Flexible pavement design for frost protection taking into account subgrade soils variability

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Abstract: The serviceability of flexible pavements in northern environments is an important issue when the effect of frost heave is experienced at the surface of these structures. As frost heave is rarely uniform, the pavement roughness usually increases during winter due to differential frost heave. In this paper, a design methodology for the determination of allowable frost heave based on subgrade soils variability is proposed. The method also allows proposing allowable frost heave criteria based on the presence of buried utilities, which trenches are usually filled with materials non sensitive to frost, in the case of residential and arterial roads in the urban context. The allowable frost heaves are a function of subgrade soils variability, and therefore function of the risk of differential frost heave, and are in good agreement with data found in the literature.

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1. Introduction

The phenomenon of ice lens formation in subgrade soils submitted to frost action is a complex process that affects the performance of flexible pavement structures in northern environments [1]. The cryosuction developed inside the thin layer of soil that contains a significant amount of unfrozen water content, the frozen fringe, contributes to upward water migration that feeds growing ice lens [1, 2]. Because unfrozen water content is associated with capillary and adsorbed water, the susceptibility to ice lens formation is mostly a fine grained soils problem [3]. As a result of ice lens formation in subgrade soils, flexible pavements surface may experience frost heave that can reach 200 mm for the most severe cases.

Flexible pavements design in seasonal freezing environments generally takes into account frost heave by the selection of an adequate total pavement thickness in order to obtain partial frost protection [1, 4]. This implies that the total thickness of the pavement structure is sufficient to delay frost penetration and shortened freezing conditions in the subgrade soils so that surface frost heave remains at acceptable level. However, the flexible pavements affected by seasonal frost rarely show uniform heaving at the surface [5]. This is due to the fact that subgrade soils characteristics, such as gradation, density and water content, vary along the longitudinal axis of a road [6]. Construction operations such as levelling the subgrade surface with fill materials are likely to increase subgrade soils variability. Moreover, in the municipal context where buried utilities are generally filled with non-frost sensitive materials, the behaviour of subgrade soils submitted to frost action may differ significantly. As a result, the riding quality, often quantified by the International Roughness Index (IRI), may significantly deteriorate (increase of IRI) during winter to reach the worst conditions just prior spring thaw [5]. Therefore, based on the subgrade soils variability, this paper presents a comprehensive approach for flexible pavement design in order to take into account the risk of differential frost heave during winter.

2. Design principle, database and model implementation

The effect of soils variability was previously considered in past researches [6, 7, 8]. These approaches are often based on geostatistical functions like the semivariogram, defined as mathematical function allowing to represent and quantify spatial variability of a phenomenon [9]. The semivariogram is expressed as

(1) $$\gamma^{*}(\mathrm{d})=\frac{1}{2\mathrm{N}}\Sigma\left[\mathrm{g}(\mathrm{x})+\mathrm{g}(\mathrm{x}+\mathrm{d})\right]^{2}$$

in which N is the number of pair samples, g(x) is the value measured at a distance x, g(x+d) is the value measured at a distance d of the measurement at x and $\gamma^*(d)$ is the experimental semivariogram as it is presented in Figure 1. The semivariogram can be represented by various models characterized by variables such as the sill, nugget and range. The sill represents the value of the semivariogram obtained when the variation of the studied parameter becomes independent from the distance. It corresponds to the variance of the considered characteristic and; therefore, the square root may be associated with the standard deviation. Previous researches [6, 10] worked with several test sites which subgrade soils were characterized every 4 m. This distance corresponds to half the critical wavelength of 8 m which was identified as problematic regarding users conmfort [1, 11]. Working with the fine particles percentage (< 80 µm) as it is related to subgrade soils sensitivity to frost heave, the index of longitudinal variability V_L was proposed [6] and was associated with differential frost heave. This index is expressed as

(2) $$V_L = \frac{\sqrt{\gamma(4)}}{\bar{x}} \times h = CV_G \times h \simeq \Delta h_{4m}$$

in which h is the average frost heave (measured or calculated), $\bar{x}$ is the mean of the physical parameter considered (percent passing 80 µm), Δh_{4m} is the differential heave at a distance of 4 m and $\sqrt{\gamma(4)}$ is the square root of the semivariogram measured at a distance of 4 m (the standard deviation). Based on these definitions, the ratio of $\sqrt{\gamma(4)}$ to $\bar{x}$ can be associated with the coefficient of variation CV_G. Thus, the multiplication of CV_G with the average frost heave allows obtaining the differential frost heave at a 4 m interval Δh_{4m}.

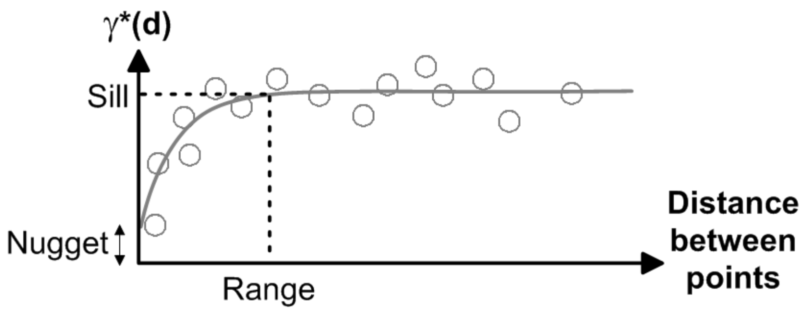

Figure 1. Example of a semivariogram [12]

Throughout this research process, it is proposed to revisit the database gathered from previous research [6, 10]. This database is presented in Table 1, in which data from experimental sites in Quebec and Minnesota are presented. The data available for these sites include the semivariogram at a distance of 4 m $\gamma(4)$, the average fines content x, the average frost heave h, the maximum IRI (IRImax) experienced at the end of the winter period for a given pavement age, the long term IRI (IRI_{LT}) measured at a given pavement age for the summer/autumn period and the seasonal deterioration of IRI (IRIs), corresponding to the difference between IRImax and IRI_{LT}. For the model implementation, IRI_{Max} was used because it is associated with the worst riding comfort conditions. Therefore, the analysis of the database allowed proposing a riding comfort degradation model with pavement age and V_L, presented in Figure 2 and Figure 3, which is expressed as

(3) $$\frac{IRI_{Max}}{AGE^{0.2323}} = 0.0788 V_L + 1.2431$$

with a determination coefficient of 0.49, in the same range than other relationships previously proposed in the literature for related studies [6]. As the IRI may be influenced by numerous factors, such as surface phenomenon like crack heaving and deterioration which contribute to a decrease in riding comfort quality, the proposed relationship is considered satisfactory.

Table 1. Database used for the model implementation

Site	$\gamma(4)$ (mm²)	x (%)	h (mm)	V_L (mm)	IRI_{Max} (mm/m)	IRI_{LT} (mm/m)	$\Delta IRIs$ (mm/m)	Age (yrs)
SMC				26.6	3.38	1.9	1.48	0.5
MnRoad	1.01	11.2	11.8	1.06	1.35	1.15	0.2	2
MnRoad	1.22	4.6	1.2	0.23	1.1	0.76	0.34	2
MnRoad	0.02	4.9	12.6	0.38	1.85	1.24	0.61	2
MnRoad	0.07	9.9	16.1	0.48	1.96	1.54	0.42	2
St-Augustin N	28	13.4	40.6	15.56	4.06	1.49	2.57	2
St-Augustin S	18	20.4	38.9	7.74	6.01	2.19	3.82	20
Ste-Catherine	0.03	0.3	5	2.71	5.22	3.07	2.15	20
St-Prime N	5.8	30.76	80.7	6.31	2.86	1.46	1.4	20
St-Prime S	98	52.13	58.3	11.08	3.04	1.45	1.59	20
Dosquet	2.37	3.78	25	10.18	1.5	1.38	0.12	2.5
Victoriaville	5.5	16.22	37	5.35	3.3	2.9	0.4	15
SMC	12	7.8	60	26.65	5.3	3.02	2.28	6
St-Célestin	10.5	21.55	25	3.76	1.77	1.34	0.43	1.5
St-David	336	34.5	10	5.31	1.2	1.4	0.01	8
West Ditton	43	16.47	55	21.9	3.65	2.65	1	22
Donnaconna	10.7	14.7	6	1.34	1.9	2	0.01	18
Scott-Ste-Marie	2.2	10.45	26	3.69	1.5	1.3	0.2	16
Fleurimont	7	7.7	3	1.03	2.9	1.5	1.4	5
Champlain	0.1	0.52	0	0	1.1	0.8	0.3	9
La Prairie	56.6	100	2	0.15	1.1	1	0.1	0.5
St-Célestin	10.5	21.55	25	3.76	1.69	1.31	0.38	0.5
Plessisville			4		2.2	1.4	0.8	22

$\gamma(4)$=semivariogram at a distance of 4 m; V_L=longitudinal variability; $\Delta IRIs$=seasonal variation of IRI; ΔIRI_{LT}=long-term IRI; IRImax= Maximum seasonal IRI; h= average frost heave; x=average fine particles content

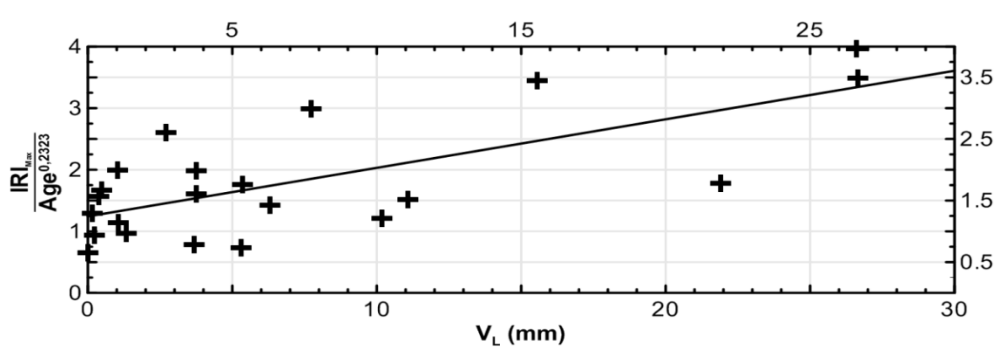

Figure 2. Proposed model between IRImax, V_L and pavement age [12]

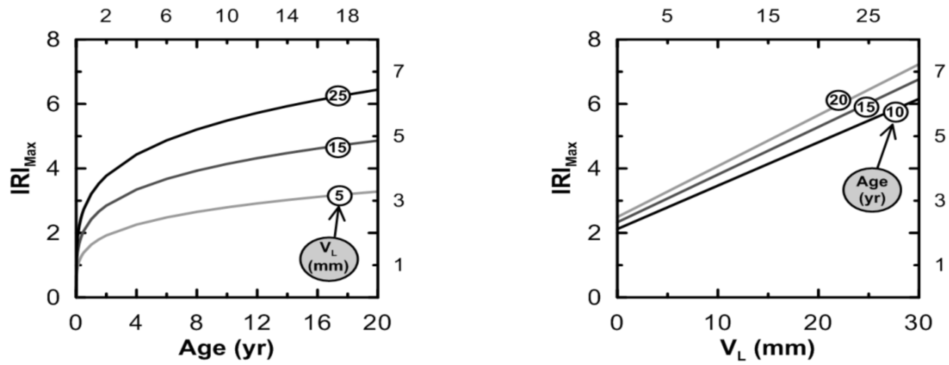

Figure 3. Effect of V_L and pavement age on IRImax [12]

3. Establishment of frost heave design criteria

The research work performed allowed to revisit previously published data and to propose a relationship (Equation 3) that relates IRI to pavement age and V_L. When used in a combined manner, Equation 2 and 3 can be at the basis of the determination of frost heave design criteria for a given pavement category. One of the necessary inputs for the use of Equation is CV_G, which can be determined by obtaining at least 6 to 7 pair of samples collected at a distance of 4 m. Previous work [6, 10] proposed typical values according to the geological context (Table 2). Nevertheless, the particular urban context remains to be characterized in terms of CV_G values as the presence of buried utilities filled with granular materials induces more variability. In order to consider this phenomenon, the experimental sites used in this study were also analyzed with modified fine particles content along the pavement profile. The semivariogram was calculated with a fines content fixed at 8% at distances of 10, 12 and 14 m. An example of the effect on the computed semivariogram is presented in Figure 4 and Table 3 for the Donnaconna test site. This was done for each of the considered test sites, which allowed obtaining the $\gamma(4)$, average fine particles percentage and CV_G for the modified fines content conditions. Table 4 summarizes the results of this analysis for three soil variability classifications (uniform, moderate and high) based on observed fines content. It is noticed that the modification of the fines profile has a significant impact on CV_G. The impact is more pronounced if the soil is considered uniform prior fines profile modification. Moreover, it appears that the consideration of cuts and trenches is the primary influence factors on CV_G, as the obtained values range around 0.5 in all cases. It is postulated that this value can be used for the implementation of a frost heave criteria in the urban context.

Table 2. Suggested CV_G values for the rural and urban context

Variability	Classification	CV_G Rural	CV_G Urban
Uniform (Alluvial terrace, Delta deposit, Marine or lacustrine Flood plain)	SP, SW, GP, GW, CL	<0.1	<0.5
Moderate (Deposition basin border, Alluvial deposit, Fluvio-glacial deposit)	SP-SM, GP-GM, CL-ML	>0.1 and <0.3	<0.5
High (Glacial till, Varved clay, Soil with silt layers, Soil/Rock contact)	GM, GC, SM, SC, ML, CL	>0.3	<0.5

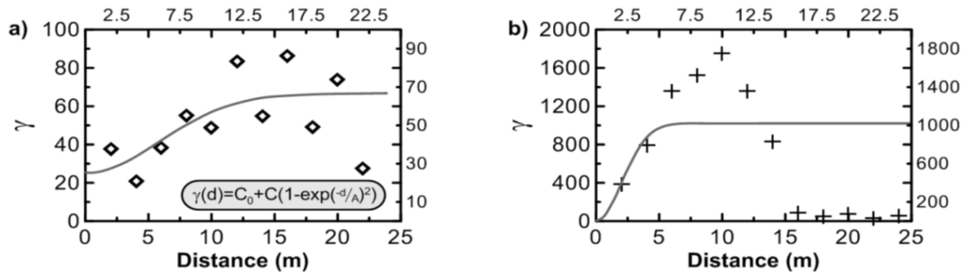

Figure 4. a) Observed and b) modified variogram for the soil fine particles content for the Donnaconna site [12]

Table 3. Observed and modified variogram data for the soil fine particles content for the Donnaconna site [12]

	Soil characteristics longitudinal profile (observed)		Soil characteristics longitudinal profile (modified)*	
Distance (m)	**< 80 µm (%)**	**γ(d) (m²)**	**< 80 µm (%)**	**γ(d) (m²)**
0	71.2	-	71.2	-
2	72.5	37.78	72.5	382.2
4	67	20.77	67	795.75
6	71.3	38.32	71.3	1356.53
8	63.7	55.1	63.7	1523.94
10	76.2	48.7	8*	1753.66
12	64.3	83.68	8*	1358.6
14	79	54.87	8*	832.96
16	83.5	86.41	83.45	86.41
18	76.2	49.2	76.2	49.2
20	85.7	73.95	85.7	73.95

*Value of <80µm fixed at 8% at distance of 10, 12 and 14 m

Table 4. CV_G values for each soil variability classification [12]

	CV_G (as observed)	CV_G (modified)	Increase (%)
Uniform	0.082	0.468	570
Moderate	0.142	0.435	307
High	0.556	0.655	118

Using the concepts presented in this paper, a six step design methodology is proposed. The methodology is based on the rearrangement of Equation 2 and Equation 3, and on the use of the data in Table 2. The methodology allows obtaining the allowable frost heave for the urban, where buried utilities can be found on arterial and residential roads, and rural context. The output of the method is presented in Figure 5. The six steps design methodology goes as follow [12]:

1. Establish the design period (Age) and the maximum roughness (IRI_{Max}) that can be tolerated considering the classification of the road;
2. Determine V_L for the design period (AGE in years) and IRI_{Max} with the use of a rearranged Equation 3 which is expressed

(4) $$V_L\,(mm) = 12.69\left(\frac{IRI_{Max}}{AGE^{0.2323}}\right) - 15.775$$

3. Determine CV_G to be used from Table 4 or by field sampling of the subgrade soil (at least 6 to 7 four meters spaced sample pairs);
4. Determine the allowable frost heave h_{adm} using Figure 5 or with the rearrangement of Equation 2 (V_L in mm) which is expressed

(5) $$h_{adm}\,(mm) = \frac{V_L}{CV_G}$$

5. Calculate the theoretical frost heave h_{est} using an appropriate model, such as the Saaralainen-Konrad approach [4], for a trial pavement structure and typical conditions;
6. If $h_{meas} \leq h_{adm} \rightarrow$ Adequate protection against frost action
   If $h_{meas} > h_{adm} \rightarrow$ Modifiy structure (step 5) or modify design period and/or IRI_{Max} (step 1)

The determined allowable frost h_{adm} is based on the differential characterization of the deformation at the surface of the pavements during freezing period, which is associated with longitudinal variability of properties such as the fine particles content. The method can lead to the computation of very high h_{adm} for low CV_G values. This was expected as the method is based on differential frost heave. Therefore, uniform soils with low CV_G values presents a low risk of showing differential frost heave. If frost heave would be completely uniform, there would be no degradation of the surface profile. This is the main reason why the method can lead to high allowable frost heave. However, it is suggested to use threshold values that are realistic based on agencies experience. Typical results are presented in Table 5 for arterial, residential and local roads. Arterial and residential roads are associated with urban pavements in this example because it is assumed that these pavements have buried utilities, while local roads may be associated with rural or urban pavements. In order to propose the results in Table 5, a design of 20 years is selected, as well as IRI_{Max} of 7, 9 and 7 for the arterial, residential and local roads respectively [13, 14]. For the local roads case, the CV_G values were fixed at 0.09 (uniform), 0.28 (moderate) and 0.4 (high). For residential and arterial roads, the CV_G value was set at 0.5 because of buried utilities. For the uniform conditions, an allowable frost heave of 120 mm is proposed, which was reduced from 317 mm. The threshold value was based on the analysis of the data found in the literature (Table 6). As it can be observed, the obtained allowable frost heaves for the calculation example are in good agreement with the literature data.

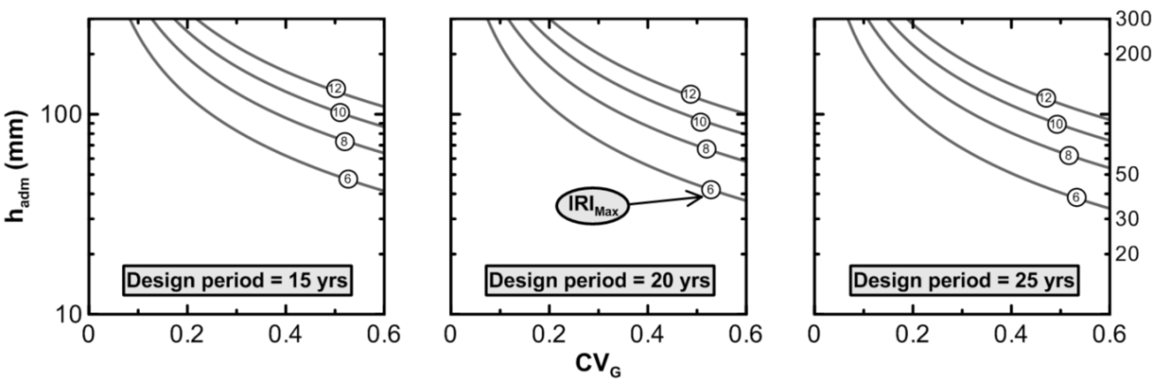

Figure 5. Design charts to determine allowable frost heave [12]

Table 5. Allowable frost heave for typical urban pavement conditions [12]

Soil variability conditions	Allowable frost heave (mm)*		
	Arterial	Residential	Local
Uniform	60	90	120**
Moderate	60	90	100
High	60	90	70

*Rounded values
**Reduced from 317 mm

Table 6. Examples of allowable frost heave for various class of roads in Quebec and Finland [1]

	Quebec	Finland
Freeways	< 50 mm	< 30 mm
Main Highways	< 55 mm	< 50 mm
Regional roads	< 60 mm	
Local roads	70 to 80 mm	< 100 mm

4. Conclusion

The serviceability of flexible pavements in northern environments is an important issue when frost heave is experienced at the surface of these structures. As frost heave is rarely uniform, the pavement roughness usually increases during winter due to differential frost heave. In this paper, a design methodology for the determination of allowable frost heave based on subgrade soils variability is proposed. The method also allows proposing allowable frost heave criteria based on the presence of buried utilities, which trenches are usually filled with materials non sensitive to frost, in the case of residential and arterial roads in the urban context. The allowable frost heave are a function of subgrade soils variability, and therefore function of the risk of differential frost heave, and are in good agreement with data found in the literature.

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