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<p>When a culvert is placed under a road, the presence of air at freezing temperatures in the culvert may induce differential frost conditions in pavements. Also, a differential frost heave pattern can appear when the culvert is placed in a frost-susceptible soil. In this project, computer simulations of temperature distributions and frost heave patterns around culverts were carried out, and the effects of various insulation techniques were analyzed under weather conditions representative of Minnesota winters. The pavement slope variance, which is a commonly used variable describing the roughness (or loss of serviceability) of a given pavement section profile, proved to be a valuable indicator under frost heave conditions. Results indicate that culvert insulation reduces the value of the pavement slope variance throughout the freezing period: the higher the insulation thickness, the lower the resulting slope variance (or loss of serviceability).</p> <p>7 references, 14 figures</p>															
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# FROST HEAVE PATTERNS AND OPTIMAL DESIGN OF INSULATED CULVERTS

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## CHAPTER 1

### INTRODUCTION

The objective of the research project presented herein was to generate information on the effect of thermal insulation on the frost heave patterns and thermal differential conditions of pavement sections overlying culverts. A computer simulation code was used to evaluate the impact of various culvert insulation levels and different climatic environments on pavement responses.

Chapter 2 describes the main features of the GELSOL program, which was used to conduct the numerical experiments. This code is one of the few available engineering simulation programs producing the mechanical response of a two-dimensional soil-structure complex under frost heave conditions. It was implemented on workstations at the University of Minnesota's Underground Space Center and Civil and Mineral Engineering Department.

The basic design adopted for the culvert-pavement structure is described in Chapter 3 as well as the insulation strategy to be examined. Three different weather patterns modelling different winter conditions encountered in Minnesota are also presented in this chapter. The subgrade soil is considered highly frost susceptible and its physical properties chosen accordingly. All case parameters are finally translated into simulation parameters used by the computer code to perform the subsequent simulations.

The simulation results are presented in Chapter 4 and followed by an analysis of their significance.

Conclusions are drawn regarding the potential application of these results in design practice.

## CHAPTER 2

### DESCRIPTION OF THE SIMULATION CODE

The GELSOL program used in this project was developed in France at the Laboratoire Central des Ponts et Chaussées, Paris (Blanchard and Frémond 1984, 1985) and was used at the Underground Space Center for two previous research projects (Hovan 1986, 1989), both related to pavement applications.

The code is based on a continuum approach of the frost heave phenomena, and the governing equations are numerically solved in the finite element method framework. The principal assumptions leading to the model are the following:

- The soil is saturated, isotropic and non-saline.
- Fourier's law of heat conduction is assumed for the transfer of sensible heat, and the thermal conductivity depends on the temperature, making the heat transfer problem nonlinear.
- Heat transfer is affected by the latent heat released by pore water freezing at the frost front, which is thus a free boundary.
- The unfrozen water content of the frozen soil depends on temperature.
- Water accumulation in the frozen soil may be described by a constitutive law: the porosity rate is a known function of freezing temperature.
- Heat and mass transfers are coupled by the porosity constitutive law and the supply of latent heat to the freezing front by the water flow.
- Pore water pressure and water flow are related by Darcy's law.

- The frozen soil is a viscoelastic material for which mechanical properties depend on temperature.

- Stresses in the soil are small enough for the water accumulation in the frozen soil to be independent of the mechanical variables.

- All the computations are assumed to take place in a small strains theory framework: the variables are computed in an undeformed geometry.

Due to the assumed independence of the heat and mass transfer from the stresses in the soil, a first procedure computes the temperature distribution as well as the water movements, and a second one is devoted to the stress-strain analysis only.

As the numerical procedure is based on the finite element method, the soil domain is discretized into a triangular mesh.

The problem unknowns, namely the temperature, pore water pressure and soil displacements, are determined for each time step at the mesh nodes, which are the triangular elements vertices.

Once the soil domain is discretized into a triangular mesh, the code needs the following sets of parameters in order to perform the simulations:

- domain geometry description parameters
- material properties
- boundary conditions for the unknowns
- initial conditions for the unknowns
- time discretization parameters

The following chapter describes the cases studied in terms of basic design characteristics, insulation levels and weather patterns. Also detailed are the simulation parameters deduced from these assumptions.

## CHAPTER 3

### CASE AND SIMULATION PARAMETERS DESCRIPTION

#### 3.1. Culvert and pavement structure basic design.

A diagram of the design adopted for this study is shown in Figure 1. It consists of a concrete culvert (24-inch inside diameter, 30-inch outside diameter) placed 48 inches below grade in a uniformly frost-susceptible field soil, under a 10-inch bituminous pavement.

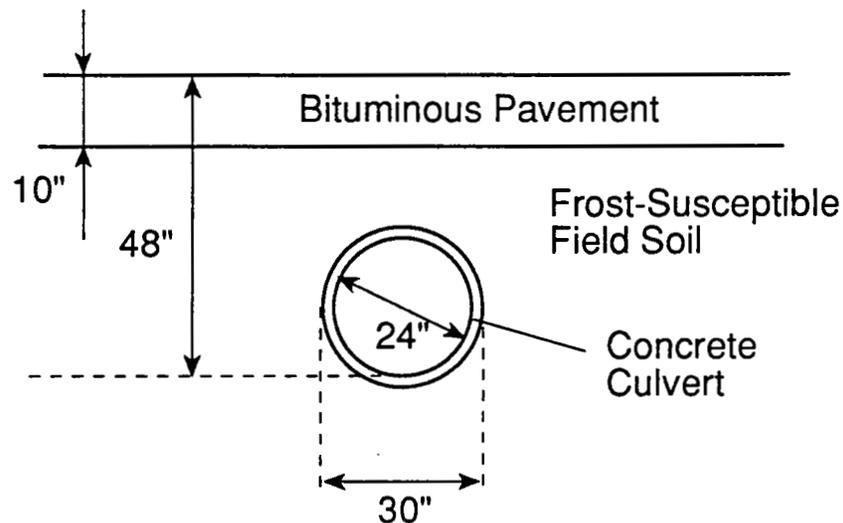


Figure 1. Pavement-culvert basic design.

### 3.2. Insulation strategy.

The insulation strategy examined in this project consists of a circular insulating layer wrapped around the culvert (Figure 2). Three different values of the insulation thickness are considered: 1 inch, 2 inches, and 3 inches.

These insulation strategy cases as well as their associated simulation nomenclature are summarized in Table 2, Section 3.4.

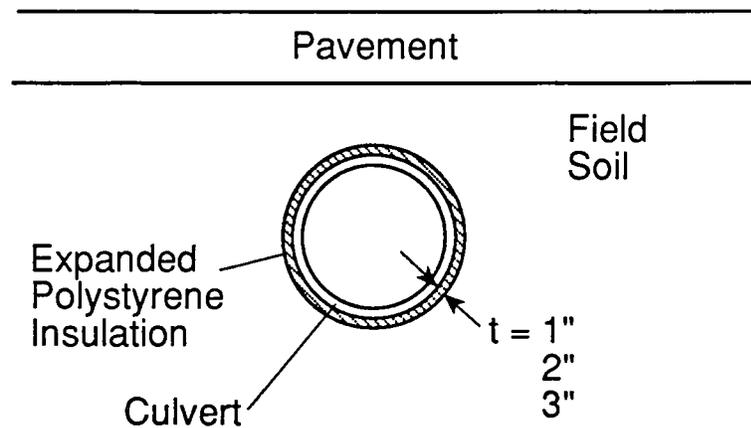


Figure 2. Circular insulation strategy.

### 3.3. Weather patterns.

Three different freezing patterns are chosen in terms of freezing index versus time relationship (Figure 3). In all cases the mark 3060°F.days (1700°C.days) is reached at the end of the freezing period. The current design freezing index for Central Minnesota is 3000°F (1667°C) (Labs et al. 1988).

In the **late** freezing pattern, high value freezing indices are reached later than in the **average** freezing pattern, and therefore at the end of the season temperatures for the late freezing pattern are lower than those for the average freezing pattern. It is exactly the reverse case for the **early** freezing pattern, where temperatures decrease earlier in the first part of the season but also increase earlier toward thawing. For a precise description of the temperature histories associated with the different patterns, see Figures 5 through 7 in Section 3.4.

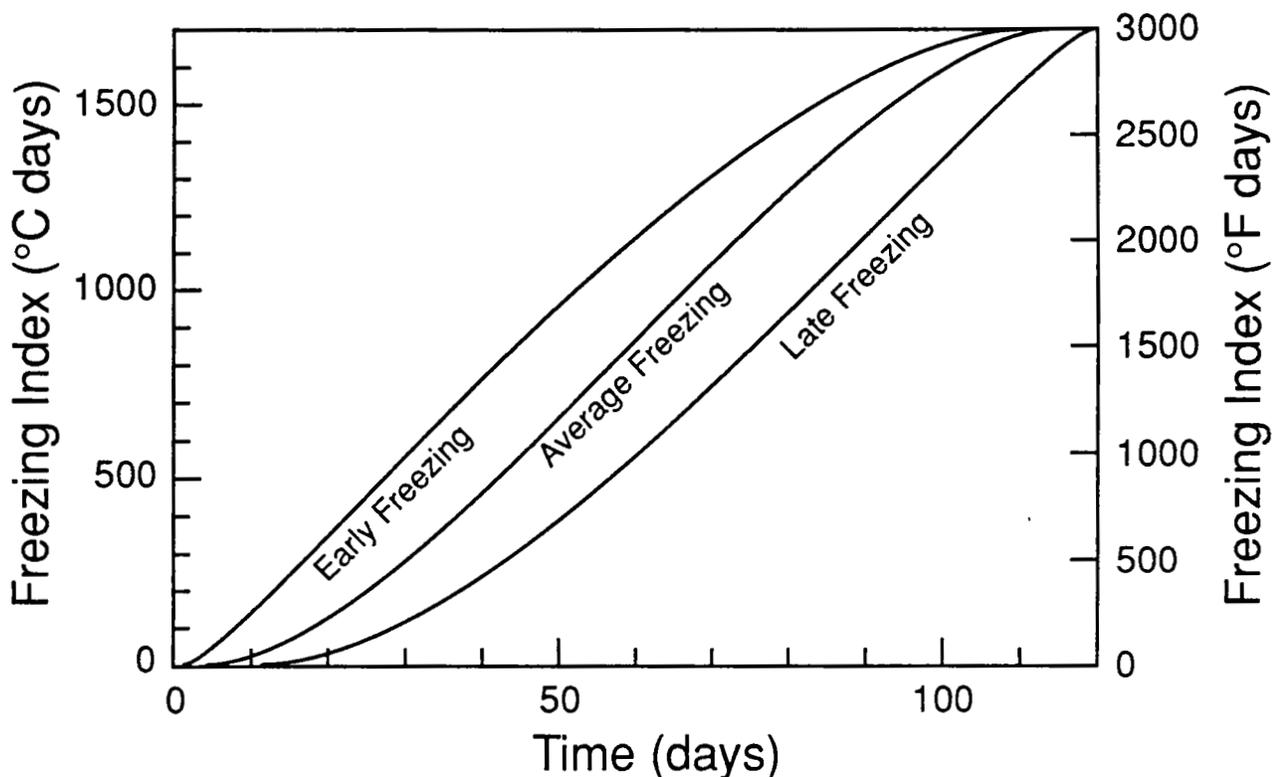


Figure 3. Freezing index vs. time for different freezing patterns.

### 3.4. Simulation parameters.

Geometrical characteristics for the simulations' soil domain are given in Figure 4. This figure shows the pavement and culvert characteristics mentioned earlier as well as the size of the soil domain considered to be representative of the field situation (a 9-foot-wide, 13-foot-deep block of soil is thought to be sufficient in this case). Figure 4 illustrates that, because of the symmetry of the problem, only half of the culvert is considered in the simulations, provided that the boundary conditions are carefully chosen on the symmetry axis.

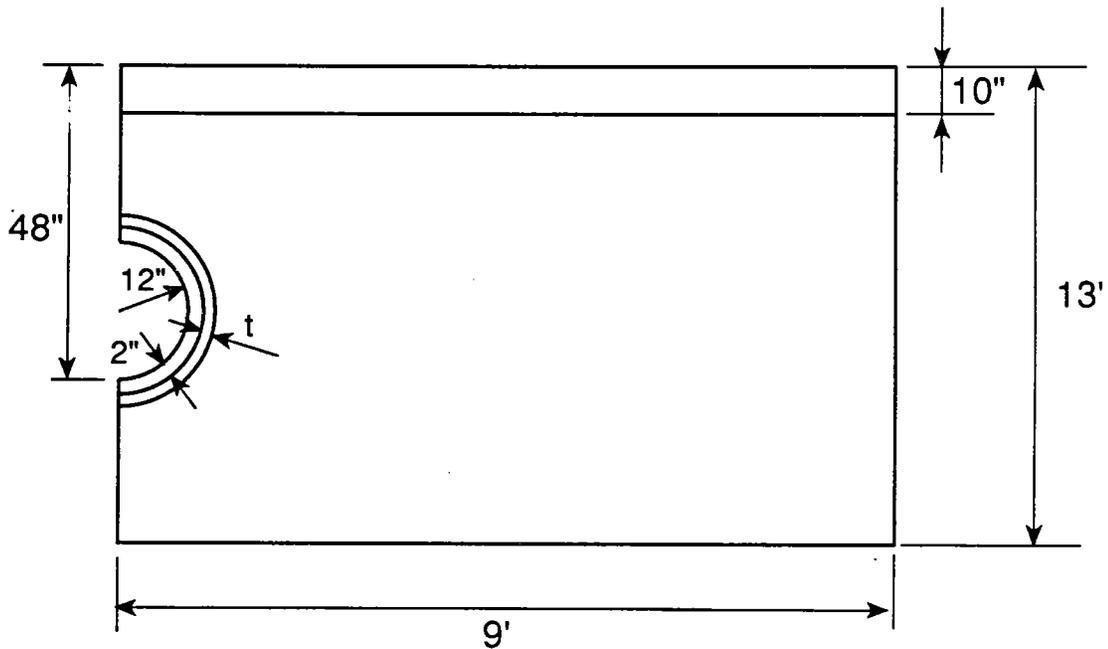


Figure 4. Simulations soil domain geometrical characteristics.

The nominal properties for concrete and the characteristics of a typical frost-susceptible soil, Fairbanks loam, are listed in Table 1 and are used in the simulations<sup>1</sup>.

Material properties	Concrete	Fairbanks Loam	Expanded Polystyrene
Dry density pcf (kg/m <sup>3</sup> )	144 (2,300)	100 (1600)	2.5 (40)
Water content (%)	3	25	0
Unfrozen thermal conductivity BTU-in/sqft-hr-°F (W/m.°C)	11.76 (1.7)	11.76 (1.7)	0.249 (0.036)
Frozen thermal conductivity BTU-in/sqft-hr-°F (W/m.°C)	13.15 (1.9)	14.53 (2.1)	0.249 (0.036)

**Table 1. Material properties for the simulations.**

Additional frost-susceptibility data are drawn from Hovan (1986) and Duquenois (to be published).

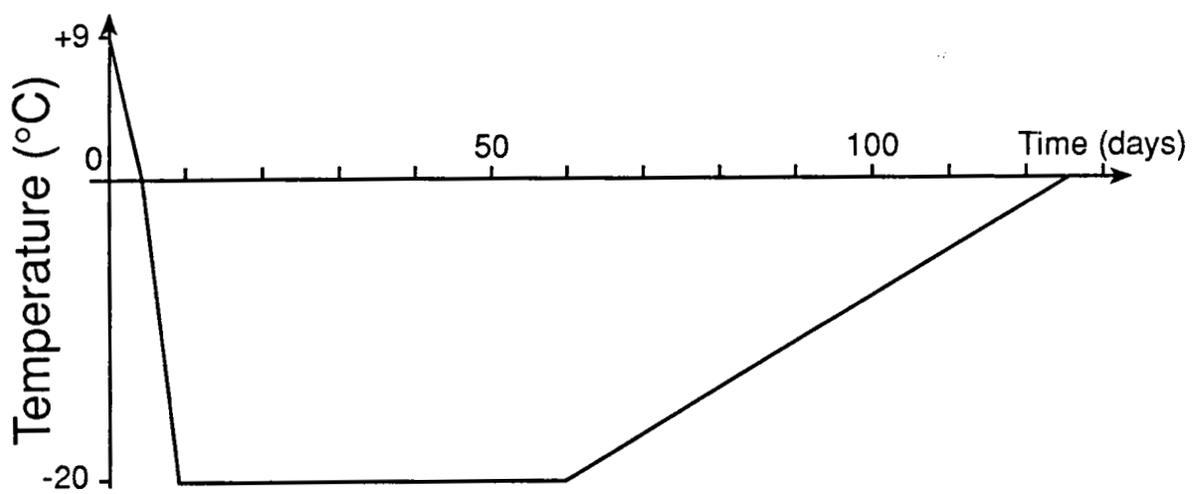
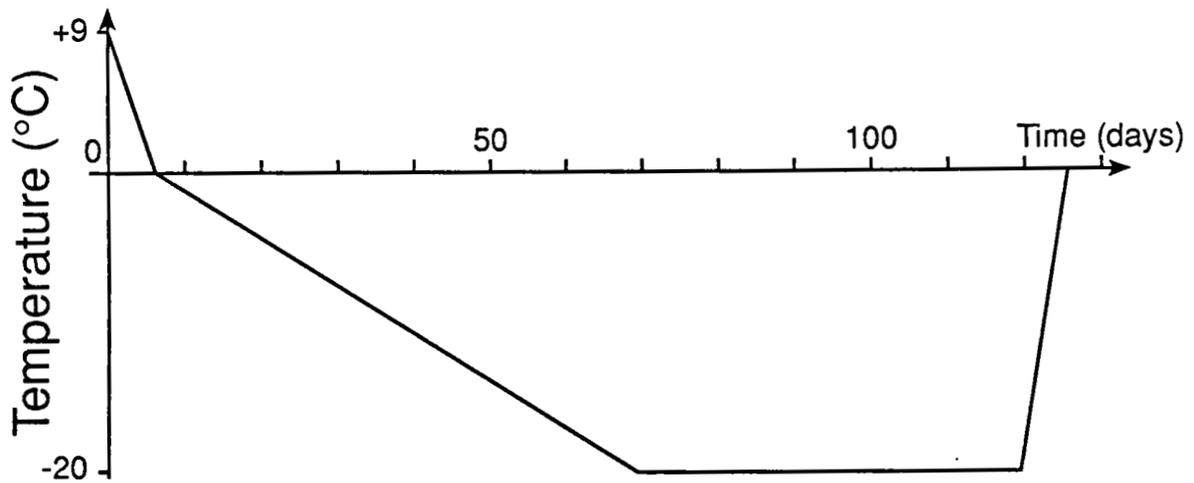
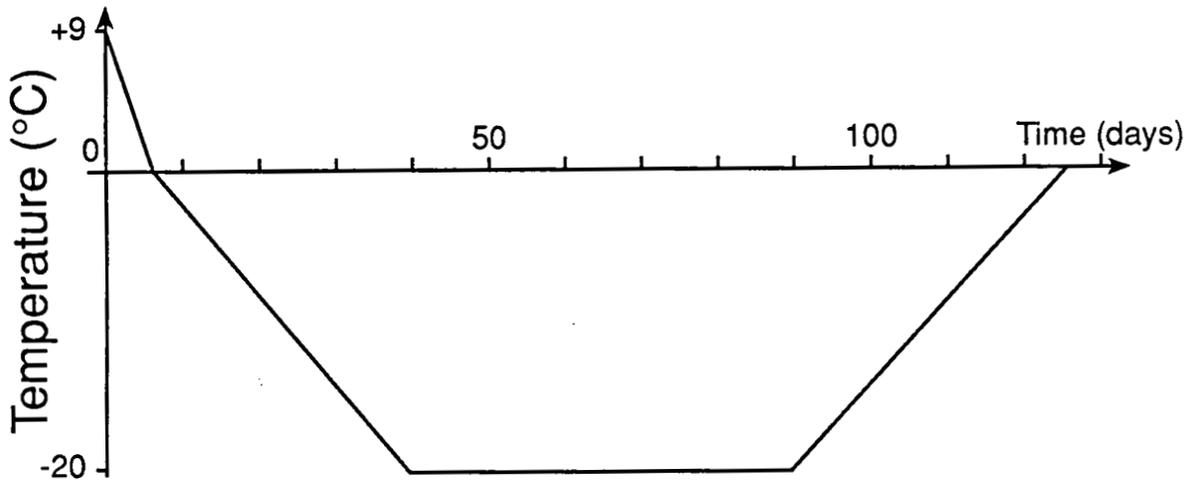
The boundary conditions are the following:

- The bottom boundary is under a fixed water pressure, arbitrarily set to zero. Its displacements are set to zero and its temperature is set to 9°C (48°F), which is a reasonable Minnesota deep ground temperature.

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<sup>1</sup> All material properties as well as the major part of the results presented herein are also given in the metric system because of the input/output format of the simulation code.

- The right side boundary is adiabatic and nonpermeable. Its horizontal displacements are set to zero and its vertical displacements are free.
- The top boundary is nonpermeable, free from any force or fixed displacement, and its temperature varies according to Figures 5 through 7 for one of each freezing patterns.
- The left side boundary except for the inside of the culvert is adiabatic and nonpermeable. Its vertical displacements are free and its horizontal displacements are set to zero.
- The inside of the culvert is nonpermeable and free from any force or fixed displacement. Its temperature follows the same pattern as the top boundary.



The initial temperature of the soil domain is set to 9°C, its initial pressure and displacement field to zero.

Table 2 summarizes the different simulations performed and their characteristics.

Insulation position	Thickness	Width (if horiz.)	Freezing pattern	Simulation name
No insulation	-	-	Average	00_a
	-	-	Early	00_e
	-	-	Late	00_l
Circular	1"	-	Average	c_01_a
	1"	-	Early	c_01_e
	1"	-	Late	c_01_l
	2"	-	Average	c_02_a
	2"	-	Early	c_02_e
	2"	-	Late	c_02_l
	3"	-	Average	c_03_a
	3"	-	Early	c_03_e
	3"	-	Late	c_03_l

**Table 2. Simulation nomenclature and characteristics.**

Each simulation is performed until either the end of the calculation interval (125 days) or the beginning of the thawing period (characterized by the recession of the freezing front). This test is performed in order to avoid thawing simulations which are not, with the present model, as reliable as the freezing ones.

## CHAPTER 4

### RESULTS PRESENTATION AND ANALYSIS

#### 4.1. Thermal differentials.

Safety is the first factor which must be examined in this study. Using thermal insulation to lessen frost propagation in frost-susceptible soils requires the monitoring of temperatures at the pavement surface in order to avoid the thermal differential situation, which may trigger differential ice formation on the pavement. Thus, the temperature is checked at each node of the pavement surface and an output flag is activated each time freezing and non-freezing temperatures appear together on the surface.

Among all the simulations, only the case without insulation under a late freezing pattern (00\_1) produced such a thermal differential at day 8. Table 3 lists the temperature of the pavement surface versus distance from the culvert centerline at that time.

x	8'10 $\frac{1}{4}$ "	7'4 $\frac{1}{2}$ "	3'28 $\frac{1}{2}$ "	4'	35 $\frac{1}{2}$ "	12 $\frac{1}{2}$ "	6 $\frac{3}{4}$	0
(m)	(2.7)	(2.25)	(1.8)	(1.35)	(0.9)	(0.51)	(0.17)	(0)
T								
°C	0.24	0.24	0.24	0.23	0.18	0.07	-0.02	-0.01

Table 3. Temperature T vs. distance x from culvert centerline showing thermal differential at day 8 of simulation 00\_1.

Noting that the results above are given on half the structure, one can notice that the width of the thermal differential area does not exceed 1 meter, which provides safe road conditions for most vehicles. In all the other simulations, no thermal differential involving both freezing and non-freezing temperatures was detected.

However, the temperatures exhibited in this case are all very close to the freezing temperature. Further studies are needed to predict more accurately if this thermal differential is sufficient to cause differential ice formation on the pavement under conditions of alternating freezing and thawing air temperatures.

#### 4.2. Slope variance.

At each time step of a simulation a displacement vector is produced for each node of the finite element mesh. The raw data consisting of displacements for pavement surface nodes are inconvenient to represent and interpret.

A commonly used variable describing the roughness (or loss of serviceability) of a given pavement section profile is the slope variance<sup>2</sup> (AASHTO Road Test 1962). It basically quantifies the amount from which a given pavement profile deviates from a straight profile. Once it is shown through the estimation of the slope variance that the pavement section over the culvert presents an intolerable roughness because of frost heave, it is then reasonable to examine a potential failure of the pavement structure. However, as long as the pavement section exhibits an admissible slope variance, it is thought that the pavement structure is not susceptible to fail from frost heave effects.

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<sup>2</sup>The slope variance  $sv$  of a given pavement section is given by equation (1), p. 14, where  $n$  is the number of sampled slopes which are measured along the pavement section,  $s_i$  is sampled slope # $i$  and  $\bar{s}$  is the average slope for the pavement section.

Experimental field data presented in the AASHTO Road Test (1962) show a relationship between slope variance and pavement serviceability rating. It is clear from these data that a slope variance lower than 20% does not correspond to serviceability ratings less than 2.5 (on a scale from 0 to 5).

It is possible to compute a slope variance for the simulated pavement section using the mesh nodes displacements at each time step. An elemental slope  $s_i$  is computed between two displaced nodes. The pavement section slope variance, noted  $sv$ , is then at a given time step:

$$sv = \frac{1}{n} \frac{\sum_{i=1}^n (\bar{s} - s_i)^2}{\bar{s}^2}, \quad (1)$$

where  $n$  is the number of elemental slopes (number of intervals separating the pavement surface nodes), and  $\bar{s}$  is the average slope for the pavement section.

Figures 8 through 14 show the evolution of the slope variance for each simulation case throughout the representative part of the simulation (i.e., for simple freezing, the calculation stopped at the outbreak of thawing). The results in these figures are plotted versus freezing index, which is thought to be the major climatic influence of frost propagation. Freezing-index-based plots are also designed to avoid the bias of a time-based plot, which would be irrelevant in this study since the freezing index at a given time is different for two distinct weather patterns.

The conclusions drawn from these results can be grouped in two different categories and are presented in Sections 4.3 and 4.4.

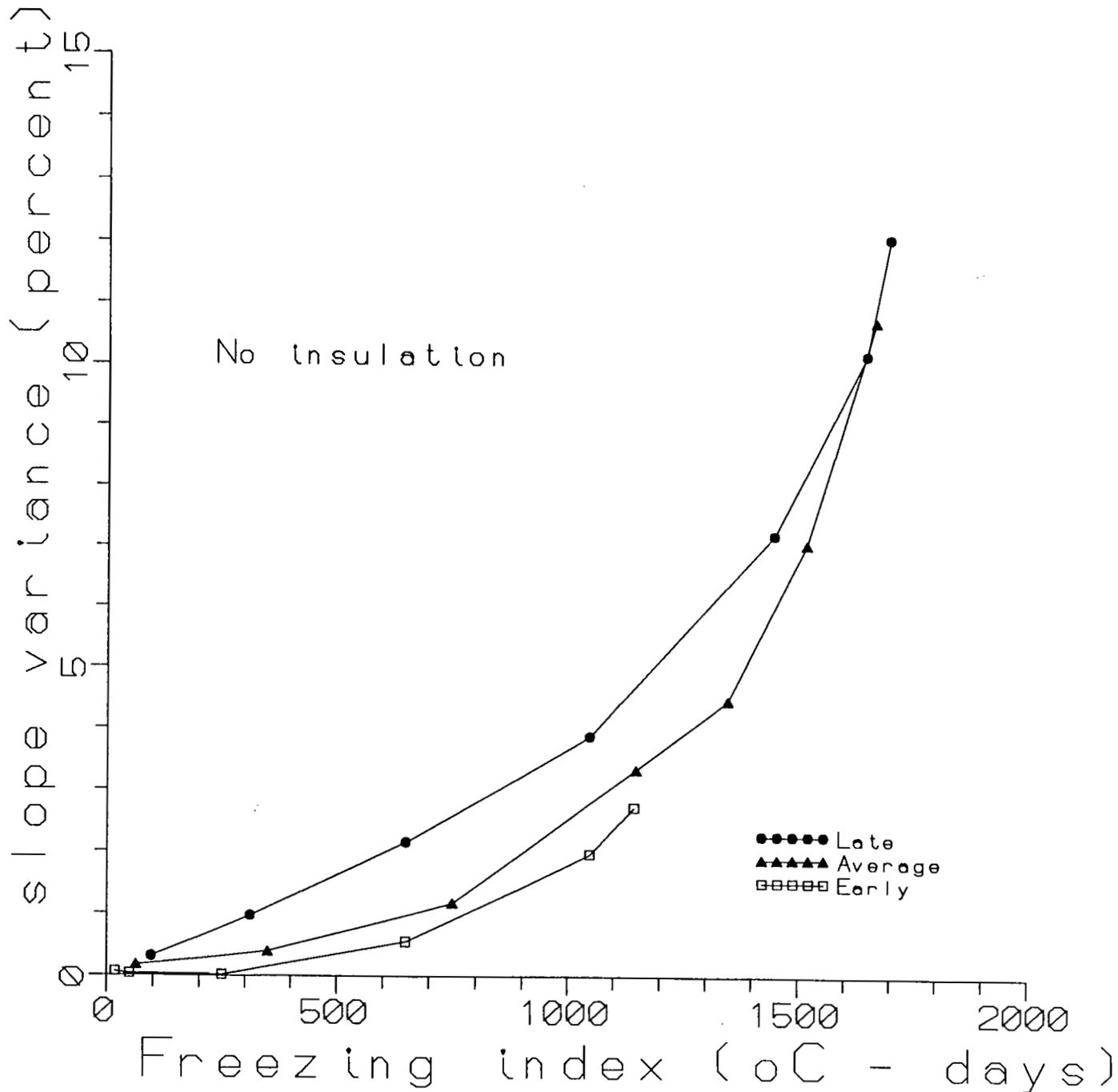


Figure 8. Slope variance vs. freezing index, configuration without insulation

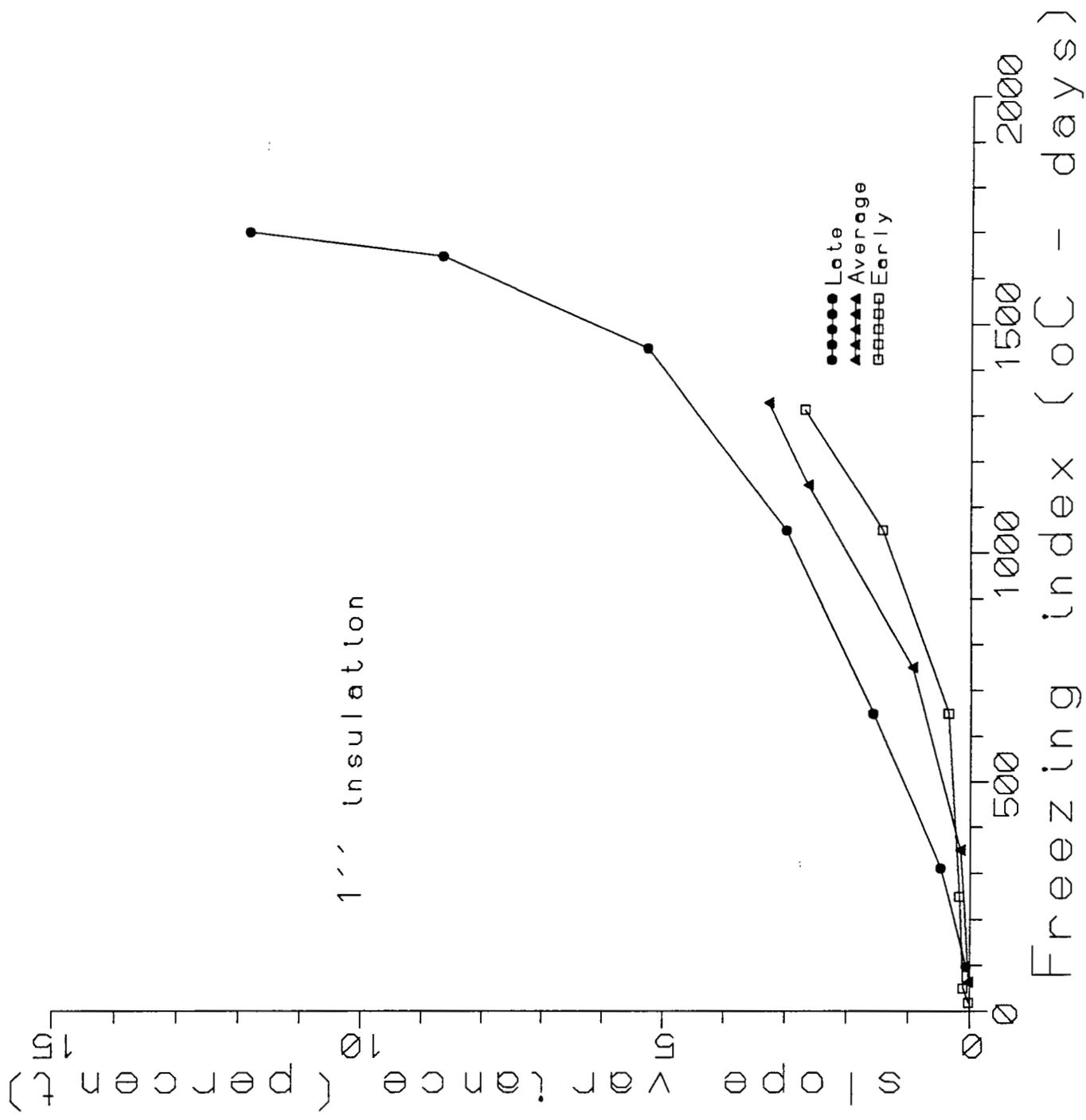


Figure 9. Slope variance vs. freezing index, 1-inch insulation configuration.

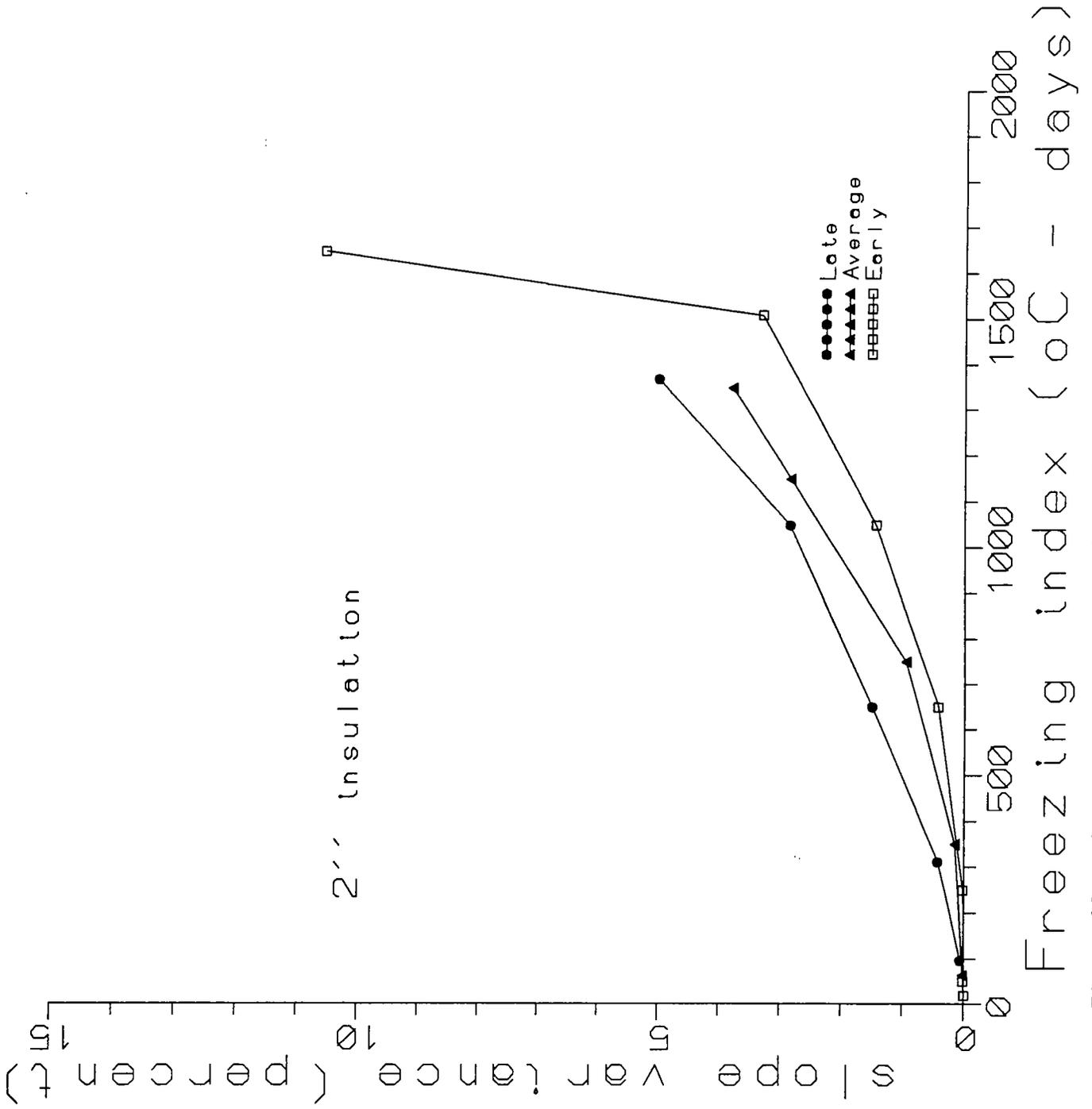


Figure 10. Slope variance vs. freezing index, 2-inch insulation configuration.

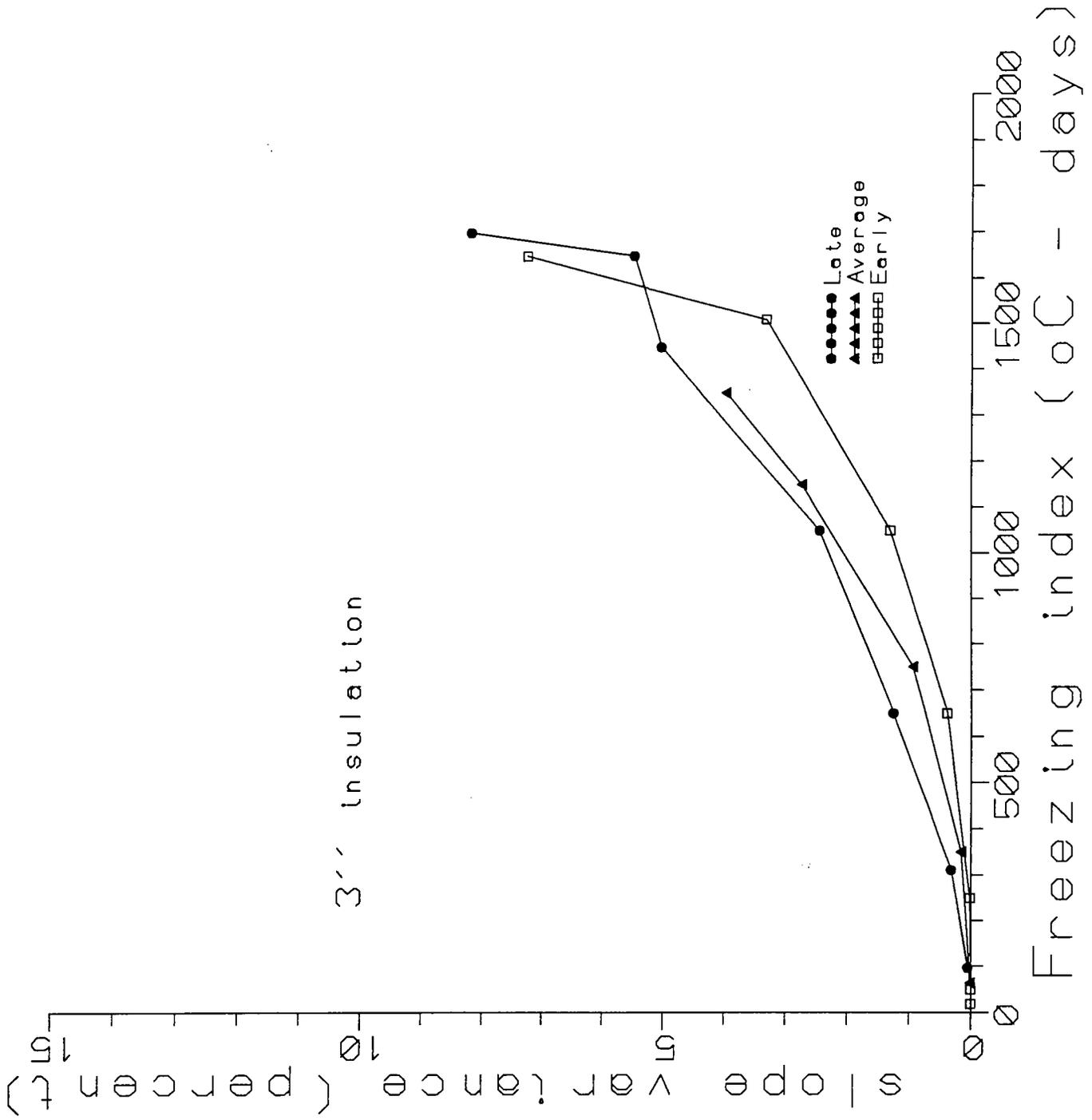


Figure 11. Slope variance vs. freezing index, 3-inch insulation configuration.

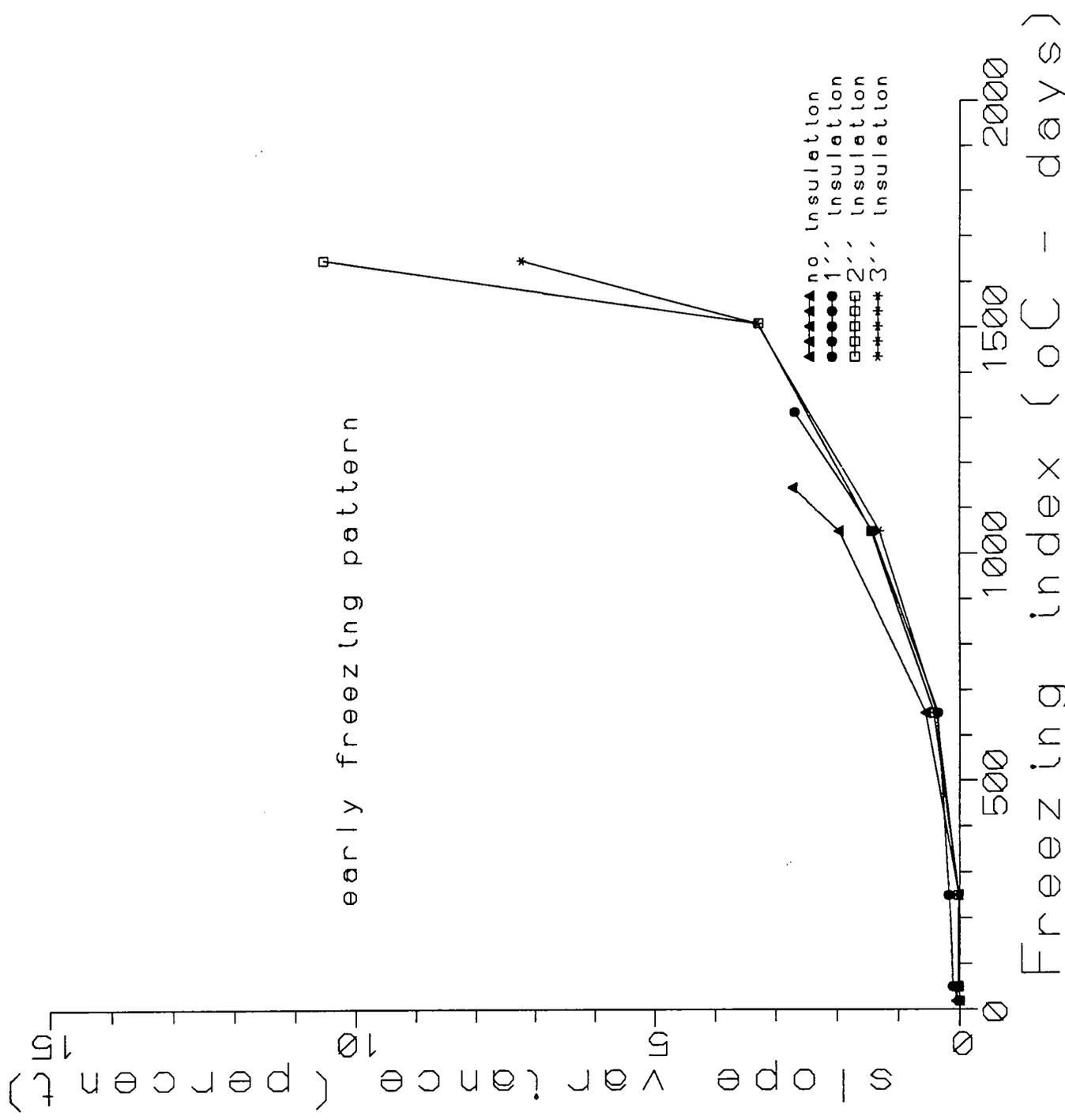


Figure 12. Slope variance vs. freezing index, early freezing pattern.

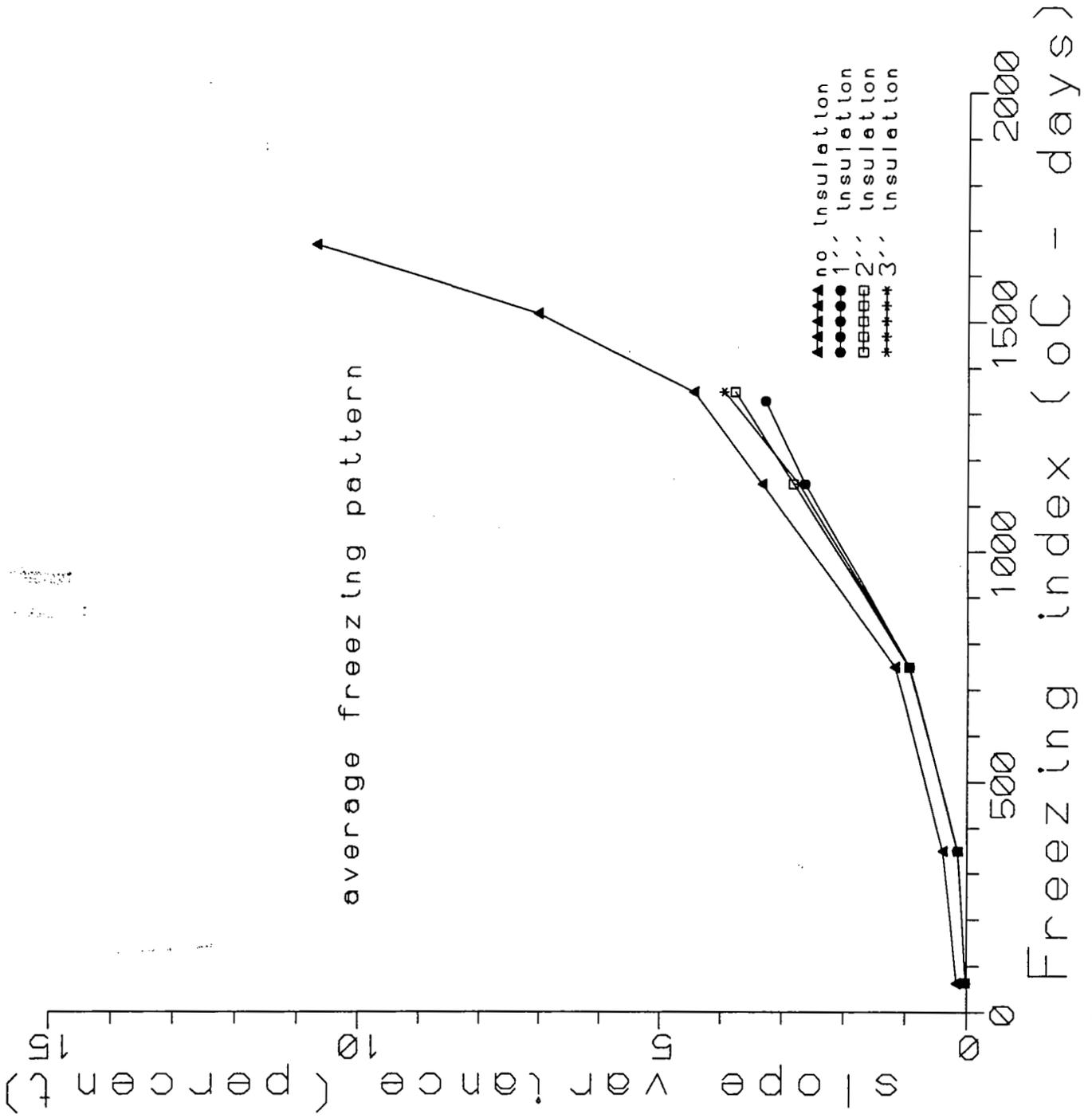


Figure 13. Slope variance vs. freezing index, average freezing pattern.

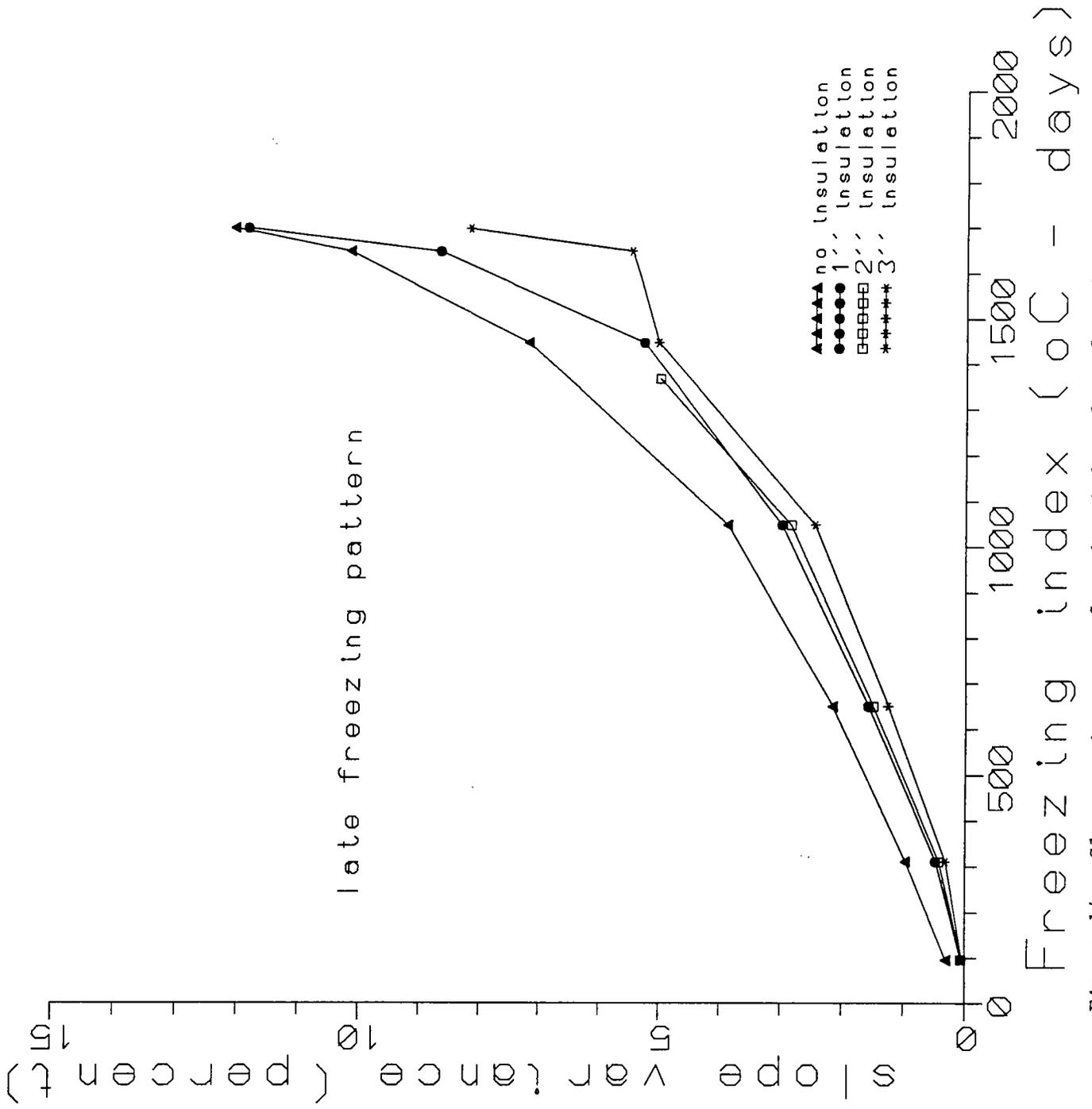


Figure 14. Slope variance vs. freezing index, late freezing pattern.

#### **4.3. Influence of the freezing pattern.**

From Figures 8 through 11, it is apparent that the weather pattern influences the value of the slope variance of a given insulation case at a given freezing index.

All the examples exhibit the greatest slope variance with the late freezing pattern. This pattern has the slowest temperature decrease and therefore the slowest frost propagation, so it is responsible for the largest frost heave pavement deformations. This is because the frost front remains almost still under the pavement structure and around the culvert, and thus produces high levels of ice accumulation in the soil structure.

Following this phenomenon, the average freezing pattern yields smaller slope variances than the late one, and the early freezing pattern, with the highest frost penetration rate during the freezing period, produces the smallest deformations.

#### **4.4. Influence of the insulation level.**

Although the same conclusions can be drawn from the different cases in terms of influence of the freezing pattern, it is apparent from Figures 12 through 14 that the influence of the increase of insulation level (i.e., insulation thickness) is to decrease the slope variance at any freezing index for a given freezing pattern. The only exception may be the average freezing pattern where the advantage of a high-level insulation may not be as important (or even nonexistent) as for the other freezing patterns (early and late). However, for all freezing patterns, the slope variance reducing effect of insulation can be easily noticed when compared with the uninsulated configuration results.

The effect of insulation levels on the date of thawing onset around the culvert is also apparent:

- For an early freezing pattern, insulating the culvert postpones thawing compared with an uninsulated situation.

- For an average freezing pattern, insulating the culvert causes thawing to appear earlier than in an uninsulated situation.

- For a late freezing pattern, insulating the culvert seems to hasten thawing, though not as markedly as for an average freezing pattern, probably because of the sharp temperature drop (see Figure 6), which levels the response of the different insulation options.

- The effect of culvert insulation is to reduce the value of the pavement slope variance throughout the freezing period: the higher the insulation thickness, the lower the resulting slope variance. A high level of insulation seems particularly effective at the end of the freezing period when the slope variance increase is at its maximum and for late and early freezing patterns. For an average freezing pattern, the difference between three different levels of insulation (1 inch, 2 inches, and 3 inches) is less significant during the freezing period, in terms of slope variance.

- The combined effects of culvert insulation level and freezing pattern seem particularly significant on the date of thawing onset around the culvert. The location of the thawing areas at this onset were not investigated here but are thought to be highly dependant on the above-mentioned parameters (insulation level and freezing pattern) and to be markedly influential on the pavement surface deformation during the thawing phase. The simulation code used for this study could not provide data for a structural pavement analysis during thawing.

It is thought that the effect of thawing is to further increase the pavement deformation. Additional studies are needed to clarify this problem.

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