Frost Depth Prediction for Seasonal Freezing Area in Lithuania

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ABSTRACT

The calculation of the frost depth is included in the geotechnical design for the Lithuanian region. The average temperature could be below zero for three months a year and maximum seasonal frost depth reaches more than 1.5 m. The analysis has shown that the frost has been declining for the last 200 years, which has intensified particularly in recent years. The purpose of this study is to review two different methods (LST EN ISO 13793 and RSN 156-94) for determining frost depths. The frost depth calculations performed for dry and saturated sandy soils, which are mainly observed in road construction. Obtained results are compared with frost depth map based on road weather stations data.

Keywords: Frost Depth, Prediction, Lithuania

1 Introduction

Frost depth is very actual for the countries in which territories experiencing negative temperature during winter time. One of the countries, where design rules demand to evaluate seasonal frost depth is Lithuania. The depth of frozen ground in Lithuania was started to be measured in 1923 (Juknevičiūtė et al. 2008). In Lithuania, since 1994 there have been national frost depth evaluation rules according to RSN 156-94, which were update in 2002. Before issue of RSN 156-94 in Lithuania, SNirT 2.01.01-82 was valid. Later, when Lithuania became a European Union member in 2004, soil frost depth can be also evaluated by LST EN ISO 13793. Permafrost (Slade et al. 2020; Tinivella et al. 2019) in territory of Lithuania does not exist and it is not evaluated.

Two different technical documents of freezing depth evaluation (RSN 156-94 and LST EN ISO 13793) give two different results. The difference is also obtained between theoretical frost depth evaluation according to technical documents (RSN 156-94 and LST EN ISO 13793) and data measured at weather stations (Vaitkus et al. 2016). Also, due to climate change (Rimkus et al. 2006) and average annual temperature increase, more freezing thawing cycles (Shirmohammadi et al. 2021; Sadeghi et al. 2018) appear during one winter period. According to weather prognosis in Lithuania, maximum precipitation quantity will also increase up to 15% and largest precipitation increment will be during winter with increment up to 24% (Skuodis et al. 2021). Due to rising annual average temperatures (Galvonaitė et al. 2013), increasing amounts of winter precipitation will be drizzle and sleet (Skuodis et al. 2021).

This research paper is oriented to soils, which are mostly used in road construction. That means, soil frost depth must be evaluated without snow coverage (Roustaei et al. 2022; Iwata et al. 2018). Main Lithuanian roads are divided into different temperature and freezing index areas and calculations of frost depths are provided. Obtained results are compared with existing data collected at road weather stations (Vaitkus et al. 2016). After comparison of theoretical and measured frost depth results, most suitable frost depth theoretical method is suggested, which gives similar results to measured data.

2 Environmental Conditions

Average annual temperature in Lithuania in 1981-2010 was 6.9 °C and average decadal air temperature since 1961–1970 increased from 5.8 °C up to 7.3°C in 2001–2010 (Galvonaitė et al. 2013). Officially

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measured absolute minimum air temperature in Lithuania is -42.9 °C, but in most parts of Lithuania, negative maximum air temperature is observed 50–60 days per year, the lowest number of such days is on the coast (30 days per year), and highest number is in the north-eastern part (70 days) (Galvonaitė et al. 2013). Kabailienė (2006) prepared Lithuania average annual temperature map (Fig. 1) for period in 1961-1990. Lithuanian Hydrometeorological Service (2021) prepared Lithuania average annual temperature map (Fig. 1) for period in 1991-2020.

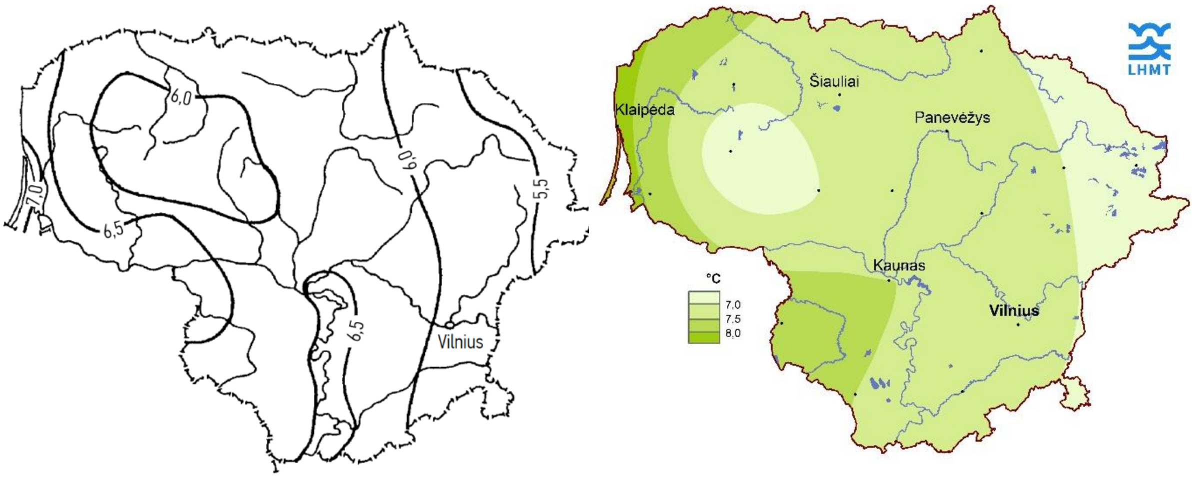

Figure 1. Lithuania average annual air temperature °C in different periods: on the left – 1961-1990 (Kabailienė, 2006), on the right – 1991-2020 (Lithuanian Hydrometeorological Service, 2021)

Sližytė et al. (2012) prepared freezing index (FI) map for Lithuanian area (Fig. 2). This map of FI is based on average decadal air temperature since 1961–1970 (average temperature 5.8 °C). Later, Vaitkus et al. (2016) prepared FI map for Lithuania territory (Fig. 2), which is less accurate (only three areas are included), but based on 2012–2014 average annual temperature.

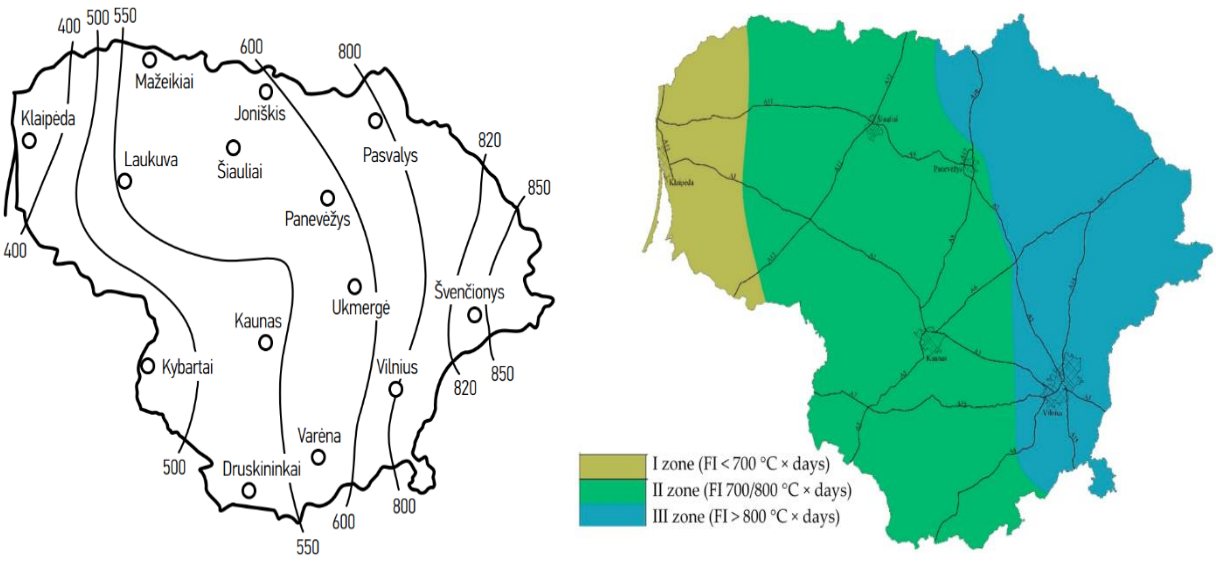

Figure 2. Lithuania territory division to FI: on the left – according to average annual air temperature in 1961–1970 (Sližytė et al. 2012), on the right – according to average annual air temperature in 2012–2014 (Vaitkus et al. 2016)

Vaitkus et al. (2016) performed statistical analysis of 2012–2014 data pertaining to 26 road weather stations and prepared Lithuania frost depth map (Fig. 3). The real-time data from road weather stations are automatically registered every 30 min in a warm period and every 12 min in a cold period

(Žilinksienė et al. 2015). Frost depth analysis showed that maximum frost depths vary from 110.4 cm to 179.1 cm.

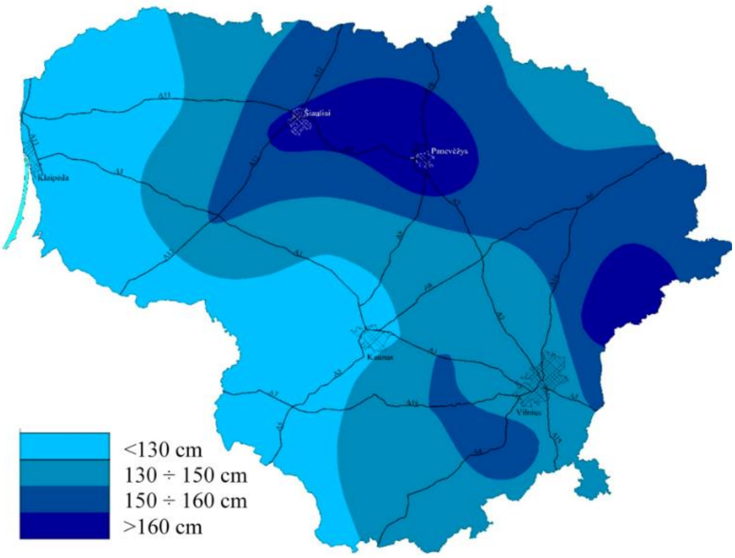

Figure 3. Lithuania frost depth map based on road weather stations data (Vaitkus et al. 2016)

3 Frost Depth Evaluation

As it was mentioned in the introduction part, frost depth evaluation in the Area of Lithuania can be evaluated according to RSN 156-94 and LST EN ISO 13793. First of all, in this manuscript it is presented LST EN ISO 13793 frost depth evaluation methodology. LST EN ISO 13793 provides formula for calculating the frost depth H_0:

$$H_0 = \sqrt{\frac{7200 \cdot F_d \cdot \lambda_f}{L + C \cdot \theta_e}} \quad \textbf{(1)}$$

where freezing index F_d

$$F_d = 24 \sum (\theta_f - \theta_{d,j}) \quad \textbf{(2)}$$

where:

Symbol	Description	Units of measurement
F_d	Design freezing index	K·h
λ_f	Thermal conductivity of frozen soil	W/(m·K)
L	Latent heat of freezing of water in the soil per volume of soil	J/m^3
C	Heat capacity of unfrozen soil per volume	J/(m^3·K)
θ_e	Annual average external air temperature	°C
θ_f	Equal to 0°C	°C
$\theta_{d,j}$	Daily mean external air temperature for day *j*	°C

It is generally accepted to use daily mean external air temperature data ($\theta_{d,j}$) under Lithuania average annual temperature map (Fig. 1) for period in 1961-1990. Data have been updated in the face of climate change. Lithuanian Hydrometeorological Service (2021) prepared Lithuania average annual temperature map (Fig. 1) for period in 1991-2020.

It is worth to note that LST EN ISO 13793 standard does not provide thermal properties for different soil types. The recommended characteristics λ_f, L and C are given in the general case based on

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homogeneous frost-susceptible soil (Table 1). For different soils, actual thermal property λ_f can be found in VDI 4640-4 (Table 2).

Table 1: Thermal properties of frost-susceptible soil (LST EN ISO 13793)

Description	Thermal properties
Thermal conductivity (unfrozen)	λ = 1.5 W/(m·K)
Thermal conductivity (frozen)	λ_f = 2.5 W/(m·K)
Heat capacity per volume (unfrozen) Heat capacity per volume (frozen)	$C = 3 \cdot 10^6$ J/(m^3·K) $C_f = 1.9 \cdot 10^6$ J/(m^3·K)
Latent heat of freezing per cubic meter of soil dry density	$L = 150 \cdot 10^6$ J/m^3

Table 2: Thermal properties for different soils (VDI 4640-4)

Ground type	Thermal conductivity λ_f, in W/(m·K)	Typical calculated value
Sand, dry	0.3 to 0.8	0.4
Sand, water-saturated	1.7 to 5.0	2.4
Gravel, dry	0.4 to 0.5	0.4
Gravel, water saturated	Approx. 1.8	1.8
Clay or silt, dry	0.4 to 1.0	0.5
Clay or silt, water-saturated	0.9 to 2.9	1.7
Peat	0.2 to 0.7	0.4

Calculation of the frost depth d_f can be realized according to RSN 156-94:

$$d_f = d_0 \cdot \sqrt{M_t} \qquad \textbf{(3)}$$

where d_0 = frost depth when M_t=0, M_t = sum of non-dimensional coefficient of negative monthly temperatures, absolute value.

The frost depth d_0 depends on the soil type and is equal to:

Clay and sandy loam – 23 cm;

Clayey or silty sand, silt and fine sand – 28 cm;

Medium coarse sand, coarse sand and gravelly sand – 30 cm.

Frost depth d_0 calculations lead to the problem related to classification of soil based on non-valid normative documents. According to the actual normative documents (LST EN ISO 14688-1), clay and sandy loam classified as sandy clay (saCl) and clayey or silty sand, silt and fine sand classified as sandy clay (saCl), clayey sand (clSa) or silty sand (siSa). Also, there is a difference between geotechnical and road soil classification (Table 3).

Table 3: Compliance with soil labeling (LST 1331:2015)

LST 1331:2015	LST EN ISO 14688-1
ŽB, ŽG, ŽP, ŽD, ŽM	Gr
SB, SG, SP, SD, SM	Sa
ŽD0	siGr
ŽM0	clGr
SD0	siSa
SM0	clSa
DL, DV, DR	Si
ML, MV, MR	Cl
OD, OM, OH	orSi, orCl, orSa
HU, HN	Or

In order to find the M_t (3), it is necessary to evaluate monthly air temperatures. For this investigation it was chosen to analyze four main cities in Lithuania territory, namely: Klaipėda, Kaunas, Vilnius and Utena (Table 4).

Table 4: Average monthly air temperature in °C (RSN 156-94)

Air measuring station	Months											
	1	2	3	4	5	6	7	8	9	10	11	12
Klaipėda	-2.8	-2.6	0.3	5.0	10.6	14.3	16.6	16.8	13.3	9.0	3.9	-0.1
Kaunas	-5.2	-4.3	-0.4	5.8	12.4	15.8	16.9	16.4	11.9	7.1	1.8	-2.3
Vilnius	-6.1	-4.8	-0.6	5.7	12.5	15.8	16.9	16.3	11.6	6.6	1.2	-2.9
Utena	-6.0	-5.2	-1.2	5.5	12.2	15.6	16.8	15.9	11.4	6.6	1.4	-3.2

The design value of frost depth d_{fd} can be found:

$$d_{fd} = k_h \cdot d_f \quad \textbf{(4)}$$

where k_h = temperature coefficient (the frost depth was calculated for a road structure that is not affected by constant heat (as it could be for buildings case), therefore $k_h = 1$).

The results of frost depths calculated by five different methods (Figure 4). First calculation is realized according to LST EN ISO 13793 using 1961-1990 temperature data. Second calculation is provided by LST EN ISO 13793 using 1991-2020 temperature data. Third and fourth calculations are based on LST EN ISO 13793 methodology, but it used VDI 4640-4 actual thermal properties for different soils (dry and saturated cases). The last calculation of frost depth is accomplished with RSN 156-94 methodology. For all cases it was assumed, that frost depth is evaluated for sandy soil type.

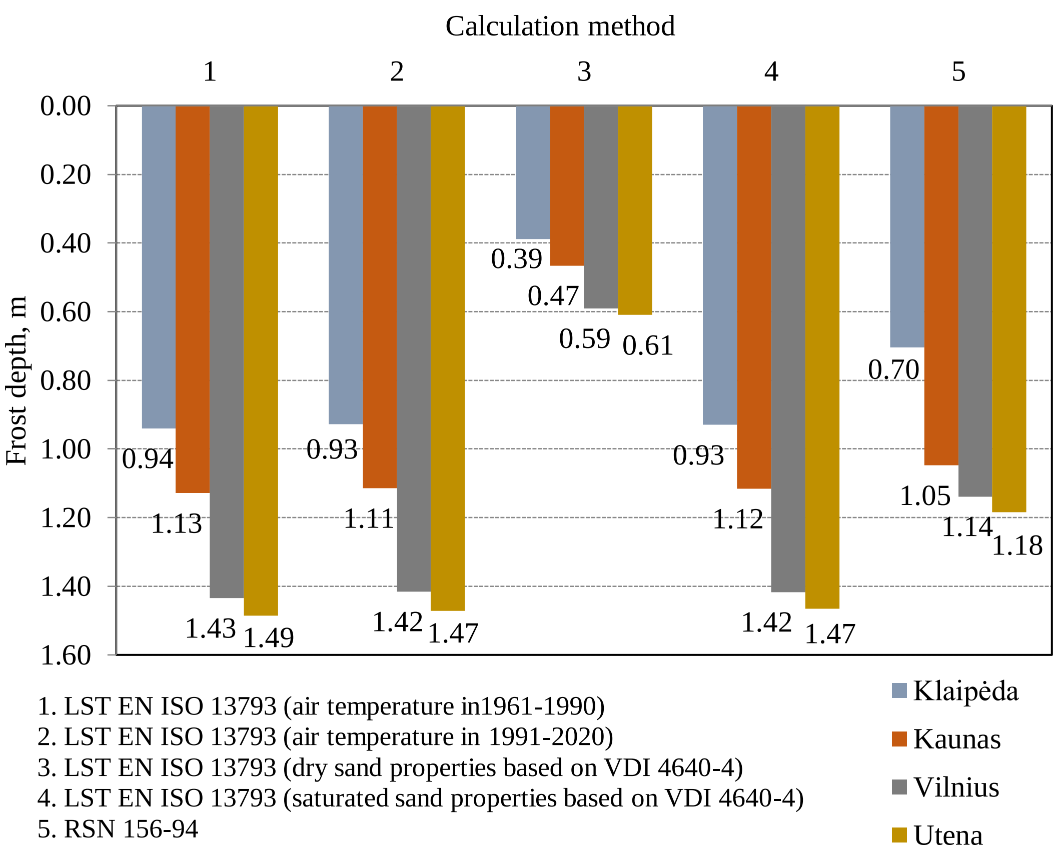

Figure 4: Summary of frost depth evaluation in different cities

The results of frost depths evaluation by different methods (Figure 4) showed that Lithuania's average annual temperature increased approx. 1.5 °C, but frost depth decreased about 1-2 cm (Figure 4, calculation methods 1 and 2). The smallest frost depth is obtained for dry sand (Figure 4, calculation method 3). Evaluating actual thermal properties given in VDI 4640-4 and using those properties in LST EN ISO 13793 methodology for frost evaluation (Figure 4. Calculation method 4), very similar results are obtained for Figure 4 (calculation methods 1 and 2). Frost depth evaluation by RSN 156-94 (Figure 4, calculation method 5) gives smaller frost depth results comparing with LST EN ISO 13793 (Figure 4, calculation methods 1 and 2). Comparison of Lithuania frost depth map based on road weather stations data (Figure 3) and calculated frost depths (Figure 4) are presented in Table 5.

Table 5: Summary of frost depth evaluation in different cities

Area\Method	Road weather stations data (Vaitkus et al. 2016)	LST EN ISO 13793 (air temperature in 1961-1990)	LST EN ISO 13793 (air temperature in 1991-2020)	LST EN ISO 13793 (dry sand properties based on VDI 4640-4)	LST EN ISO 13793 (saturated sand properties based on VDI 4640-4)	RSN 156-94
Klaipėda	<1.30 cm	0.94 cm	0.93 cm	0.39 cm	0.93 cm	0.70 cm
Kaunas	<1.30 cm	1.13 cm	1.11 cm	0.47 cm	1.12 cm	1.05 cm
Vilnius	1.30-1.50 cm	1.43 cm	1.42 cm	0.59 cm	1.42 cm	1.14 cm
Utena	1.50-1.60 cm	1.49 cm	1.47 cm	0.61 cm	1.47 cm	1.18 cm

The most similar frost depth evaluation results are obtained by using LST EN ISO 13793 method using actual saturated soil thermal properties according to VDI 4640-4. Evaluation of dry sand thermal properties is not recommended, because calculated frost depths are almost three times smaller than those measured at the road weather stations. Frost depth results obtained by RSN 156-94 method are lower than those obtained by LST EN ISO 13793. For road construction frost depth evaluation, it is not recommended to use RSN 156-94 method, because calculated frost depth values are too small.

4 Conclusions

Frost depth evaluation methodology is very important for final results. Realized different calculations of frost depth showed main differences between LST EN ISO 13793 and RSN 156-94. Frost depth calculations according to LST EN ISO 13793 showed that for sandy soil it is obtained almost the same results in both evaluated cases: 1) calculating by LST EN ISO 13793 suggested soil thermal properties; 2) calculating by LST EN ISO 13793 and using actual saturated soil thermal properties, which can be found in VDI 4640-4. It is not recommended to use dry soil thermal properties given in VDI 4640-4, because predicted frost depth decreases approx. 3 times. Frost depth results obtained by RSN 156-94 method are lower than those obtained by LST EN ISO 13793. For evaluation of road construction frost depth, it is recommended to use LST EN ISO 13793 based on air temperature in 1961-1990 and applying actual saturated soil properties, which are given in VDI 4640-4. Such evaluation gives the most similar frost depth results to those measured at road weather stations.

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