BETHEL AIRPORT

THERMOSYPHON STUDY

FINAL REPORT

by

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for

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IMPLEMENTATION STATEMENT

This project involved the performance evaluations of 31 thermosyphons installed by near-horizontal drilling beneath a portion of the Bethel Airport runway. The installation was successful in stopping the long-term progression of permafrost thawing and settlements which had plagued this runway segment in prior years. However, two problems have become evident. The first is that an undetermined number of the installed thermosyphons have not remained pressure-tight. Since leakage of the gas-charge renders thermosyphons inoperative, future installations must utilize better installation, testing, and acceptance procedures to assure long-term performance. The use of field-fabricated, drilled-in thermosyphons is not recommended. The second problem with this installation was that it did not extend far enough. Adjacent runway areas have since settled requiring temporary runway closures, followed by patching and levelling work. The use of more extensive exploratory drilling, sampling, and testing is recommended to more accurately determine the extent of problem soils and the required lengths of special treatments.

The following implementation activities leading toward increased understanding and use of thermosyphons are in progress at this time:

1) Laboratory testing of thermosyphon heat transfer coefficients has been recently completed by the University of Alaska at the U.S. Army Cold Regions Research and Engineering Laboratory, under funding provided by the DOT&PF. The report is in the publication stage.

2) Developmental testing of dual tube thermosyphons which will function in horizontal installation of the subsurface evaporator sections, is currently underway at the above facility (February, 1990).

3) An experimental installation of 49 thermosyphons is scheduled for construction in 1990 on the Bethel Highway. In this work the thermosyphons will be shop fabricated, tested, and installed in trenches across the roadway, followed by insulation and paving of the overlying roadway structure. Instrumentation will be precisely located around the thermosyphons to test predicted versus actual performance levels. Finally, recorders will be installed to more fully evaluate this new installation.

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Performance Monitoring - 1984 through 1988

Abstract: This paper reports the results of a study to monitor the performance of natural convection heat transfer devices (thermosyphons) that were installed in a section of the main runway at the Bethel, Alaska airport. The thermosyphons were installed as an experiment to determine if a permafrost subsidence in the runway could be stabilized using these devices. The study monitored the soil temperatures beneath the thermosyphon section of the runway to determine how well the thermosyphons performed. Soil temperatures were measured with 185 thermistors in 13 thermistor strings which were installed vertically from the runway surface to a depth of 25 feet. The soil temperatures allowed an assessment of the condition of the permafrost and compared it to conditions under the runway which were not cooled by the thermosyphons. The study determined that the thermosyphons had significantly improved the stability of the permafrost and had lowered its temperature 0.6 to 0.8°F below the temperatures at the same depth in the control zone

1.0 Introduction

1.1 Background

The original airport, which was located on the flood plain across the river from the town of Bethel, was replaced by the present one in 1958. The present airport site is located on the same side of the river as the town and is well above the reach of flooding from the river, but it is in an area of permafrost.

The Bethel area is in the zone of continuous permafrost and is noted for areas of extensive ice-rich silty soils. Extensive areas of polygonal ground are visible from the air. The permafrost of the region is, therefore, relatively warm and fragile. Small changes in thermal regime will result in significant changes to the characteristics of any permafrost which is this close to the melting temperature.

The new runway was built in five stages. The initial construction started in 1955 and continued through the summer of 1956. The second phase proceeded during 1956 and into 1957. During the third phase in 1958 a 6" cement treated base course (CTB) was constructed over the 4000 foot runway and parking apron. The third stage construction was completed with the application of a 2.5" to 3.5" surface course of asphalt concrete (AC).

Fourth phase construction was begun in 1968 and completed in 1969. It included the earthwork for a 2450 foot extension of the runway and parking ramp enlargement. The fifth stage began in 1970 to place a CTB over the extension of the runway, to widen the runway and taxiway, to extend the main parking apron and to overlay the existing runway pavement and the new CTB with a new surface course of asphalt concrete (Vita, et al., 1986)

During the construction of the extension to the runway in 1968 through 1971, it was necessary to construct a fill across a small gully a few hundred feet wide and 20 to 30 feet deep near station 50+00 (see Figure 1A). The subbase material in the gully contained some frozen soils of high water content. The change of the thermal regime, initiated by heat input from an uninsulated culvert placed in the fill and the addition of the black asphalt runway, resulted in melting of some of the ice-rich frozen silt. Upon thawing, the previously ice-rich material slumped and a depression in the runway surface resulted.

The first reports of surface distress were recorded in 1978 and were particularly evident in the vicinity of the culvert that had been placed to allow drainage from the west side of the runway to the natural drainage cut on the east side. Pilots using the airport quickly dubbed the subsidence area the "Bethel Bump" and voiced their concern over safety aspects. Soon the slump became too large to tolerate and was repaired by removing the culvert and cold patching the asphalt surface. The area continued to slump and repair was soon required a second time.

The subsidence reappeared and grew to a point that prevented aircraft from using that portion of the runway, reducing the effective length from 6450 ft to approximately 4900 ft. Re-leveling the runway only solved the problem temporarily, as the continuing subsidence, due to the progressively deepening annual thaw layer, very quickly re-established the depression in the runway surface.

The Alaska Department of Transportation and Public Facilities was determined to stabilize the runway. The strategy was to use two-phase-convective-heat-transfer tubes (thermosyphons) to remove heat from the subgrade during the winter months thus cooling and refreezing the soil so that it would not thaw as deep during the summer. If the seasonal thawing could be constrained to the upper, dryer layers, the underlying permafrost portion of the subgrade, which was ice-rich, could be kept frozen all summer. This should stop the subsidence. To accomplish this, 31 thermosyphons were installed below the runway in December of 1981. Thermistors were installed at various locations and depths in the soil beneath the runway at the same time. Soil temperatures were monitored periodically several times a year after the installation.

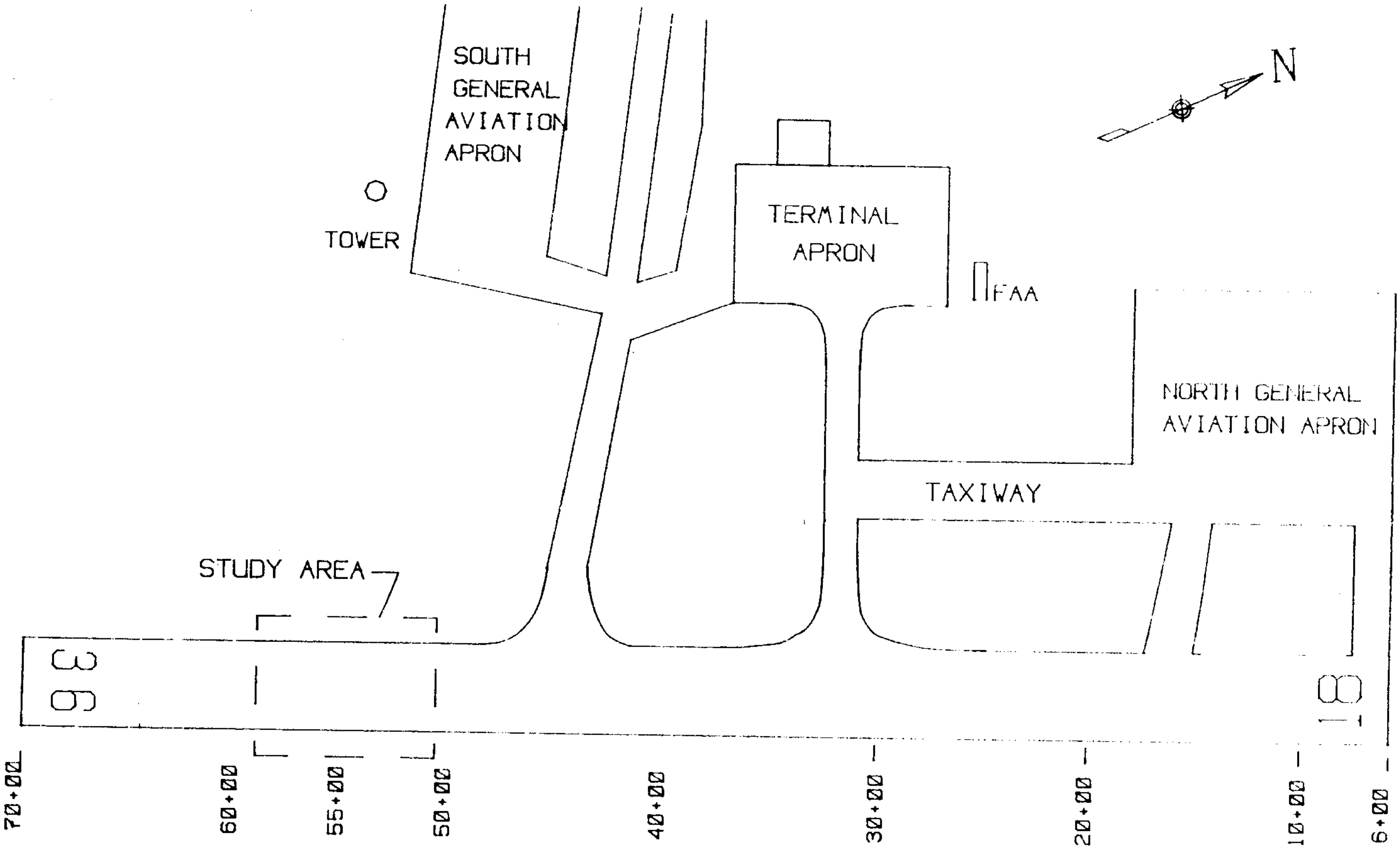

FIG. 1A - BETHEL AIRPORT

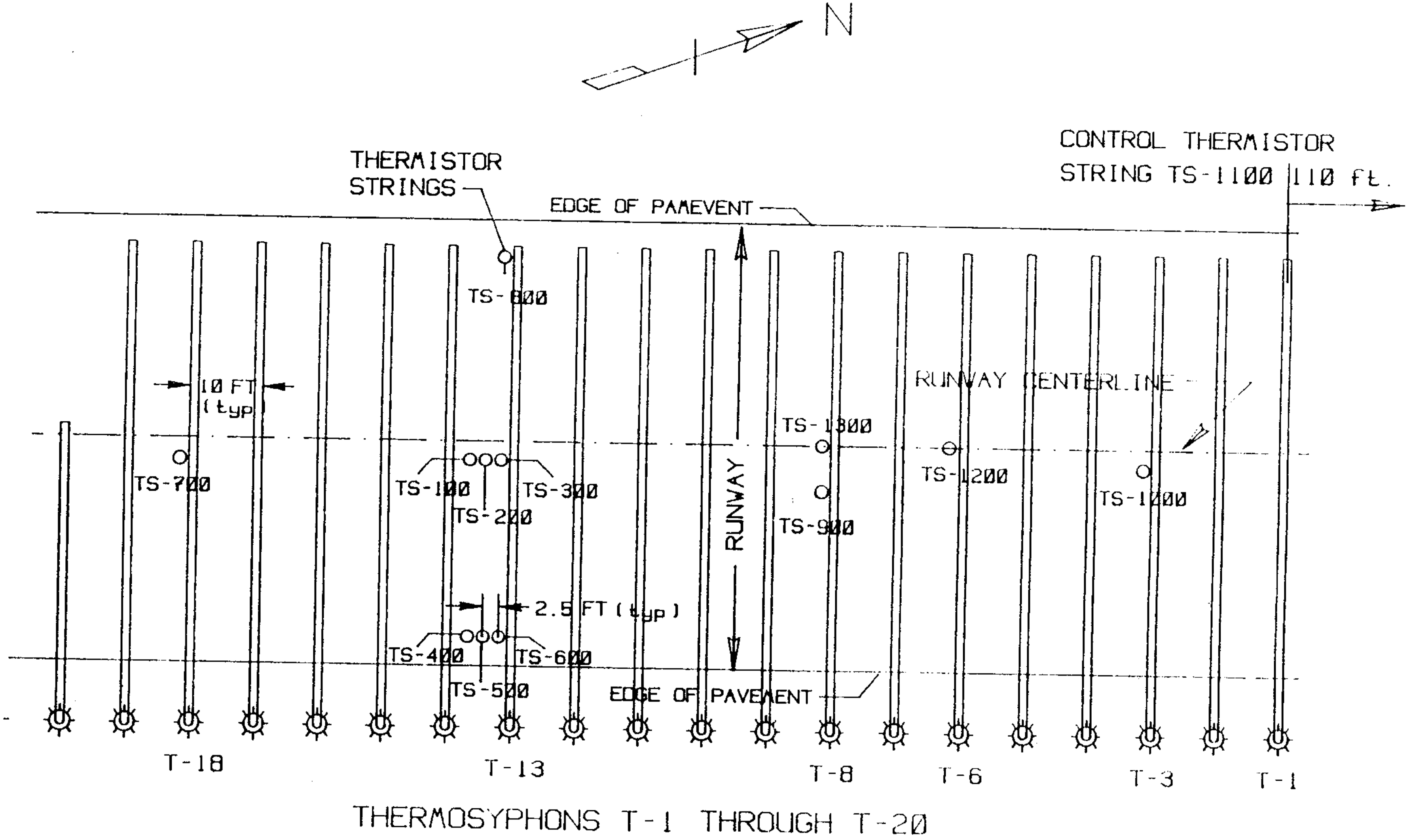

FIGURE 1B- LOCATION OF INSTRUMENTATION AT BETHEL AIRPORT

1.2 Purpose

This report is the final report of a study of the performance of the thermosyphons. It supplements and references a prior report "Performance of the Thermotube Permafrost Stabilization System in the Airport Runway at Bethel, Alaska" McFadden 1986. The performance was monitored by measuring the temperature of the soil surrounding the thermosyphons. In this manner the ability of the thermosyphon devices to remove heat energy from the soil could be determined. The study was designed to determine the ability of thermosyphons to stabilize marginal permafrost in roads and runways under actual field conditions. The location and climatic conditions of the Bethel airport are a good example of the marginal conditions at many Alaskan locations. The permafrost at Bethel is fragile because soil temperatures are typically withi the melting point and climatic conditions are only marginally cold enough to support permafrost. If thermosyphons are successful in stopping or even slowing the degradation of permafrost at this location, they will also be adequate at other Alaskan sites where weather conditions are more favorable for permafrost preservation.

1.3 Scope

The installation covered the entire width of the runway for a length of 200 feet. Thirty one thermosyphons were installed in the subbase below the surface of the runway. The thermosyphons enter the east shoulder of the runway and extend at a slope of 15:1 beneath the runway to near the west shoulder. The above ground condenser sections of the thermosyphons are located on the east side of the runway. Thirteen thermistor strings were installed at strategically chosen positions near selected thermosyphons. The purpose was to monitor the temperature of the soil beneath the runway.

A complete set of temperatures from the study area consists of 186 readings. Data sets were collected at various times during the year until the critical time periods, which would yield the most information, could be established. It was determined that although midsummer and midwinter data sets provided useful information, the most important data sets were from the late spring (just before summer thaw begins) and late fall (after summer thaw has ended). It was from these two sets that the relative overall thermal stability of the site could be evaluated. A total of fifteen data sets were collected during this study between October 1984 and June 1988.

1.4 Location

Bethel, Alaska is located in southwestern Alaska, approximately 390 miles west of Anchorage. The area is underlain by continuous permafrost. The mean annual temperature of the Bethel area is 28.3°F and it accumulates 3700°F-days of freezing and 2700°F-days of thawing. Maximum annual precipitation is 40.8 inches. (Environmental Atlas of Alaska 1978).

The experimental area is near the south end of the north-south runway approximately 500 feet from the end. The finned condenser sections of the thermosyphons were positioned nearly horizontal to comply with Federal Aviation Administration regulations that required the top of the condenser sections to be lower than the elevation of the runway surface at the centerline. The horizontal orientation was necessary to provide enough condenser surface area for successful thermosyphon operation.

2.0 Approach and Methodology

2.1 Thermistor strings

The thermistor strings were designed to provide temperature information at two foot increments along their length. This spacing was uniform except in the region where the string was expected to be in close proximity to the thermosyphon. Here the thermistors were to be spaced at the depth of the thermosyphon and 6 inches above and below it. Initially, eleven strings were installed, each contained 15 thermistors spaced from one foot below the surface to a depth of 25 feet. Later two additional shorter strings were installed in existing holes that were uncovered and made accessible during the runnway repaving in 1984 (see Figure 1B).

The location of the thermistor strings was chosen to provide information on the soil temperatures along the length of the thermosyphons as well as radially around them. Thermosyphon number T-13 was randomly chosen to be studied in detail. Seven of the thirteen thermistor strings were installed at three positions along it, and at two of these positions strings were located at 2.5 foot intervals radially from the centerline of the thermosyphon. These thermistor strings were numbered ts-1, 2, & 3 near the centerline of the runway, ts-4, 5, & 6 near the east edge of the pavement and and ts-8 near the west edge of the pavement. An unfortunate result of the installation method (discussed below), however, left this thermosyphon (T-13) inoperative. This was a major loss to the completeness of the study and severely limited the amount of performance information that could be obtained from these thermistor strings. The detailed study of performance along the length of the thermosyphon was, therefore, not possible.

2.2 Measurement Accuracy

Thermistors are small temperature sensitive resistors. Electrical resistance of the tiny thermistor spheres changes very linearly with temperature. Careful measurement of the resistance allows a very precise measurement of the temperature. Accuracy is achieved by calibration of the thermistor against a known temperature standard. These thermistors were calibrated to 0.1^{o}F. This calibration information was incorporated into the temperature transformation computer program which is used to convert the resistance values, obtained during data collection, into temperatures. Overall accuracy is also dependent upon the accuracy of the resistance measurement. A change of 0.1^{o}F corresponds to a resistance change of approximately 46 ohms. The instruments used for resistance measurements were capable of measuring to plus or minus one ohm. Thus the measurement error was less than 1/40 of the overall possible error. Or the possible error from the resistant measurement device was less than 0.025^{o}F. Since resistance measurements must be made by applying a voltage across the resistor and measuring the resulting current, the possibility of heating the resistor with too much current must be considered. Thermistors that are heated during the measurement procedure obviously will not yield correct soil temperatures. To avoid this, a scale of 200,000 ohms/volt was used. Such a small trickle of current was found to allow resistance values that were very stable and did not change even when the current was applied for long periods of time (several tens of seconds).

One final check was made before each string was measured to be sure that the instrument was performing properly. Each string was connected to a switch box which allowed each individual thermistor to be connected to the multimeter resistance measuring instrument. The switch box contained a calibrated precision resistor whose resistance was in the same order of magnitude as the thermistors being measured. This resistor was switched into the circuit before each string was measured, and the instrument was checked to ensure that it was indeed reporting the proper value. Thus ensured, the entire string of thermistors would be recorded.

Another precaution that was routinely taken to ensure stable and accurate readings was cleaning the 24 pin telephone connector on the end of the thermistor string before each string was connected to the switch box. Since these strings were exposed above ground, even though they had covers and were in a protective box, they were subject to dirt and other contamination. A careful cleaning with a compatible spray contact cleaner was found to enhance the reliability and stability of the data obtained.

2.3 Frequency of Data Sets

Ideally data should be taken weekly on a study such as this where soil temperatures at depth change very slowly. This frequency was not practical or economical. The cost of sending a trained technician to Bethel to collect the data was prohibitive and, therefore, limited data collection to a few trips per year. The cost of setting up a remote data collection system and communications link was also above the funding level of the study. An initial schedule of several visits per year at strategic times was gradually replaced as the investigators became familiar with the dynamics of the system. The most critical information on the condition of the sub-base, and thus the potential for surface distress, was obtained from spring and fall data sets. Thus an early October and mid-May collection was decided upon. The best information on the actual performance of the thermosyphons, however, is obtained from mid-winter data sets when the units are in full operation. A mid-January collection satisfied this requirement. Thus three data sets per year appears to be optimum. Each set should be taken within a week of the same time as the previous year's data set so that the performance over time can be evaluated.

3.0 Thermosyphons

3.1 Theory of Operation

Thermosyphons (also referred to as thermotubes, thermoprobes and thermopiles) are being used with increasing frequency to remove heat from the soil and to depress the subsurface temperature in permafrost regions. The purpose is to cool permafrost soil below its normal equilibrium temperature. This serves to protect it from the damaging effects of heat from the environment. By sub-cooling the permafrost, its load carrying capacity can be maintained or increased.

This can be achieved even with increased thermal input due to disruption of the original thermal regime. Disruption can be brought on by construction or other changes both natural and man induced. These devices were originally used for stabilizing the pile foundations of buildings constructed in permafrost. Their use has increased in recent years to include many new applications. They are now being used to stabilize many other types of foundations. Applications include road sub-grades, runways, and pad foundations for buildings.

A typical thermosyphon consists of a pipe sealed at each end and filled with a working fluid. Current working fluids include carbon dioxide, ammonia and butane. The tubes are buried in the soil which is to be cooled, with one end extending above ground. This end is usually equipped with an enhanced heat transfer surface such as fins. The operation of thermosyphons is well explained in the literature (Zarling 1985; Johnston 1981; Lunardini 1981). Generally, operation is as follows: Heat is absorbed by the below ground part of the device referred to as the "evaporator" of the thermosyphon. The above ground portion (where it is exposed to the cold winter air) dissipates heat as the vapor condenses. This section is referred to as the "condenser" of the thermosyphon.

Thermosyphons are one of two basic types of natural convection devices used for cooling subsurface soil. Natural convection devices are categorized according to the process going on inside the tubes i.e., single or 2 phase, open or closed. Thermosyphons, like those used for this experiment, are two phase, closed convective heat transfer devices. This category specifies that the working fluid changes phase from liquid to vapor and back to liquid during the course of operation, and that the device is sealed so that the working fluid remians in the tube. A two phase thermosyphon is charged with the working fluid which absorbs latent heat while boiling in the evaporator section, then surrenders the latent heat to the cold air as it condenses in the above ground section of the tube.

Every working fluid has a different temperature-pressure equilibrium at which it operates. The working fluid used in the Bethel thermosyphons was carbon dioxide at a pressure of approximately 450 psi. Figure 2 shows the temperature pressure relationship for carbon dioxide. The soil to be cooled must be warm enough to boil the liquid in the evaporator of the unit. Operation of the tube begins when the air temperature drops below the temperature of the gas inside the tube. Vapor in the above-ground portion of the tube condenses. The cold condensate collects on the side of the tube and runs down to the evaporator section at the bottom. Since the condensate liquid is colder than the surrounding soil, heat energy moves from the soil into the liquid. Condensation of the vapor reduces the pressure inside the tube. The lower pressure results in a lower thermodynamic equilibrium temperature. This initiates boiling of the liquid. The vapor produced by boiling rises to the above-ground condenser section. If the outside air temperature remains below the equilibrium temperature of the vapor, condensation takes place. The latent heat of evaporation is transferred to the atmosphere and the cycle repeats. Working fluids used in thermosyphons are typically carbon dioxide or ammonia. However, propane, butane and Freon are also used, and a number of other fluids are potential candidates.

Perhaps the biggest attraction of thermosyphons is that they have no moving parts to wear out or break. They also require no external energy source to drive them other than the temperature difference between the soil and the atmosphere. They, therefore, lend themselves to use at remote sites where power is either expensive or not available.

3.2 Practical Limitations on operation

There are limitations on the use of natural convection devices, however. The most important is that they will only operate during the winter months. This is just the time of year when they are least needed. In the summer when heat removal is most needed, they sit idle. Although they do allow some heat to enter the soil by conduction down the metal pipe, it is generally considered to be an inconsequential amount. Since operation is restricted to the winter months, they must remove enough heat during that period to sub-cool the soil to such a degree that summer heat will not be sufficient to cause melting. This limits their application.

The quantity of heat that can be removed is a function of the length of time the units are operating and the difference between the air temperature and the soil temperature (the severity of the climate), the internal resistance of the working fluid as the vapor molecules move past one another from evaporator to condenser and back (the choice of working fluid influences this parameter), the thermal resistance between the working fluid and the outside air (fins help here, as does exposure to available wind), and probably more important than all others, the thermal resistance of the soil around the evaporator section. Johnson (1971) felt that this was the limiting parameter on thermosyphon operation. Heat must move through the soil toward the cold evaporator section. The thermal resistance of the particular soil that surrounds the thermosyphon determines how fast heat can be conducted through the soil. As the soil layers around the thermosyphon cool to the same temperature as the evaporator, heat must travel from soil which is farther away from the thermosyphon. This slows the operation of the device and eventually becomes the limiting factor in how much heat can be extracted from the site. Moist dense soils will have lower resistance than dry porous ones. However, they will also have more thermal energy to extract, and a soil that thaws each summer will present more heat to be removed by the thermosyphon than if it were in permafrost. The heat transfer conditions around the evaporator portion of the thermosyphon are very important to its operation. Theoretically the evaporator should be finned to extend its heat transfer surface area, but this is not a practical possibility in most cases. Close attention should be paid to the soil around the evaporator. It should be compacted, if possible, and if the unit is installed in a hole larger that its own diameter, it should be grouted or slurried in place to enhance heat transfer.

If the thermal resistance of the soil is the limiting parameter, then the choice of working fluid or thermosyphon type becomes a secondary consideration that has less importance.

3.3 Installation Problems

Installation of the thermosyphons was hampered by the requirement that airport operations must not be impacted. A technique which did not interfere with the aircraft using the runway had to be developed for installing the thermosyphons. The method chosen was to drill nearly horizontally from the south shoulder of the runway.

The thermosyphon pipe must be able to withstand equilibrium pressure for the maximum summer temperature to which it will be exposed. The evaporator temperature should be close to the soil temperature of approximately 30°F. The condenser should be closer to the maximum summer air temperature which could be as high as 80°F. The mean temperature inside the tube will be at some temperature between these extremes, say an average of 55°F. The equilibrium pressure for carbon dioxide at this temperature is approximately 700 psi (see Figure 2a) requiring the pipe to be a pressure vessel. Pressure pipe was used for the drill stem and was left in place in the hole to be used for the thermosyphon tube. To accomplish this, the drill bit was welded to the first piece of pressure pipe to be drilled into the hole. The central air supply pipe was used to provide drilling air. When these pipes were drilled all the way into the ground, a second set of pipes (pressure pipe and air pipe) were welded to them by a certified pressure vessel welder. The drill stem very quickly became too long to be removed from the hole, so the bit could not be changed or cleared. This led to a very difficult installation which was slow and expensive.

Another problem which resulted from the installation procedure was even more devastating to the experiment. The stresses involved in drilling the units into the ground and the extremely long drilling time required to insert the pipe the required distance resulted in cracks or flaws which caused many of the units to leak. The most likely location of the leaks was assumed to be at the point where the air pipe connects to the drill bit. An attempt by the thermosyphon manufacturer to inject epoxy into this region met with success on some of the units. Unfortunately, several other units never were successfully sealed and are no longer operating. These included the heavily instrumented thermosyphon number T-13.

Still another problem with the installation surfaced later. The heavy-wall pressure pipe was assumed to remain straight as the pipes were drilled into the ground. However, they did not necessarily follow a straight line. Although the 3" diameter pipe appears to be very rigid, when several 20 foot lengths of the pipe are connected the resulting string is quite flexible. If the pipe encounters resistance as it is drilled into the hole, it will deflect in the direction of least resistance. The result is that, although the expected position of the pipe can be calculated from its slope and point of entry into the ground, its actual position may be several feet away. Thus the relationship between the thermosyphon tube and the thermistor string which was supposed to monitor it is not accurately known. Although the temperatures recorded by the thermistor strings will yield qualitative information, the quantitative value is not necessarily accurate. Clearly an improved installation procedure is necessary if this technique is to be used elsewhere.

3.4 Leaking Thermosyphons

After a few months of operation, temperature data indicated that some of the thermosyphons were no longer operating. An infrared survey by the installing contractor confirmed that several of the units were inoperative. A two step rehabilitation program was attempted by the thermosyphon manufacturer and installing contractor. The dead units were opened by cutting off the finned condenser section. Epoxy was injected into the suspected leak area at the lower end of the thermosyphon. The units were then welded again and recharged with working fluid. However, the working fluid was changed to butane which achieves its thermodynamic equilibrium for 25°F at a pressure very close to atmospheric pressure. Since the lower pressure difference between the inside and outside of the tube would result in a lower driving force, this would reduce the amount of future leaking for these units at the expense of somewhat reduced internal performance. Since the internal performance is secondary to the thermal resistance of the soil, this reduction was not a severe impact on the units.

3.5 Performance Monitoring

Several methods are used to monitor the performance of the installed thermosyphons. Measuring the operational performance is difficult. In fact, just determining whether of not the device is operating at all is not trivial, since there are no moving parts to watch, no sound emitted, and very few visual clues. Two indicators of operation are the inside pressure and the temperature in the condensing section. If the pressure of the tube is in the correct range for thermodynamic equilibrium, then it is often assumed that the device is operating. Unfortunately, this is only valid if the working fluid is pure. However, an unknown contaminant (such as hydrogen) in the fluid can change the partial pressure of the working gasses so that total pressure is a meaningless indicator of operation. Measuring the temperature difference between the condenser pipe and air gives a qualitative indication that the thermosyphon is operational. Since the unit dissipates heat when it is operating, the base of the fins will be slightly warmer than the surrounding air. If the measurement is made during a period of stable air temperature, with very little or no wind, and if the sun is not striking the fins, then this method can provide an indication of operation or lack of same.

Infrared heat emmission can be measured to determine the temperature of the exposed surface of the thermosyphon. Although this can give a good indicator of positive operation, it is difficult to determine the level of performance by this method. It is a good qualitative indicator but not particularly valuable when quantitative measurements are needed.

Quantitative indications are much more difficult to achieve. Measuring soil temperatures in the vicinity of the thermosyphon is one method of assessing the long term performance level of the thermosyphon. It also is not without its limitations and problems. For best accuracy, the precise relationship (i.e. distance, direction and soil type) between the thermosyphon and the temperature measuring points must be known. And since weather patterns and specifically air temperatures can change rather rapidly in winter, monitoring the soil temperatures near the thermosyphon should be done on a regular basis several times a day. Since thermosyphon temperatures follow the air temperature with a relatively short lag time, the effect on soil temperatures needs to be known as the air temperature changes.

Surveillance of all of these conditions was not possible on this study. The exact relationship between the location of the thermistor string and the thermosyphon was not known for the reasons discussed above. The tri-annual frequency of measurement was adequate for the long term assessment of performance, and especially at locations several feet distant from the thermosyphon tube. Hourly air temperatures were available from the airport weather station a few hundred yards away, but it was not economically possible to monitor the temperatures near the thermosyphon more frequently. Nevertheless, some quantitative indications of operation are possible with the data available.

4.0 Analysis of Results

4.1 Thermosyphon T-7

Throughout this study, thermosyphon (T-7) and the adjacent thermistor string set (ts-700) have provided the best information on performance of an active thermosyphon. The mid-winter performance is particularly striking. Although the exact distance between the thermistor string and the thermosyphon tube is not known, they must be in close proximity to yield soil temperatures which follow the weather changes as closely as these. Figure 3 shows the progression of January temperatures over the past three years through January 1987. No midwinter collection was done in 1988 due to budget limitaions. The dramatic drop in temperature at the depth of the thermosyphon clearly shows the ability of the device to remove heat from the soil and to reinforce the permafrost. The depth of the temperature depression is impressive - over four degrees Fahrenheit. More significantly, however, is that the temperature depression is becoming broader with time. That is, the cooling effect of the thermosyphon is extending farther from the source each year. Note that although the lowest temperature in Figure 3 is much lower in 1986 than in 1987, the soil temperatures both above and below the thermosyphon are lower in 1987. This suggests a progressive cooling may still be continuing. Although this is not also shown in Figure 4, the temperature of the permafrost at the 25 foot level is slightly lower in 1988 than in either 1986 or 1987. The overall level of cooling of the permafrost at this level appears to be 0.6 to 0.7^{o}F.

The depth of the minimum temperature is a function of air temperature during the recent past. A cold period will drive the cooling action of the probe, and the soil in the immediate vicinity of the probe will follow the temperature of the probe with less lag time than the soil farther away. This results in a very steep, relatively narrow temperature depression such as that for 1986 in Figure 3. When the air temperature warms up, the soil temperature depression becomes shallower and broader as heat energy moves from the warmer soil to the cold soil around the thermosyphon.

More important is the overall cooling effect at the end of winter, when air temperatures are no longer colder than the soil around the thermosyphon, and the units become dormant. Figure 4 shows the May temperature profiles. These data give insight into the overall cooling effect. The cooling effect at the end of the 1986 winter was significantly lower (0.7^{o}F in soils above 15 feet deep) than either 1987 or 1988. Clearly the last two warmer than average winters have taken their toll, but the overall cooling is still well below the control area. Deeper soil temperatures do not yet show the warming trend. Below 22 feet the temperature is essentially the same for all three years.

When the temperature at the 12 foot depth is compared to the control temperatures throughout the entire period of the experiment, the overall cooling effect can be seen (see Figure 5). A substantial "cooling reserve" has been established that keeps the maximum temperature well below freezing even during late summer and fall when soil temperatures at this depth are at their highest.

Figure 5 also points out one of the other significant advantages of cooling the sub-base. At this depth, the soil temperature in the uncooled control area rises to several degrees above freezing each fall. At the same time, the cooler fall temperatures are activating the thermosyphons so that they are beginning to cool the soil around them, and temperatures never do get above freezing.

4.2 Thermosyphon T-6

Another thermosyphon which has demonstrated positive performance is T-6 which is monitored by thermistor string ts-1200. This thermistor string was installed after the repaving of the runway in 1984 to take advantage of a previously drilled exploratory hole. The relationship between the locations of the thermistor string and the thermosyphon were not planned to coincide, but from its location on the runway centerline it appears that the thermistor string monitors thermosyphon T-6. At any rate, the performance of this thermosyphon is encouraging. Figure 6 shows the temperature depression with depth at this location in January 1985 through 1987. Considering the lack of knowledge as to the proximity of the thermistors to the thermosyphon, the performance of this unit could be judged to be from good to excellent.

The spring temperature curves in Figure 7 show a sizeable temperature depression and present somewhat of a surprise. During the course of the monitoring project, this thermosyphon was considered to be one that showed encouraging but marginal performance. Temperature depression was mild by comparison to T-18. The latest data set, however, indicates that the performance of this unit has been excellent during the last two years and especially between May 1987 and June 1988. During the same time period, when the temperature depression for T-18 had warmed decidedly ($0.8^{o}F$), the performance of T-6, by comparison, has cooled $1.7^{o}F$. This suggests several possibilities, for example:

1. The unit may have been recharged during that period. However, there is no record of recharging by any of the many groups working on the experiment.

2. The data is in error due to reading errors or thermistor drift over time. This is unlikely since the

shape of the temperature vs depth curve matches those of earlier data. This string has an interesting anomoly at the 11.7 foot depth that is present in every data set. If the thermistor string were giving false readings, they would not likely follow the same shape. It is possible that some resistance was introduced into the data set for this particular thermistor string. However, a change of this type normally results in an unstable, fluctuating data set, not a uniformly displaced one.

3. The condenser section of this unit was cooled more efficiently. This could be the result of clearing brush which had accumulated around the condensers on the east side of the runway or of less snow accumulation in and around the finned condensers. In the interim report of August 1986 it was noted that the brush had grown high enough to impede operation of the condensers. During the summer of 1987 it was noted that the brush had been removed. During the June 3, 1988 visit, it was noted that the slope of the shoulder had been changed dramatically. If this changed the snow drifting pattern in the area and left the condenser for this thermosyphon more exposed to the winter winds of the area, the unit would certainly perform much better during the last two years. This is the more likely explanation.

Whatever the reason, the fact that the unit is performing much better is welcome news and serves to confirm the evaluation of the effects of the experimental installation which were, up until now, based only on the performance of thermosyphon T-18.

Another measure of the overall performance of the thermosyphons is the depth to frozen soil at the end of summer. A decrease in the thaw depth at this time of year is a good indication that the units are cooling the soil enough to withstand the detrimental effect of the summer heat gains. Even during the warmer than average weather of the last two years, the depth to frozen soil has progressively decreased from the beginning of the experiment until the present. At T-6 the depth was approximately 10 feet on October 26, 1984 and decreased to approximately 8 feet on October 16, 1987. Likewise, at T-18 the depth decreased from approximately 11.5 to 7.5 feet over the same time period. Although the thaw depth appears to have increased slightly between 1986 and 1987 at thermosyphon T-18, T-6 does not show any increase, but rather a steady progressive decrease.

Finally the temperature at the 12 foot depth near T-6 is shown in Figure 8. As with T-18, this figure shows that T-6 indicates a progressively greater difference between itself and the control area temperatures at the same depths. Unlike T-18, however, the gap has continued to widen during the last two winters. This is encouraging but difficult to explain. If milder than normal winters were the cause of T-18's decline, as was speculated above, then the same effect should be apparent in T-6. Since it is not, one must suspect the viability of T-18. A slow progressive leak in T-18 could cause it to gradually decline in performance over time. Only a continued monitoring of the soil temperatures around both units will resolve this question.

4.3 Thermosyphon T-13

This thermosyphon, on which 54% of the instrumentation installed was invested, is the real disappointment of the experiment. It has not shown any signs of positive operation from the first data set taken. All of the working fluid has apparently leaked and it has remained a dormant lifeless relic to an installation system that leaves much to be desired. Figures 9 and 10 show the temperature vs. depth profile for the thermistor strings ts-100 and ts-800 respectively at the beginning of the experiment in early 1983, at the beginning of this monitoring study in 1984 and during the latest data collection in 1988. It is clear from these curves that no heat removal has been taking place.

4.4 Thermosyphon T-3

Thermistor string ts-10 was installed to monitor thermosyphon T-3. The record of temperatures shows no evidence of thermosyphon activity at this location. This is another dead unit.

4.5 Thermosyphon T-8

Two thermistor strings are in place to monitor this unit. Thermistor string ts-9 was installed at the beginning of the experiment in 1982, while ts-13 was installed after the summer repaving in 1984. Ts-13 like ts-12 was installed to take advantage of an existing exploratory hole that became accessible during the repaving. Like ts-12, it is shorter than strings 1 through 11. Once again, however, the temperatures from both thermistor strings show not a glimmer of activity from the nearby thermosyphon.

5.0 Conclusions

The units which are working are performing well. Unfortunately, we can only say conclusively that two thermosyphons (T-6 and T-18) are working. Over the 5 year period of the study, T-18 has decreased the active layer depth at the end of summer by 53% from 16 feet in December 1982 to 7.5 feet in October 1987. This change has continued throughout the study, however it is somewhat diminished toward the end of the period. Since the beginning of this portion of the overall study in the fall of 1984, the decrease has been 42%, from 12.5 feet to 7.5 feet. The minimum soil temperature has decreased from $31.7^{\circ}F$ to $31.0^{\circ}F$ over the same period. This is commendable performance.

Thermosyphon T-6 has a similar overall performance. Monitoring of this unit started in the fall of 1984. During this time it has decreased the active layer by over 4 feet from 12 feet down to approximately 7.8 feet. The minimum permafrost temperature decreased from 31.9^{o}F to 31.1^{o}F, also a drop of 0.7^{o}F. A temperature drop of this amount in soils at this temperature corresponds to a 450% increase in adfreeze strength from 2 psi to 9 psi (Johnston 1981). These are the results at the most critical time, the end of summer.

Even though several of the 31 thermosyphons failed, the overall performance of the units can be appraised by the level condition of the runway. Since the 1984 repaving, the area protected by the thermosyphons is still stable and serviceable, while serious subsidences have developed in the runway to the North and South of the protected area. This suggests that the majority of the 31 thermosyphons have been operating. This experiment may have been inordinately unlucky in having instrumentation installed only on some of the few thermosyphons which failed.

If a suitable, economic installation procedure can be developed, these units hold the promise of greatly reducing the maintenance costs from permafrost subsidence problems. They could increase reliability and safety for both runway and road embankments while paying for themselves in maintenance savings.

6.0 Recommendations

A method for installing thermosyphons in existing embankments which are experiencing distress due to permafrost melting needs to be developed. The current method of using the thermosyphon tube as the drill pipe is clearly unsatisfactory and far too expensive. Several possible alternatives are available depending on the size and nature of the installation.

6.1 Trenching and Excavation

If the site is small, such as a road embankment, thermosyphons can be installed in a trench cut from the top surface of the embankment. Factory premanufactured and pretested units can then be used. This would virtually eliminate the leakage problems experienced in the Bethel installation. The limitations to this alternative include the practical limitation of trenching depth, the exposure of the permafrost to melting if the installation is done during the summer, and the difficulty in excavating ice-rich soil and the interference with traffic during installation. Massive excavation may overcome the trenching depth limitation, but then cost may become excessive. Winter or late fall installation could be used to avoid permafrost damage, but once again costs will be higher when working in the cold. These variables must be evaluated on a site specific basis.

In spite of these limitations, where the required depth is not prohibitive, and where traffic interference can be accomodated, installation of the thermosyphons in trenches is one of the more attractive and cost effective approaches. Control of both the thermosyphon and monitoring instrumentation is positive, costs are manageable, and thermal conditions around the evaporator sections of the thermosyphons can be controlled and even enhanced.

6.2 Drilling

For large sites such as this one at Bethel, where trenching depth becomes excessive, and traffic interference cannot be tolerated, thermosyphons may still have to be installed by angle drilling. Again several possible approaches are available. The method used on the Bethel project of using the thermosyphon tube for the drilling pipe has not proven to be acceptable. On this project and others, the resulting installation has suffered excessive installation costs and leaking units that are soon inoperable. The purpose of drilling with the thermosyphon tube is to avoid the problem of hole sloughing in the unfrozen portion of the embankment.

Unfortunately this technique eliminates the opportunity to change bits to meet the needs of changing conditions. A rock bit must be used to permit drilling of hard materials should they be encountered. The rock bit however, quickly loads in unfrozen material, making progress slow and expensive. A more aggresive auger bit is needed, along with the ability to change to the rock bit or whatever other bit is needed as conditions change. To avoid sloughing, the hole will have to be cased and, when finished, the pretested thermosyphon can be installed in the cased hole. For good heat transfer conditions, the annulus between the thermosyphon and the casing will need to be filled with a heat transfer medium. Sand slurry could be used, or possibly silicon oil, if the expense can be justified and the casing rendered leak tight.

Generalized cost estimates are practically impossible since site conditions and permafrost properties vary so widely. The cost savings in drilling time have to be far less with this approach than they are with the agonizingly slow procedure used for this project.

6.3 Alternative Installation Techniques

If the embankment can be closed on one side, for example a road where traffic can be restricted to the opposite side during installation, it may be possible to install the thermosyphons vertically in the embankment to within a few feet of the surface and then route them to the side of the embankment in a shallow trench (see Figure 11).

This procedure will allow the drill to be operated in its most efficient position, using the best techniques for the site conditions. The hole can remain uncased in most situations, and a shallow trench to the shoulder of the embankement will present no problems. A premanufactured and tested thermosyphon can then be installed in the hole and either "slurried in" or "driven in" to the hole to provide good thermal contact in the evaporator section.

The condenser section will extend from the shoulder out of the way of traffic and winter snow plows. Since the thermosyphons are vertical they need not be as long, so that logistics and handling are easier and installation time is minimized. In the vertical position thermosyphons operate at their maximum efficiency (Zarling and Haynes 1985) thus reducing the number of units needed to protect the embankment.

7.0 Implementation

This project proves that wide sections of embankments, such as runways and parking lots, which are failing due to thaw settlement can be stabilized using thermosyphons. These results should also apply to narrow embankments such as roads and railroads. Thermosyphons provide the unique ability to transport heat from the subgrade and even subbase materials beneath the surface while insulation placed above the thermosyphons reduces the amount of heat that flows back in during the summer. If the winter freezing season is long enough, the progressive result is to thermally stabilize the permafrost and even to allow it to move into the embankment itself.

Candidate sites should have cause of the embankment failure clearly identified by a drilling program to determine the soil types, density, moisture content and temperature. Ice forms encountered should be cataloged with respect to their location and size. Surrounding ground water conditions should be observed both in the summer and winter, and any instances of aufeis formation should be studied. Wind conditions and surrounding terrain and vegetation, particularly trees, should be noted for design purposes.

The spacing, depth, slope, etc. of the thermosyphons should be designed based on the field data. The location of the condenser sections of the thermosyphons should be chosen to take maximum advantage of local wind conditions and to be safe from snow plows or other equipment using the embankment. The location should be one which will not allow the condenser sections to become drifted over by snow or snow plowed under by maintenance crews.

The installation procedure should be chosen to meet the needs of the particular site. Operational parameters should be noted; can the site be closed to traffic during installation, can traffic detours be used, are there time windows when the site could be closed to use while opened at other times. These constraints should be considered when the type of installation procedure is chosen.

It must be realized that embankment stabilization by this means is not an instant solution. It may require several years, and several levelling projects may be necessary before the surface is stable.

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