Project No. 01-59

CALIBRATION OF THE FROST HEAVE DETERMINISTIC MODEL

APPENDIX 7

SIMPLIFIED 1-D MODEL CALIBRATION AND VALIDATION

MAY 2023

LIST OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

7. CALIBRATION OF THE FROST HEAVE DETERMINISTIC MODEL

This document presented the work of the calibration and validation of the simplified 1-D model as discussed in Appendix 6. To perform case analysis, different databases were reviewed. Data from LTPP database, SMP database, and site measurement of the European Finland sites were collected, compiled, and applied for the 1-D model verification. The LTPP database provided inputs of pavement geometry and layer material properties for the 1-D model. The SMP database has well-documented time-series soil properties and climatic data, which are the necessary input of the 1-D model. More importantly, the SMP has TDR measured historical ground temperature which is required for model frost depth verification. However, SMP did not record site-monitored frost heave, so the frost heave estimation of the 1-D model cannot be validated via SMP database. Through literature review, it was found that the thesis by Saarelainen (1992) documented detailed field frost depth and frost heave for six sites in Finland. Then the data from Saarelainen's thesis was re-organized and used for the frost heave verification of the 1-D model.

The study objectives in this chapter are summarized below:

1. Compile data of SMP sections for the validation and calibration of the simplified 1-D model.
2. Based on the evaluated subgrade frost susceptibility, sort data of the SMP sections and perform case analysis to verify the 1-D model.
3. Collected and re-organized the data from six sites in Finland. Verify the FH prediction and calibrate the simplified 1-D model using the Finland data.
4. Compared the 1-D model prediction with site-measured frost heave and frost depth of the six Finland sites and the SSR model (Saarelainen, 1992) predictions.
5. Evaluate the 1-D model performance based on the SMP section and Finland site case study results.

1.1 Calibration and Validation for case of SMP sections

To select suitable case analysis sections for 1-D model from SMP, the criteria used for judging sections was first proposed. Then 9 sections were picked out and a level 3 analysis was performed for these 9 sections. Next, the general 1-D model results were presented and compared with site data. Lastly, the model performance was discussed.

1.1.1 Frost susceptible sections

The classification of frost-susceptible soils presented by Christopher et al. (2006) was used to identify whether the road-section-subgrade-soil is frost susceptible. Table 7-1 and Figure 7-1 summarizes the criteria used for frost classification for LTPP SMP sections. Through data re-organization and compiling, 25 Sections in the SMP database were initially identified as potential frost susceptible sections. This initial list contained 18 sections with AC surface and 7 sections with PCC surface (see Table 7- 2 and Table 7- 3). In Table 7-2, there are 7 sections do not have recorded frost data. This is probably due to the insignificant frost influence on these sections, which can also be indicated by Figure 7- 2. As shown in Figure 7- 2, the site-monitored daily temperature fluctuation in a) Mississippi 1802 and b) Oklahoma 4165 exhibits short frozen seasons. This may imply negligible effect on the pavement. In addition, through gradation and Atterberg limit data analysis, it is found 4 sections presented in Table 7- 2 have shrink/swell subgrade. Therefore, the sections with missing SMP frost data and shrink/swell subgrade were excluded from the calibration case analysis. As a result, only 9 sections in Table 7- 2 were utilized for model calibration, where the simulation start time, end time, and duration of these sections were presented in the last three columns in Table 7- 2. Given the availability of inputs from LTPP, a series of level 3 analysis were performed for the selected 9 sections using the 1-D model.

Table 7- 1 Frost susceptibility classification of soils (NCHRP 1-37A)

Frost Group	Degree of Frost Susceptibility	Type of Soil	Percentage Finer than 0.075 mm (# 200) by wt.	Typical Soil Classification
F1	Negligible to low	Gravelly soils	3-10	GC, GP, GC-GM, GP-GM
F2	Low to medium	Gravelly soils	10-20	GM, GC-GM, GP-GM
		Sands	3-15	SW, SP, SM, SW-SM, SP-SM
F3	High	Gravelly Soils	Greater than 20	GM-GC
		Sands, except very fine silty sands	Greater than 15	SM, SC
		Clays PI>12	—	CL, CH
F4	Very high	All Silts	—	ML-MH
		Very Fine Silty Sands	Greater than 15	SM
		Clays PI<12	—	CL, CL-ML
		Varied clays and other fine grained, banded sediments	—	CL, ML, SM, CH

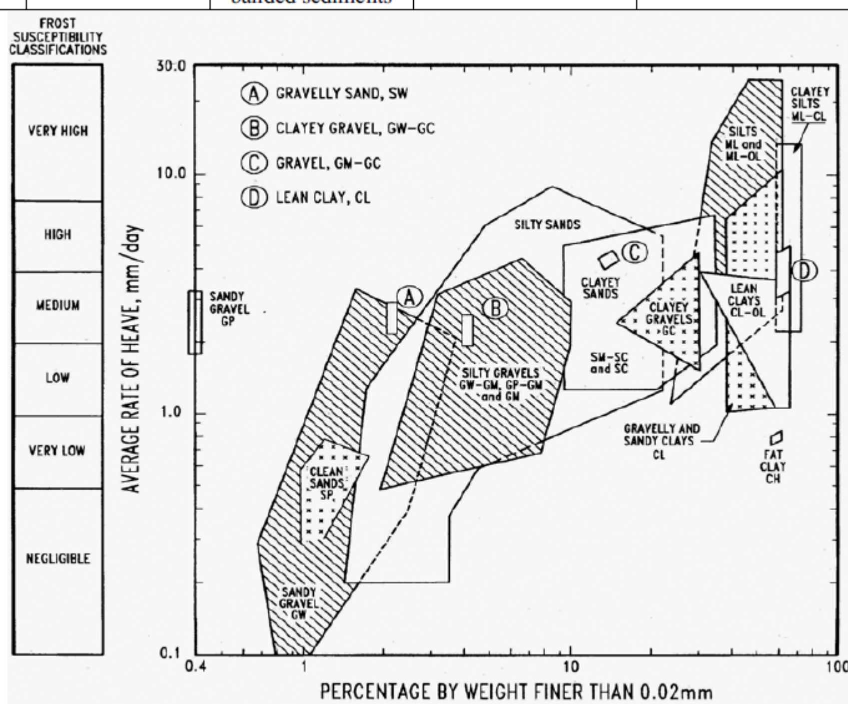
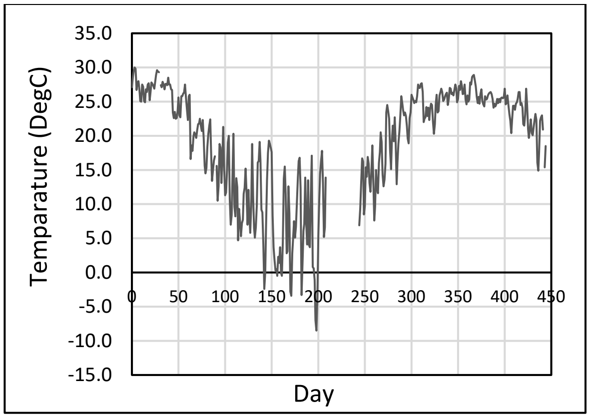
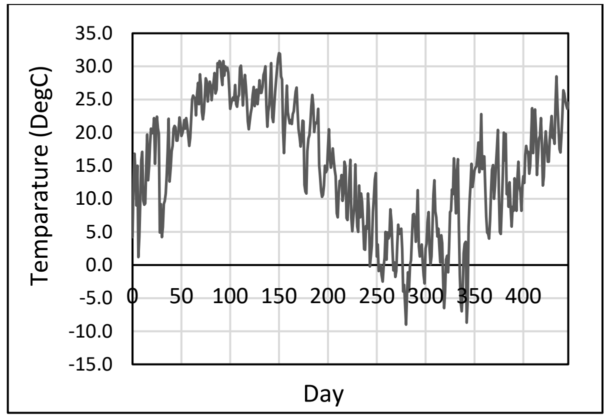


Figure 7- 1 Percentage finer than 0.02mm versus average rate of heave (Kaplar, 1974)



(a)



(b)

Figure 7- 2 Temperature variation with time: a) at Mississippi 1802 from 07/21/1995 to 10/07/1996 and b) at Oklahoma 4165 from 03/30/1994 to 06/19/1995

Table 7- 2 The summary of SMP sections with AC surface that may suffer from frost heave

State code	SHRP_ID	State name	Section subgrade characteristics	Simulation starts from	Simulation ends at	Simulation duration (days)
9	1803	Connecticut	Have site measured frost SMP data	1/21/1994	1/12/1995	356
27	1018	Minnesota	Have site measured frost SMP data	09/24/1993	11/04/1994	406
27	6251	Minnesota	Have site measured frost SMP data	09/16/1993	9/7/1994	356
50	1002	Vermont	Have site measured frost SMP data	10/6/1993	10/24/1994	383
83	1801	Manitoba	Have site measured frost SMP data	11/13/1993	12/10/1994	392
90	6405	Saskatchewan	Have site measured frost SMP data	12/11/1993	1/18/1995	403
23	1026	Maine	Have site measured frost SMP data	12/18/1993	5/27/1995	525
36	0801	New York	Have site measured frost SMP data	10/10/1995	9/16/1996	342
39	0901	Ohio	Have site measured frost SMP data	12/17/1999	7/30/2003	1321
40	4165	Oklahoma	Missing site measured frost SMP data	-	-	-
28	1802	Mississippi	Missing site measured frost SMP data	-	-	-
10	102	Delaware	Missing site measured frost SMP data	-	-	-
13	1031	Georgia	Missing site measured frost SMP data	-	-	-
24	1634	Maryland	Missing site measured frost SMP data	-	-	-
48	1060	Texas	Missing site measured frost SMP data	-	-	-
8	1503	Colorado	Contains HVC soil; Missing site measured frost SMP data;	-	-	-
30	8129	Montana	Contains HVC soil; have site measured frost SMP data	-	-	-
46	9187	South Dakota	Contains HVC soil; have site measured frost SMP data	-	-	-
46	0804	South Dakota	Contains HVC soil; have site measured frost SMP data	-	-	-

Table 7- 3 The summary of sections with PCC surface that suffer from frost heave

State code	SHRP_ID	State name	Section characteristics
13	3019	Georgia	Suitable for pure frost case analysis; have site measured frost SMP data
36	4018	New York	Suitable for pure frost case analysis; have site measured frost SMP data
39	0204	Ohio	Contains HVC soil; not suitable for pure frost case; have site measured frost SMP data
27	4040	Minnesota	Contains HVC soil; not suitable for pure frost case; have site measured frost SMP data
83	3802	Manitoba	Contains HVC soil; not suitable for pure frost case; have site measured frost SMP data
18	3002	Indiana	Contains HVC soil; not suitable for pure frost case; have site measured frost SMP data
37	0201	Quebec	Contains HVC soil; not suitable for pure frost case; have site measured frost SMP data

1.1.2 *Model verification case analysis*

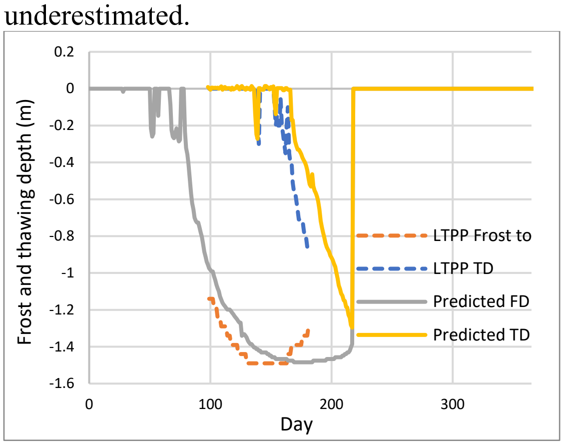
Although LTPP database provide detailed pavement layer parameters and climatic data, the verification of the model was not performed with level 1 or 2 input parameters, but rather, level 3 case analysis were performed. This is because some level 1 and 2 design required inputs are not available, whereas level 3 inputs are easily to be found from LTPP.

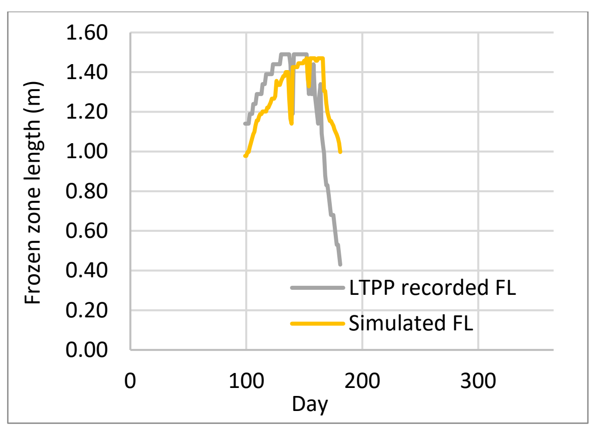
Nine sections with AC surface (as presented in Table 7- 2) were selected for the verification process. Detailed analysis results for these sections are presented in the following subsections, which include the predicted or site-measured (if available) Frost Depth (FD) and Thawing Depth (TD), Frost Length (FL), and Frost Heave (FH). The FD and TD comparison are presented for model verification. FL is the difference between FD and TD, which is utilized to evaluate the frost heave. To compare the time series of freezing and thawing process with the climatic variation, both temperature and precipitation data are presented as a temporal baseline following the FD and TD results. The daily temperature and daily precipitation are collected from the LTPP database (not the model evaluated results). Note that some sections showed time lags of frost or thaw depth when compared with the site measured data. The lag may be caused by the lack of considerations about the thermal mass by precipitation or other environmental factors. The evaluated frost heave result includes FH due to water expansion, FH due to SP, and the total FH. The FH data was evaluated based on the following assumptions: (1) the frost heave goes back to zero after the thawing ends; (2) the total frost have is only the summation of heave due to water expansion and heave due to SP; (3) the temperature gradient at the frost front is equal to the average temperature gradient between the frost front and the model bottom. Note that the last two assumptions may underestimate the frost heave. Since accurate site-measured frost heave data is not available in the LTPP database, the SMP case examples can only partially verify the simplified 1-D model.

The 1-D model simplifies the top thermal boundary requirement by only considering ambient temperature impact. This was achieved by using an equivalent and constant heat transfer coefficient h_c to evaluate the heat flux boundary on the top surface. The coefficient was calibrated through the series of level 3 analysis and was determined as a constant 4.58 BTU/h·ft²·°F (or 26 W/m^2·°C). Using the calibrated coefficient, the simulation results of the nice sections were shown in the below subparts. Note that the time in the result figures starts from day 0, which corresponds to the simulation starting time presented in Table 7- 2 above.

1.1.2.1 *Results for Vermont 1002*

The 1-D model simulated results for Vermont section 1002 are shown in Figure 7- 1, which indicate matched frost depth (FD) and thawing depth (TD) for this simulation. Both FD and TD are slightly underestimated.





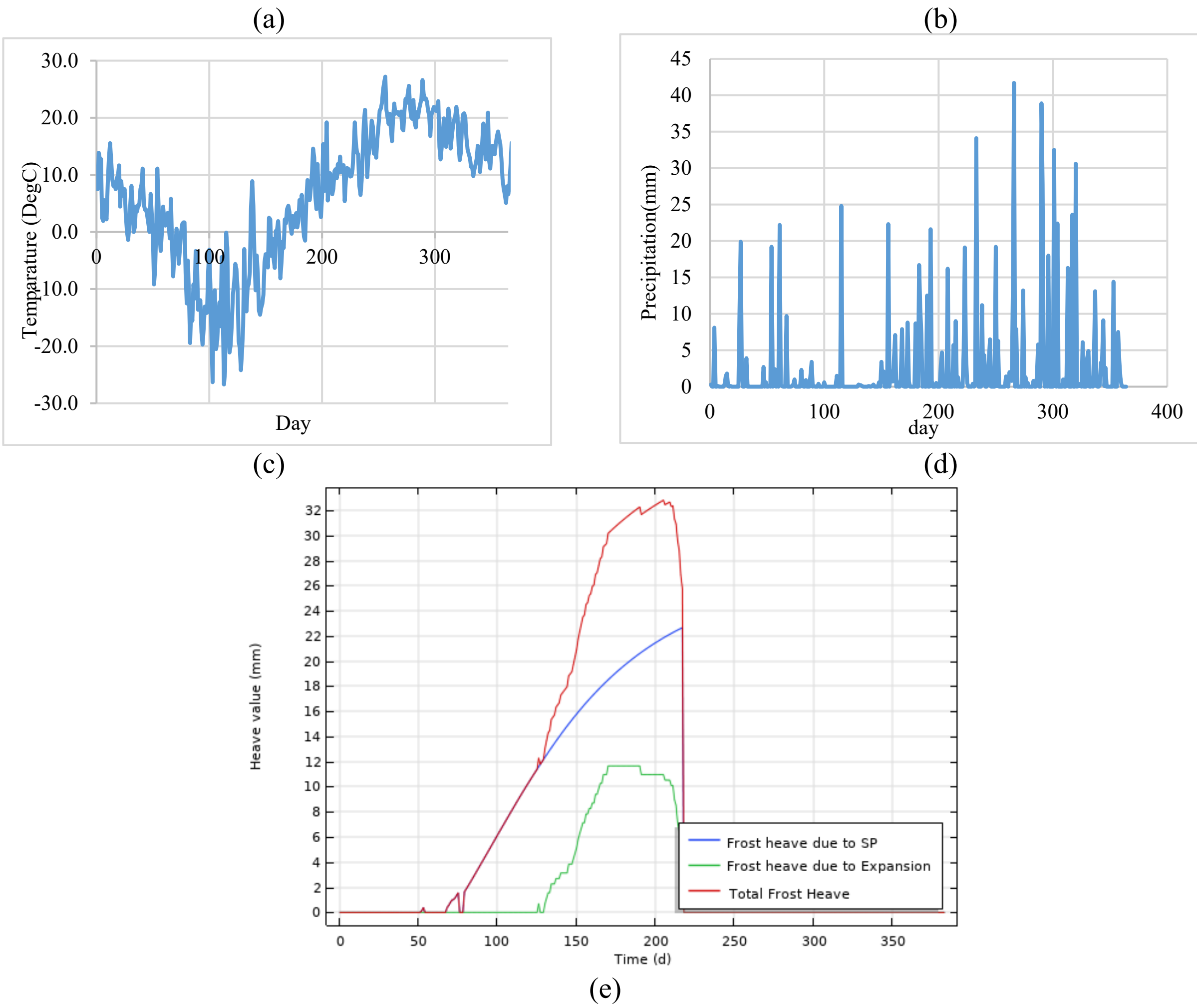


Figure 7- 3 (a)Frost depth vs. days; (b) Frozen zone length vs. days; (c) Daily ambient temp. fluctuation of the simulation duration; (d) Daily precipitation fluctuation of the simulation duration; (e) Model simulated frost heave vs. days

1.1.2.2 Results for Minnesota 1018

Results for Minnesota section 1018 showed well-matched TD and underestimated FD. The underestimation of the FD might be caused by the significant water content variation along the soil profile, which is not captured by the 1-D model in level 3 design. The soil should be much dryer than the initial conditions after 100 days, which can partially be implied by the precipitation data.

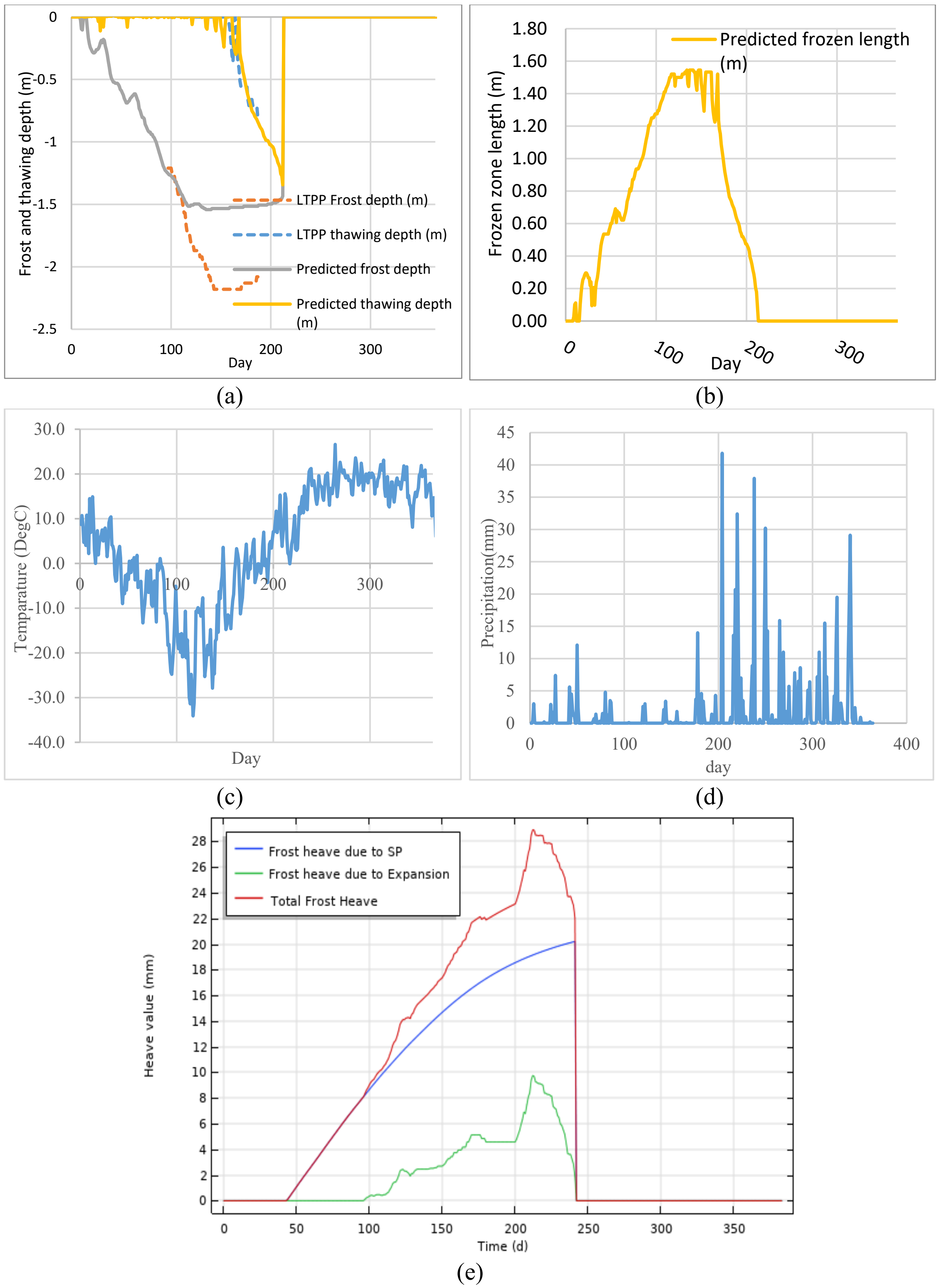


Figure 7- 4 (a) Frost depth vs. days; (b) Frozen zone length vs. days; (c) Daily ambient temp. fluctuation of the simulation duration; (d) Daily precipitation fluctuation of the simulation duration; (e) Model simulated frost heave vs. days

1.1.2.3 Results for Minnesota 6251

Given the limited site-measured data for Minnesota section 2651, it is hard to determine the prediction accuracy of FD and TD. The predicted heave induced by soil water expansion is 0, which is caused by the very low initial water content along the soil profile input under Level 3 design. As a result, most of the heave was caused by the SP.

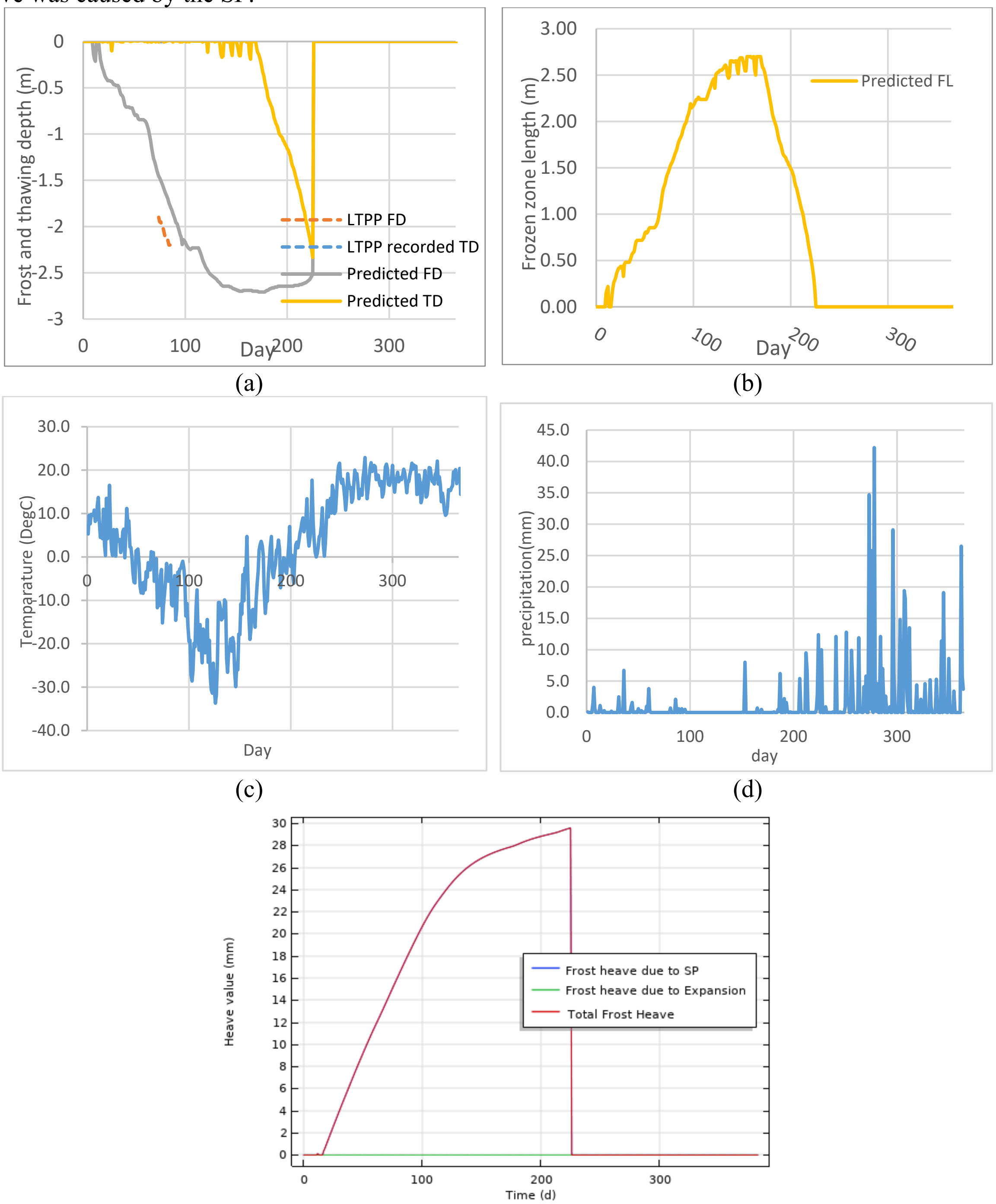


Figure 7- 5 (a) Frost depth vs. days; (b) Frozen zone length vs. days; (c) Daily ambient temp. fluctuation of the simulation duration; (d) Daily precipitation fluctuation of the simulation duration; (e) Model simulated frost heave vs. days

1.1.2.4 Results for Connecticut 1803

The simulated results showed well-matched TD and FD. The heave caused by soil water expansion was predicted to be zero, which is a result of the very low initial water content along the soil profile. As a result, most of the heave were caused by the SP.

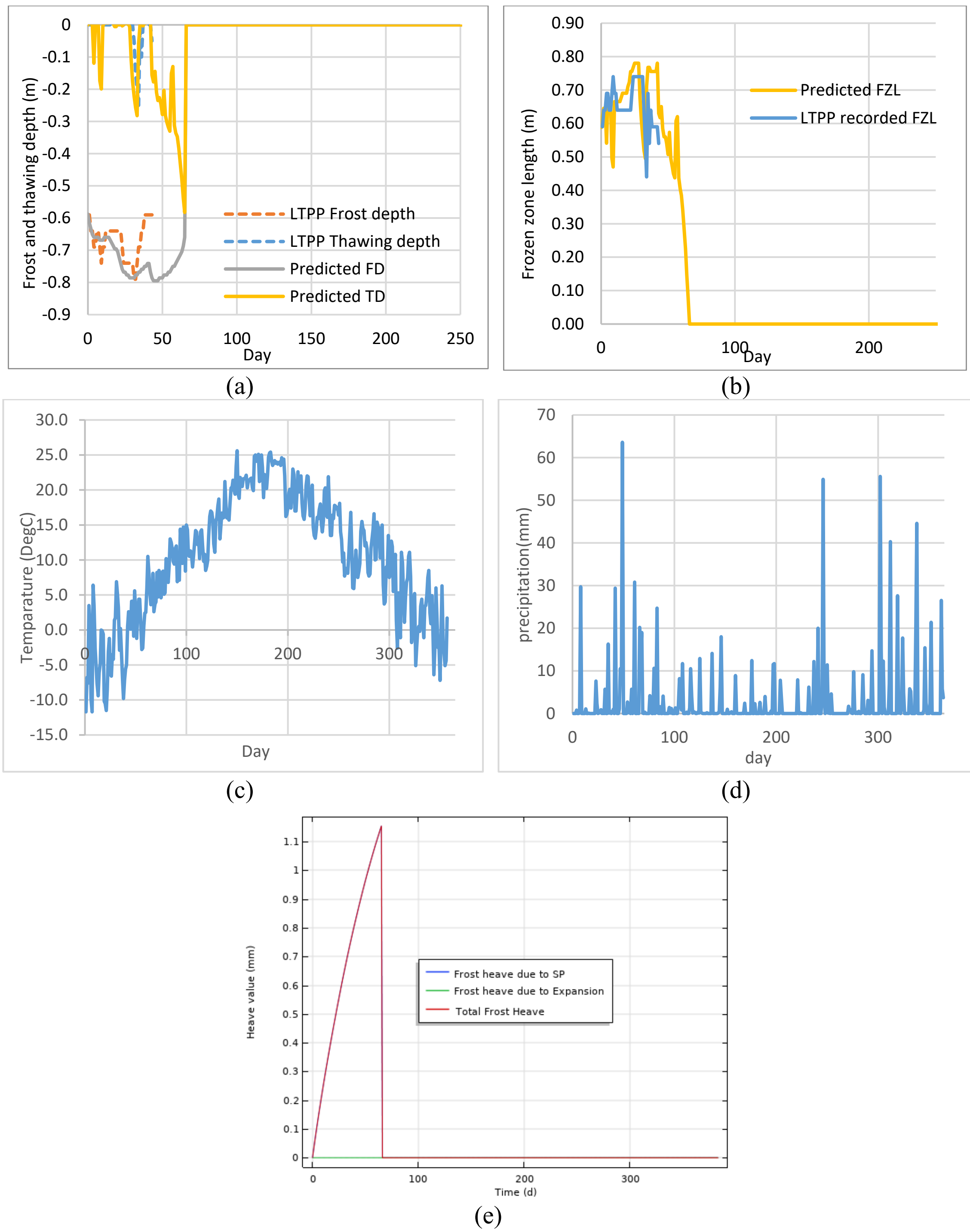


Figure 7- 6 (a) Frost depth vs. days; (b) Frozen zone length vs. days; (c) Daily ambient temp. fluctuation of the simulation duration; (d) Daily precipitation fluctuation of the simulation duration; (e) Model simulated frost heave vs. days

1.1.2.5 Results for Manitoba 1801

Overall, the results for Manitoba section 1801 showed slightly overestimated TD and FD. This might be the result from using underestimated heat capacity parameters (default values) in a Level 3 design.

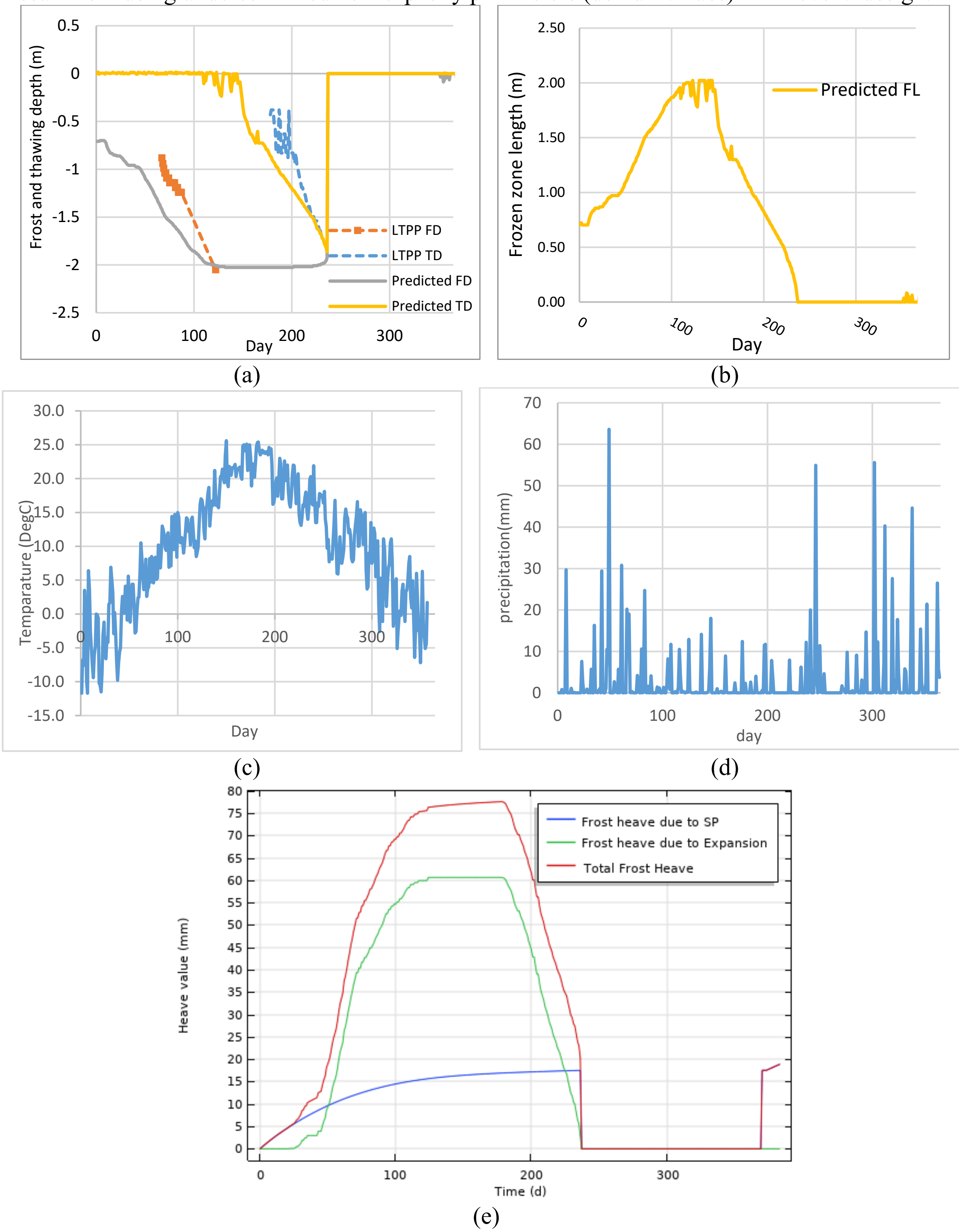


Figure 7- 7 (a) Frost depth vs. days; (b) Frozen zone length vs. days; (c) Daily ambient temp. fluctuation of the simulation duration; (d) Daily precipitation fluctuation of the simulation duration; (e) Model simulated frost heave vs. days

1.1.2.6 Results for Saskatchewan 6405

The simulation results of Saskatchewan 6405 were compared with site monitored data of two freezing seasons. Overall, the results showed well-matched FD, but the TD results showed some lag, which may be caused by the lack of extra surface heat source estimated in a Level 3 design. As shown in Figure 7- 8 (d), after 100 days, the precipitation starts to increase, which may bring extra heat into the soil to accelerate the thawing process. Another possible reason is the simulation used the constant heat transfer coefficients, whereas such coefficient might vary with seasons.

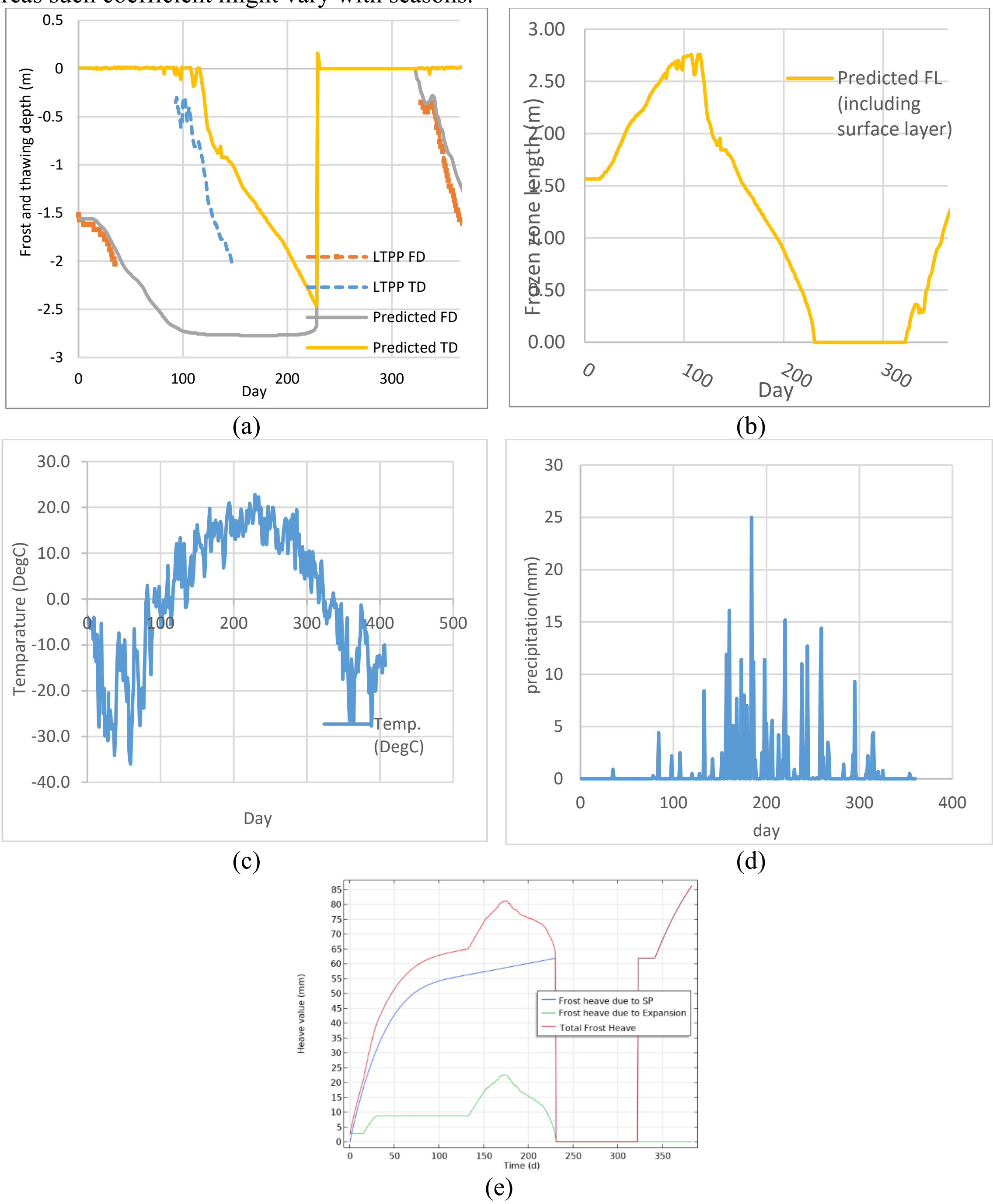


Figure 7- 8 (a) Frost depth vs. days; (b) Frozen zone length vs. days; (c) Daily ambient temp. fluctuation of the simulation duration; (d) Daily precipitation fluctuation of the simulation duration; (e) Model simulated frost heave vs. days

1.1.2.7 Results for Maine 1026

The simulation results of Maine 1026 were compared with site measured data of two freezing-thawing seasons. In the first freezing-thawing season, the model showed generally slightly underestimated FD and TD. In the second freezing-thawing season, the FD is well matched, but the TD is underestimated. It is interesting to find that the time point of freezing and thawing start of the any season are well predicted. In Figure 7- 9 (d), a maximum of 0.8mm total frost heave is predicted. This might be due to the low initial water content condition and a subgrade soil with very low SP value.

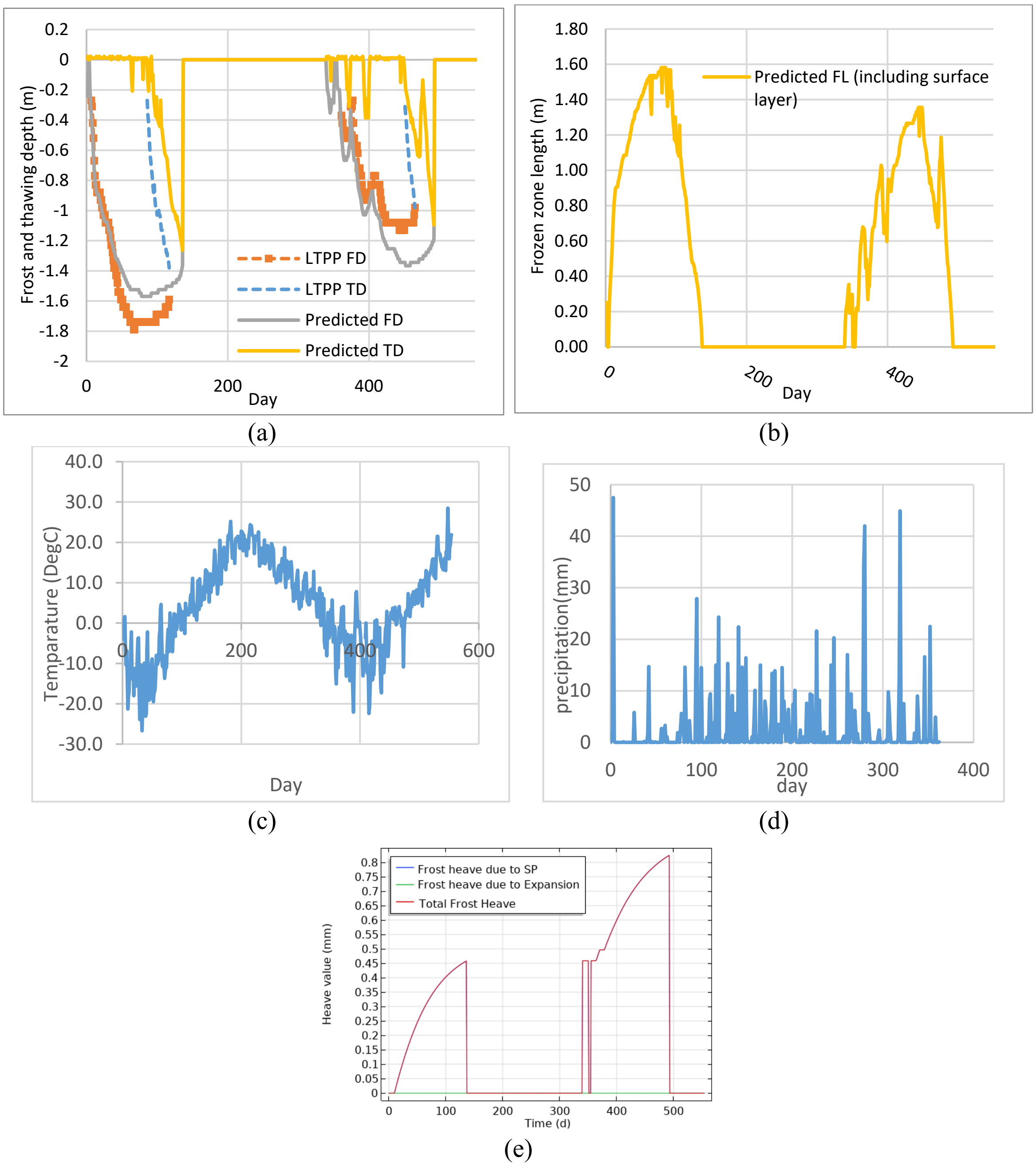


Figure 7- 9 (a) Frost depth vs. days; (b) Frozen zone length vs. days; (c) Daily ambient temp. fluctuation of the simulation duration; (d) Daily precipitation fluctuation of the simulation duration; (e) Model simulated frost heave vs. days

1.1.2.8 Results for New York 0801

The simulated FD and TD results of New York 0801 exhibits fluctuated variation with time, which is consistent with the site data. This may by caused by the fluctuations in temperature as shown in Figure 7-10 (c). Both the FD and TD are slightly underestimated.

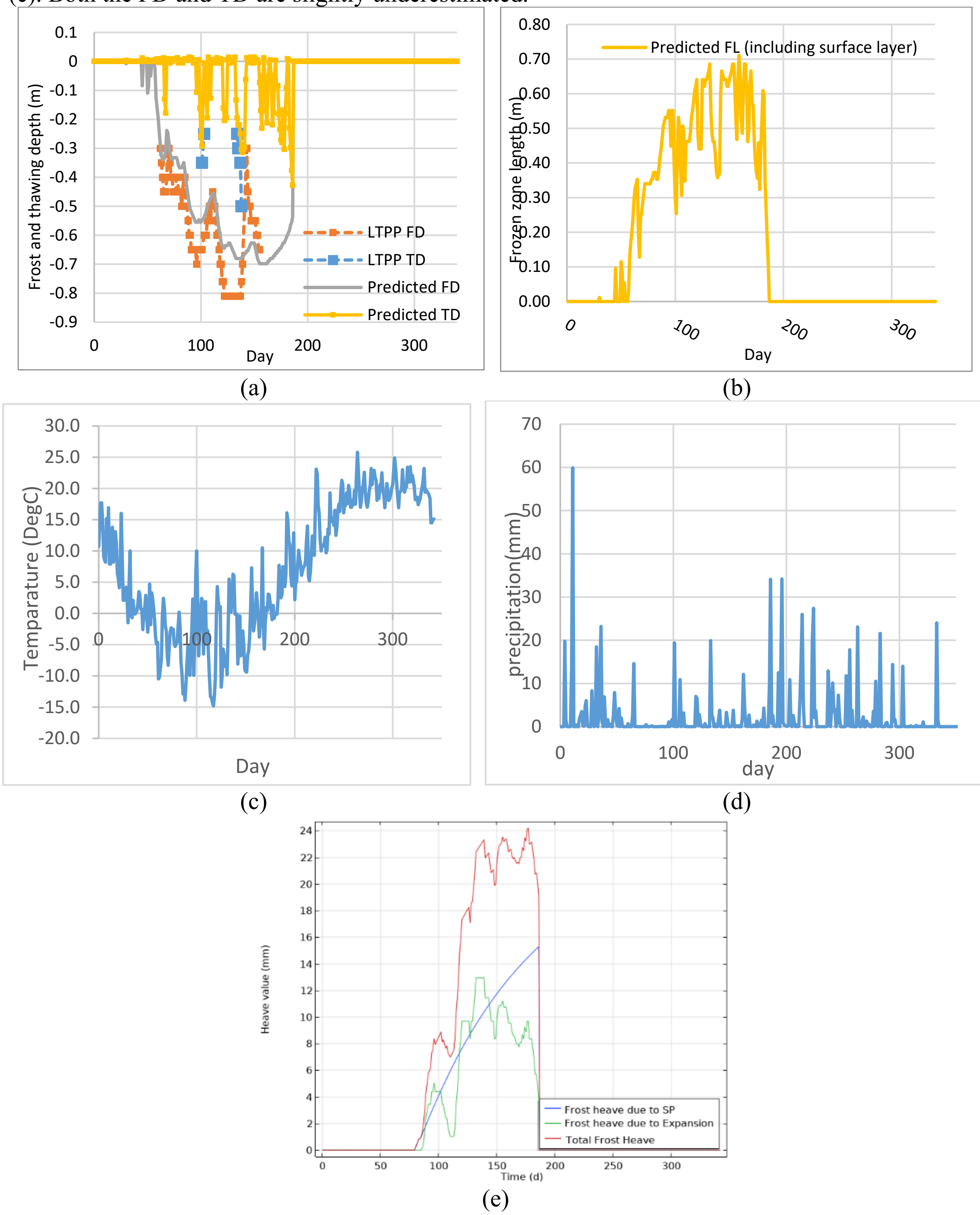
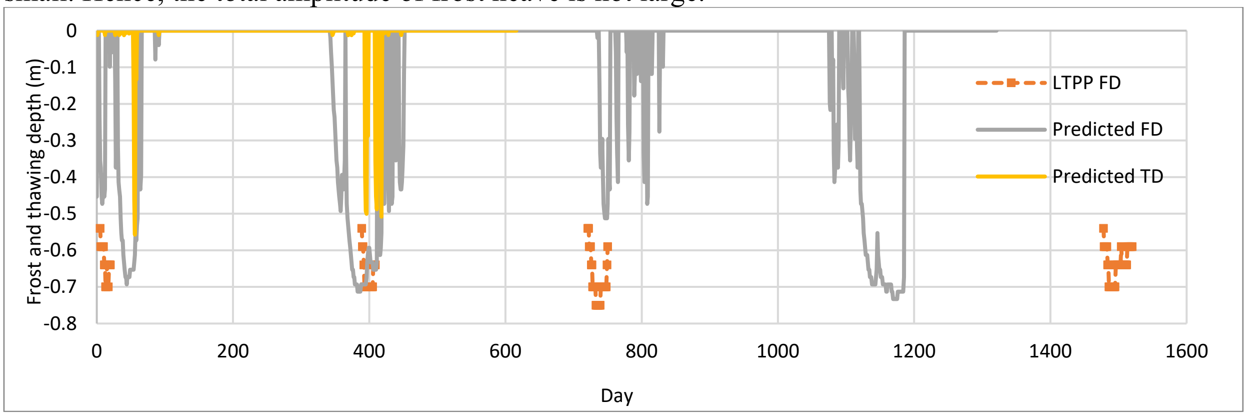


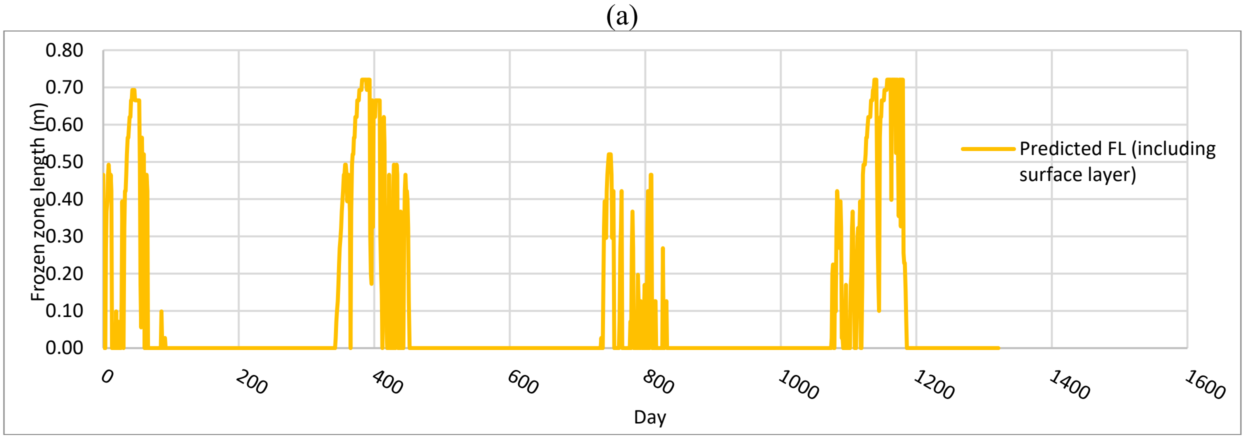
Figure 7- 10 (a) Frost depth vs. days; (b) Frozen zone length vs. days; (c) Daily ambient temp. fluctuation of the simulation duration; (d) Daily precipitation fluctuation of the simulation duration; (e) Model simulated frost heave vs. days

1.1.2.9 Results for Ohio 0901

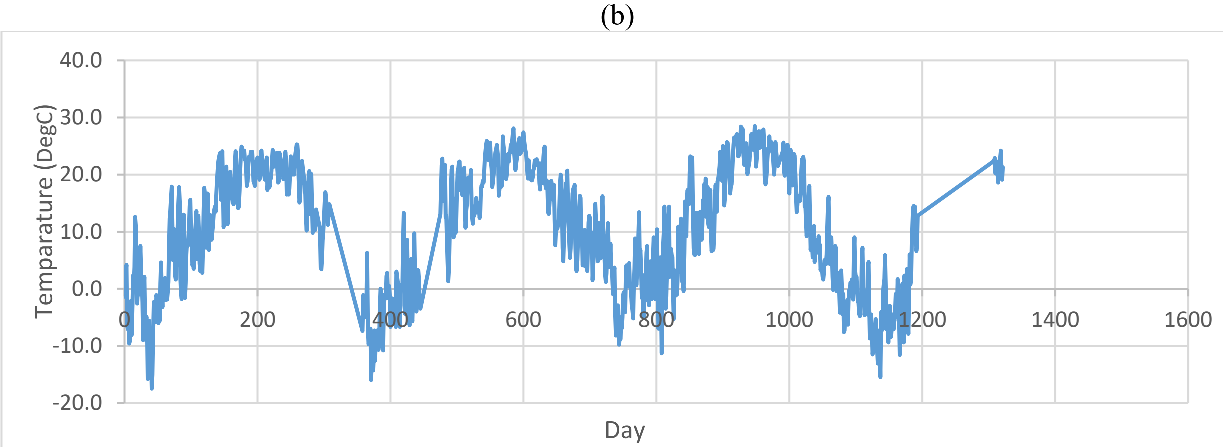
The simulation of Ohio 0901 considers a three-year duration. From this relatively long-term simulation, results showed a generally matched results in FD prediction. Since the LTPP did not record the thawing depth data of Ohio 0901, the results did not compare it in Figure 7- 11. In Figure 7- 11 (e), the calculated frost heave magnitude is small. This is due to the dry initial water content results in bare water expansion caused heave. In addition, the estimated SP of the subgrade (evaluated from site gradation data) is also small. Hence, the total amplitude of frost heave is not large.



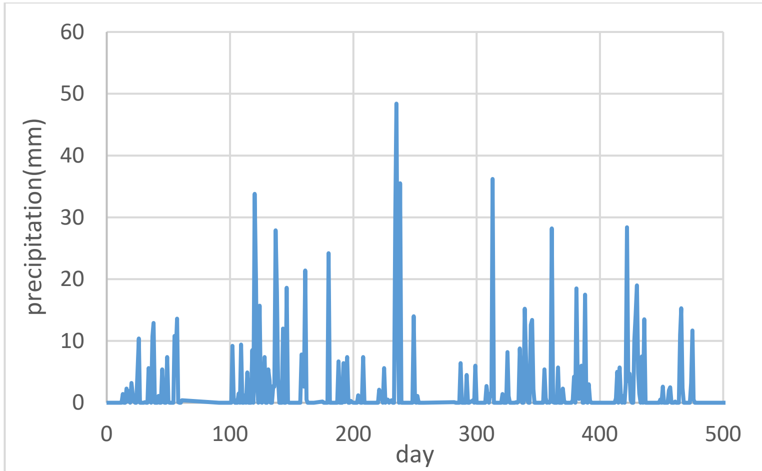
(a)



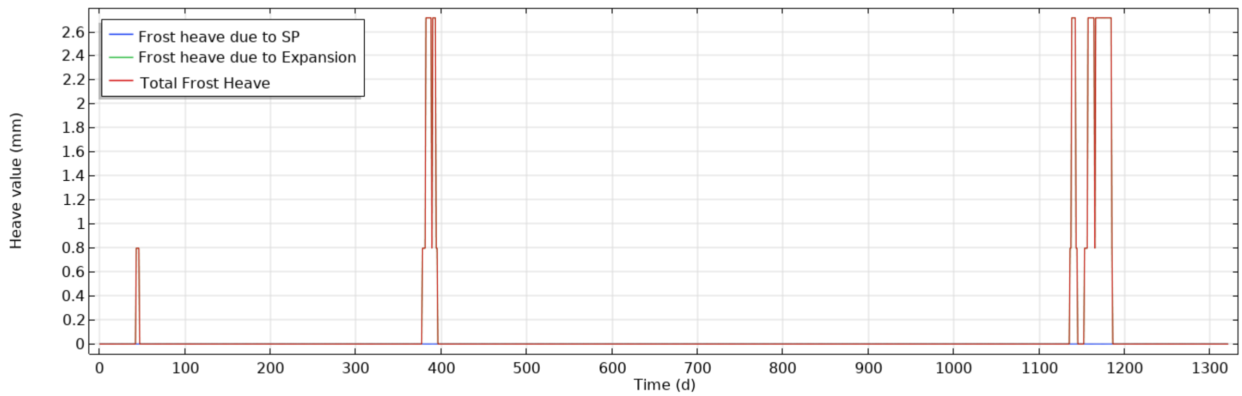
(b)



(c)



(d)



(e)

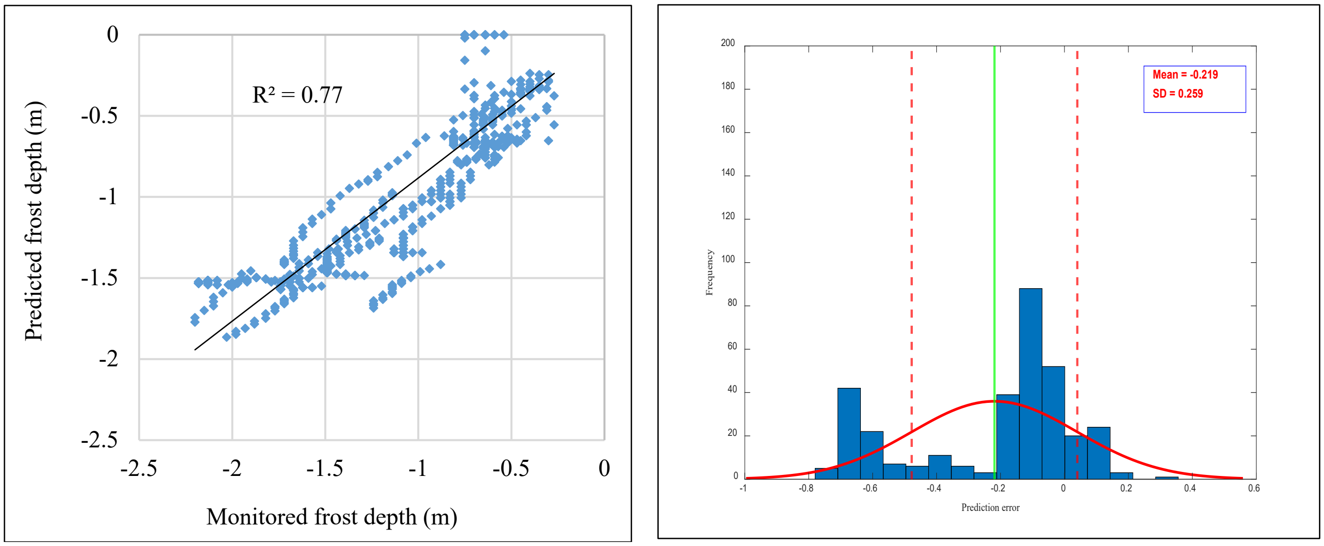
Figure 7- 11 (a) Frost depth vs. days; (b) Frozen zone length vs. days; (c) Daily ambient temp. fluctuation of the simulation duration; (d) Daily precipitation fluctuation of the simulation duration; (e) Model simulated frost heave vs. days

1.1.3 The SMP case analysis conclusions

The model estimated FD, TD, and FL results are compared with the site-monitored data for the nice SMP sections. The results of FH were also obtained and presented. The case analysis evaluates results of either single or multiple freezing-thawing season. The following conclusions from the SMP case study can be outlined:

In general, the 1-D model showed its capability to estimate the FD, TD, FL and frost heave of pavement structure. The model can conduct one-year or multi-years estimation. The model showed basically matched results with the recorded field data, under the condition of level 3 analysis.

Overall, the predicted FD of level 3 analysis well-matched the field measured frost depth for the 9 sections. As shown in Figure 7- 12 (a), a total of 714 pairs of site-measured and predicted FD points were presented in a 1-1 plot. In Figure 7- 12, the R square was 0.77 and the residual (site FD minus predicted FD) mean and standard error were found to be μ= -0.22m and σ = ±0.26m, respectively, as shown in Figure 26 (b). That indicates that the 1-D model slightly underestimate the FD in the SMP case studies. The error of the predicted frost depth is expected due to the use of level 3 input.



(a) (b)

Figure 7- 12 Summary of the predicted and field-measured frost depth for the 9 LTTP sections: (a) measured versus predicted plot, (b) mean and standard errors

The model can predict the shallow depth thawing process during thawing season. The predicted thawing depth matched well with field results for some sections; while for some sections the model predicted thawing process lagged compared with field measured data. This may be due to certain climatic effect at near surface (such as heat associated with snow melting or water infiltration) is not captured by the 1-D model.

For sections with groundwater table far below the frost depth or with low initial soil water content, the frost heave predicted by the model due to volume expansion of water in soil pore space is small (close to 0). Under such condition, the frost heave is mostly induced by segregation potential (SP).

1.2 Calibration and Validation for Finland sites

Since the LTPP database lack the data for frost heave verification, the data presented in the thesis of Saarelainen (1992) was collected and used for further model verification.

1.2.1 Finland sites data collection

The thesis by Saarelainen (1992) documented monitored FD and FH data for six sites in Finland from 1982 to 1984. The site observations were performed by the National Road Administration at Alajarvi and Piippola and the Street Planning Department at Joensuu. The 6 site details are summarized in Table 7- 4. The soil profiles of the sites are presented in Figure 7- 13. In addition to FD and FH data, the thesis presented the layer properties evaluated from site investigation data as well as the site freezing and thawing indices. Since only one freezing-thawing season frost data set is available for each site, the model can merely verify the measured data for no more than 200 days. Given the ambient temperature data (the needed inputs of the new model) in sites is not available directly from the literature review, it was back-calculated from the freezing index data, as shown in Table 7- 5. In this table, the column of Day values starts from the simulation starting time, as presented in Table 7- 6. Table 7- 6 shows the simulation duration and the assumed groundwater table (GWT) depth for each site. The initial temperature right at the beginning of the simulation along the profile is not directly available but is interpolated or extrapolated from the site-measured ground temperature at other times. The thickness, gravimetric water content, thermal conductivity, and dry density of each layer were obtained from soil investigation data. Site-measured water content at the beginning of the freezing season is used in the simulations and it is assumed to be constant during the freezing season simulation. The segregation potential was back calculated using the SSR model (Saarelainen,1992). The soil layer and properties information for all the sites are summarized in Table 7- 7 to Table 7- 12.

Table 7- 4 The six Finland sites information

Site name	Site location	Latitude	Longitude	Monitor point location
Alajarvi	About 37mile ENE of Seinajoki	63°N	23°50'E	A yard of the local road maintenance base
Pippola	About 50mile SE of Oulu	64°11'N	25°55'E	Level ground in a partly paved yard of the road maintenance base
Joensuu point 14	East Joensuu and eastern Finland	62°35'N	29°48'E	Asphalt paved street in a silt area
Joensuu point 20	About 984ft west of point 14	62°35'N	29°48'E	Slope of a moraine hill covered by silt deposits
Joensuu point 33	East Joensuu and eastern Finland	62°35'N	29°48'E	Not available
Joensuu point 38	NE of Joensuu and eastern Finland	62°35'N	29°48'E	On a paved street

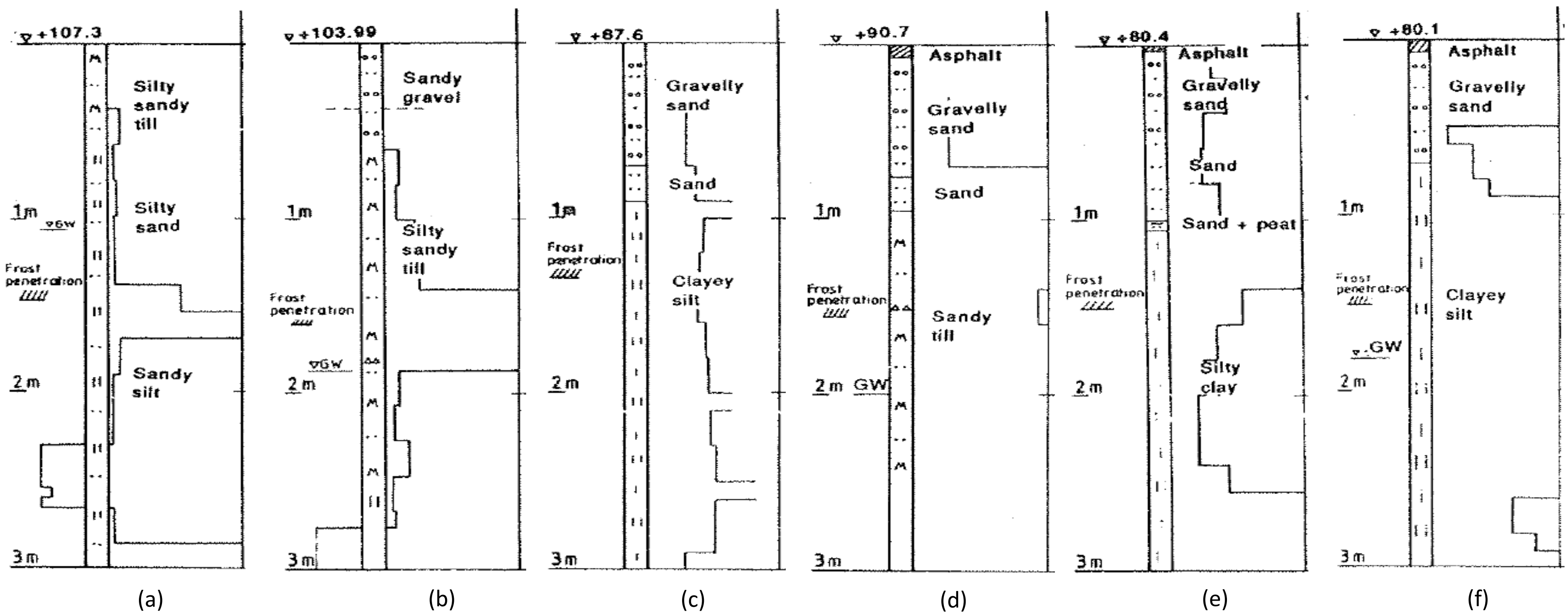


Figure 7- 13 Soil profiles of the site: (a) Alajarvi; (b) Pippola; (c) Joensuu point 14; (d) Joensuu point 20; (e)Joensuu point 33; (f) Joensuu point 38

Table 7- 5 Ambient temperature back-calculated using freezing index

Alajarvi		Piippola		Joensuu P14		Joensuu P20		Joensuu P33		Joensuu P38	
Day	Temp. (K)	Day	Temp. (K)	Day	Temp. (K)	Day	Temp. (K)	Day	Temp. (K)	Day	Temp. (K)
0.0	273.15	0.0	273.15	0.5	273.15	0.8	273.15	0.0	273.15	0.3	273.15
7.0	266.20	15.3	267.40	17.3	270.82	16.2	271.34	14.5	271.13	13.5	273.05
14.2	267.21	30.3	270.38	34.8	269.68	31.5	269.16	29.3	268.50	27.3	270.88
21.3	273.05	45.4	271.60	52.8	269.66	46.7	268.90	45.2	269.29	40.5	268.36
42.2	271.88	60.2	263.32	69.8	267.48	61.7	266.59	60.5	266.94	54.0	269.30
49.1	270.59	74.9	256.12	87.0	259.38	77.4	257.96	75.0	256.56	67.0	272.18
56.1	266.54	90.2	266.23	104.4	265.60	92.8	264.76	90.6	264.69	80.8	266.25
62.9	263.76	105.3	265.39	121.2	261.83	108.7	263.42	105.4	263.09	94.8	255.58
84.2	264.77	120.2	272.61	173.0	293.15	124.0	271.09	120.5	270.68	108.5	263.53
91.1	266.11	135.4	272.41	-	-	139.2	272.22	-	-	121.9	261.67
98.3	262.24	-	-	-	-	154.7	272.55	-	-	135.4	270.69
119.1	271.76	-	-	-	-	180.0	281.15	-	-	165.0	283.15

Table 7- 6 Simulation durations and assumed GWT of the 6 sites

Site name	Simulation start time	Simulation end time	Simulation duration	Assumed GWT depth (ft)
Alajarvi	12/1/1982	3/28/1983	117	2.62
Piippola	12/1/1982	4/15/1983	135	4.92
Joensuu P14	12/1/1982	5/23/1983	173	4.26
Joensuu P20	11/25/1982	5/30/1983	186	6.56
Joensuu P33	11/25/1982	3/25/1983	120	4.92
Joensuu P38	11/11/1982	3/25/1983	134	5.25

Table 7- 7 Soil layer properties at site Alajarvi

Layer #	Gravimetric water content (%)	Dry density (pcf)	Thermal conductivity of unfrozen soil (BTU/h·ft·°F)	Thermal conductivity of frozen soil (BTU/h·ft·°F)	Layer thickness (ft)	SP (in2/Kh)
1	31	81.16	0.75	1.33	1.64	0.039
2	15	109.25	1.27	1.73	0.98	0.014
3	25	99.89	0.98	1.27	1.64	0.039
4	25	99.89	0.98	1.27	3.28	0.099

Table 7- 8 Soil layer properties at site Piippola

Layer #	Gravimetric water content (%)	Dry density (pcf)	Thermal conductivity of unfrozen soil (BTU/h·ft·°F)	Thermal conductivity of frozen soil (BTU/h·ft·°F)	Layer thickness (ft)	SP (in2/Kh)
1	10	106.13	1.06	1.09	0.98	0.000
2	15	109.88	1.28	1.76	1.97	0.076
3	15	113.62	1.39	2.00	0.98	0.099
4	15	113.62	1.39	2.00	0.98	0.126
5	16	109.25	1.28	1.83	0.98	0.056

Table 7- 9 Soil layer properties at site Joensuu P14

Layer #	Gravimetric water content (%)	Dry density (pcf)	Thermal conductivity of unfrozen soil (BTU/h·ft·°F)	Thermal conductivity of frozen soil (BTU/h·ft·°F)	Layer thickness (ft)	SP (in2/Kh)
1	8	118.62	1.32	1.36	2.30	0.000
2	15.4	112.37	1.36	1.97	0.33	0.000
3	21	106.13	0.95	1.23	0.98	0.099
4	23.8	99.89	0.87	1.20	3.28	0.099

Table 7- 10 Soil layer properties at site Joensuu P20

Layer #	Gravimetric water content (%)	Dry density (pcf)	Thermal conductivity of unfrozen soil (BTU/h·ft·°F)	Thermal conductivity of frozen soil (BTU/h·ft·°F)	Layer thickness (ft)	SP (in2/Kh)
1	5	118.62	0.94	1.14	2.46	0.000
2	6	112.37	0.88	1.05	0.66	0.000
3	7	106.13	0.81	0.95	1.64	0.006
4	20	99.89	1.65	1.09	1.64	0.006

Table 7- 11 Soil layer properties at site Joensuu P33

Layer #	Gravimetric water content (%)	Dry density (pcf)	Thermal conductivity of unfrozen soil (BTU/h·ft·°F)	Thermal conductivity of frozen soil (BTU/h·ft·°F)	Layer thickness (ft)	SP (in2/Kh)
1	5	118.62	1.14	0.94	1.97	0.000
2	15.4	114.87	1.36	1.92	1.64	0.000
3	18.4	108.63	0.90	1.08	0.98	0.262
4	18	113.62	0.79	1.21	1.64	0.155

Table 7- 12 Soil layer properties at site Joensuu P38

Layer #	Gravimetric water content (%)	Dry density (pcf)	Thermal conductivity of unfrozen soil (BTU/h·ft·°F)	Thermal conductivity of frozen soil (BTU/h·ft·°F)	Layer thickness (ft)	SP (in2/Kh)
1	10	118.62	1.35	1.48	2.30	0.000
2	25	99.89	0.88	1.25	1.64	0.155
3	25	99.89	0.88	1.25	1.64	0.155
4	25	99.89	0.88	1.25	1.64	0.155

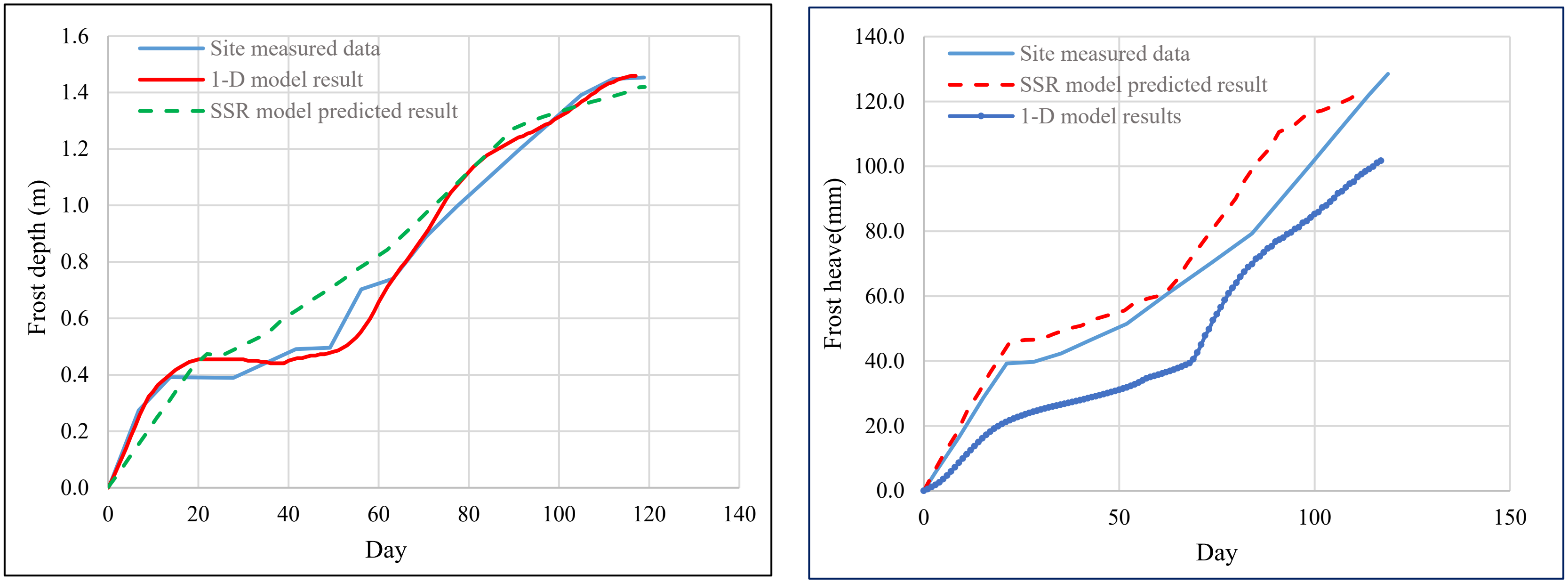
1.2.2 Model verification using Finland sites data

Since GWT and initial temperature inputs are missing, assumptions were made on them to satisfy the 1-D model inputs requirement. Hence, a quasi-Level 1 case analysis was conducted for the 6 Finland sites. The simulation starting time, ending time, and duration are summarized in Table 7- 6 above.

The simplified 1-D model predicted FD and FH are compared with the Saarelainen (1992) model (called SSR model) results and the site-measured data. The comparison is presented in Figure 7- 14 to Figure 7- 19. Note that the 1-D model FH results shown in the figures are the total heave, which is the summation of FH due to water expansion and FH due to SP.

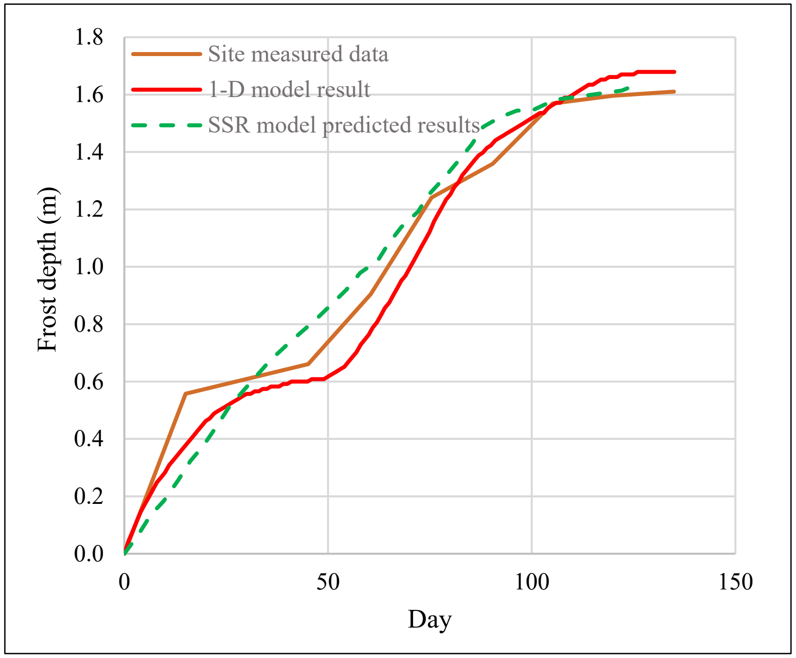
As shown in Figure 7- 14 to Figure 7- 19, the model showed well-matched FD and overall trend-matched, but underestimated FH. The predicted FH for the Joensuu P14, P20, P33, and P38 sites showed apparent lagged effect. Such lag is likely induced by the underestimation of water expansion heave. This is because the model assumes that when the soil volumetric water content is less than 0.91 of the soil porosity, no FH will be induced by water expansion. However, according to the sited-measured data, FH still occurred in the layers with volumetric water content less than 0.9 porosity and without any SP (e.g., Figure 7- 18 and Figure 7- 19). Such additional expansion may be responsible for the increasing of the water content of the unsaturated soil during freezing season.

The FD and FH 1-1 plots and the corresponding residual error statistics plots are shown in Figure 7- 20 to Figure 7- 23, where 741-pair of FD and FH values are compared. In Figure 7- 20, the R square is 0.97 with 0.95 slope of the linear fitting curve, which indicates well-matched FD. Figure 7- 21 shows -5cm mean and ±8cm standard deviation of the FD prediction error (Predicted FD minus site FD). In Figure 7- 22, the R square is 0.79 with 0.68 slope of the linear fitting curve, which indicates a trend-matched but slightly underestimated FD, while Figure 7- 23 shows -1.7cm mean and ±1.7cm standard deviation of the FH prediction error (Predicted FH minus site FH). The general underestimation is of small magnitude. This indicates acceptable FH prediction accuracy for the 5 sites using the 1-D model.

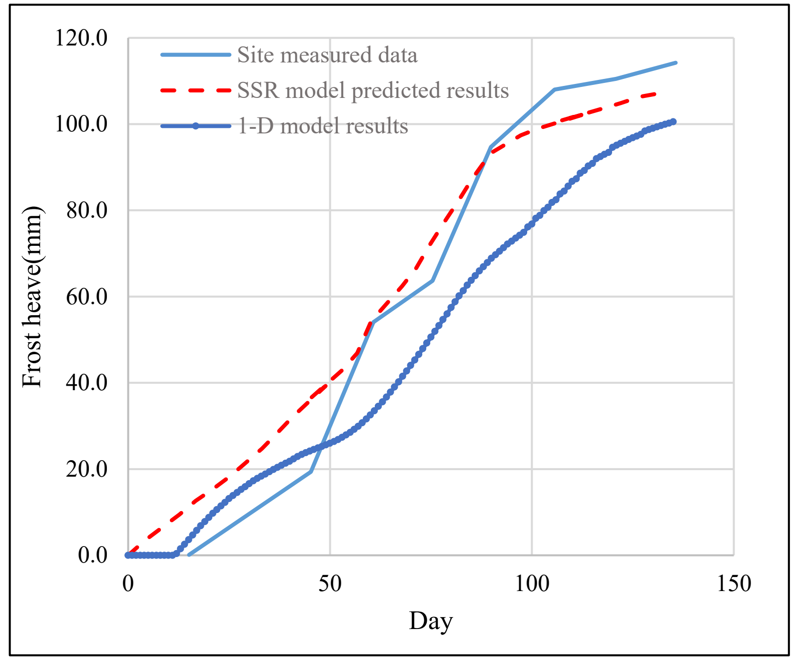


(a) (b)

Figure 7- 14 Site-measured data comparison with model predictions for Alajarvi site: (a) FD progression; (b) FH progression.



(a)



(b)

Figure 7- 15 Site-measured data comparison with model predictions for Piipola site: (a) FD vs. days; (b) FH vs. days.

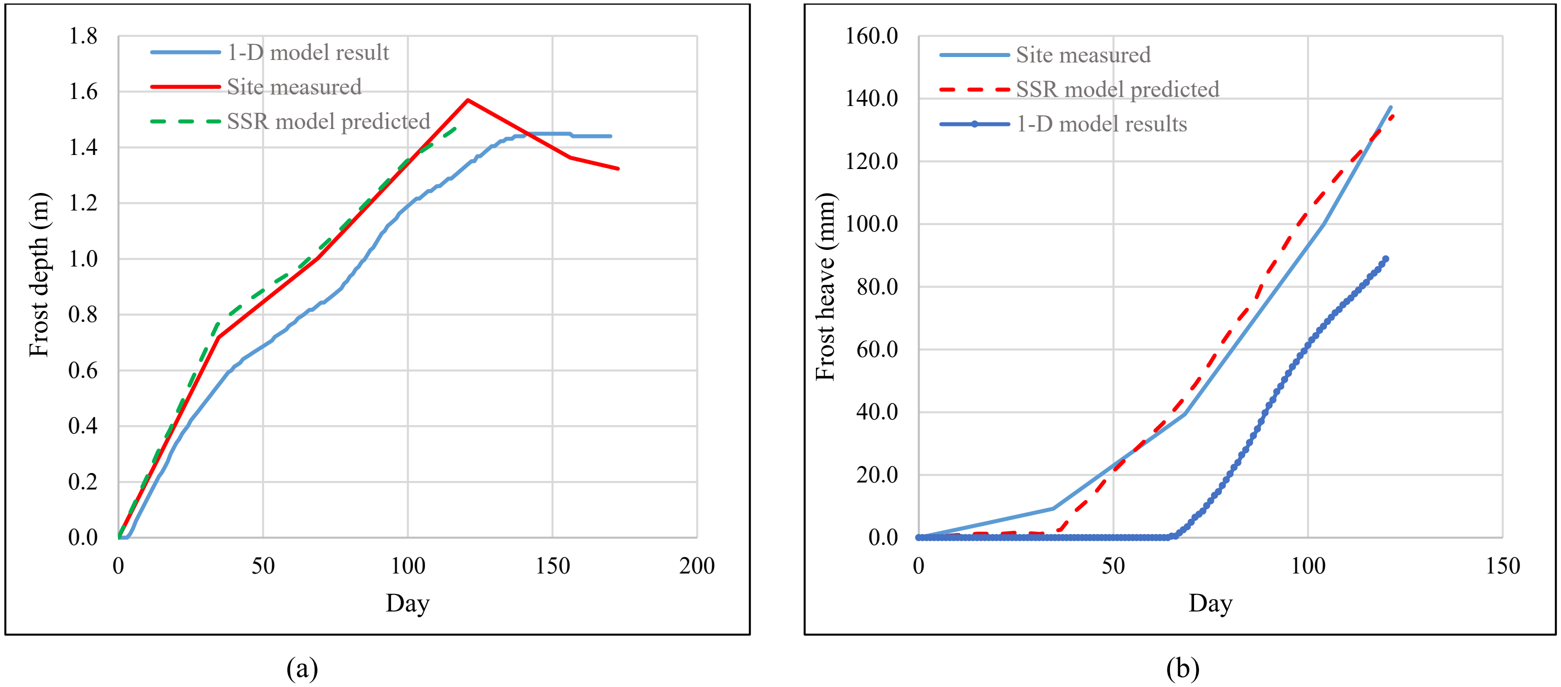


Figure 7- 16 Site-measured data comparison with model predictions for Joensuu P14 site: (a) FD vs. days; (b) FH vs. days.

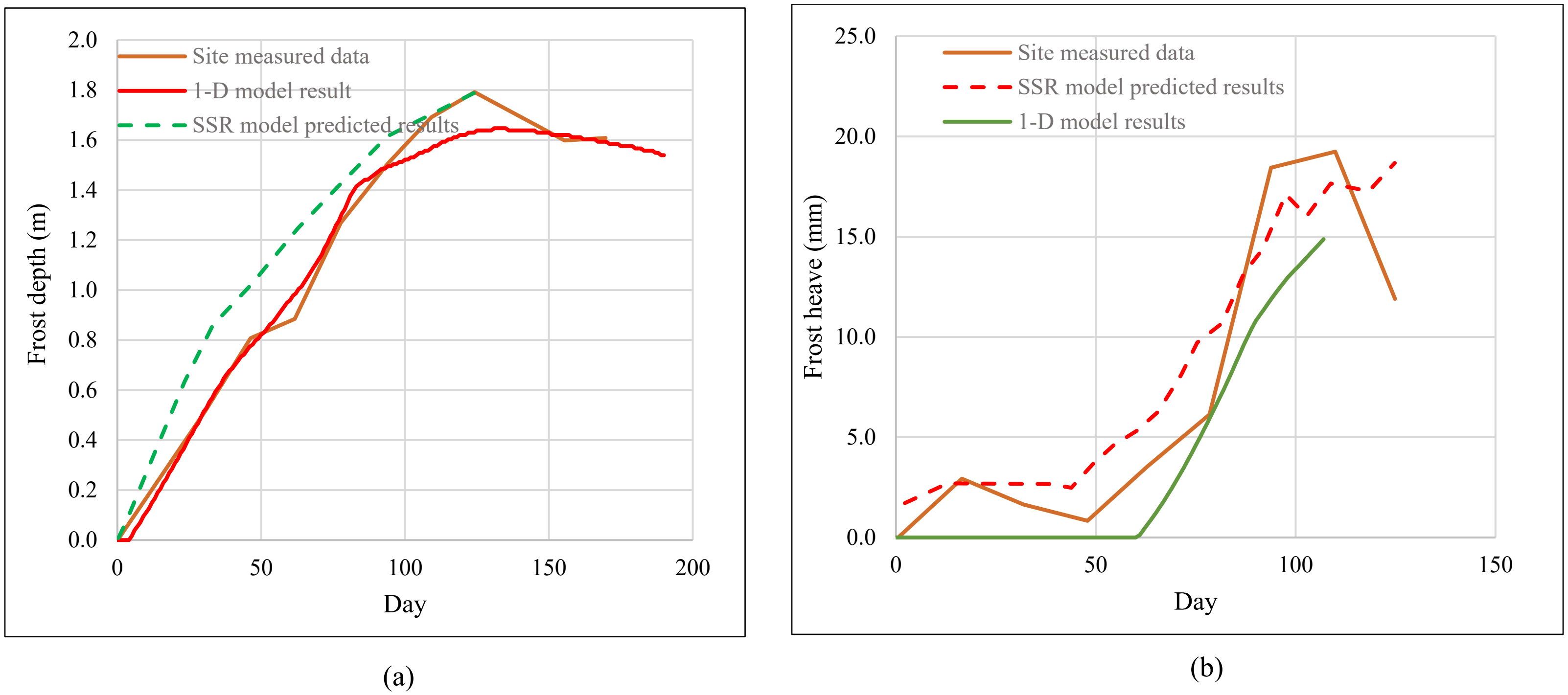


Figure 7- 17 Site-measured data comparison with model predictions for Joensuu P20 site: (a) FD vs. days; (b) FH vs. days.

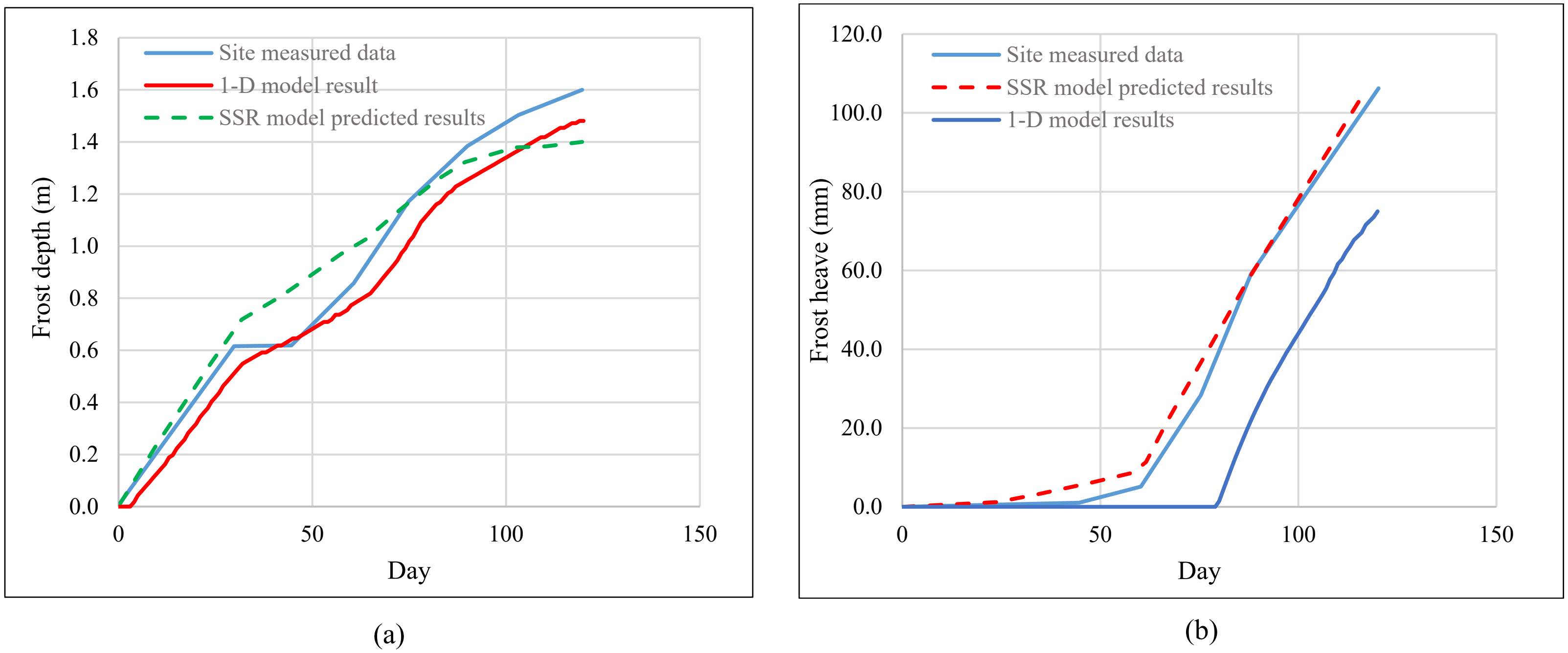
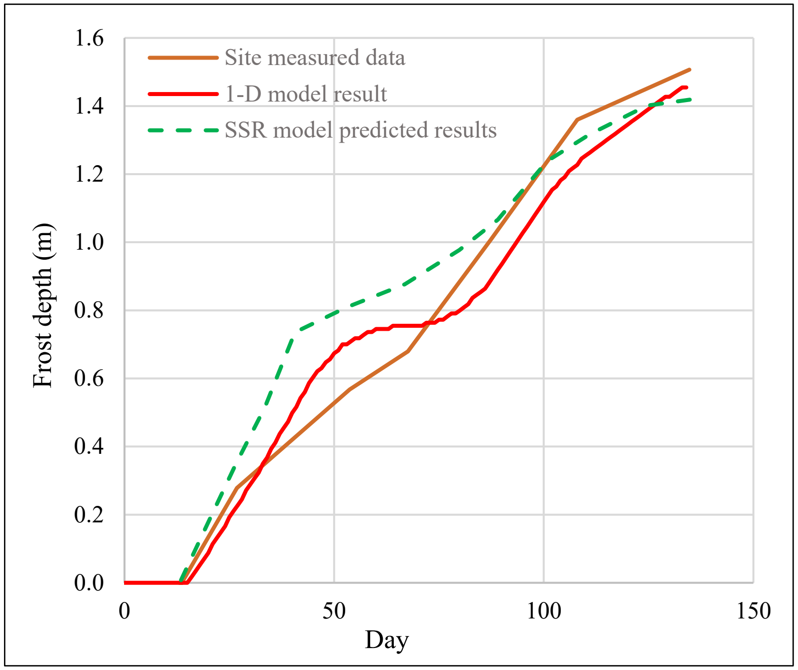
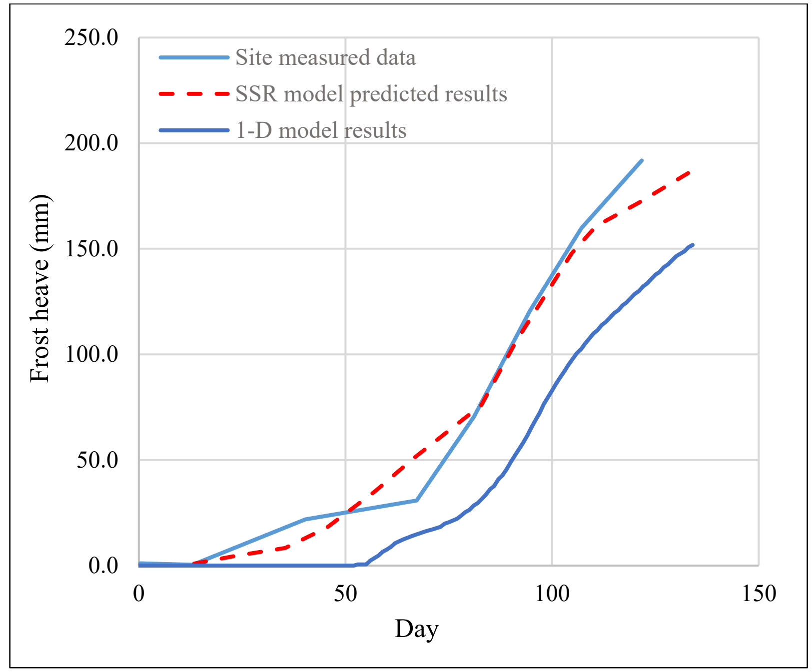


Figure 7- 18 Site-measured data comparison with model predictions for Joensuu P33 site: (a) FD vs. days; (b) FH vs. days.



(a)



(b)

Figure 7- 19 Site-measured data comparison with model predictions for Joensuu P38 site: (a) FD vs. days; (b) FH vs. days.

.

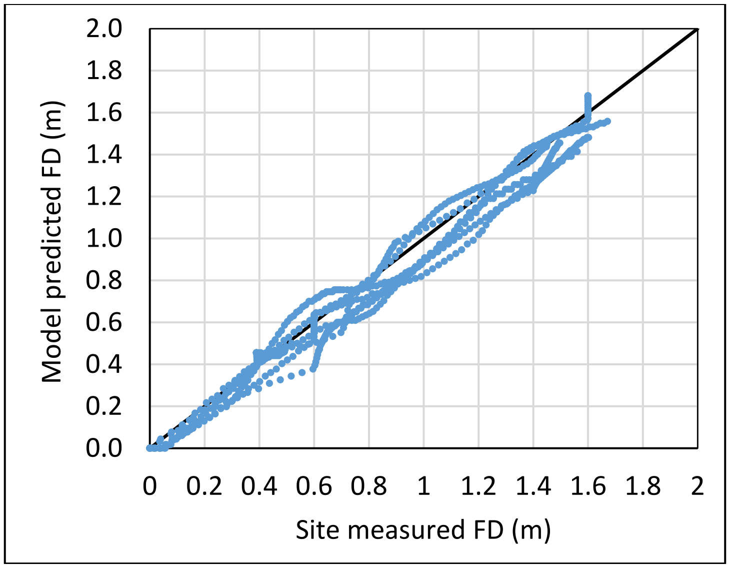


Figure 7- 20 The 1-1 plot of the 741-pair FD values

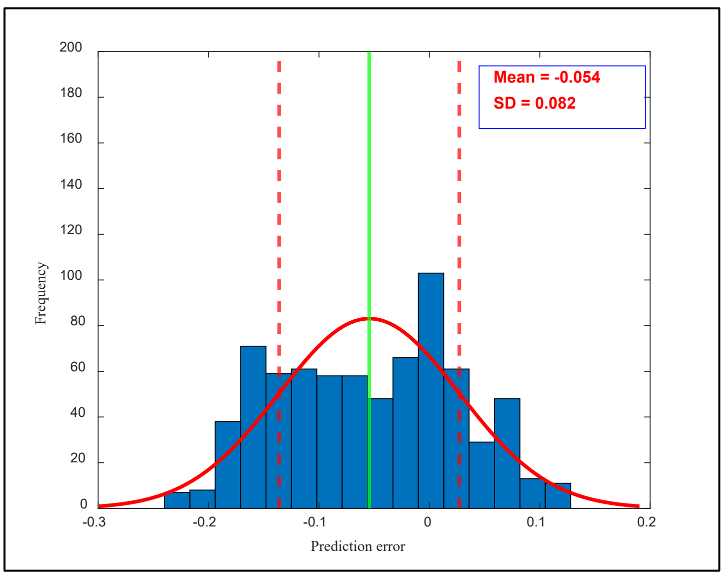


Figure 7- 21 The 741-pair FD prediction residual error statistics results

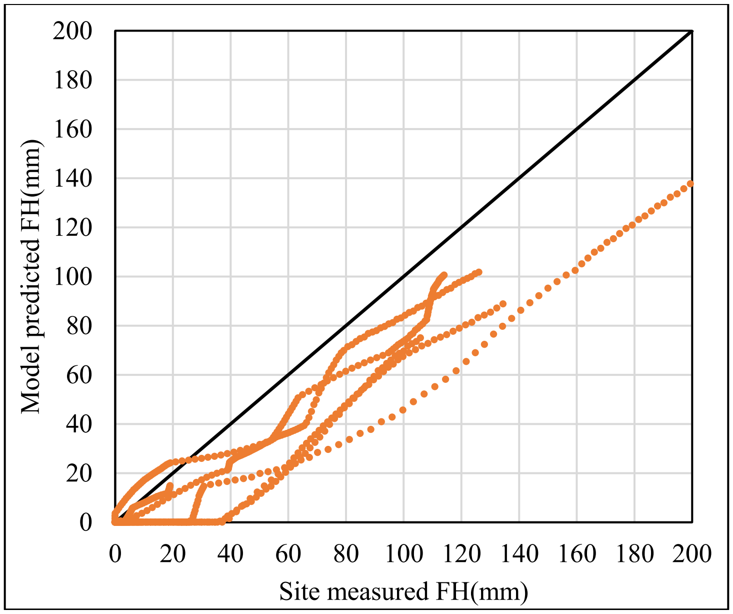


Figure 7- 22 FH Comparison plot of 741-pair FH values

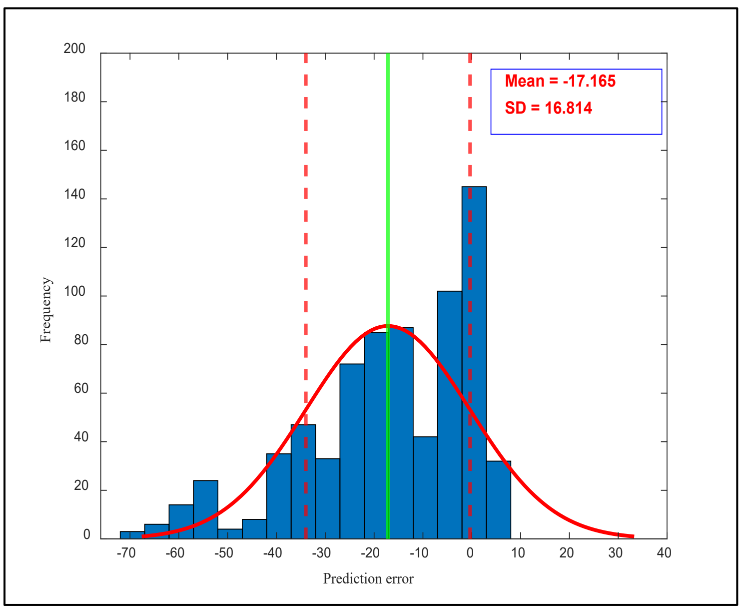


Figure 7- 23 741-pair FH (mm) prediction error statistics results

1.2.3 The Finland sites case analysis conclusions

Through a series of quasi-level 1 case study for the 6 Finland sites, the following conclusions are made:

Overall, the computed FD well-matched the field measured FD for the 6 sites as shown in Figure 7- 20 and Figure 7- 21. The minor error of FD estimation may come from the assumptions made on the GWT and initial temperature input values.

In the quasi-Level-1 analysis, the FH evaluation shows overall matched trend but somewhat underestimated values. The possible reason is current 1-D model assumed constant water content for the FH evaluation, but the water content should vary with time in practice. However, the general underestimation is not of high magnitude, so the model predicted FH should be acceptable according to the case results of the 6 Finland sites.

Only 6 sites data were used for current FH verification. Case study with more field data should give more hints for the 1-D model FH verification. If more field data was available, it may deserve a try to propose certain coefficients or equations to correct the model evaluated FH.

Note that the SP value used for the case studies are real site values. However, the SP values is usually not measured in engineering practice. That is why the 1-D model did not require SP as input for any level, whereas the gradation correlation equations (see details in Appendix 6) are utilized to evaluate SP. Due to the lack of gradation data of the Finland sites, the gradation correlation evaluated SP determined FH cannot be verified.

1.3 Reference

NCHRP 1-37A (2004). *Mechanistic-Empirical Design of New and Rehabilitated Pavement Structures*, Final Report, National Cooperative Highway Research Program NCHRP Project 1-37A, Transportation Research Board, National Research Council, Washington, D.C.

Kaplar, C.W. (1974). "A Laboratory Freezing Test to Determine the Relative Frost Susceptibility of Soils," *Technical Report TR 250*, Cold Regions Research and Engineering Laboratory (CRREL), U.S. Army Corps of Engineers, 1974.

Saarelainen, S. (1992). Modelling frost heaving and frost penetration in soils at some observation sites in Finland: the SSR model.