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EXPERIMENTAL INVESTIGATION OF AIR CONVECTION EMBANKMENTS FOR PERMAFROST-RESISTANT ROADWAY DESIGN

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Abstract

Air convection embankments have been proposed as a method for avoiding thaw-settlement of roadways in regions of warm permafrost. These embankments are constructed of poorly-graded open aggregate, resulting in a very high air permeability. Unstable air density gradients that develop within the embankment during winter result in buoyancy-induced pore air convection. This convection increases the heat flux out of the embankment and foundation material during winter months. During summer, the air density gradient is stable and convection does not occur. The net effect is an increase in winter cooling without a corresponding increase in summer warming and thawing is prevented in the permafrost layer beneath the embankment. The present study discusses thermal data collected from an experimental air convection embankment that was constructed at Brown's Hill Quarry near Fairbanks, Alaska and monitored over a two-year period. The results show a large cooling influence due to air convection within the embankment during winter.

Introduction

Thaw-unstable permafrost provides a very significant challenge to engineers working in northern climates. Over the years, techniques for avoiding damage to engineering structures because of thaw settlement have remained high on the research agenda for government agencies and universities. This research has resulted in a number of practical techniques that can be utilized to protect a wide variety of structures from thaw-settlement damage. Nevertheless, many unsolved problems remain.

When roadway embankments are constructed in permafrost regions, they typically have a large influence on the thermal regime of the ground. This is due primarily to the fact that the embankment modifies the pre-existing surface conditions and the associated ground-surface energy balance. The ground-surface energy balance is a complex function of seasonal snow cover, vegetation, solar and long-wave radiation, surface moisture content and atmospheric air temperature (Lunardini, 1981). These factors act to produce a mean annual surface temperature (MAST), which may differ substantially from the mean annual air temperature (MAAT). At undisturbed sites the MAST is typically warmer than the MAAT because of the impact of the insulating snow layer during winter months. Disturbance of the surface due to construction of a roadway embankment often increases the MAST resulting in a warmer surface condition and enhanced thawing of permafrost. This is particularly true in the side-slope region of embankments where lack of vegetation and low moisture content leads to relatively high summer-time surface temperatures and large snow layers lead to an enhanced insulating effect in the winter time. This situation often leads to a shoulder rotation phenomena where the enhanced thawing beneath the side slopes causes the sides of the embankment to subside faster than the centerline. An apparent rotation of the side slopes typically produces longitudinal cracking of the driving surface.

In order to maintain stable permafrost and avoid thawing, it is generally necessary to ensure that the MAST is maintained below 0°C. In sub-arctic regions, such as interior Alaska, warm discontinuous permafrost is often encountered due to a MAST which is only slightly below 0°C. Under these circumstances embankment construction often increases the MAST to a value above 0°C resulting in eventual thawing of underlying permafrost (and attendant consolidation and thaw settlement). As a result, several techniques for mitigating thaw settlement using surface modifications that lower the MAST have been studied in the past. These include painting of the asphalt surface to increase the albedo (Reckard, 1985), the use of snow sheds and snow removal on embankment side slopes (Zarling and Braley, 1986) and placement of rock-rubble on side slopes (Zarling, 1994). Other techniques have relied on direct removal of heat from the embankment during winter using air-duct circulation systems or thermosyphons. Zarling et al. (1983) reported on the operation of an experimental air duct system, and Zarling and Braley (1986) discussed the use of thermosyphons in roadway embankments. Esch (1987) reviewed the use of foam insulation in roadway and airfield embankments in order to mitigate thaw settlement. In general, insulation is only able to slow the thawing process rather than arresting it altogether. When applied in the field, many of these techniques have suffered from some combination of limited effectiveness, high cost, high maintenance, or safety concerns.

The present study investigates a relatively new technique that makes use of an Air Convection Embankment (ACE) for avoiding thaw settlement in regions of warm permafrost. The technique involves the use of a poorly-graded embankment material, such as gravel or rock with a low fines content, which is used to construct the main portion of the embankment. Such a material allows natural convection (similar to Rayleigh-Benard convection) of the pore air to occur within the embankment during winter months in reaction to an unstable density stratification of the pore air. During winter, colder pore air in the upper portion of the embankment will descend due to its greater density while warm pore air from the embankment base rises. This results in a pattern of convection cells within the embankment as shown schematically in Figure 1. If the embankment material possesses an adequate air permeability, these convection cells circulate with a high intensity and transport a large amount of heat from the base of the embankment to the surface where it is rejected to the cold winter environment. During summer the density stratification is stable with warmer pore air lying over colder and, thus, convection does not occur. The net effect is that the entire embankment acts as a thermal diode, efficiently removing heat from the embankment base and subgrade during winter months without re-injecting it during subsequent summers.

Goering and Kumar (1996) have investigated the performance of ACE embankments using a two-dimensional numerical model of the governing mass, momentum and energy equations. Goering (1996) compares some of the numerical results with experimental data. The present paper describes experimental results that were obtained from an experimental ACE embankment located near Fairbanks, Alaska.

Experimental Embankment

EMBANKMENT CONSTRUCTION

An experimental ACE embankment was designed during the winter of 1992-93 and installed at Brown's Hill Quarry near Fairbanks, Alaska during the summer and fall of 1993. The embankment was constructed in a level area within the quarry complex that had been cleared of natural vegetation for many years. Even though the MAAT in this area is approximately -3°C, the construction site was not underlain with permafrost

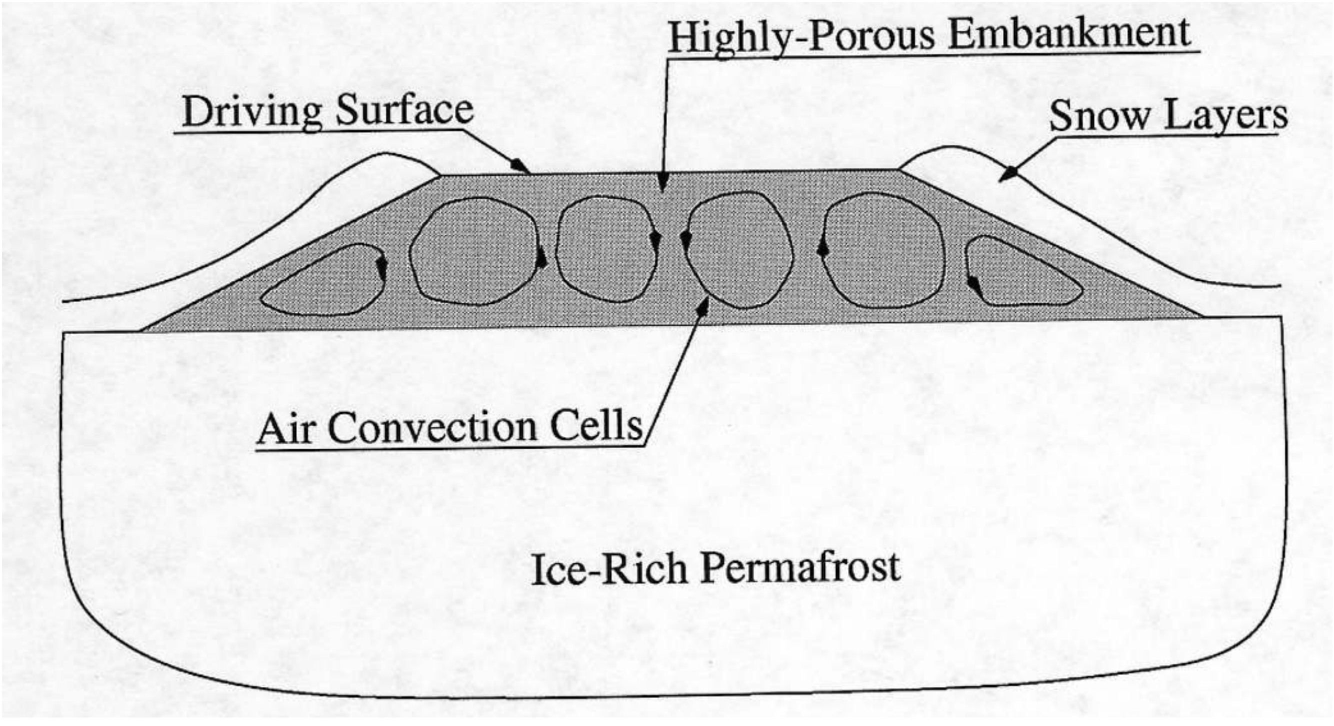

Figure 1. Pattern of embankment pore-air circulation.

indicating that the MAST was elevated somewhat above 0°C. This is typical of areas that have been cleared of vegetation, since lack of such vegetation tends to increase summer surface temperatures.

The embankment had an overall length of 40 m, a width from toe to toe of 16 m, a 6 m wide driving surface and a height of 2.5 m. This geometry results in a relatively high and narrow embankment with 2H:1V side slopes. The resulting cross-sectional shape is shown in Figure 2. Although it was not designed for traffic, nor located in an actual roadway, the embankment had ramps at either end to allow snow clearing equipment to maneuver over it. Construction was carried out by placing 5-8 cm diameter rock using a front-end loader. This material was manufactured at the quarry by crushing larger rock and then screening to remove all material outside the desired gradation range. The material, as placed, was generally clean with an extremely small fines content. Placement was carried out in separate lifts of approximately 0.6 m each. Compaction was accomplished by driving over each lift with the loader. No other compaction was attempted. The upper surface of the embankment was formed using the same 5-8 cm rock, no asphalt or other covering material was used. Despite this, the surface rock became quite well oriented as the equipment drove over it and provided a surprisingly smooth driving surface.

INSTRUMENTATION

Thermistor temperature sensors were installed at the center cross-section of the embankment in order to measure temperatures at a regular array of grid points. Before material placement began, a vertical thermistor string that extended down a distance of 2.5 m below grade was installed at the centerline of this cross-section. As construction of the main embankment proceeded, four horizontal thermistor strings were installed with a vertical spacing of 0.6 m. A transit was used to ensure that the sensors were placed accurately. Each of the horizontal strings contained 11 thermistors with a horizontal spacing of 0.6 m. This spacing was used in order to capture the spatial details of the convection cells. In total, 44 thermistors were contained in the embankment cross-section with four more installed along the vertical centerline at depths of 0.6, 1.2, 1.8, and 2.4 m beneath the original grade. The thermistor locations are indicated by dots in Figure 2. In addition to the 48 thermistors installed within the embankment, another four were used to measure surface temperatures on the embankment side slope (beneath the snow layer) and one was located in a radiation shield and used to measure ambient air temperature.

Thermistors were ±0.2°C interchangeable with a resistance of 16K Ohms at 0°C and were manufactured by YSI. Before installation, each of the thermistors were calibrated in an ice bath.

Temperature data was collected by a Campbell CR10-XT data logger connected to a multiplexer, storage module, and battery power supply. Temperature readings were collected each 15 minutes and averaged to generate hourly average values. Hourly averages were then stored and collected from the site using a laptop computer on an approximately bi-monthly schedule. Data logging began on October 26, 1993 and was continuous through October 27, 1995 with no data loss.

EXPERIMENTAL PROCEDURE

The lack of pavement or a fine grained surface coating on the upper surface of the experimental embankment was a significant departure from an actual roadway embankment that would necessarily include such a surface covering. The absence of this surface covering was of concern because of the possibility of pore air entering or exiting the embankment at the upper surface. Such pore air movement might have had a significant effect on convection within the embankment and would not be possible with an actual roadway embankment due to the relatively impermeable nature of the driving surface. In order to simulate the presence of an impermeable surface coating, the first snow of the winter season (both 1993-94 and 1994-95) was allowed to collect on the upper surface and was then compacted into an

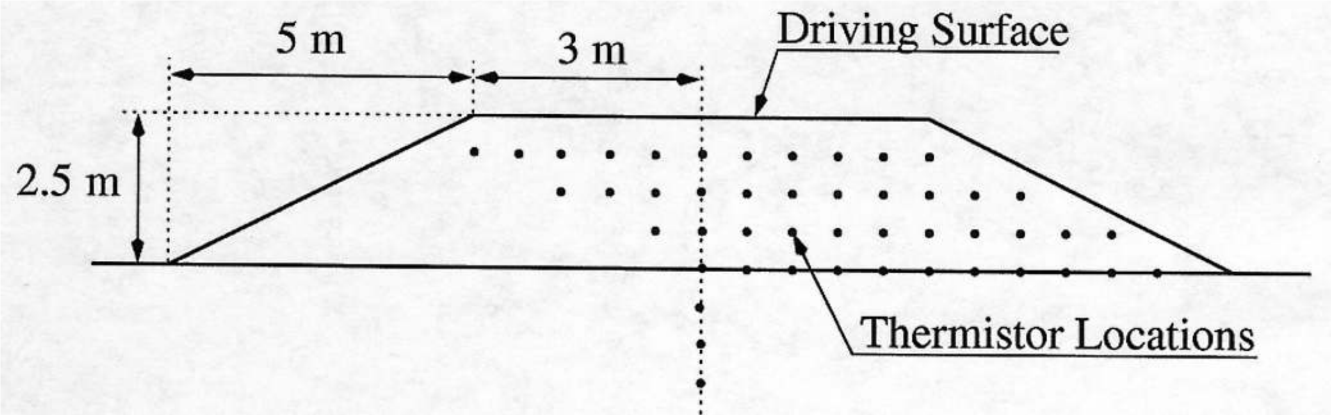

Figure 2. Experimental embankment configuration.

ice sheet by driving heavy equipment over the upper surface. The thickness of this ice sheet was maintained at approximately 10 cm throughout each winter. Once the ice sheet was established, additional snow was removed from the driving surface of the embankment on a schedule that coincided with regular snow removal operations at the quarry. Snow was plowed onto the side slope of the embankment using a standard road grader in an effort to mimic actual roadway conditions.

After snow melt in the spring of 1994, plastic sheeting was placed on the upper surface of the embankment and side slopes and left in place throughout the summer and early fall. In the fall of 1994 this sheeting was removed from the upper surface of the embankment but remained on the side slopes beneath the collecting snow throughout the winter of 1994-95.

Results

Raw data was recovered from the Brown's Hill Quarry test site and processed in order to obtain temperature values. Hourly data sets are available for the entire test period, October 1993 to October 1995. Figure 3 shows centerline subgrade temperatures at the surface of the original ground (2.5 m below the upper surface of the embankment) and at depths of 1.2 m and 2.4 m below the original ground surface for the two-year test period. The horizontal axis is listed in terms of Julian day beginning on 10/27/93 (Julian day 300), proceeding through 1994 (Julian day 1-365) and finally ending on 10/27/95 (Julian day 300).

Average ambient air temperatures were -1.36°C for the period 10/93-10/94 and -1.94°C for 10/94-10/95. In general, the ambient air temperature behavior consists of a fairly harmonic seasonal variation with large fluctuations superimposed on it. Several periods during each winter had extreme low temperatures below -40°C with summer highs exceeding +25°C.

As mentioned previously, the test embankment was constructed in an area of the quarry that had been cleared of vegetation for many years. The surface condition consisted of a level dark topsoil, which was fairly dry (although the water table in this area is known to be within 4 m of the surface). As a consequence, the MAST in this area had probably been maintained above 0°C for many years and no permafrost was present at the time of construction (although we did not probe deeper than about 3 m to confirm this).

Examination of Figure 3 indicates a subgrade surface temperature of 0°C and subgrade temperatures (at both 1.2 and 2.4 m depths) of approximately +7°C in October of 1993 immediately after embankment construction was complete. The subgrade surface temperature began falling fairly rapidly as the winter of 1993-94 progressed, gradually dropping to about -9°C by mid-March of 1994. The subgrade temperatures also displayed a uniform decrease during the first winter of operation. The temperature at 1.2 m fell below 0°C for a period of about 1 month between Julian days 85 and 115 during the spring of 1994. Note that this temperature is a total of 3.7 m below the surface (2.5 m of embankment material plus an additional depth of 1.2 m into the subgrade). During the summer of 1994 the subgrade temperatures did not rise appreciably above 0°C even though the subgrade surface reached about 5°C.

Behavior of the subgrade temperatures is similar for the winter of 1994-95 with the exception that they are generally colder. The period of sub-0°C temperatures at

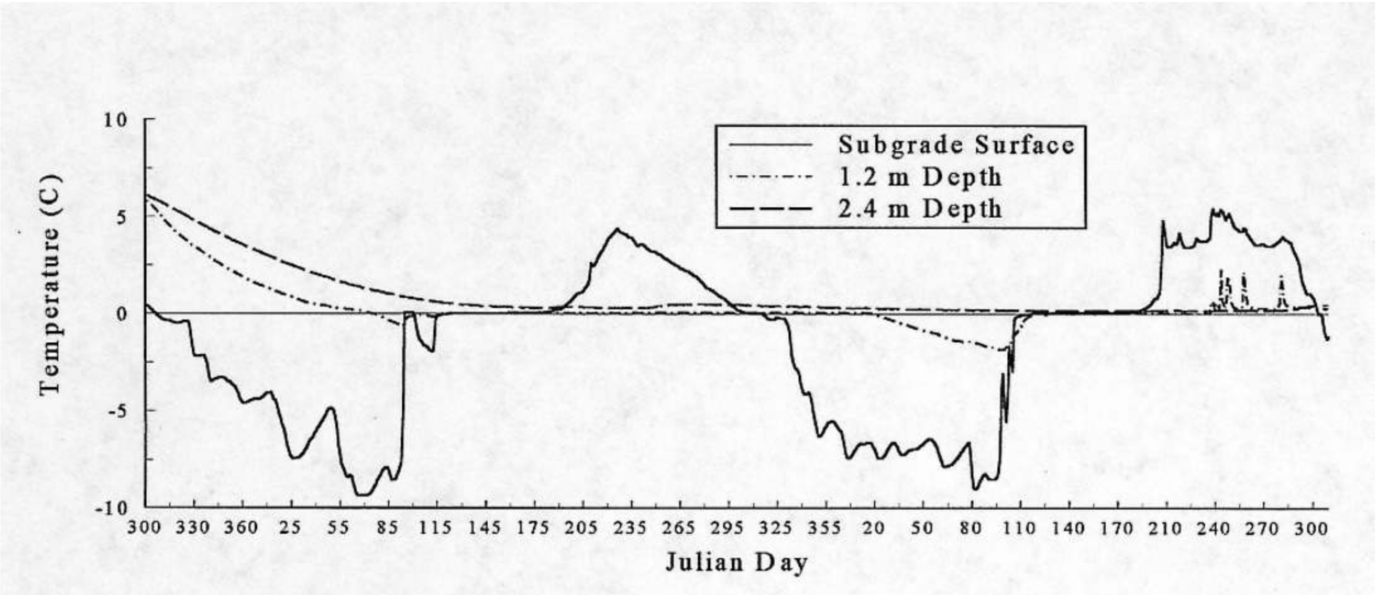

Figure 3. Temperatures beneath the experimental embankment during the two-year study.

the 1.2 m depth is significantly longer (almost 3 months) during the winter of 1994-95 than during the first winter of operation. This behavior appears to indicate that the subgrade is undergoing a gradual cooling as a result of embankment construction. Figure 3 also reveals some interesting characteristics with regard to the behavior of the embankment temperatures during the first and second summer of operation. All three temperature records are fairly smooth during the first summer of operation. In contrast, two of the three temperature records display distinct spikes during the second summer. This difference is attributed to the presence (or absence) of the plastic sheeting on the surface of the embankment. This covering was present during the first summer but not during the second. The influence of the plastic covering was two-fold. First, it prevented warming of the embankment due to any wind-generated forced convection and, second, it prevented precipitation from infiltrating at the top of the embankment. Infiltrating precipitation is likely the cause of the spikes in the temperature record during the second summer. Note that water is infiltrating as deep as the 1.2 m measurement but does not appear to infiltrate to the 2.4 m depth. Also note that the temperature record for the 1.2 m depth indicates that there is a rapid refreeze after water infiltrates. It is likely that after a few years of operation the subgrade material would become essentially impermeable because of ice accumulating in this fashion.

Embankment temperature profiles, 10/93 – 10/94

Figures 4(a)-(e) show isotherms of instantaneous embankment temperatures for 12/1/93, 2/1/94, 4/1/94, 6/1/94, and 8/1/94. Notice that the contour plot in each figure is limited to the region of the embankment which is covered by the thermistor array shown in Figure 2. The scale used in this figure corresponds to that shown in Figure 2. The isotherm contours were generated by a contouring package using the 44 thermistor measurements as input.

Figures 4(a) and (b) are typical of winter conditions when natural convection is active within the embankment. Examination of the complete data set, however, indicates that there is a considerable amount of variation in the temperature profiles on a week by week (if not day by day) basis. Convection patterns within the embankment appear to react to changes in ambient conditions on a time scale of a few days. The isotherms in figures 4(a) and (b) show large deviations from the flat horizontal profiles which would be expected within the embankment under conditions of conduction-dominated heat transfer. Notice that the isotherm shapes display what appears to be a cold air mass intruding from the right-hand side-slope region. This is due to cold ambient air entering the embankment at the toe of the side slope and moving into the interior of the embankment. It is interesting that the thick, although uncompacted, snow layer on the sides of the embankment did not prevent ambient air from entering at the side-slope boundary. In general the isotherms in Figs. 4(a) and (b) are indicative of a large amount of convective mixing within the interior portions of the embankment.

Figure 4(C) shows the embankment in a transition state between winter and summer behavior. In this case the core of the embankment is still at a relatively low temperature while the upper and lower portions are warmer. Figures 4(d) and (e) are typical of summer conditions and the isotherm shapes are in sharp contrast to those in Figures 4(a) and (b). During summer the isotherms are essentially horizontal, as expected for warming of the embankment from the top down via heat conduction. The upper portions of the embankment are much warmer than the base, resulting in very stable thermal stratification and a total absence of convective activity. Also note that the temperature gradient within the embankment is much higher than during the winter. This is due to the convective mixing which occurs during the winter that tends to produce more uniform temperatures throughout the embankment.

Embankment temperature profiles, 10/94 – 10/95

Figures 5(a)-(e) show isotherms of instantaneous embankment temperatures for 12/1/94, 2/1/95, 4/1/95, 6/1/95, and 8/1/95. Figures 5(a) and (b) show that the isotherm shapes during the second winter of operation varied significantly from those observed during the first year. In this case there appear to be one or more convective plumes of cold air originating from the upper portion of the cross section and descending, as opposed to cold air entering from the side-slope region as observed during the first winter. This is due to the presence of the plastic covering on the side slope during the second winter of operation. The covering prevented infiltration of ambient air at the embankment toe and allowed a more structured sequence of convective eddies to form within the embankment (similar to the illustration in Figure 1). Figure 5(C) indicates the effect of this convection pattern at the end of the winter season and shows a "cold spot", associated with the position of the cold plume, remaining in the embankment. Figures 5(d) and (e) show isotherm profiles for the second summer of operation which are similar to those observed during the first year.

Conclusion

The results presented here indicate that air convection embankments can have a strong influence on the thermal regime of the underlying subgrade material. Mean annual temperatures at the upper surfaces of the embankment were approximately +2°C during the two-year test. Beneath the embankment at the subgrade sur-

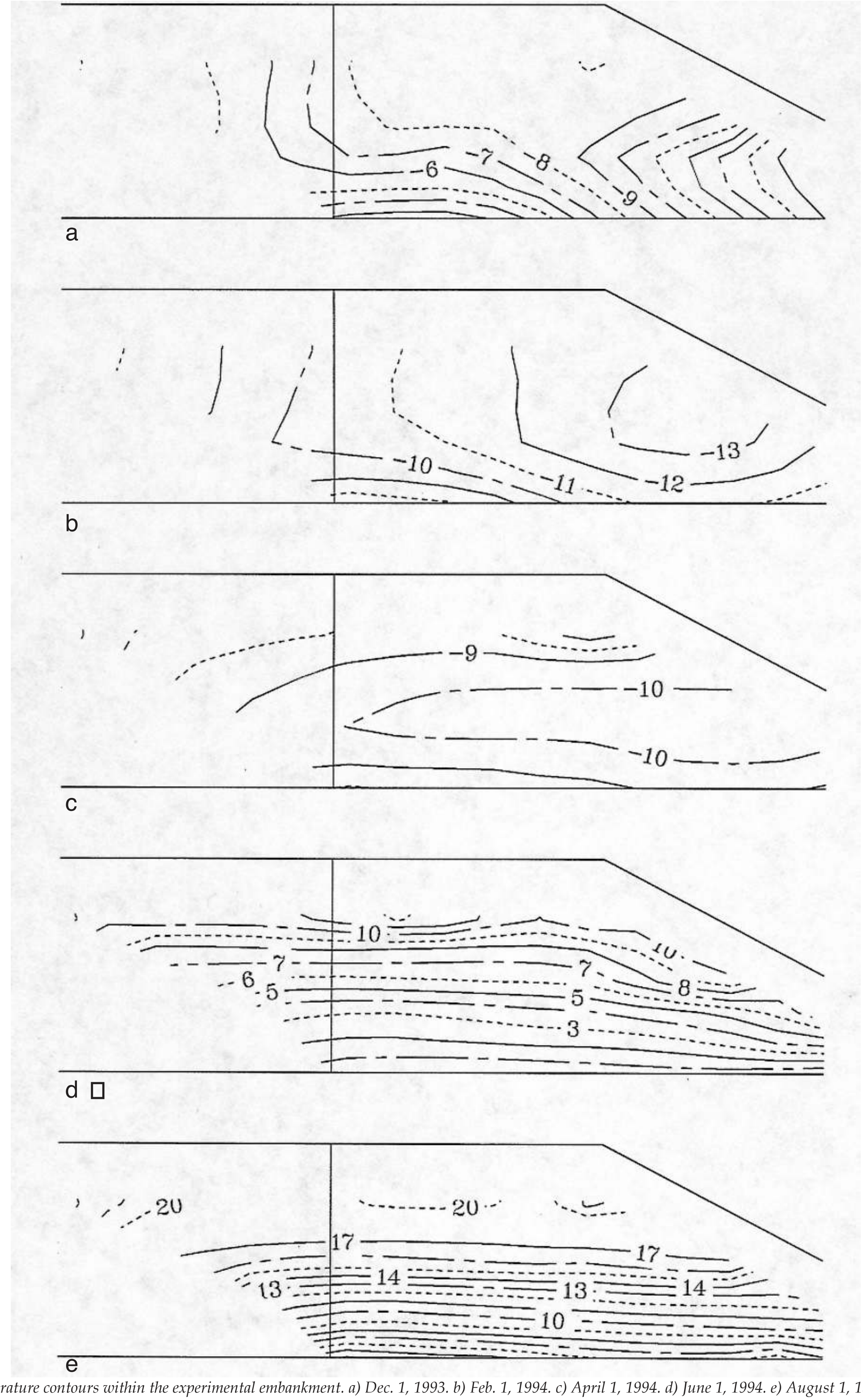

Figure 4. Temperature contours within the experimental embankment. a) Dec. 1, 1993. b) Feb. 1, 1994. c) April 1, 1994. d) June 1, 1994. e) August 1, 1994.

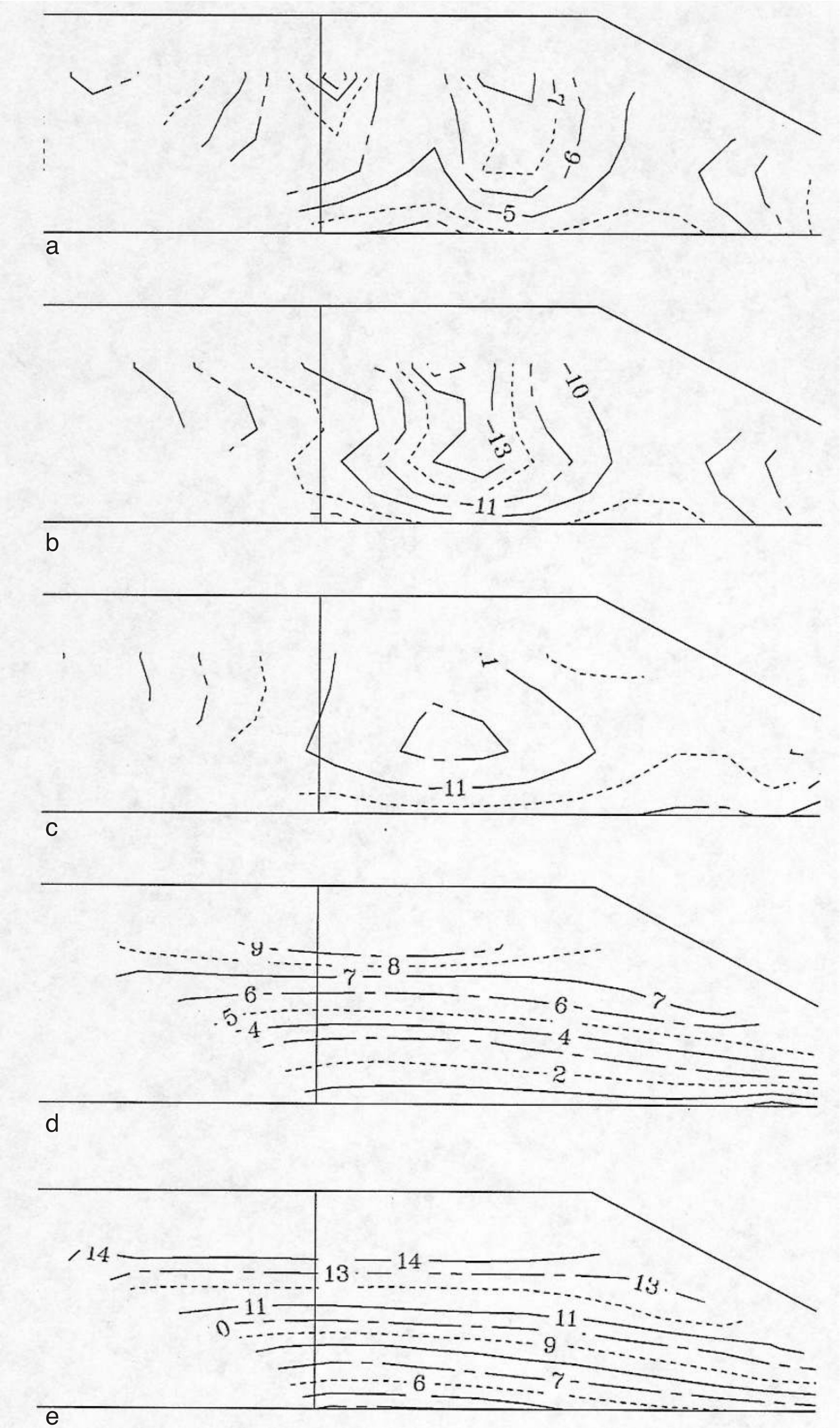

Figure 5. Temperature contours within the experimental embankment. a) Dec. 1, 1994. b) Feb. 1, 1995. c) April 1, 1995. d) June 1, 1995. e) August 1, 1995.

face, mean annual temperatures ranged from –1.2°C to –3.6°C during the same period. The depression of mean temperatures at the base of the embankment is strong evidence of the enhanced cooling provided by wintertime convection within the embankment. The results indicate that air convection embankments should be effective at limiting or eliminating thaw consolidation and thaw settlement problems beneath roadways in permafrost regions.

Acknowledgments

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