Predictive Modeling of Freezing and Thawing of Frost-susceptible Soils

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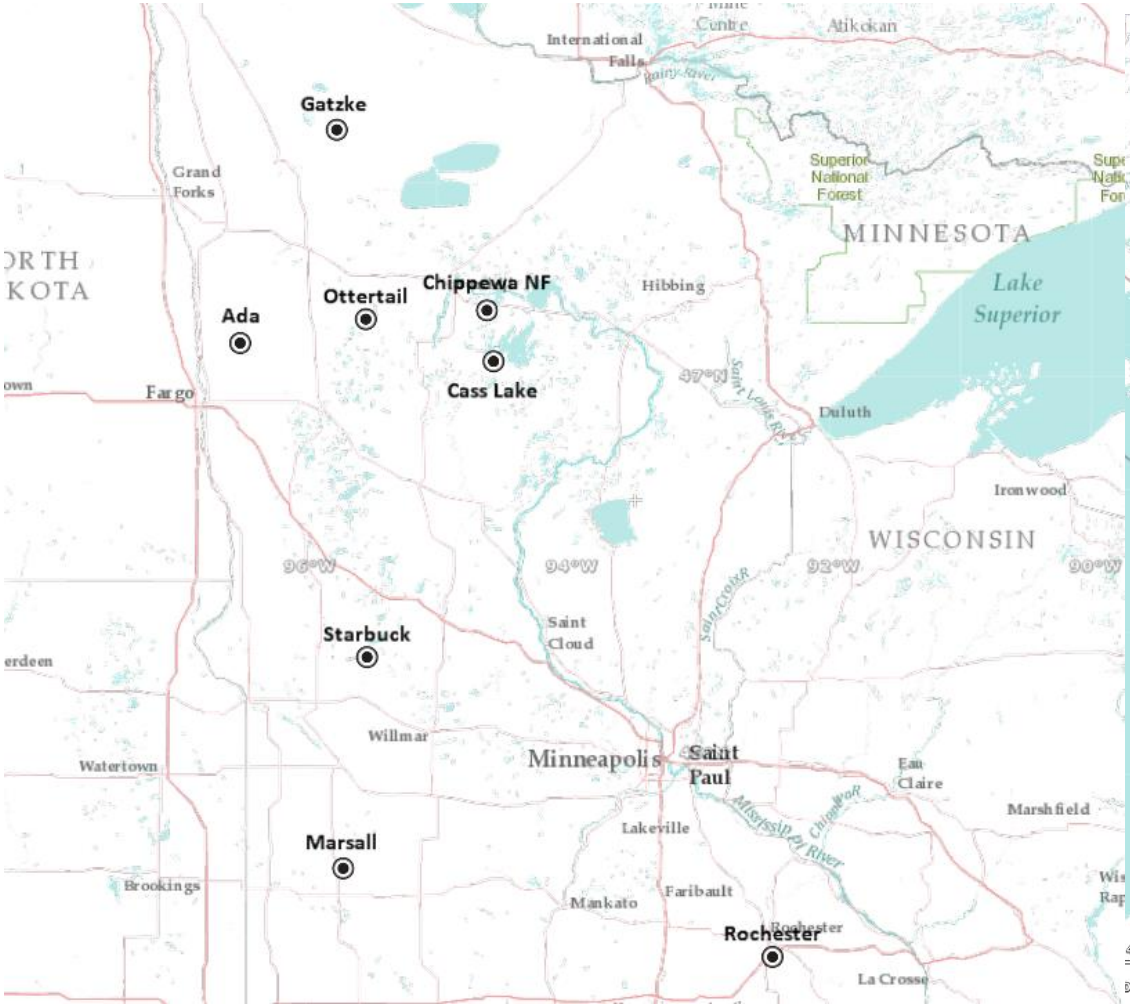
Soil Temperature Database



Minnesota Database

Soil Thermal Properties Data

The thermal conductivity and heat capacity of six disturbed and saturated soil types measured in the lab using a KD2 pro thermal properties analyzer (ASTM D5334-08).

Station Name	Material	Moisture Condition	Thermal Conductivity (Btu/(ft.hr.°F))	Heat Capacity (Btu/(ft^3.°F))
Houghton Lake	SILTY fine SAND with trace of GRAVEL	Saturated	1.49	39.84
	Fine SAND		1.48	42.37
Wolverine	Fine SAND with trace of GRAVEL		1.44	40.13
	Fine SAND		1.40	40.13
	Soft CLAYEY SANDY , some SILT & some GRAVEL		1.01	44.46
Williamsburg	SILTY CLAY		0.88	46.25
Rudyard	SILTY CLAY		0.65	47.74

Frost Depth Model – All Soils

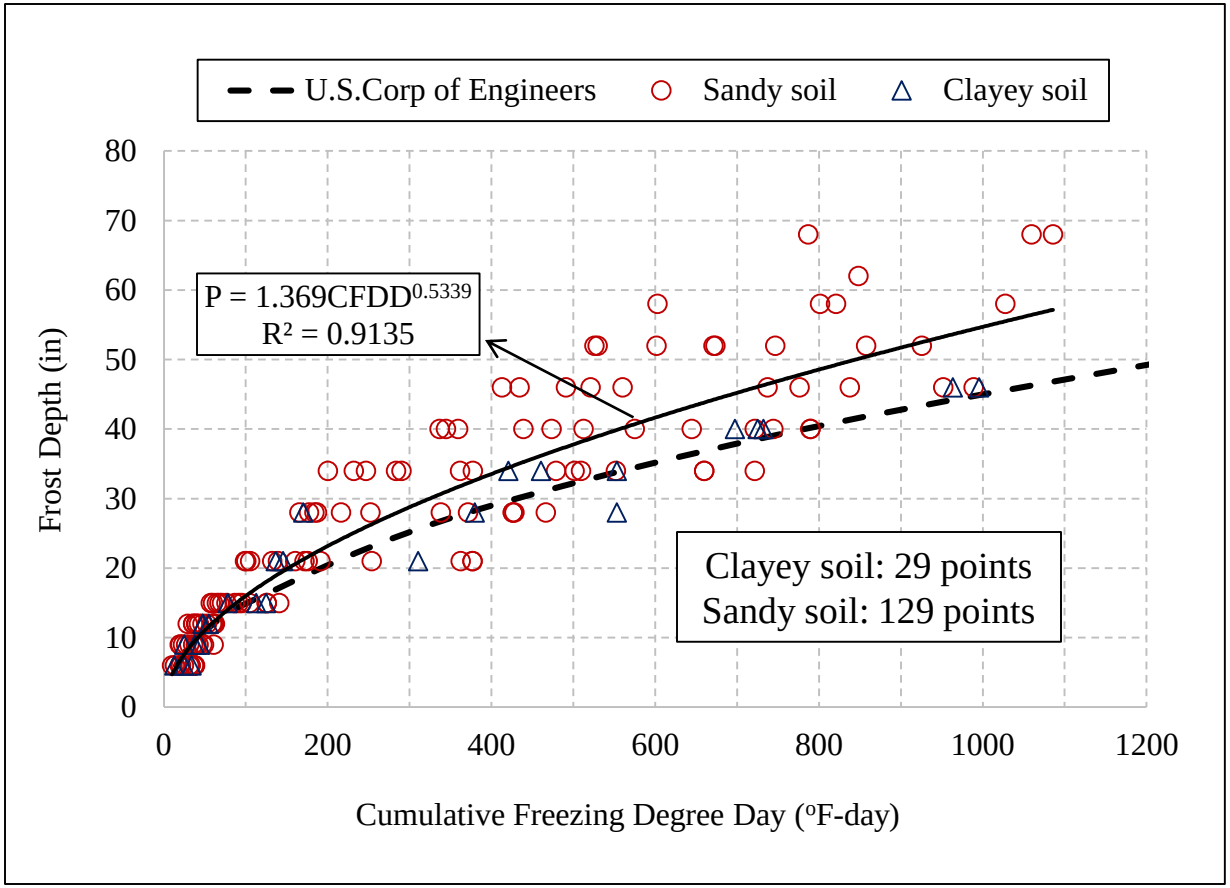
- ***Developed empirical models using measured frost depth data in the state of Michigan***

$$P = 1.369 * CFDD^{0.5339}$$

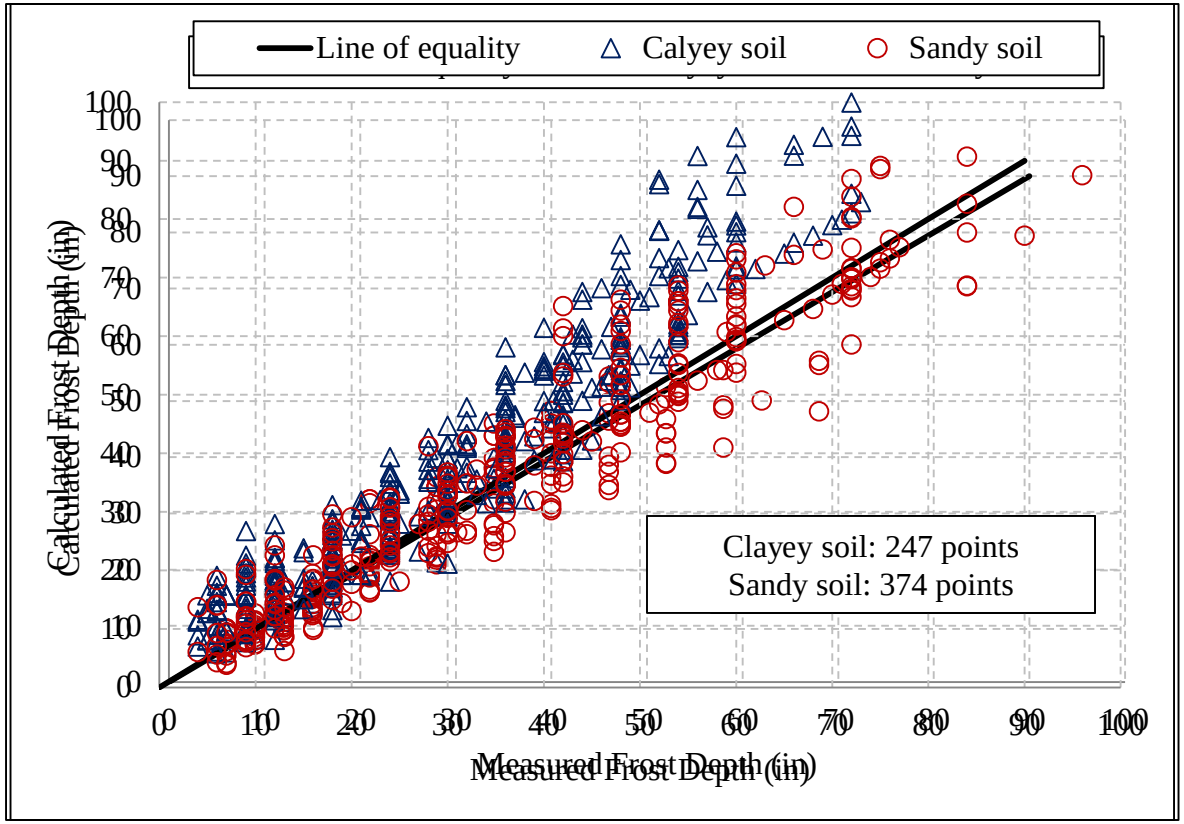
Where P= frost depth (in);and

CFDD= cumulative freezing degree day (^{o}F-day).

$$CFDD = \sum_{i=1}^{n} T_i - 32^o, The\ absolute\ value\ of\ CFDD\ is\ used\ in\ the\ equation$$



Measured frost depths versus cumulative freezing degree day for clayey and sandy soils in the State of Michigan



Calculated versus measured frost depths for clayey and sandy soils in the State of Minnesota

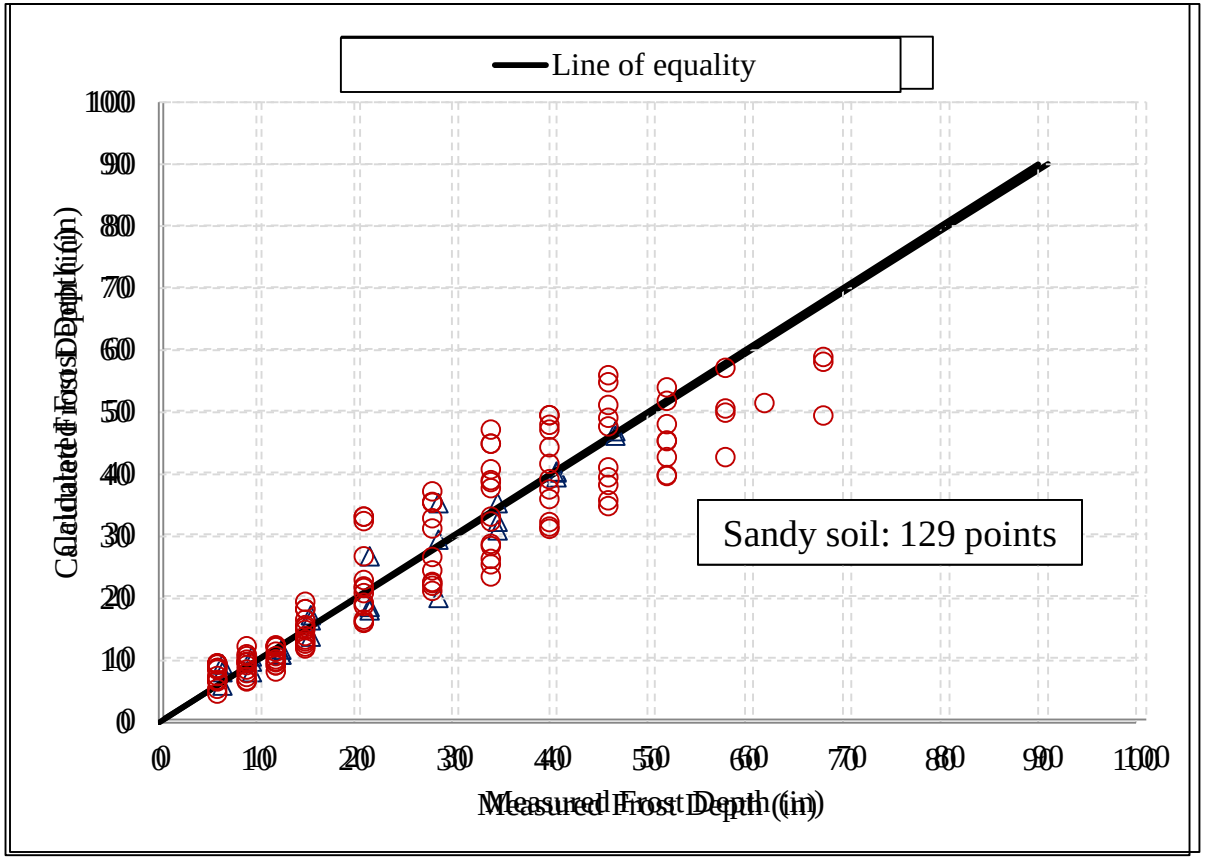
Frost Depth Models

- ***Developed two empirical models for measured frost depth data in the state of Michigan; one model for clayey and one for sandy soils***

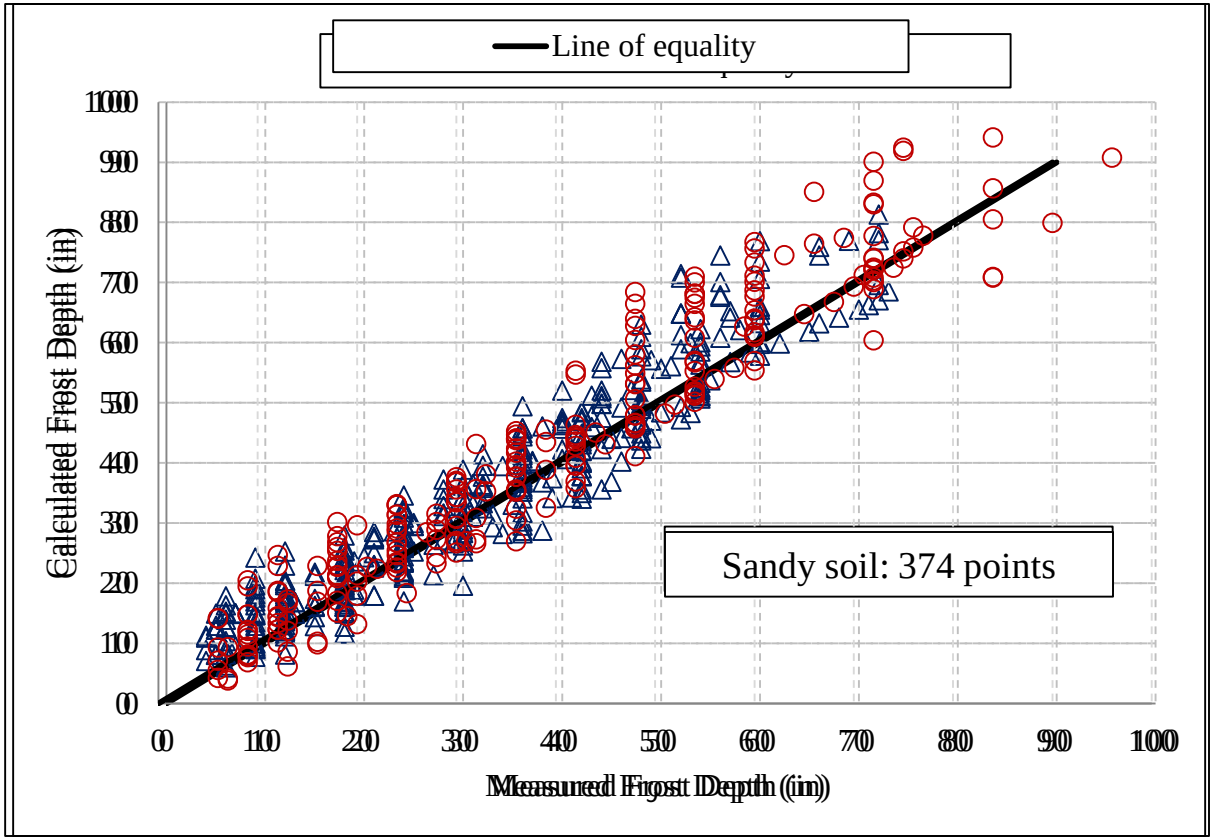
For clayey $P_c = 1.5901 * CFDD^{0.4896}$

For sandy $P_s = 1.3302 * CFDD^{0.5423}$

Where P_c= frost depth in clayey soils(in);
P_s= frost depth in sandy soils(in) ; and
CFDD= cumulative freezing degree day (^{o}F-day).



Calculated versus measured frost depths for sandy soil in the State of Michigan



Calculated versus measured frost depths for sandy soil in the State of Minnesota

Introducing Thermal Conductivity

So far, We Got $P_c = 1.5901 * CFDD^{0.4896}$ for clayey soils

and

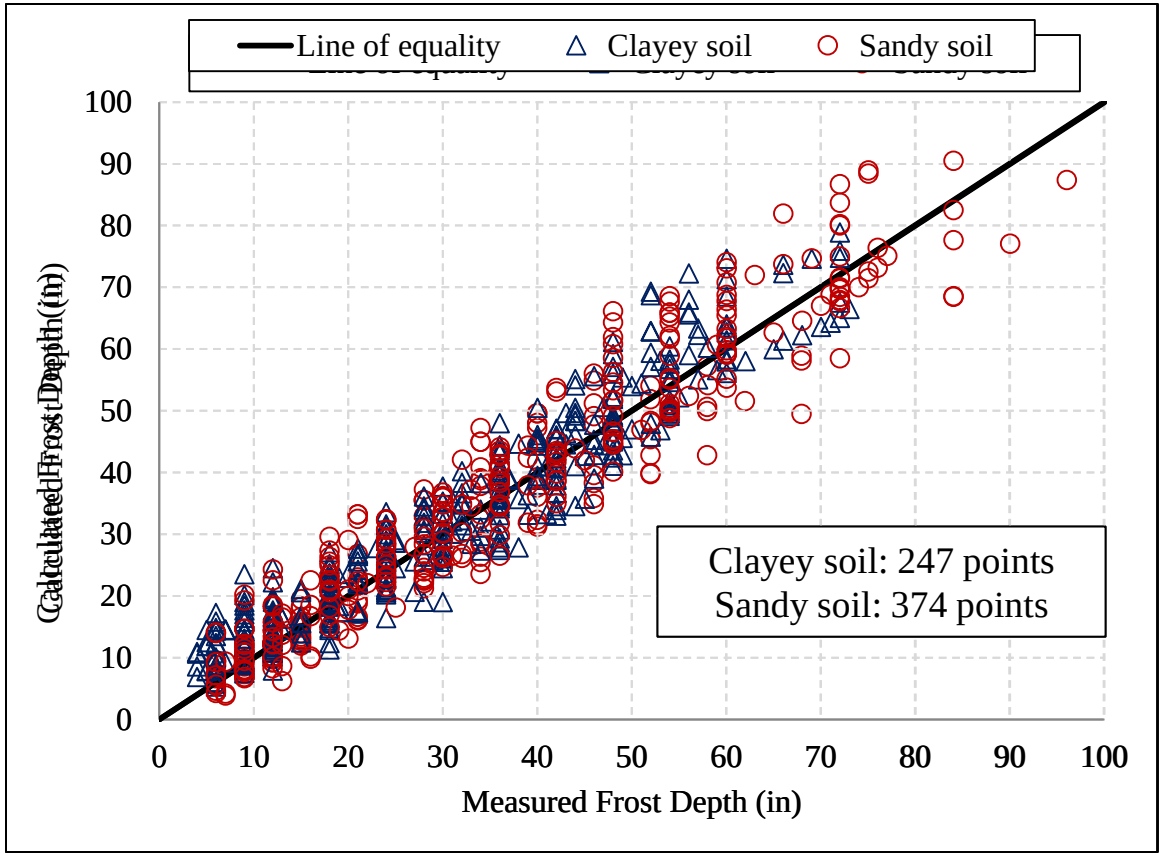
$P_s = 1.3302 * CFDD^{0.5423}$ for sandy soil

- ***The above equations were combined into one equation based on the average measured thermal conductivity of two soil types.***

$$P = (-0.45\,k + 1.9614) * CFDD^{(.0913k+0.4143)}$$

Where k = thermal conductivity [0.825 and 1.4025 Btu/(ft.hr.°F) for clayey and sandy soils, respectively]; and

All other parameters are the same as before.



Calculated versus measured frost depths for clayey and sandy soil in the State of Minnesota

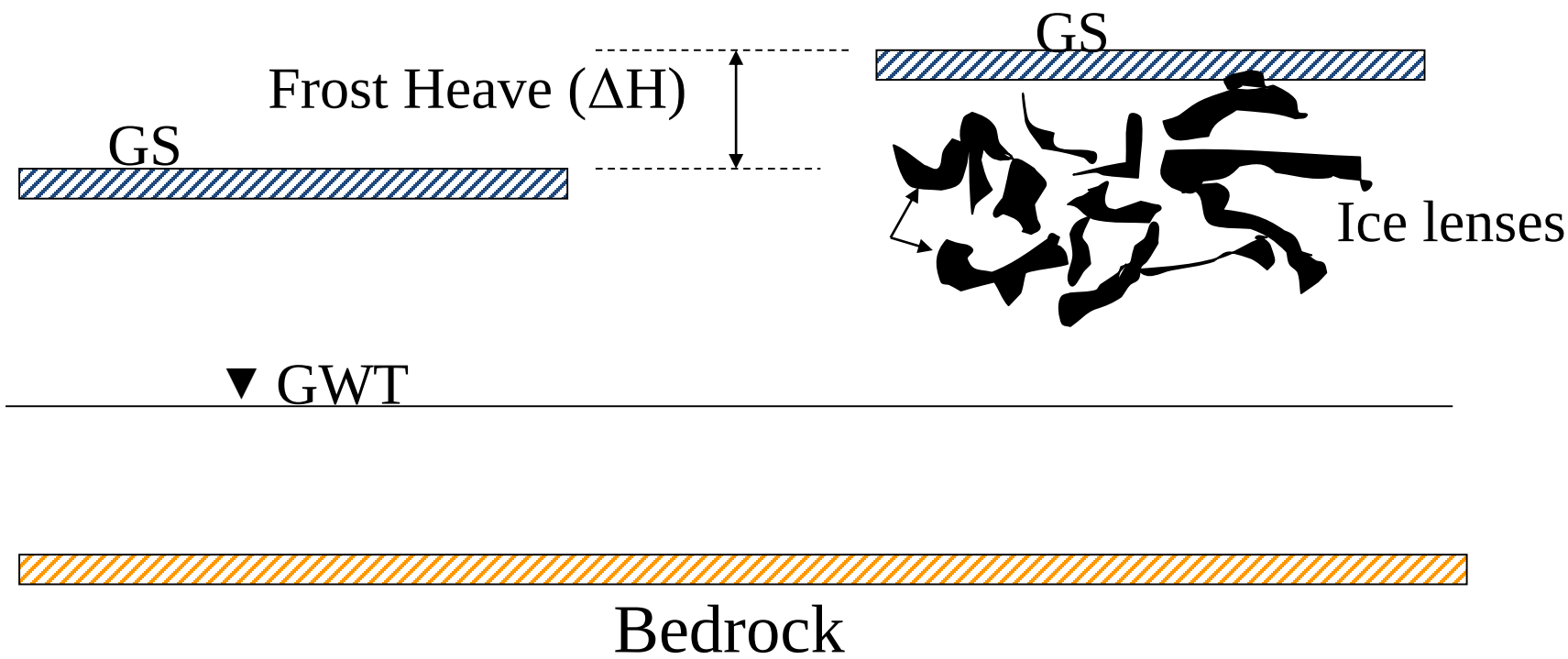
Calculated versus measured frost depths for clayey and sandy soil in the State of Michigan

Frost Action

- When pore water freezes, it causes 10% volume expansion.
- When ice lenses are formed, additional water is drawn toward the freezing front by vapor and capillary action.
- When the ice lenses melt they cause saturation, low strength, which result in possible pavement failure (potholes, depressions, etc.).

Frost Heave

The growth of ice lenses causes ground heave causing damage to pavements, shoulders, utility lines, and unprotected foundations (Liu et al. 2012).



Frost Heave

- Frost susceptible soils
- Temperature below freezing point
- Availability of water source

Frost Heave Theories

Taber (Taber, 1930) was the first to address frost heave.

During the freezing process, water migrates toward the frozen front causing ice lenses to grow.

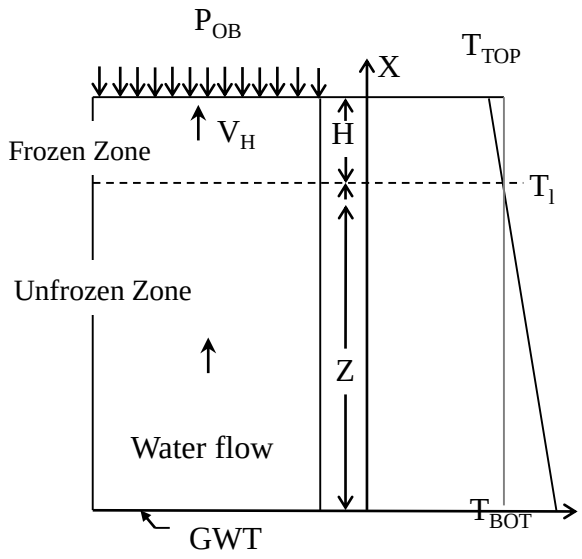
Frost heave is a function of soil type, grain size, freezing rate, availability of water and the overburden pressure.

Theories

- **Capillary theory (primary frost heave)**
- **Frozen Fringe (secondary frost heave)**

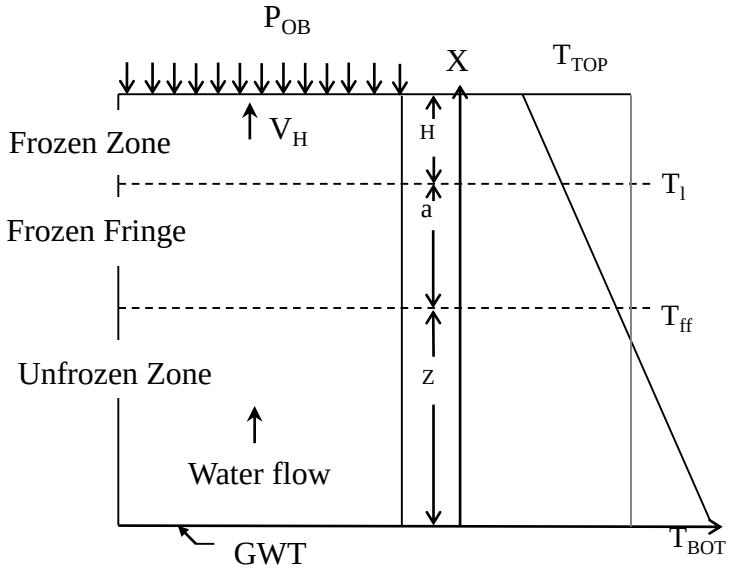
Capillary Theory

- based on the Clapeyron equation
- Frozen region
- Unfrozen region (water moves upward toward the frozen front)

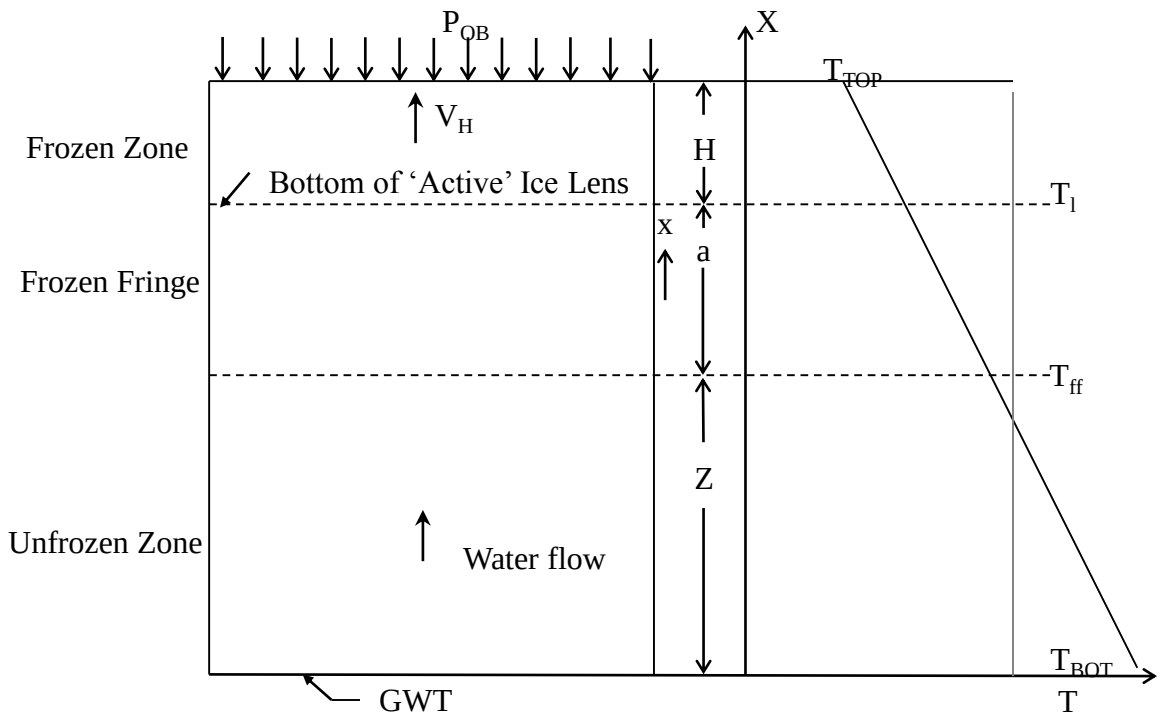


Frozen Fringe Theory

- Frozen region
- Frozen fringe region (Water might exist in temperature below freezing)
- Unfrozen region (Dash et al. 2006).



The Revised Gilpin Frost Heave Model



In this study, the Gilpin model was simplified

- Simplification of the required input data.
- Inclusion of a statistical frost depth model.
- The modified model was evaluated using field data

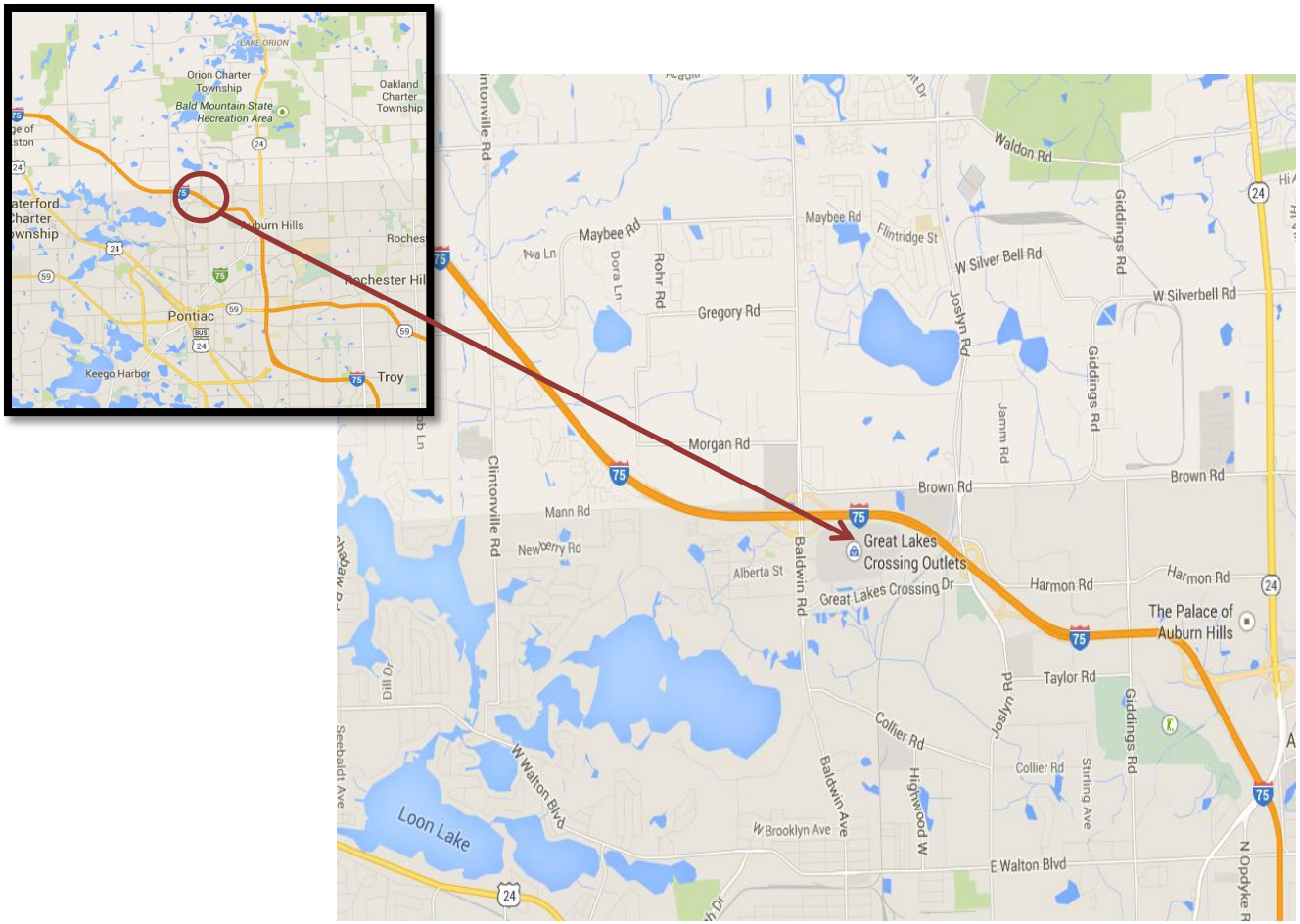
The Revised Gilpin Frost Heave Model

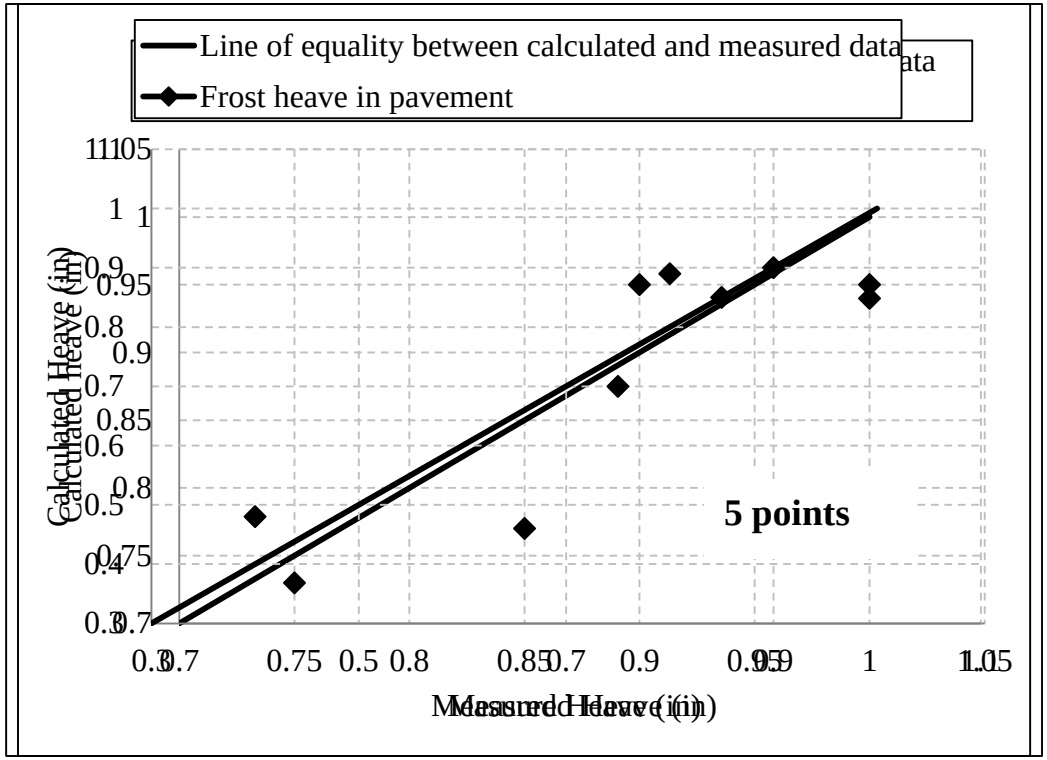
- ✓ The modified equation was coupled with the heat balance equation to predict the temperature at the top of the frozen fringe.

- ✓ Results of the heat balance equation were used in the mass balance equations to predict frost heave rate.

Evaluation

The revised frost heave model was evaluated using measured frost heave data provided by MDOT under the shoulders and pavements of five sites located in Oakland County, Michigan.





Measured versus calculated frost heave for 5 sites in Oakland County, Michigan (pavement heave)

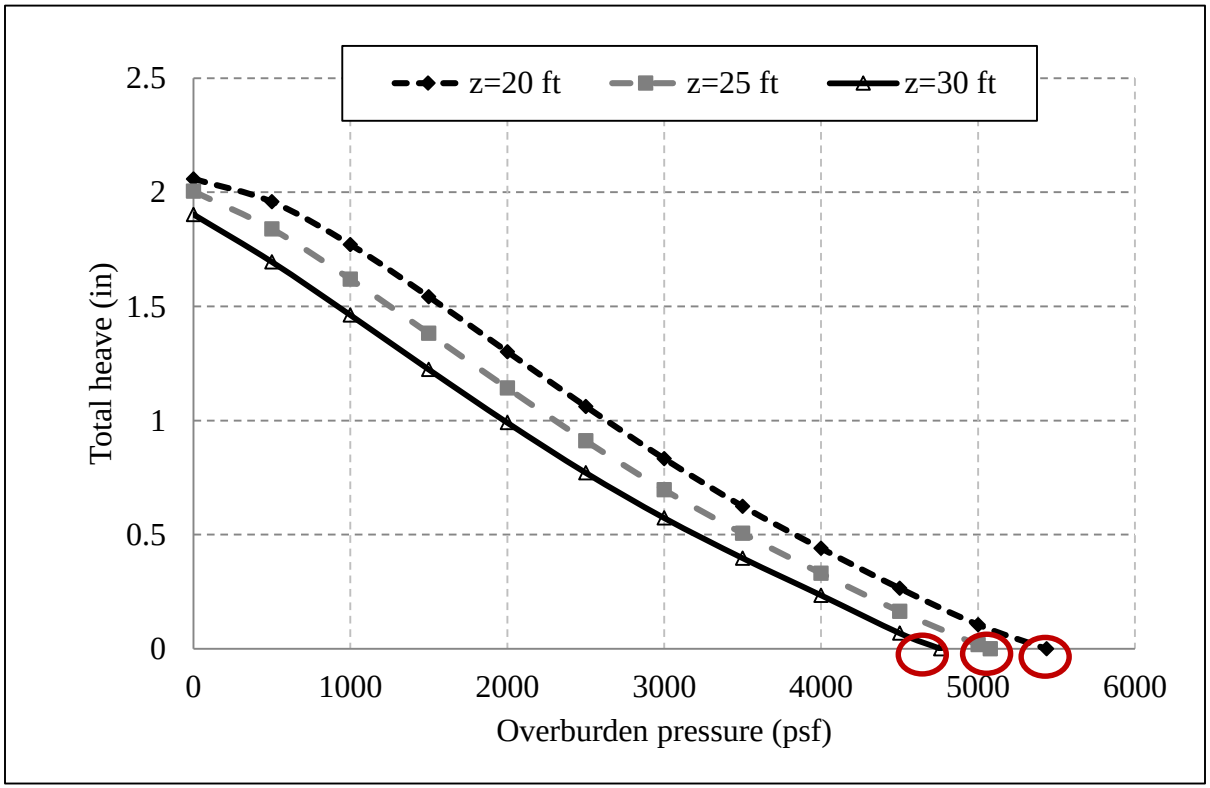
Heave Pressure

- Frost heave will cause upward pressure against the foundation. When the upward pressure becomes higher than the downward pressure the foundation will move upward.

- Behind most retaining structures, the frost pressure is oriented horizontally against the wall. The combination of frost and active earth pressures may cause the wall to slide horizontally along its foundation.

Heave Pressure Model

Equilibrium Overburden Pressure



Calculated total heave versus overburden pressure for clayey silt with pebbles in different ground water table depths when T_{TOP}= 26 ºF in 100 days

Heave Pressure Model

The heave pressure can be calculated as follows:

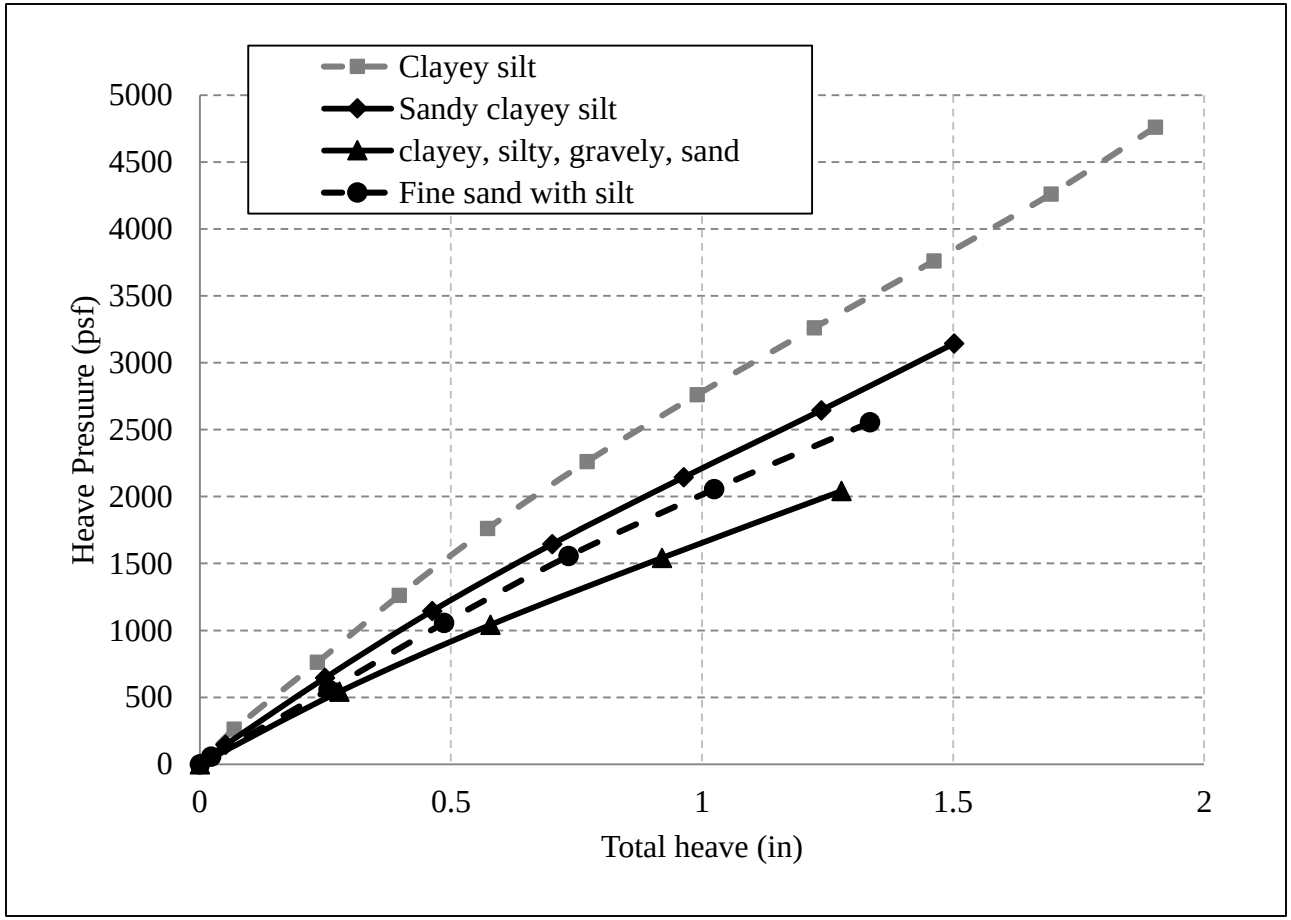
$$P_{FH} = P_E - P_{OB}$$

Where P_{FH} = pressure due to heave (psf);

P_E = the equilibrium overburden pressure (psf); and

P_{OB}= the actual overburden pressure (psf).

Heave Pressure Model



Calculated total heave versus calculated heave pressure in four soil types.

Frost Heave Mitigation

- Eliminate the water resource
- Remove frost susceptible soil
- Reduce frost depth using insulation material

Reducing Frost Depth Using Insulation

Temperature variation in a soil layer can be obtained by solving the following equation:

$$C\frac{\partial T}{\partial t} = -k\frac{\partial^2 T}{\partial z^2}$$

Where t= time (hr);

T= temperature in the soil layer (^oF);

k= thermal conductivity of the soil layer (Btu/(ft.hr.^oF));

C= volumetric heat capacity (Btu/(ft^3.^oF)); and

z= depth from the ground surface (ft).

After solving the heat balance equation and using frost depth model, the insulation layer thickness can be calculated as

$$P = (-0.45k_{soil} + 1.9614) * FI^{(.0913k_{soil}+0.4143)}$$

$$t = [\mathrm{P} - d_{insulation}] * \sqrt{\frac{k_{insulation}}{k_{soil}}}$$

Where FI= freezing index in the design year (F degree-day);

P= frost depth in the design year (in);

K=thermal conductivity (Btu/(ft.hr.^{o}F));

d= depth of insulation (in) ; and

t= insulation thickness (in).

Conclusion

- One statistical model was developed for each of clayey and sandy soils using the measured frost depth data in Michigan. The two models predicted the measured frost depth data in Minnesota relatively accurately.

- The statistical model developed based on the average thermal conductivity of saturated clayey and sandy soils produced relatively accurate results for both soils in the states of Michigan and Minnesota.

Conclusion

- The modified Gilpin model yielded frost heave data that are representative to the measured data under the shoulder and under the pavement in Michigan.

- Heave pressure model was developed based on the result of frost heave model. However, since pressure data were not available, the accuracy of the model could not be evaluated.

Future Work

Seasonal Load Restriction (SLR), State of Practice

- ✓ Engineering judgment and visual observations
- ✓ Fixed dates for posting and removing the SLR signs
- ✓ Quantitative approaches based on location and observed severity of the winter season
- ✓ Deflections measured using the falling weight deflectometer (FWD)

MDOT SLR Policy

According to MDOT, March 12 2015

(http://www.michigan.gov/mdot/0,4616,7-151--349740--,00.html)

- "MDOT determines when weight restrictions begin each spring by measuring frost depths along state highways, observing road conditions, and monitoring weather forecasts. In many parts of the state, frost depths currently exceed the limits of MDOT's frost tubes, which generally measure to 6 feet. Weight restrictions remain in effect until the frost line is deep enough to allow moisture to escape and the roadbeds regain stability. "

- County road commissions and city public works departments post their own SLR, which usually, but not always, coincide with the state timing of SLR.

Existing Models
Washington DOT (WSDOT), 1986

Pavement Thickness	Necessary Action	CTDD(^{o}F -day)
2 inches or less	SLR signs should be posted	10
	SLR signs must be posted	40
More than 2 inches	SLR signs should be posted	25
	SLR signs must be posted	50
For all pavements	SLR signs must be removed	D=25+0.01 (FI) Or CTDD=0.3(FI) Where D=thaw duration (day) FI= Freezing Index (^{O}F –day)

Existing Models
Minnesota DOT (MnDOT), 2000

MnDOT revised the CTDD calculation and used floating reference temperature.

SLR signs are posted when the CTDD is forecasted to reach 25 ^{o}F-day, they Remove the SLR signs after 8 weeks.

Existing Models
South Dakota DOT (SDDOT), 2004

- ✓ Used different CTDD threshold value based on the precipitation from August to November.
- ✓ Removed SLR when the CTDD reaches a certain percentage of the maximum freezing index. This percentage is based on the amount of precipitation and changes every year

Current Pool Fund Study Seasonal Weight Restriction Decision Support Tool (Aurora)

- ✓ Used the Enhanced Integrated Climate Model (EICM) to simulate pavement, sub-base, and sub-grade conditions based on observed weather conditions and weather forecast parameters.

- ✓ The tool provides graphic profiles of subsurface conditions down to 48 inches and forecasts up to approximately three weeks.

Recommendations for Future Work

- Collecting comprehensive soil temperature database Using RWIS database;

- Evaluation of the Existing CTDD calculation approaches and developing a more accurate approach based on the RWIS database;

- Developing a thaw depth predictive model based on CTDD and soil thermal conductivity values using the developed frost depth models;

- Based on the developed models , establishing the time for posing and removing the seasonal load restriction.

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