ICE ENGINEERING FOR ROCK GLACIERS

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ABSTRACT: Construction of fixed facilities on rock glaciers is rarely undertaken. These masses of ice/rock aggregate move downhill under the influence of gravity and are subject to ablation of the ice. The Big Sky Tramway project required construction of a major facility on a rock glacier near Lone Mountain, Montana. Through careful engineering and research, appropriate mitigation techniques were developed that allowed for construction of the facility. Discussion is provided of the technical issues involved and the engineering solutions that were used to address those issues. Evidence of the success of this work is the continued operation of the tramway system five years after installation. The base terminal of the tramway may require installation of a thermosyphon system that was planned for during the initial construction if ice ablation is later found to affect the facility.

KEYWORDS: rock glaciers, thermosyphon, thermopile, ice engineering

1. INTRODUCTION

For many years, skiers have hiked and skied from the summit of Lone Mountain near Big Sky, Montana. During the fall of 1994, Big Sky Resort began a project to build an aerial tramway from near the top of their existing lift system at the 9,600 ft elevation in the Lone Mountain Cirque, to the top of Lone Mountain at 11,160 ft. A monocable reversible tramway design was chosen for the project.

Arriving on the site in the middle of May, 1995, project staff found out there was a possibility of encountering glacier ice in the excavations for the base station footings. The existence of the East Rock Glacier of Lone Mountain is well known. Ice was encountered on previous probes in the site area, and it was thought that moving the terminal to the base of the south-facing slope adjacent to the rock glacier would avoid any ice problems. Work began right away to clear an access road to the site with snowcats to get an early start of construction effort. The road to the site was open in early June.

On June 10, 1995, a preliminary excavation was made at the originally planned lower terminal site. Within two meters of the surface, a solid surface consisting of an ice/rock aggregate was encountered. This suggested that the rock glacier was more extensive than was thought when the site was selected. Subsequent digging around the site revealed the presence of this ice surface throughout the sloping site area. Due to the extent of the ice surface under the steep unstable talus slope, along with the presence of run-off channels and the requirement to over-steepen the slope during the excavation, this site was found to be unsuitable for construction and an alternative base station site had to be found.

There were major limitations where the alternate site could be located because the tramway was already engineered and mostly fabricated to fit the restrictive terrain that included the original base station location. The importance of finding a suitable alternate site considering the associated limitations placed the project at considerable risk. Fortunately, about 100 meters southeast of the original site, a fairly flat knob of glacier debris provide a potential alternative. This site was then analyzed for technical suitability. After overcoming a number of technical obstacles and planning for future contingencies, the tramway was installed with the lower terminal built on the active East Rock Glacier. We are not aware of other such installations in North America.

2. TECHNICAL REVIEW

In contemplating the construction of a major facility on an active rock glacier, numerous technical questions needed to be answered. The first was to identify the nature of the rock glacier itself. A diamond core drill rig was contracted to evaluate the sub-surface ice geometry, including lateral extent and thickness of the ice.

Core drilling found rock glacier ice in all eight bore holes that were drilled on the new terminal pad. The rock glacier surface was found at 2 to 6 meters below the level talus surface of the pad. Drilling was continued in eight holes to at least 13 meters below the surface. A uniform ice/rock aggregate that is typical of rock glaciers in this region was found in all eight bore holes below the surface talus. In one bore hole, drilling was continued until the penetration stopped for technical reasons (frozen bit, plastic material) in order to determine the thickness of rock glacier above bedrock.

Previous studies on rock glaciers identified two general types. One type consists entirely of rock clasts embedded in a matrix of ice (i.e. the ice/rock aggregate). This material forms from snow avalanche debris that accumulates sufficiently in cirques along with abundant scree and rock clasts that fall from the cirque walls until ice forms and the mass then starts to flow. This type of rock glacier is a geologically modern phenomenon. The other type of rock glacier may have a pure or nearly pure ice core that is a remnant of a pre-existing Pleistocene glacier below the ice/rock aggregate and a mantle of talus formed by the process above (Goolsby, 1971; Potter, 1972).

In an ice-cored rock glacier, at some depth the presence of rock in the matrix disappears, giving way to solid ice. An ice-cored rock glacier is expected to have more dynamic movement than the pure ice/rock aggregate types. Goolsby (1971) postulated that the East Rock Glacier of Lone Mountain may be an ice-cored type. In our deepest test hole, relatively solid ice started appearing at the 18 meter depth. By 23 meters below the surface, over 80% of the core was ice with relatively few rock clasts. This evidence supports Goolsby's hypothesis. Unfortunately, the drilling rig was unable to penetrate any deeper. Considering the significant thickness of the rock glacier and that it appeared to have an ice core, it was considered to be active and there was a strong need to consider design refinements for the base terminal. Figure 1 shows the core from the bottom of the deepest test hole that has the highest ice/rock ratio.

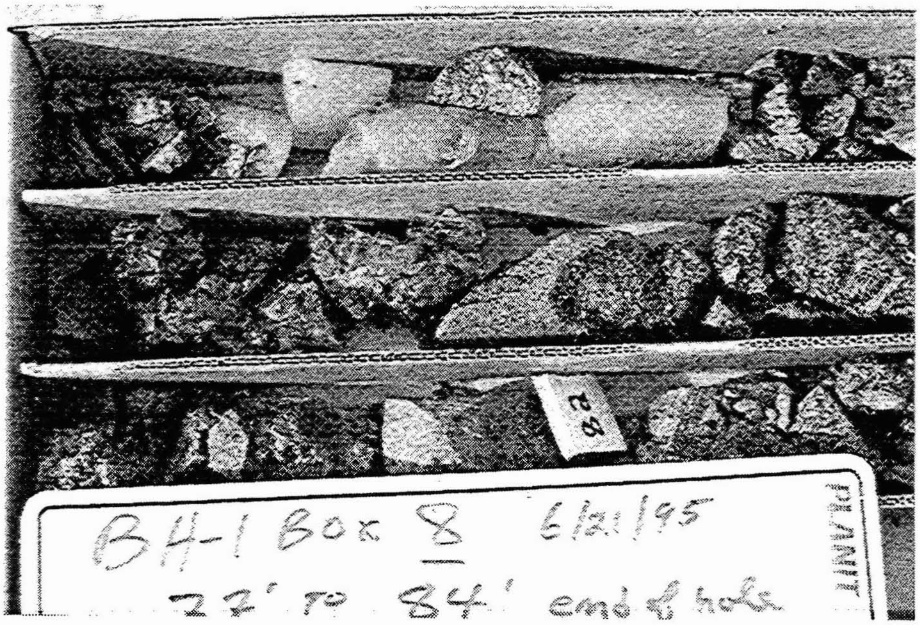


Figure 1
Core Samples

The new design concerns were as follows:

2.1 Ice Movement

Since the rock glacier was active, it might be moving downhill at a rate faster than the tramway design could accommodate. Figure 2 delineates the active, partially active, and inactive portions of the rock glacier as determined by Goolsby (1972).

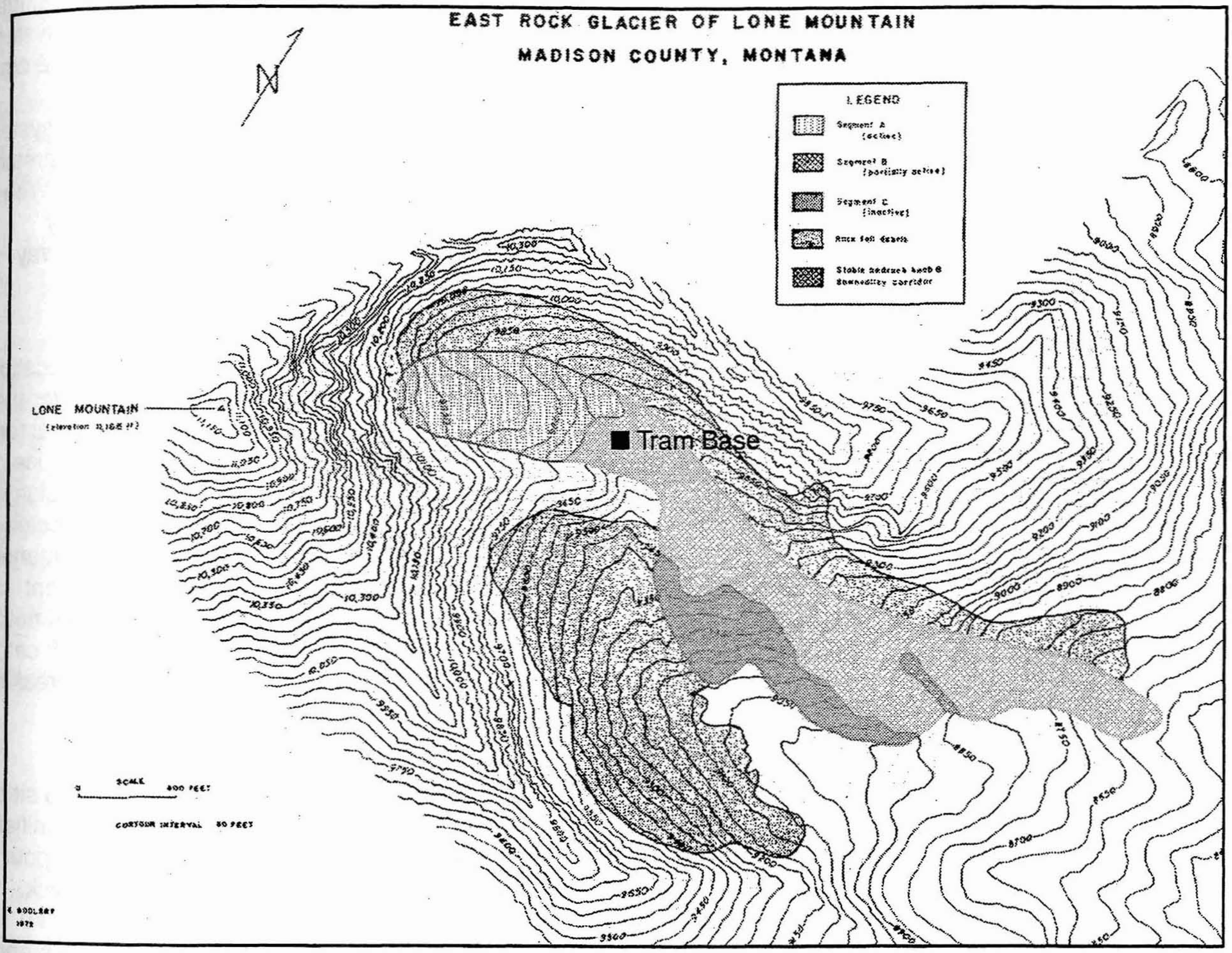


Figure 2 Map showing the segments of the East Lone Mountain Rock Glacier (from Goolsby, 1972)

2.2 Ice melting from heat conduction

Building a large, concrete structure on or near the ice surface could conduct the summer heat through the concrete and into the rock pad and ice surface underneath the terminal. This in turn could cause the underlying ice to melt, creating voids in the fill. Such a process, combined with a meltwater pool forming around the terminal, could lead to the terminal literally sinking into the rock glacier over time.

2.3 Shear Movement across the Surface

Given that the tramway has a constant lateral tension in the haul rope, there was the possibility of developing a lateral shear boundary between the terminal concrete and the underlying ice. The same thing could happen if the terminal was built on too steep of a slope. This was a factor in rejecting the first terminal location.

2.4 Meltwater Induced Ablation

Surface water running on the ice surface below the talus mantle could cause melting and the formation of channels in the ice surface. Without appropriate controls, this could undermine the foundation of the terminal. This was the other primary factor for rejecting the first terminal location, but it also had to be considered for any final location.

2.5 Breakup of the terminal from differential settlement

Without appropriate structural design and reinforcing, if ice ablation occurred under the terminal and created a void space, it could cause a critical failure of the terminal concrete.

Once the sub-talus ice surface of the rock glacier was mapped and determined to be continuously thick, work began to design the appropriate engineering solutions. All these concerns were interrelated to some degree. The first concern was to address the ice movement.

3. ENGINEERING SOLUTIONS

In order to accommodate the design challenges, a number of modifications were made to the original designs of the project.

3.1 Determine the rate of movement

Fortunately, previous work had been done which helped determine the approximate rate of downhill movement for this portion of the East Rock Glacier. Montagne (1976) calculated the movement just uphill of the terminal site to be 15 cm per year over a period of three years. Downhill of the terminal, the same study found movement of 8 cm per year. Goolsby (1971), over a period of two months in 1971, found the active front of the rock glacier to be moving at 61 cm per year. In a study over a period of 5 years, Von Allmen (1995) found the area uphill of the terminal site to be moving at 17 cm per year.

Additional work on the Galena Creek rock glacier in Wyoming by Potter (1972),indicated movement in the range of 44 cm per year for slope angles of 7-9 degrees in the upper section, 40-83 cm on slopes of 5 to 10 degrees in the middle section, and 3-14 cm per year on the 5 degree slopes of the lower section.

Given the above parameters, the estimated downhill movement of the glacier at the terminal was approximately 10-12 cm per year. All indications were that this would be a fairly uniform movement without much potential for differential shear planes developing in the rock glacier at this location. Since there are no towers on the tramway, the only alignment problem this movement would create is on the incoming/outgoing sheave trains. These were mounted on a long lateral beam which allows for considerable alignment adjustment in the unlikely event the bottom terminal would rotate due to downhill movement. When ropeways are installed they typically undergo a period of fairly rapid stretch of the haul rope in the first year, after which rope stretch slows but continues for the life of the cable. On a 1000 meter system, long term rope stretch is approximately 8-12 cm per year (Trefileurope, 1988).

Estimates of downhill flow rates for the system roughly match estimates of long term rope stretch, making the system viable for construction. With any luck, downhill movement would roughly match long term rope stretch and the tramway would never have to be re-spliced.

3.2 Provide a better pad

Material from up-slope of the terminal location was moved downhill to create a level pad for the terminal to sit on. This negated the potential for shear movement of the terminal across the ice interface. Additional material also created a larger buffer zone between the surface areas affected by annual thawing, and the underlying permanent ice. The underlying ice provided an excellent bearing surface in it's frozen state. It could not be ripped with a large excavator, and a D-8 cat with a ripper had only marginal success in breaking up the ice/rock aggregate.

3.3 "Build a Boat"

The bottom terminal was redesigned to sit on a single, monolithic slab of concrete. This initial slab of concrete was designed for a single pour of 340 yards of concrete in a slab 2 feet thick. Imbedded in the concrete is approximately 70 tons of rebar. The combination of thickness and rebar strength allows the terminal to "float like a boat"(Jewitt, personal comm.) on top of the rock glacier. It is also sufficiently strong so any void spaces created by ice ablation will not affect the integrity of the slab or the equipment above.

3.4 Isolate the pad from runoff

Ditches were provided uphill of the terminal to isolate any runoff and channel it away from the terminal pad. This keeps the terminal knob from suffering any affects from warmer runoff water running through the gravel material of the pad and causing melting of the underlying ice.

3.5 Thermally isolate the terminal from the pad

Calculations of annual thermal balance clearly demonstrated that transfer of summer heat through the terminal concrete by conduction would have an adverse affect on the underlying ice. It was critical that this heat transfer be prevented. The terminal was re-designed to use an insulating barrier of 8" of foam insulation under the terminal pad. With a total terminal weight of 2,600 tons, the foam needed to resist high crushing loads. Dow Hi-60 foam was used in this application because it has the ability to withstand 60 P.S.I. of pressure before failing. This foam was tapered out from the terminal in decreasing thicknesses as well.

3.6 Resist lateral forces

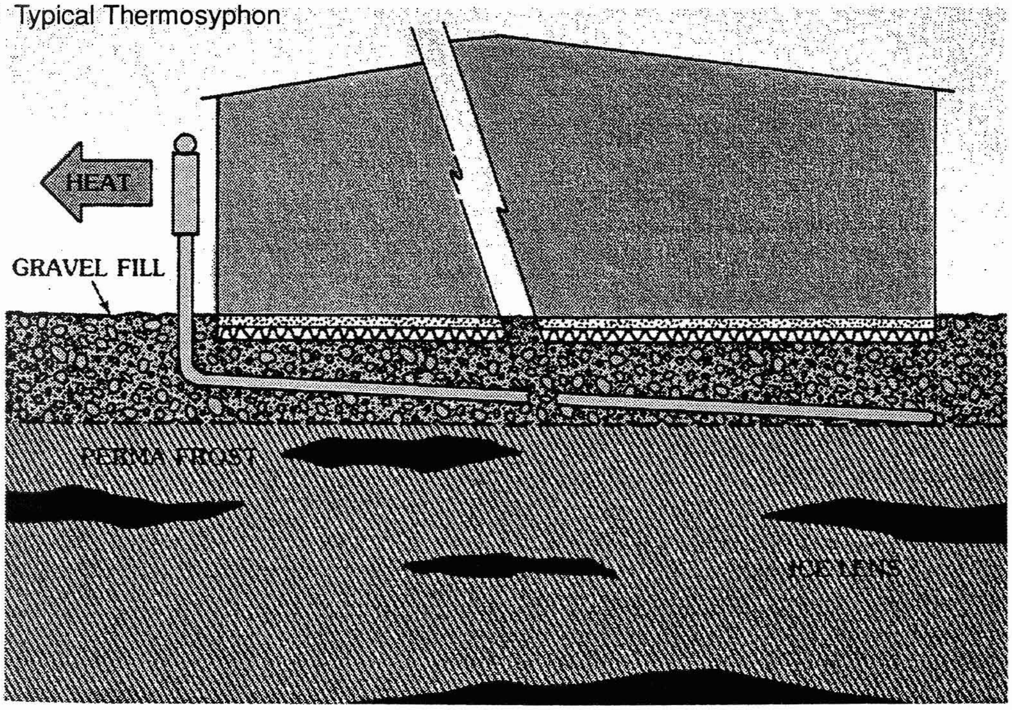
There was concern that lateral forces from cable tension would induce a shear across the relatively low friction of the underlying insulation. In order to prevent this, the terminal was designed to increase it's dead weight. In this case, almost 700 metric tons of backfill was used inside portions of the terminal to increase weight. Additionally, slightly less than 1 meter of backfill was used around the perimeter of the terminal to provide shear resistance. While this provides some shear resistance, any more fill for shear resistance would result in increased conductivity of terminal heat into the underlying pad, producing undesirable effects.

3.7 Provide a passive cooling system

Construction on permafrost in northern regions typically employs the use of thermosyphons to accelerate heat removal in winter in an effort to offset the warming effects of summer. These techniques have been well documented in previous work (Heuer, et al., 1985), but had never been used on a rock glacier. Analysis of weather records is necessary to determine the feasibility of this technique. In this case, weather records of the site existed for a period of more than 20 years, providing favorable data to support the use of thermosyphons.

Typically, a thermosyphon uses an enclosed, pressurized tube installed into the ground with a condensor(radiator) above the ground level. Heat transfer is provided by phase change between liquid and vapor. Inside the closed tube is a two-phase working fluid, commonly carbon dioxide, propane, or ammonia. The tube typically has a small volume of the working fluid as liquid and the remaining volume as vapor. The internal pressure is dependent on the temperature that is in contact with the liquid phase of the working fluid. In warmer months, the density of the gas above the liquid decreases with increasing temperature while the pressure remains constant. This prevents the thermosyphon from working. When the temperature of any portion of the vessel above the liquid pool, typically that part above

Figure 3 Typical Thermosyphon



ground, is reduced below that of the pool, the cooling cycle commences. Condensation of the working fluid on the cooled area occurs. As the condensate flows down the tube, it vaporizes and cools the embedded portion of the tube. In repeated cycles over the course of the winter, this process cools the ground well below the temperature of the initial state at the high point at the end of the summer season. The cooled area is then insulated throughout the following summer so that it stays below freezing. This type of passive system is considerably more efficient for heat transfer than a convection type system because it uses phase change instead of specific heat for heat transfer, and there are no moving parts or non-renewable energy costs associated.

For the Big Sky project, thermal calculations indicated the need to install a thermosyphon system to ensure the long term stability of the tram pad and terminal. However, cost and time considerations precluded their installation. Based on the re-inforcements built into the terminal design, it was determined that ice ablation would become apparent before any threat was presented to the terminal base. Lateral, sloped tubes were installed in the terminal pad between the ice of the rock glacier and the bottom of the foam insulation. If the foam insulation is insufficient to stop melting of the underlying ice, these tubes can be retrofitted with thermosyphons (See Figure 3) to stop the degradation of the terminal pad and re-freeze the underlying ice structure. However, this process takes a full season to accomplish. In the interim it is also possible to use an active-based cooling system to re-freeze the pad.

4. CONCLUSIONS

If the need exists to build a structure on a rock glacier in a temperate climate, it is critical to conduct a through site evaluation and consider the specific nature of the site in the engineering of the structure. Sufficient climatic data must be available to evaluate the design of passive heat exchangers if they are determined to be necessary to maintain the integrity of the substrate. Provided that the downhill movement rate will not adversely affect the structure and a suitable inclination can be found, engineering and design concepts typically used in permafrost environments can be adapted for use on rock glaciers.

In the case of the Big Sky Tram, the system has been functioning for five years without any major impacts due to its location on a rock glacier. Downhill movement has totaled 3 cm per year during that time period, which is lower than the anticipated rate. There has been no need to re-splice the haul rope as of this time. There is a current tendency for one corner of the terminal to develop a small melt-water pond in the spring and a sense that the terminal may be tipping in that direction. This situation is driving increased scrutiny to determine if it is the precursor of ablation-related subsidence. If so, passive thermosyphons may need to be retroactively installed to prevent further subsidence and degradation to the structure.

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