east of Chitina, Alaska along the McCarthy Road, adjacent to the confluence of the Chitina and Copper Rivers.

Slide 54:

Slide 54 contains a video that was taken from the banks of the Copper River looking south towards the location of the Chitina Dump Slide. The slide is on an east-facing slope with an overall slope angle of about 23º and covers an area of roughly 1.8 acres. The slide is located in a zone of discontinuous permafrost, nestled between an old cemetery near the crest of the hill and a channel of the Copper River at the toe.

Slide 55:

The road follows the alignment of the historic Copper River and Northwestern Railway, which originally ran from Cordova to McCarthy. Slide 55 contains an image from 1910, looking to the north from along what is now the McCarthy Road, showing the railroad bridge crossing the Copper River (photograph courtesy of USGS).

Slide 56:

The soils in the area consist of a surficial organic silt (or loess), overlying clayey glaciolacustrine soils, which overlie bedrock. This slide is referred to as the “Chitina Dump Slide” because the area was previously used as a dump during the 1960’s and 1970’s.

Slide 57:

Slide 57 contains photographs that were taken in the area south of the road and show portions of the dump, which contains anything from cans and bottles to abandoned vehicles and appliances.

Slide 58:

The site has been the focus of ongoing maintenance, as the slide has been continually, albeit slowly, moving for years. Slide 58 contains a short video, looking south along the McCarthy Road to the center of the slide, or the slide axis. A slight dip is present in the road, even though this area was regraded earlier in the summer of 2011.

Slide 59:

Slide 59 contains a photograph of the same stretch of road, and dashed lines delineate the approximate location of the right flank of the slide and the approximate slide axis.

Slide 60:

Maintenance personnel indicated that the river channel was actively eroding the toe of the slope during the 1970’s, which resulted in extensive slope movement and required the road to be realigned upslope. In recent decades, movement of the Chitina Dump Slide generally has occurred during the summer months, with the rate of movement varying from about 3 ft/yr in the mid-1990’s to the current rate of just less than 1 ft/yr. To obtain a better understanding of this slide, we conducted field work during the summer of 2011, consisting of general landslide feature mapping, seismic surveys, collecting tree rings for dendrogeomorphology, and collecting soil samples for laboratory testing. We incorporated this information into a model to determine the nature of slope movement.

Slide 61:

All along the hillside, we found numerous cracks, scarps, and leaning and falling trees. Slide 61 contains photographs of large cracks immediately downhill of a “jayed” tree that fell over at one point, and then corrected its orientation, and another large crack that splits into two directions downslope. These are all indications of general slope instability.

Slides 62 and 63:

Slide 62 contains a photograph of a scarp near the top of the hill that has split the trunk of a tree and contains several jayed trees on the failed mass. The short video in Slide 63 shows some willows that have been pushed down flat by a lobe of soil that is overriding them. This is suggestive of basal sliding, and may be the possible toe of the slide in the dump area.

Slide 64:

Slide 64 contains still images of the same location in Slide 63, showing the willows laid down flat, and the lobe of overriding soil. Mapping in the dump was difficult due to the covering of trash, and also due to the thick vegetation present in the area.

Slides 65 – 68:

These slides contain a portion of an aerial photograph taken of the area on August 31, 2008. North is to the right in the photographs, and McCarthy Road traverses the hillside. The area that served as a dump for many years is visible. In this photograph, a few of the cars can be seen, as well as an area of the highest trash concentration (Slide 65). At the time of this photograph, the trees in this area were turning yellow, whereas the rest of the vegetation remained green. A cemetery is located at the top of the hill above the active sliding area (Slide 66). The map has been annotated to show cracks, scarps, and grabens that we mapped in the area in 2011. These features generally parallel the Copper River along the hillside. Analysis of tree cores collected from jayed trees indicates that there were two major episodes of movement along the hill side, one occurring in the 1940's, and the other occurring in the 1990's. The field mapping indicates that there is episodic instability throughout the hillside, which appears to be translational in nature, but the cause for that movement is not the same as the localized movement along the McCarthy Road. The active slide area is annotated on the map (Slide 67); also annotated are the locations of borings made by the Alaska DOT&PF, as well as the sites where we collected soil samples in 2011, with borings into frozen ground delineated with a different color. As part of the 2011 field program, we conducted seismic surveys (Slide 68).

Slide 69:

The results of the seismic surveys correlate well to drilling in the area. Slide 69 contains a figure of the three seismic profiles (Obermiller 2011). Areas of low velocity are shown in orange near the surface. These areas correspond to the loose, organic silt immediately below the ground surface. In contrast, very high velocities are shown in yellow to red. We interpret this area to indicate the presence of bedrock at depth. The intermediate velocities are indicative of the clayey soil, which was sometimes frozen.

Slide 70:

Applying the results of the seismic surveys and all of the drilling conducted in the area, we were able to create a stratigraphy generally representative of the area (Obermiller 2011). Through slope stability analysis, we determined that the failure is rotational in nature. Back-calculation yielded values for residual soil strength after sliding.

Slide 71:

To summarize, the entire hillside displays signs of instability, mostly as translational movement. The difference in movement appearance, as well as the dating of the movement through tree-ring analysis, indicates that the movement mechanism is different for the active slide area. During previous investigations of the Chitina Dump Slide, a water table was noted at the sliding surface. From this, we postulate that the initiation of movement may have been due to high pore pressures generated by thawing permafrost. Results of drilling programs in the area suggest that within the active slide area, the depth to permafrost has increased with time. Similarly, the overall rate of slide movement has decreased with time. From this, we infer that thermal effects of the dump may be a contributing factor in the initial and ongoing movement of the active slide area.

6.0 SUMMARY

Slide 72:

All three of the slides we presented occur in frozen, clay-rich soils. The Rich113 and Chitina Dump Slides occur within glaciolacustrine soils, whereas the Nelchina Slide is in soft, clay-rich bedrock that exhibits many of the same properties as the glacial lake clays. For all three locations, thawing permafrost is a contributor to slope movement, which either acts as a source of water or as an impermeable surface to groundwater flow. The type of movement varies among the three locations, with translational movement at the Nelchina Slide, deep-seated creep at Rich113, and rotational failure at the Chitina Dump Slide.

Slide 73:

Because each of the three sites is unique when it comes to remediation measures, we present the following general suggestions that can be applied to any of the three sites or to areas demonstrating similar problems:

1) When analyzing areas of slope instability, the preservation of permafrost should be a major component of the final slope design and construction.
2) For the final slope design, engineers should consider the thawed state of the slope mass with residual soil strength properties.
3) The history of the Nelchina site, and our preliminary analysis, indicates that long-term stability cannot be maintained for these soil conditions; however, for short-term stability, design engineers should consider reinforcement, such as piles or retaining structures, to achieve a higher factor of safety.
4) Although dewatering in and of itself is not completely effective in these clayey soils, it provides marginal improvement in slope stability.

ACKNOWLEDGEMENTS

Slide 74:

We would like to acknowledge the Alaska University Transportation Center for funding, and Jeff Currey with the Alaska Department of Transportation and Public Facilities for information on on-going slides in Northern Region. Kala Hansen (INE) was instrumental in helping us process our video from the field. We also acknowledge Carla Hilgendorf for her invaluable help and information about Chitina, and we would like to thank Lei Xu for his tremendous help in the field.

Slides 75 and 76 in the companion presentation contain references cited in the presentation. This reference section is more comprehensive, including a review of the literature on mass movement in permafrost areas; it is intended to serve as a concentrated resource. The references are separated into categories corresponding to topic or to case study location.

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