NTNU – Trondheim
Norwegian University of
Science and Technology

PhD Outlines

Benoit Loranger

Frost susceptibility of crushed rock aggregates and field assessment of frost heave and frost depth

Supervisor: Pr. Inge Hoff
Co-supervisors: Pr. Guy Doré and PhD Elena Scibilia

NADim seminar

December 2nd, 2021

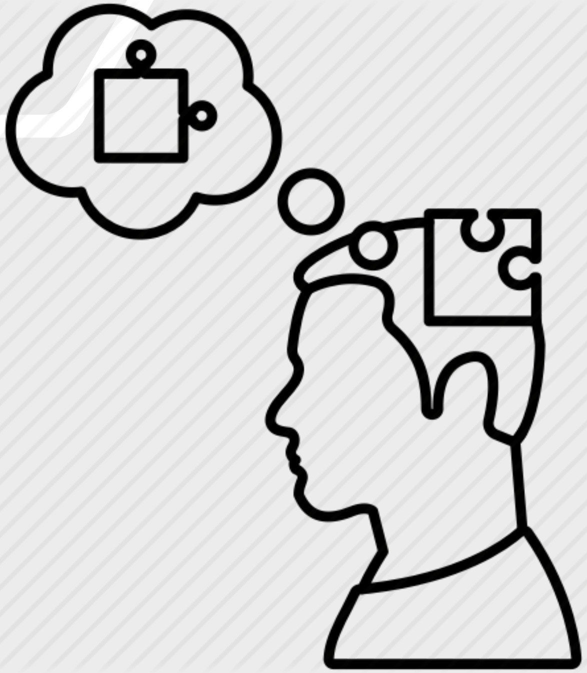
Background

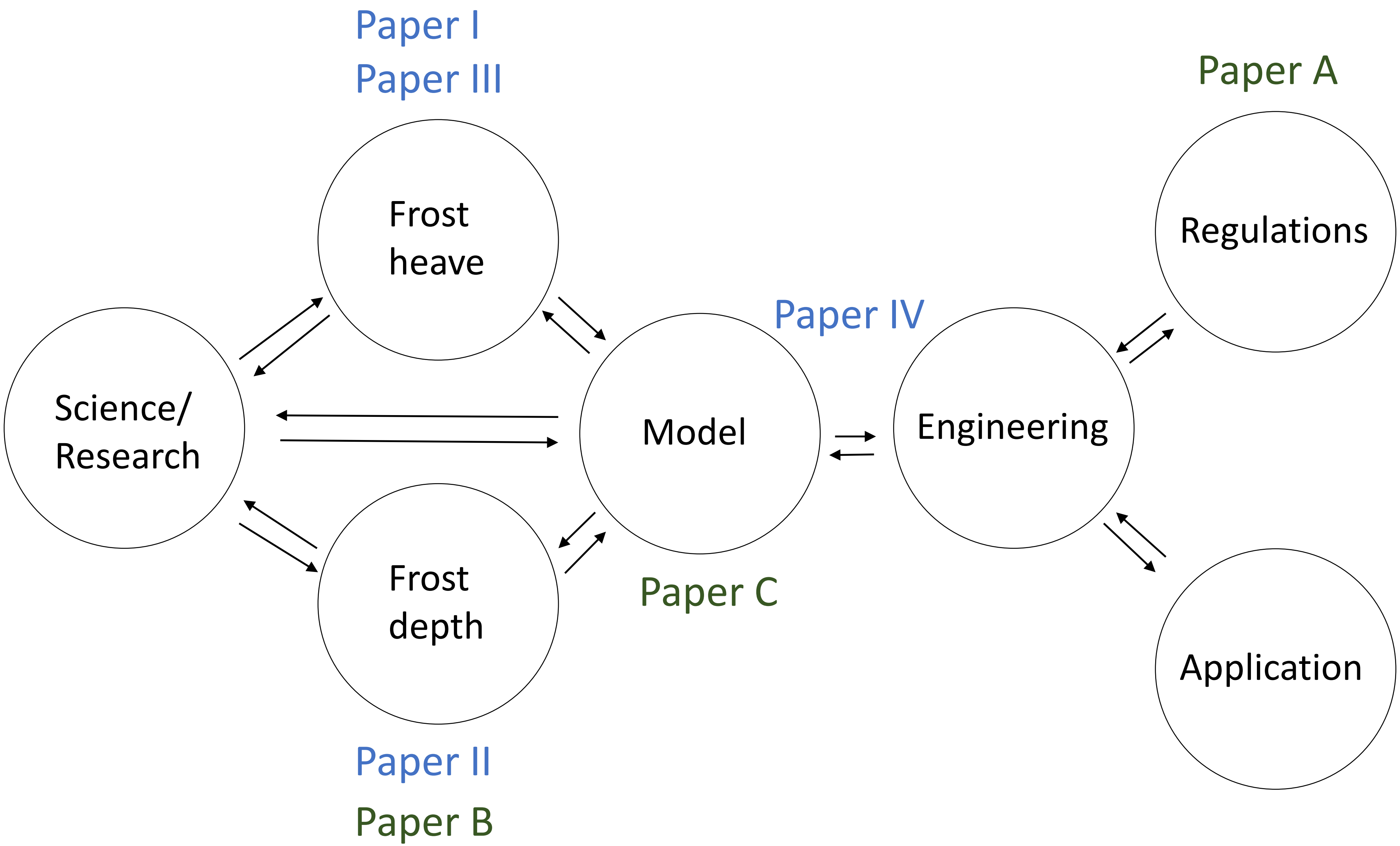
- Winters 2009/10 and 2010/11
  - Revision N200 in 2014
    - Question related crushed rock aggregates behaviour

Background

- FROST project
  - Initiated in 2015
  - 2 Ph.D.'s:
    - Karlis Rieksts (thermal considerations of CRA)
    - Myself (Frost susceptibility)
  - 4 Ph.D.'s on crushed rock aggregates
    - Marit Fladvad (Optimization use in road construction)
    - Diego Maria Barbieri (Use of local materials)

- What is the frost susceptibility of crushed rocks?
- How the frost heave affect main and secondary roads?
- What is the effect of having different frost protection layer composition?
- Is a model adapted to predict frost depth and frost heave in thick road structures




Paper I
Paper III
Frost
heave
Paper A
Regulations
Paper IV
Science/
Research
Model
Engineering
Frost
depth
Paper C
Application
Paper II
Paper B

Part I: Laboratory investigation

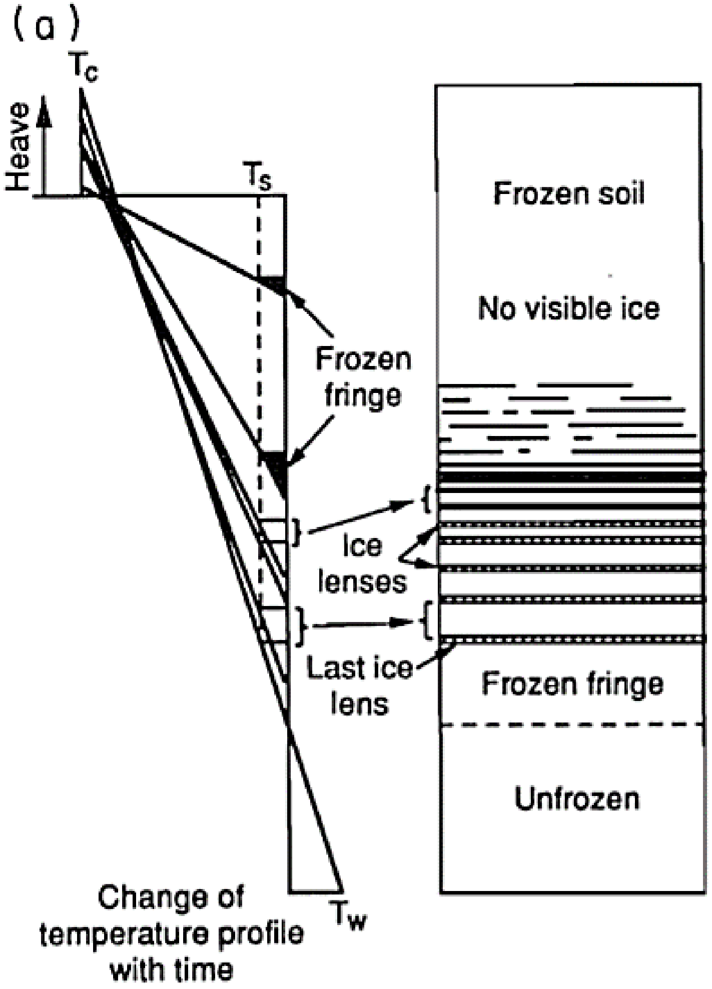
- Paper I: Frost heave laboratory investigation on crushed rock aggregates.

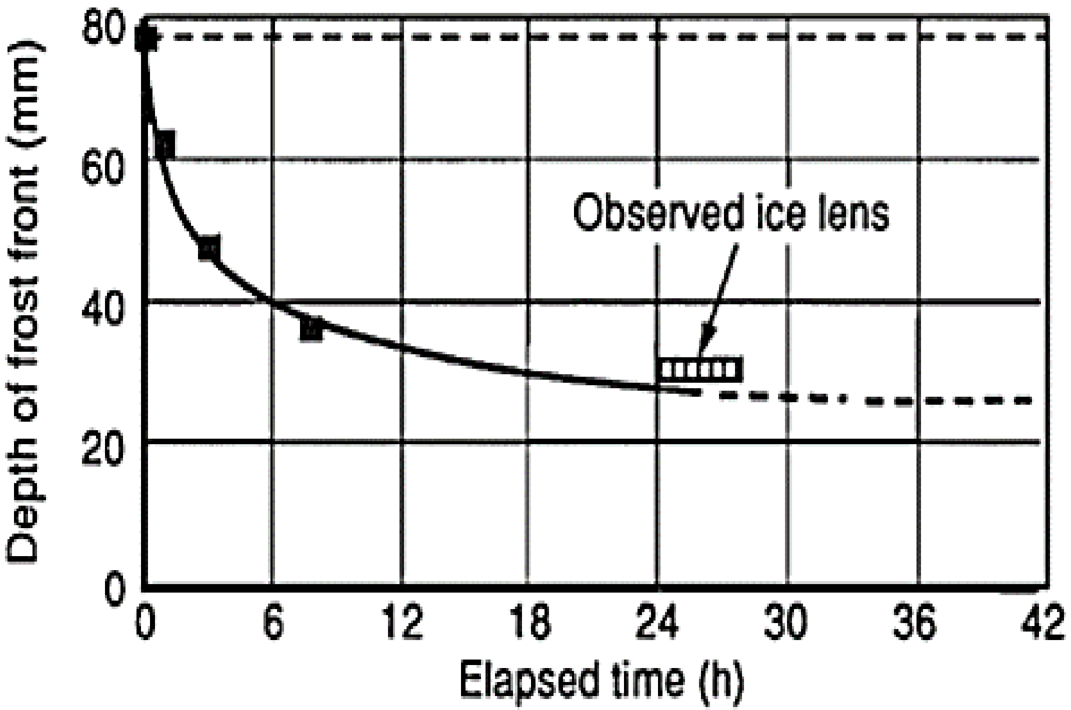
  Québec 2019: 18th International Conference on Cold Regions Engineering and the 8th Canadian Permafrost Conference. Quebec City, Canada. (August 18th to 22nd 2019).

- Paper III: Assessing soil index parameters to determine the frost susceptibility of crushed rock aggregates.

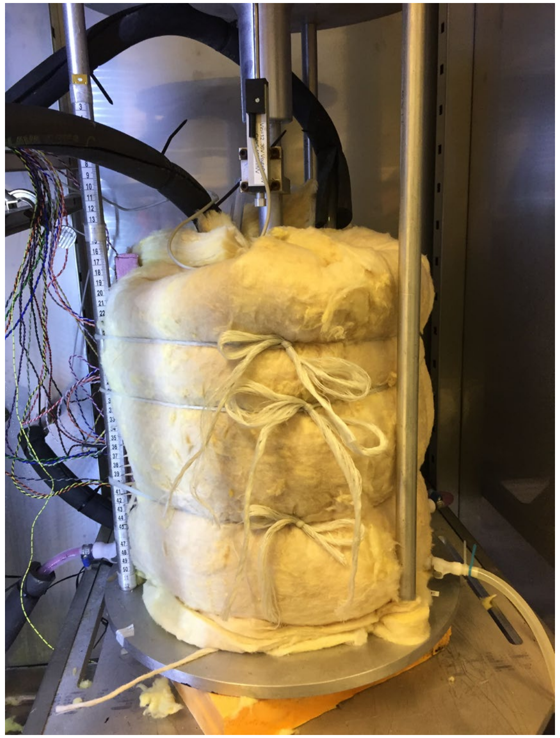
  Re-submitted with minor correction to Cold Regions of Science and Technology Journal (November 10, 2021).

Frost heave

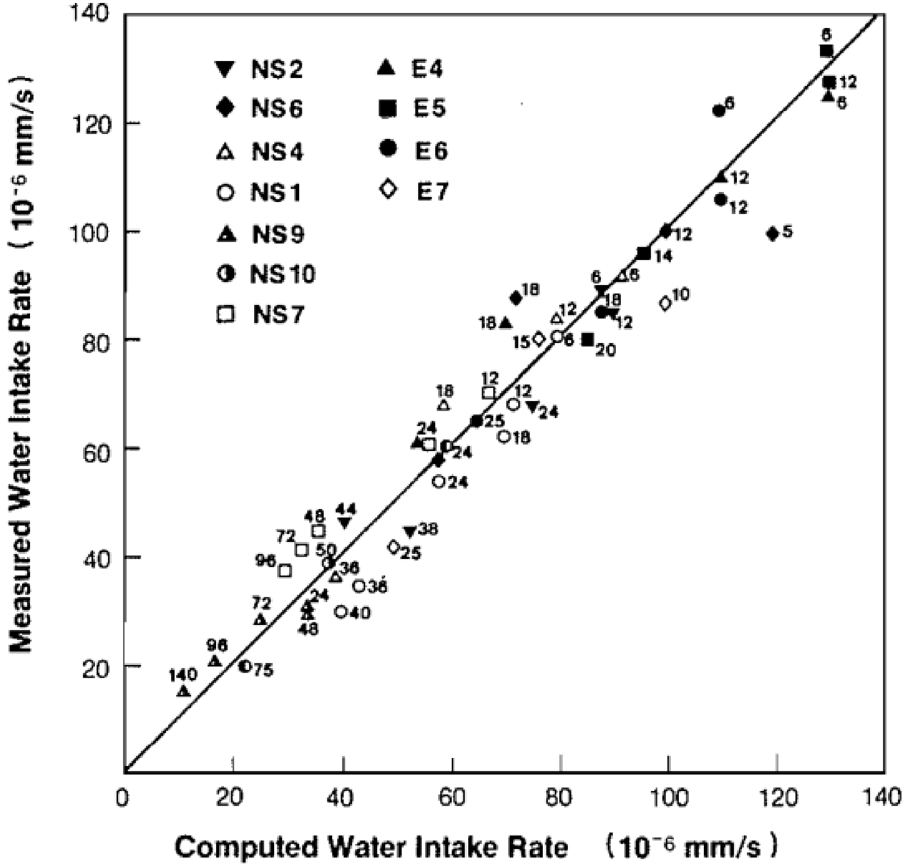

(a)
Tc
Heave
Ts
Frozen fringe
Ice lenses
Last ice lens
Tw
Change of temperature profile with time
Frozen soil
No visible ice
Frozen fringe
Unfrozen


Depth of frost front (mm)
80
60
40
20
0
Observed ice lens
0
6
12
18
24
30
36
42
Elapsed time (h)

Test procedure



Segregation potential



$$v_u = \frac{P_w - P_u}{d}\overline{K}_f = \left(\frac{P_w - P_u}{T_s}\overline{K}_f\right)\text{Grad } T = \text{SP Grad } T$$

$$\boldsymbol{dh = dh_p + dh_s}$$

Where : $dh_{sp} = 1{,}09 \cdot Sr \cdot n \cdot dt$

$$dh_s = 1{,}09 \cdot SP \cdot \nabla T_f \cdot dt$$

Granite/ gneiss are within the range found in literature (Konrad 2005; Nurmikolu 2005)

Adding reference values for granodiorite, porphyr, anortosite, slate and gabbro

Quarry	rock type	< 63 µm %	< 20 µm %	< 2 µm %	SP $mm^2/°C·d$
Aplitt	Granodiorite	12.5	7.4	1.23	149
Hadeland	Porphyr	16.1	9.7	2.30	176
Hellvik	Anortosite	22.4	13.2	2.45	197
Legruvbakken	Slate	25.6	11.5	0.56	60
Vassfjell	Gabbro	24.9	14.8	2.05	111
Lørenskog	Gneiss	16.2	7.1	0.53	105
C.S. Lør.+ Velde	Gneiss/Granite	20.0	9.1	1.41	130
Velde	Gneiss/Granite	30.7	15.2	2.83	197

Frost susceptibility	Class	Material < 22,4 mm Mass %		
		< 2 µm	< 20 µm	< 200 µm
Non/ Negligible	T1	--	< 3	--
Low	T2	--	3-12	--
Moderate	T3	>40[1)]	> 12	< 50
High	T4	< 40	> 12	> 50

1) Soils with more than 40% of < 2 µm are considered as moderatly frost susceptible (T3).

frost-susceptibility	SP $mm^2/°C·h$	SP $mm^2/°C·d$	Frost heave rate mm/d	Frost heave ratio $Δh/h_{frozen}$ (%)
Negligible	< 0.5	< 12	< 0.5	< 1
Low	0.5 - 1.5	12 - 35	0.5 - 2	1 - 4
Medium	1.5 - 3	35 -75	2 - 4	4 - 8
High	3 - 8	75 -200	4 - 8	8 - 20
Very high	> 8	> 200	> 8	> 20

Soil index parameters (Konrad 2005)

Soil index parameters to measure

Average diameter of the fine fraction ($d50_{ff}$)
-> hydrometer

Initial water content -> in situ

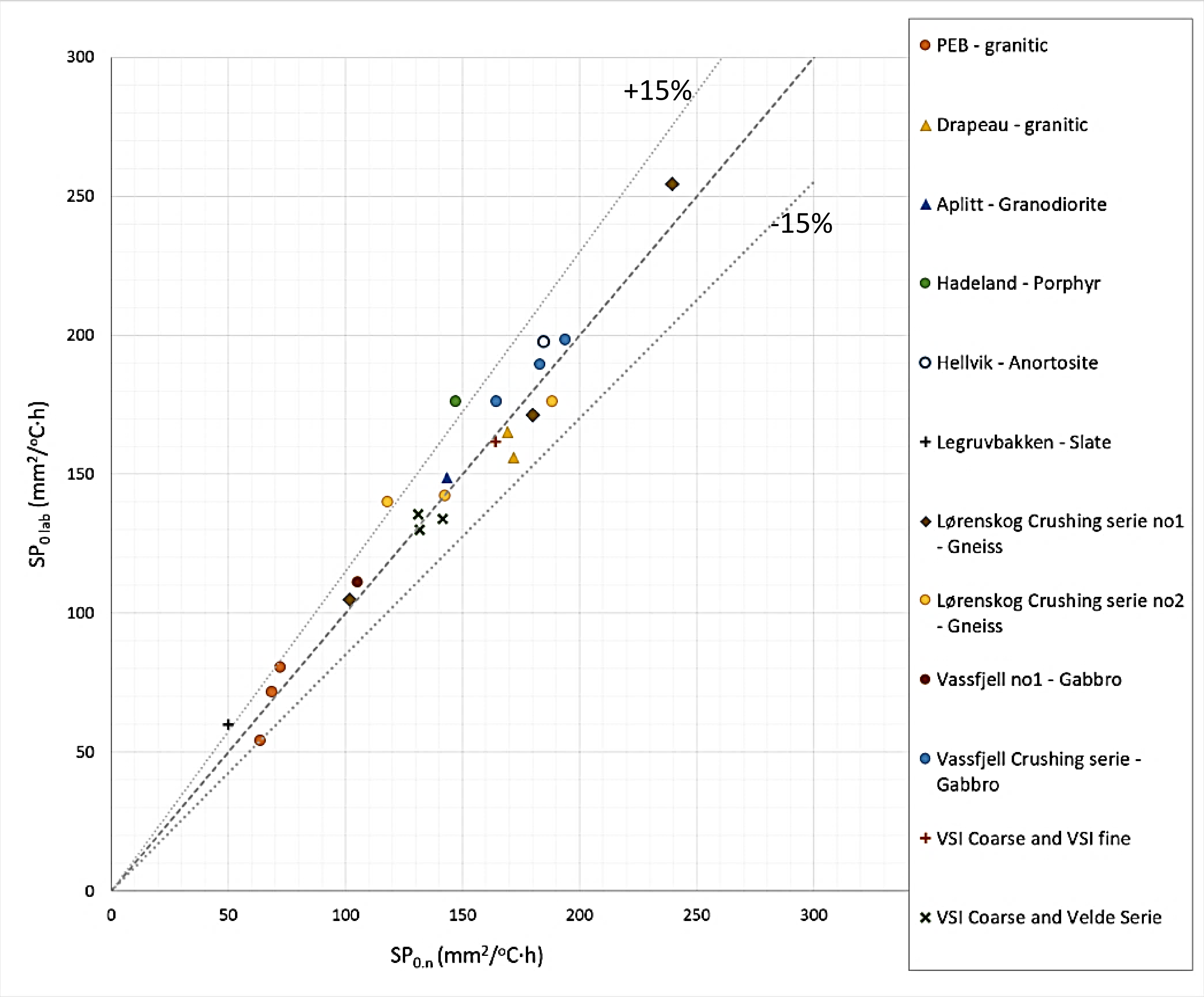
Liquid limit -> cone penetration

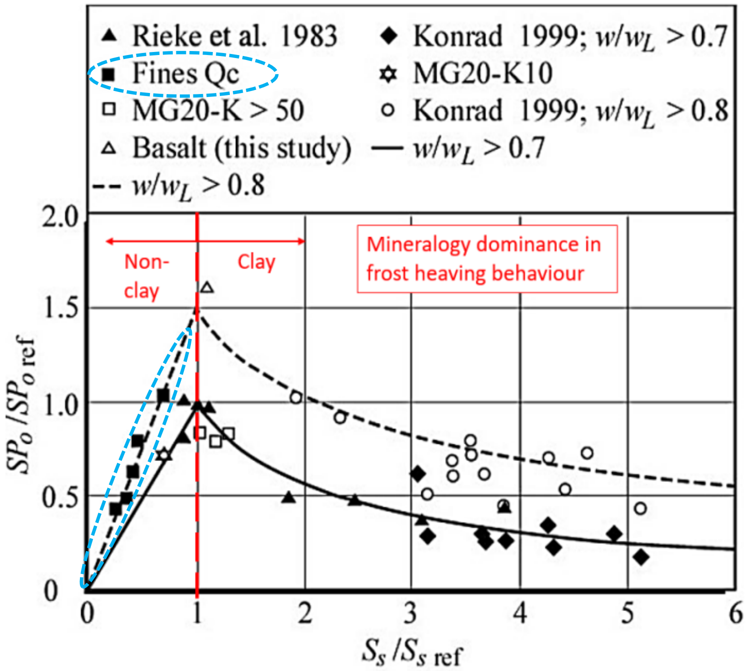
Specific surface area -> methylene blue test

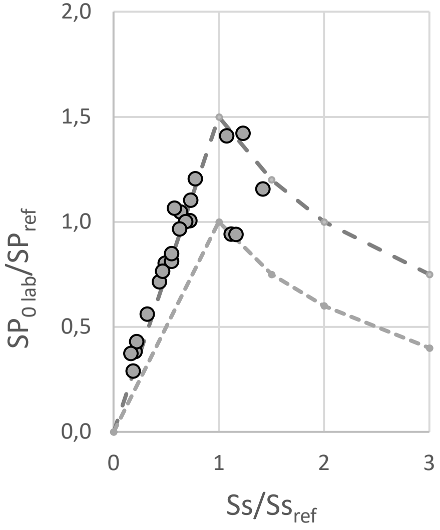
23 frost heave tests

variation in rock type

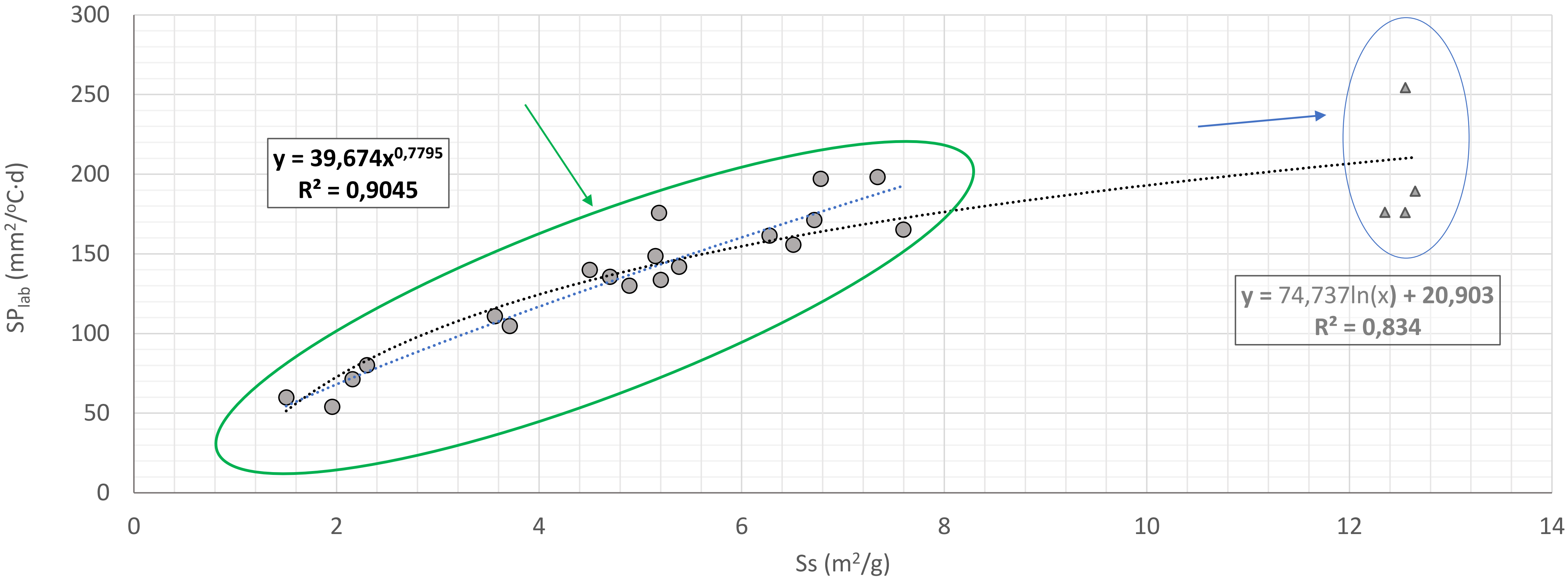
variation in crushing step


+15%
-15%
300
250
200
150
100
50
0
0
50
100
150
200
250
300
SP0 lab (mm²/°C·h)
SP0.n (mm²/°C·h)
PEB - granitic
Drapeau - granitic
Aplitt - Granodiorite
Hadeland - Porphyr
Hellvik - Anortosite
Legruvbakken - Slate
Lørenskog Crushing serie no1 - Gneiss
Lørenskog Crushing serie no2 - Gneiss
Vassfjell no1 - Gabbro
Vassfjell Crushing serie - Gabbro
VSI Coarse and VSI fine
VSI Coarse and Velde Serie


Rieke et al. 1983
Fines Qc
MG20-K > 50
Basalt (this study)
w/wL > 0.8
Konrad 1999; w/wL > 0.7
MG20-K10
Konrad 1999; w/wL > 0.8
w/wL > 0.7
Non-clay
Clay
Mineralogy dominance in frost heaving behaviour
2.0
1.5
1.0
0.5
0
0
1
2
3
4
5
6
SPo /SPo ref
Ss /Ss ref


2,0
1,5
1,0
0,5
0,0
0
1
2
3
SP0 lab/SPref
Ss/Ssref

Last stage crushed aggregates



Part II: Field test investigation and modelling

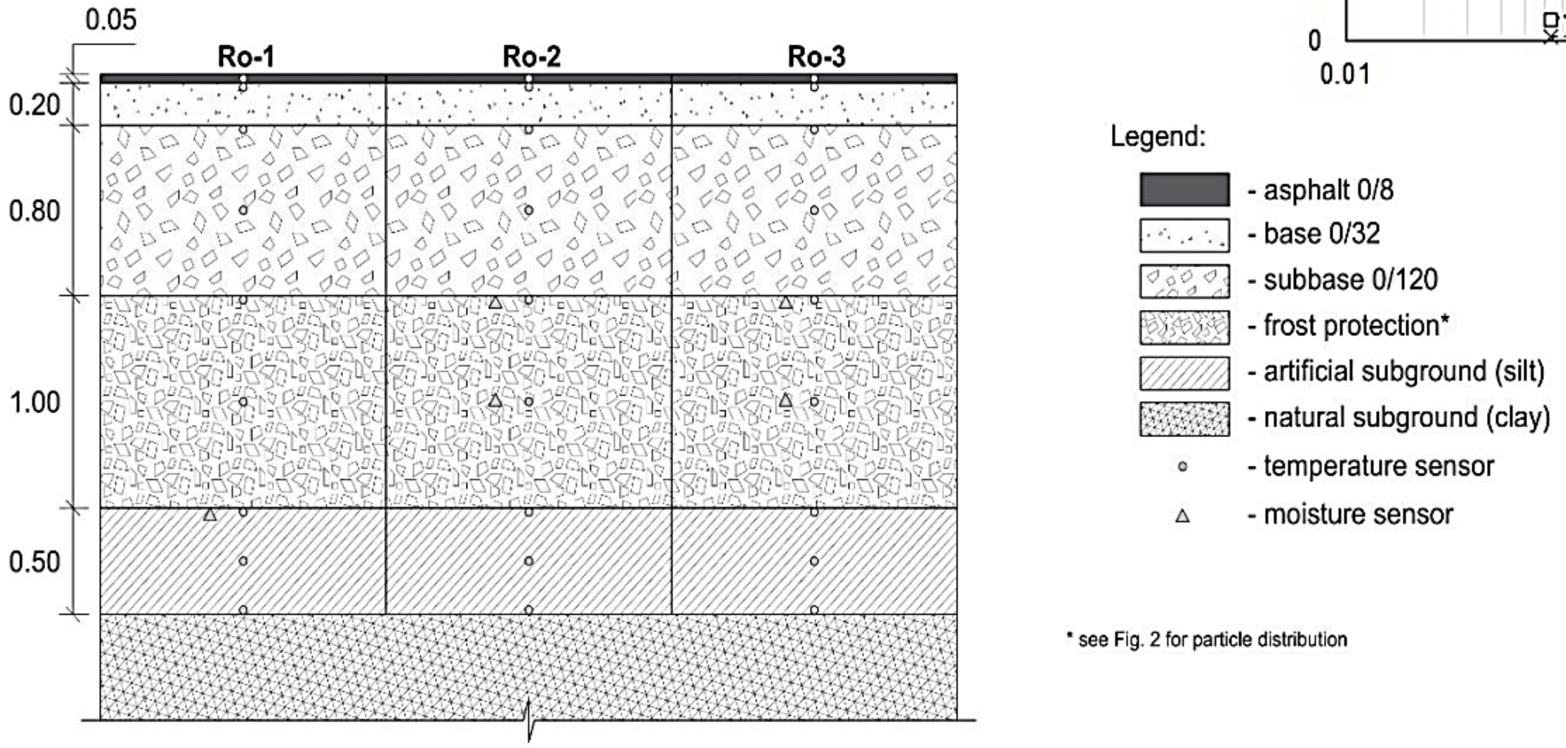
- Paper II: Frost depth and frost protection capacity of crushed rock aggregates based on particle size distribution.
  Québec 2019: 18th International Conference on Cold Regions Engineering and the 8th Canadian Permafrost Conference. Quebec City, Canada. (August 18 to 22, 2019).

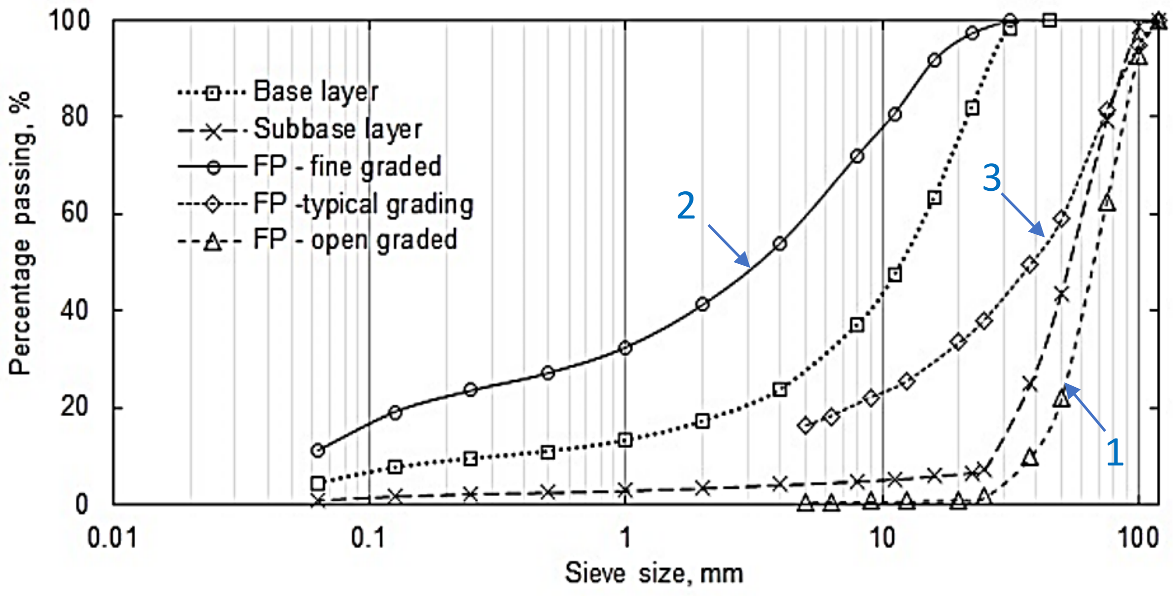
- Paper IV: Evaluation of the SSR model on thick-layered road structures using the I3C-ME frost module and analyses of key parameters.
  To be re-submitted.

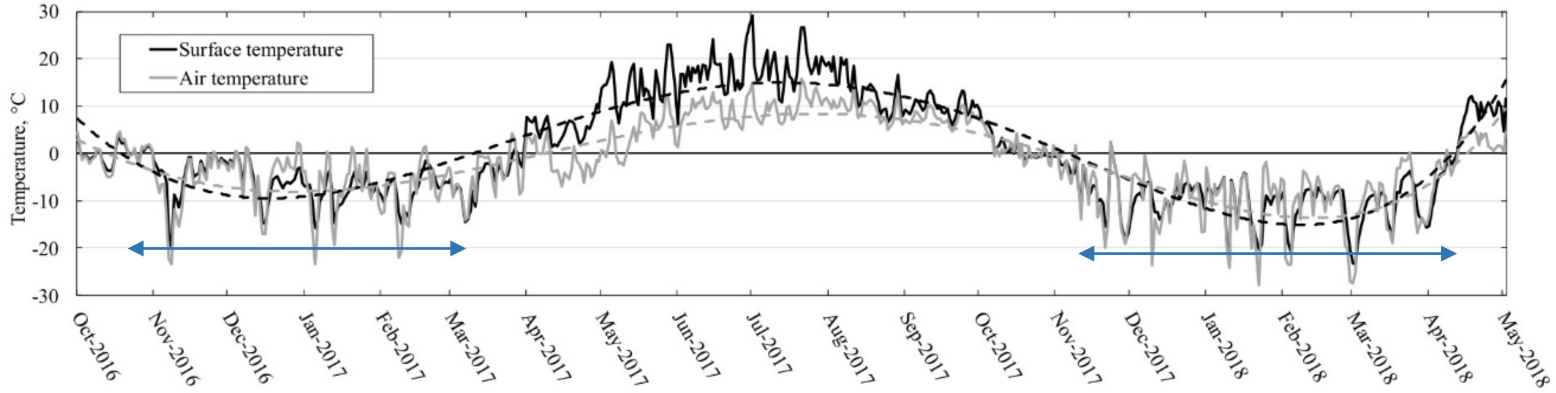
Field test site: Røros

Locality	MAT	FI_2	FI_{10}	FI_{100}
Røros	0.2	21000	39000	61000
Oslo	6.4	5000	12000	21000
Bergen	7.6	1000	2000	4000
Trondhein	5.3	4000	11000	19000
Tromsø	2.8	8000	15000	24000

FI_x: Return period in x years of a freezing index magnitude event

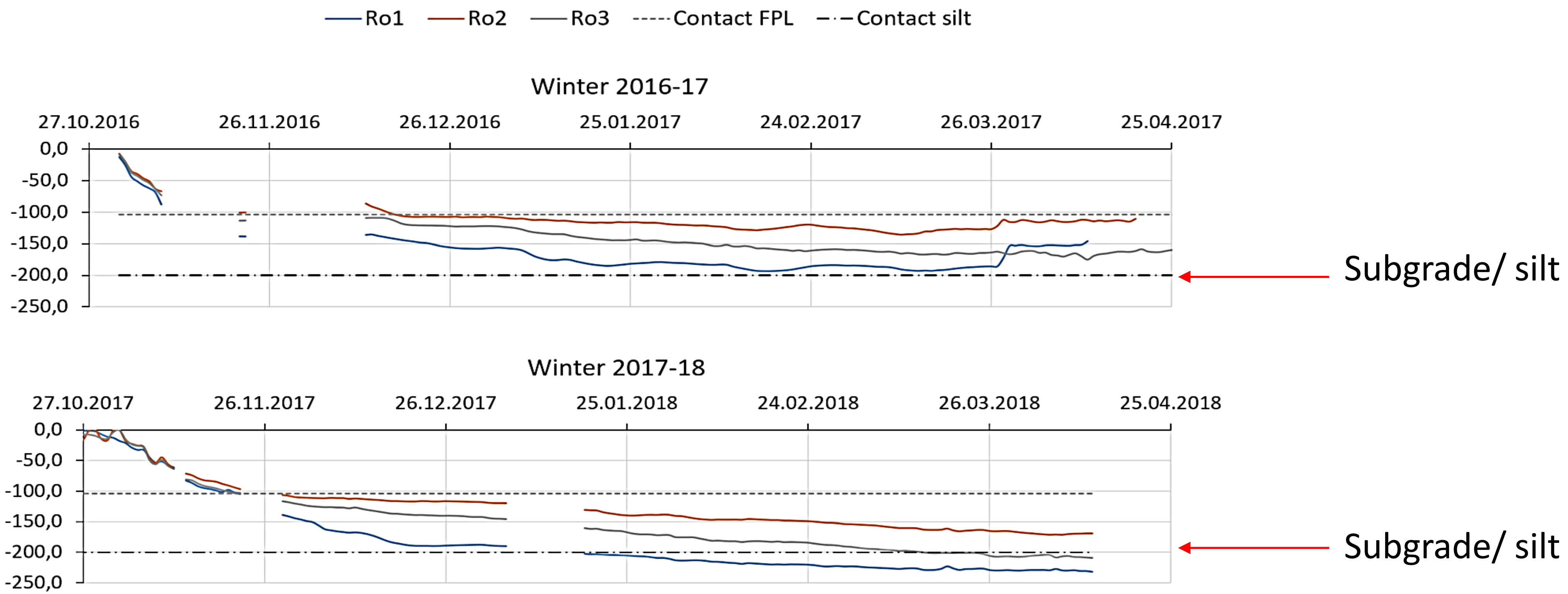




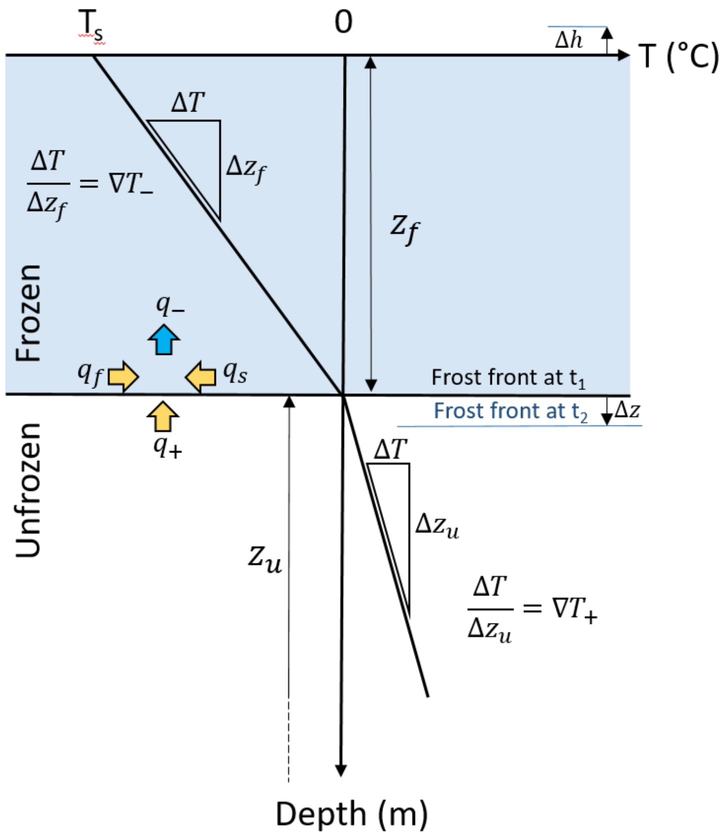


FI_s = 22630 °C·h // 943 °C·d ≈ F_3

FI_s = 36683 °C·h // 1528 °C·d ≈ F_9



SSR Model



Energy balance at frost front

$$q_- = q_f + q_+ + q_s$$

$$\lambda_f \frac{\Delta T}{\Delta z_f} = L_s \frac{\Delta z}{\Delta t} + \lambda_u \frac{\Delta T}{\Delta z_u} + SP \cdot L_w \frac{\Delta T}{\Delta z_f}$$

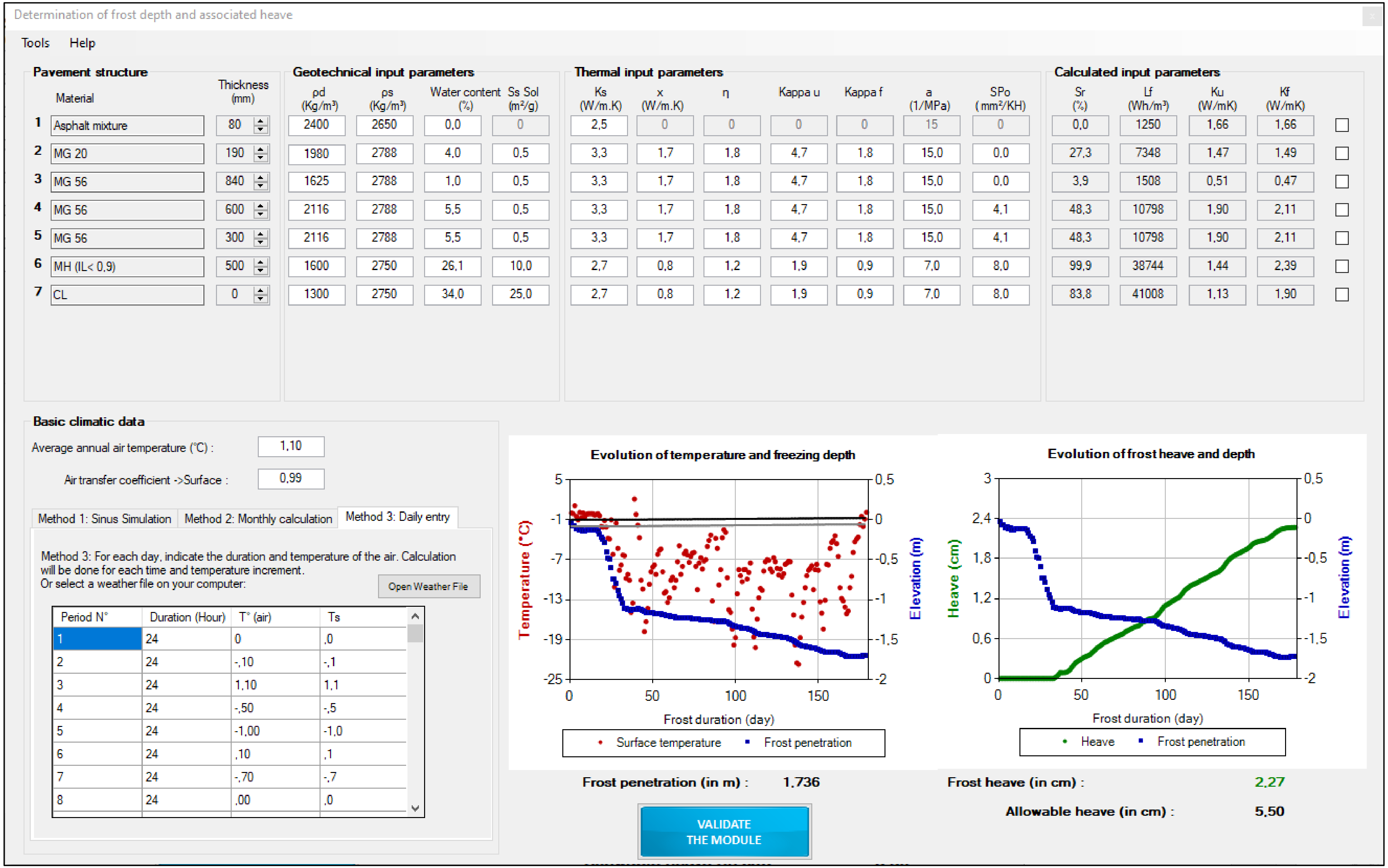
$$\lambda_f \nabla T_- = L_s \frac{\Delta z}{\Delta t} + \lambda_u \nabla T_+ + SP \cdot L_w \nabla T_-$$

Stefan (1891) | Saarelainen (1992) | Konrad (1980)

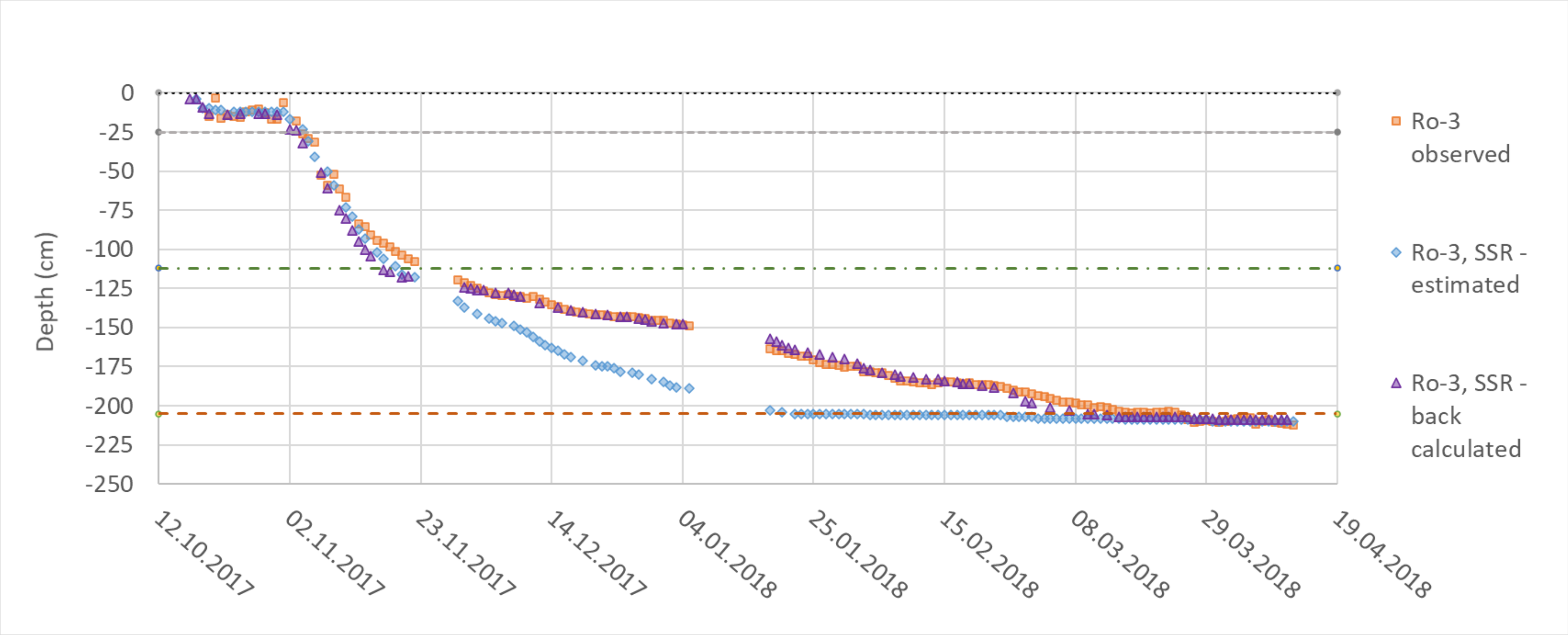
$$\Delta h = \Delta h_s + \Delta h_p$$

$$\Delta z = (T_f - T_s) dt \frac{(1 - SP \cdot L_w/\lambda_{fz})}{\left(L_{fz} \cdot \sum(z_i/\lambda_{fi})\right)} - \frac{S \cdot \nabla T_+ \cdot \lambda_{uz}\, dt}{L_{fz}}$$

$$\Delta h_s = 1.09 \cdot [SP \cdot \nabla T_-]\, dt = 1.09 \cdot SP \cdot \frac{(T_f - T_s) dt}{\left(\lambda_{fz} \sum(z_i/\lambda_{fi})\right)}$$

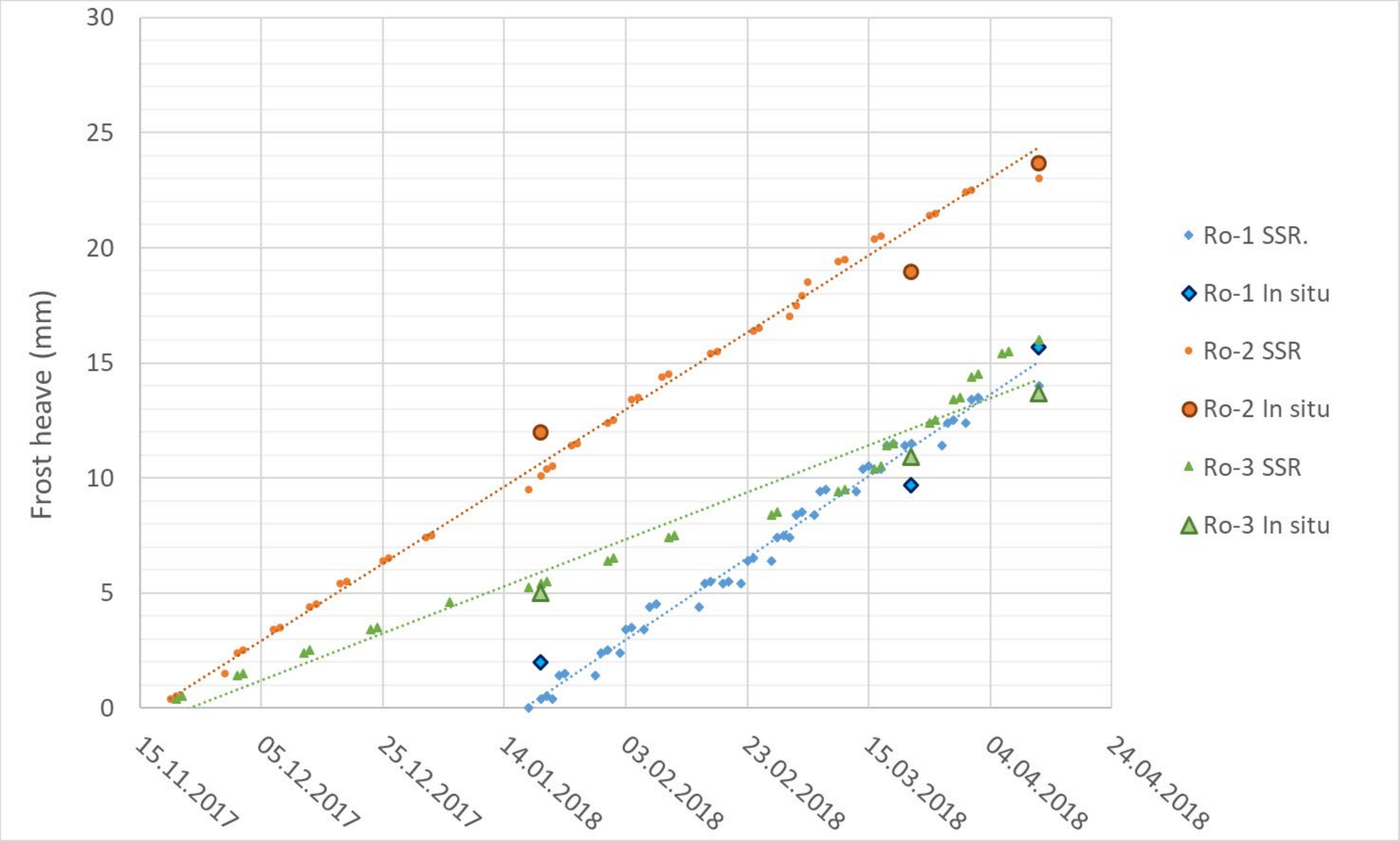

Determination of frost depth and associated heave
Tools
Help
Pavement structure
Material
Thickness (mm)
1 Asphalt mixture 80
2 MG 20 190
3 MG 56 840
4 MG 56 600
5 MG 56 300
6 MH (IL< 0,9) 500
7 CL 0
Geotechnical input parameters
ρd (Kg/m³) ρs (Kg/m³) Water content (%) Ss Sol (m²/g)
2400 2650 0,0 0
1980 2788 4,0 0,5
1625 2788 1,0 0,5
2116 2788 5,5 0,5
2116 2788 5,5 0,5
1600 2750 26,1 10,0
1300 2750 34,0 25,0
Thermal input parameters
Ks (W/m.K) x (W/m.K) η Kappa u Kappa f a (1/MPa) SPo (mm²/KH)
2,5 0 0 0 0 15 0
3,3 1,7 1,8 4,7 1,8 15,0 0,0
3,3 1,7 1,8 4,7 1,8 15,0 0,0
3,3 1,7 1,8 4,7 1,8 15,0 4,1
3,3 1,7 1,8 4,7 1,8 15,0 4,1
2,7 0,8 1,2 1,9 0,9 7,0 8,0
2,7 0,8 1,2 1,9 0,9 7,0 8,0
Calculated input parameters
Sr (%) Lf (Wh/m³) Ku (W/mK) Kf (W/mK)
0,0 1250 1,66 1,66
27,3 7348 1,47 1,49
3,9 1508 0,51 0,47
48,3 10798 1,90 2,11
48,3 10798 1,90 2,11
99,9 38744 1,44 2,39
83,8 41008 1,13 1,90
Basic climatic data
Average annual air temperature (°C) : 1,10
Air transfer coefficient ->Surface : 0,99
Method 1: Sinus Simulation
Method 2: Monthly calculation
Method 3: Daily entry
Method 3: For each day, indicate the duration and temperature of the air. Calculation will be done for each time and temperature increment.
Or select a weather file on your computer:
Open Weather File
Period N° Duration (Hour) T° (air) Ts
1 24 0 ,0
2 24 -,10 -,1
3 24 1,10 1,1
4 24 -,50 -,5
5 24 -1,00 -1,0
6 24 ,10 ,1
7 24 -,70 -,7
8 24 ,00 ,0
Evolution of temperature and freezing depth
Temperature (°C)
Elevation (m)
Frost duration (day)
Surface temperature
Frost penetration
Evolution of frost heave and depth
Heave (cm)
Elevation (m)
Frost duration (day)
Heave
Frost penetration
Frost penetration (in m) : 1,736
Frost heave (in cm) : 2,27
Allowable heave (in cm) : 5,50
VALIDATE THE MODULE

Frost depth: Ro-3



Section (FPL)	Water content (%)		Dry density (kg/m³)	
	est.	adj.	est.	adj.
Ro-1	1	1.5/2.5	1535	1535
Ro-2	5.5	5.5	2116	2116
Ro-3	2	4/4.5	1780	1850

Frost heave



Silt tested in laboratory

Granular material (Ro-2 and Ro-3) are back-calculated ($mm^2/K \cdot h$)

$SP_{0\ Silt}$ = 8.1

$SP_{0\ gm\text{-}Ro\text{-}2}$ = 4.1

$SP_{0\ gm\text{-}Ro\text{-}3}$ = 1.3

Road category

- Main (30%)
  - No frost penetration allowed
    - Max thickness 2,4 or 1,8 m
- Secondary (70%)
  - Limiting differential frost heave
    - Max thickness 1,8 m
    - Frost heave is then allowed, but not calculated…

Frost susceptibility criteria T3, T4

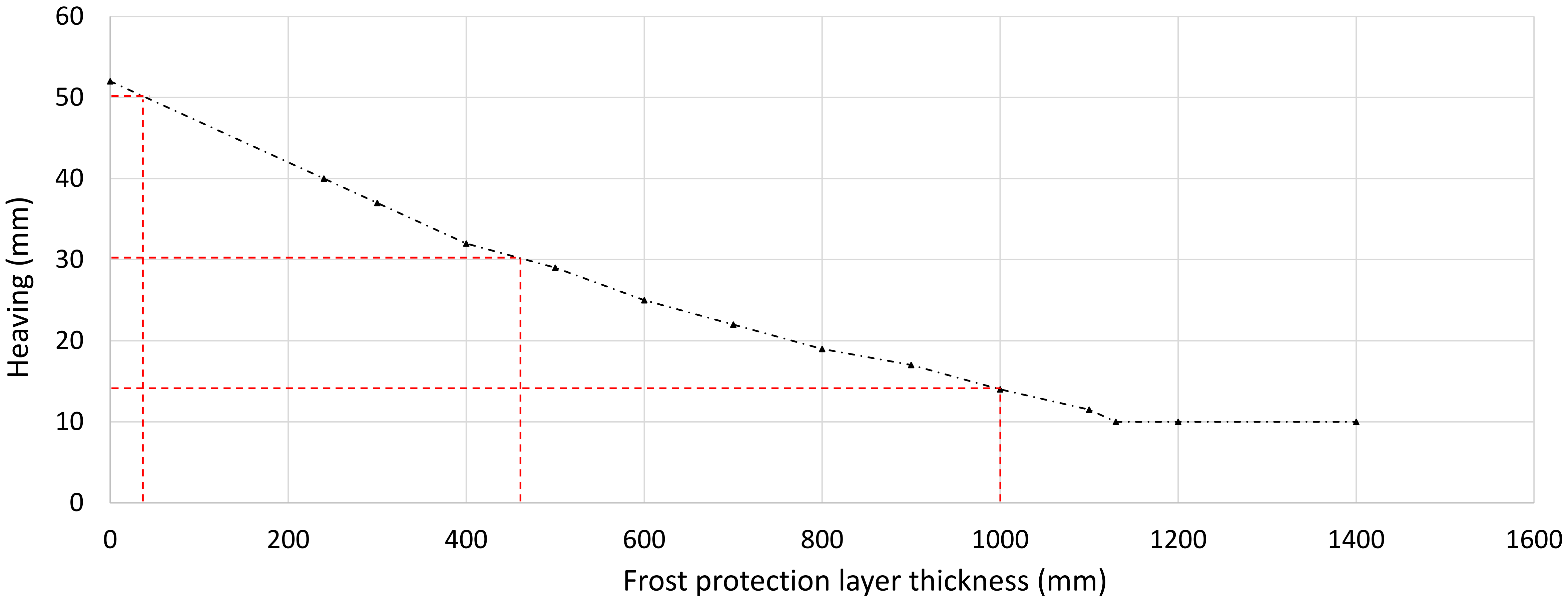
Road class	Freeways	National	Regional	Local
Finland	<30	<50	---	<100
Canada	<50	<55	<60	<70

Speed limit	110	100	90	70	<50
Sweden	<20	<50	<80	<120	<160

Doré and Zubeck, 2009

Design optimization, Ro-3

Varying the FPL thickness
Evething else's the same; FIs ≈ 35000°C·h



Continuations

- **Post doctoral project with Statens Vegvesen**
  - **VegDim and EraPave,**
    - **EraPave**
      - **Soil and aggregates parameters list**
    - **SSR ASSESSMENT**
      - **Field instrumentation**
      - **FH tests on different material**
      - **Field Assessment**
  - **FS evaluation of FPL from 0-4 mm data**

Other significant contribution

- **Loranger, B**., Kuznetsova, E., Hoff, I., Aksnes, L. and Skoglund, K.A. (2017). Evaluation of Norwegian gradation-based regulation for frost susceptibility of crushed rock aggregates in roads and railways. *10th International Conference of the bearing capacity of roads, railways and airfield. Athens, Greece. (June 28th to 30th 2017).*

- Rieksts, K., **Loranger, B**., Hoff, I. and Scibilia, E. (2019). In situ thermal performance of lightweight aggregates expanded clay and foam glass in road structures. *Québec 2019: 18th International Conference on Cold Regions Engineering and the 8th Canadian* Permafrost Conference. Quebec City, Canada. (August 18th to 22nd 2019).

- C. Kjelstrup, S., Ghoreishian Amiri, S.A., **Loranger, B**. and Grimstad, G. (2020). Transport coefficients and pressure conditions for growth of ice lens in frozen soil. Acta Geotechnica journal (doi.org/10.1007/s11440-021-01158-0).

Thank you!
Takk!