Using Particle Size Distribution to Determine Thaw Strain in Coarse-grained Sediments

Zakieh Mohammadi, Jocelyn L. Hayley
Department of Civil Engineering – University of Calgary, Calgary, AB, Canada

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ABSTRACT
This study presents a new approach for estimating the thaw settlement of coarse-grained permafrost sediments by means of estimating maximum and minimum void ratios (index void ratios). This approach uses published predictive tools with input parameters such as mean grain size, coefficient of uniformity, and fine content to obtain index void ratios. These values are then used to draw conclusions about the thawed void ratios of coarse-grained permafrost samples and their thaw strain. A dataset containing results of 65 thaw settlement tests on coarse-grained permafrost samples along with corresponding properties, collected by the Centre d'Études Nordiques, was used to validate the predicted thaw strains against measured values. The results of this validation exercise showed the estimated thaw strains are in good agreement with the measured values, demonstrating the accuracy and reliability of this approach. Tailored specifically for granular materials and relying only on particle size distributions (commonly reported in site investigation reports), this approach is a reliable and cost-effective method for predicting thaw settlement of coarse-grained permafrost sediments.

RÉSUMÉ
Cette étude présente une nouvelle approche pour estimer le tassement dû au dégel des sédiments de pergélisol à grains grossiers au moyen de l'estimation des rapports de vide maximums et minimums (rapports de vide indexés). Cette approche utilise des outils prédictifs publiés avec des paramètres d'entrée tels que la taille moyenne des grains, le coefficient d'uniformité et la teneur en matières fines pour obtenir des rapports de vide indexés. Ces valeurs sont ensuite utilisées pour tirer des conclusions sur les rapports de vide dégelés des échantillons de pergélisol à gros grains et sur leur contrainte de dégel. Un ensemble de données contenant les résultats de 65 essais de tassement au dégel sur des échantillons de pergélisol à gros grains ainsi que les propriétés correspondantes, recueillies par le Centre d'Études Nordiques, a été utilisé pour valider les déformations de dégel prédites par rapport aux valeurs mesurées. Les résultats de cet exercice de validation ont montré que les déformations de dégel estimées sont en bon accord avec les valeurs mesurées, ce qui démontre la précision et la fiabilité de cette approche. Conçue spécifiquement pour les matériaux granulaires et s'appuyant uniquement sur les distributions granulométriques (couramment rapportées dans les rapports d'enquête), cette approche est une méthode fiable et rentable pour prédire le tassement dû au dégel des sédiments à gros grains du pergélisol.

1 INTRODUCTION

The thawing of permafrost due to climate change has significantly impacted infrastructure built in the Arctic and Subarctic regions. Thawing permafrost can lead to settlement, ground instability, and landslides, which can damage roads, buildings, and pipelines and result in costly repairs and disruptions. Thaw settlement is a frequently reported issue for infrastructure built on permafrost and contributes to high maintenance costs, reduced life cycles, and compromised serviceability of infrastructure (Brooks, 2019; Deimling et al., 2020; Flynn et al., 2015; Fortier et al., 2011; Hjort et al., 2018, 2022). Thaw settlement occurs when excess water, originating from melting ground ice, is expelled under the overburden loads, resulting in ground subsidence. Characterizing thaw settlement and predicting its magnitude allows engineers to plan, design, and manage new structures with consideration of upcoming changes and reduce costs associated with settlement by taking necessary preventative measures and implementing appropriate adaptation strategies.

The process of thaw settlement of permafrost involves a combination of heat flow and consolidation, which creates a coupled thermo-hydro-mechanical system. Numerous studies have been conducted to improve the modelling of these systems, with a focus on thermal and mechanical components and their coupling (Dumais & Konrad, 2018, 2019; Morgenstern & Nixon, 1971; Qi et al., 2013; Wang et al., 2016; Yao et al., 2012; Yu et al., 2020). While successful in theory, these methods are not always feasible for engineering practices due to their costly and time-consuming nature. Moreover, there is still a need for experimental studies to characterize the mechanical and thermal properties of ground materials.

On a more practical basis, thaw settlement properties at the site scale can be determined by conducting an extensive site investigation, obtaining an adequate number of minimally disturbed permafrost samples, and determining the thaw settlement parameters experimentally under controlled thermal and loading conditions. This is, however, not feasible in many cases because of remoteness, harsh weather conditions, and the high costs associated with testing, travel, and sample handling. Alternatively, empirical correlations relating thaw strain to properties such as water content and frozen bulk density of permafrost samples have been commonly employed to estimate settlement (Luscher & Afifi, 1973; Nelson et al., 1983; Speer et al., 1973; Watson et al., 1973). Although these correlations were derived from relatively large datasets, applying them to new experimental data has resulted in significant differences between predicted and measured values. A contributing factor to these discrepancies is that the same approach and predictive variables are used for all soil types, overlooking the impact of soil type in defining settlement behavior. Furthermore, these methods rely primarily on initial water content and frozen bulk density, which are related to the initial state (i.e. ground ice content) only. However, comparing these initial values with their respective values measured after the completion of thawing and consolidation could enhance the estimation accuracy of thaw settlement.

Crory (1973) worked to develop a more accurate relation by considering the dry unit weight of the initial frozen state and thawed state, along with the impact of unfrozen water content in the frozen sample. Values for thawed dry unit weight were calculated using other measured parameters like water content at the initial and thawed states, and assuming saturation and a specific gravity based on the soil type. The study only used the phase relations to show that thaw strain at each state can be calculated having the initial and thawed dry density at those states. However, permafrost samples are rarely measured for water content and bulk density after the completion of thawing and subsequent consolidation.

To simplify characterizing the thawed state of coarse-grained permafrost sediments, this study proposes an approach for estimating the void ratio in the thawed state using maximum and minimum void ratios of granular soils. Predicted void ratios are used to calculate the thaw strain, and the predicted thaw strain is finally verified against thaw strain measurements. This approach has the potential to improve the prediction of thaw settlement of permafrost by utilizing a more physically sound basis for estimating thaw strains.

2 THAW SETTLEMENT

During the formation of permafrost, a considerable amount of ice can accumulate in the ground due to various mechanisms such as pore water freezing, access to free water during freezing, and buried water bodies or buried blocks of glacier ice. Climate warming and changes in surface conditions can disturb the ground's temperature profile and initiate thawing. The thawing rate is determined by the environmental conditions and thermal properties of the ground material. When thawing occurs, the ground ice gradually melts and generates water, which can lead to an increase in pore water pressure if the released water is more than the adsorption capacity of soil and drainage is insufficient. When excess water drains out from the soil structure under a combination of overburden pressure and potential surface loading, soil reaches a new equilibrium void ratio. This process is called thaw consolidation, and the settlement induced by it is thaw settlement.

Figure 1 shows a typical void ratio vs pressure curve alongside a thaw strain vs pressure curve obtained through a thaw consolidation test of an ice-rich coarse-grained permafrost sample. The sample is subjected to thawing at the initial loading step of 2.5 kPa, and the loading is increased in 3 steps to about 75 kPa to characterize the settlement behaviour under regular construction loads.

As shown in Figure 1, thaw strain is directly dependent on the thaw void ratio. If the thaw void ratio is taken to represent the void ratio immediately after thawing, under a light applied load, then thaw strain signifies the volume change that occurred during thawing. On the other hand, if the thawed void ratio is taken to denote the condition after thawing and consolidation under a significant applied load, then thaw strain represents the entire volume change during thawing and subsequent consolidation.

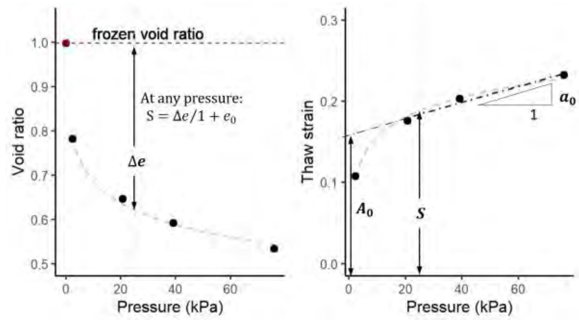

Figure 1. Typical thaw settlement test results for a coarse-grained sample. Data used are reported by Northern Engineering Services Company Limited (1977).

The thaw strain vs pressure curve is traditionally used for obtaining the thaw settlement parameter A_0 (%) and coefficient of compressibility, a_0 (1/kPa). After determining these parameters for a representative soil sample as shown in Figure 1, settlement S (m) for a layer of thawed permafrost with the height of h (m) and under average stress of σ (kPa) can be calculated as:

$$S = (A_0 h) + (a_0 \sigma h) \quad [1]$$

Therefore, by obtaining A_0 and a_0 from thaw consolidation test results, one would be able to calculate the settlement of a given layer of thawed permafrost under a known applied load.

3 INDEX VOID RATIOS AND THEIR APPLICATION

Maximum and minimum void ratios, also known as index void ratios, represent the loosest and densest conditions for soil. They have been commonly used to characterize the way that particles of granular soils interact when they are placed in a confined environment. They are also used as an indicator to estimate other properties such as stress-strain response, permeability, and volumetric compression potential. Index void ratios are measured experimentally using the procedures specified in standards such as ASTM (ASTM D4253 and ASTM D4254).

Based on the available literature, index void ratios are influenced by several factors, including the grain size distribution (uniformity coefficient, mean particle size, fine content), the shape of the particles (roundness, sphericity), and the mechanical procedure used to determine these parameters. Some relationships correlate parameters obtained from particle size distribution and particle morphology, such as coefficient of uniformity (C_u), mean grain size (D_{50}), fines content (*FC*), roundness (*R*), and sphericity (*Sph*) with maximum void ratio (e_{max}), minimum void ratio (e_{min}), and the range of them (e_{max}-e_{min}) of cohesionless soils (Bradley & Cubrinovski, 2013; Cetin & Ilgac, 2021; Chen & Kulhawy, 2014; Cubrinovski & Ishihara, 2002; Sarkar et al., 2019; Yilmaz, 2009; Zheng & Hryciw, 2016). These methods and their application in this study will be discussed in more detail in the next section.

3.1 Models for predicting index void ratios

There are a number of research studies that attempted to correlate the index properties of coarse-grained soils and their particle morphology to the minimum and maximum void ratios of these soils. As one of the first studies on this topic, Youd (1973) examined the effectiveness of using mean grain size (D_{50}), coefficient of uniformity (C_u), and particle roundness (*R*) for predicting void ratio limits and range (e_{max}-e_{min}) of sandy soils. It was concluded that D_{50} was not an effective parameter to assess these values. However, the database used for the study was limited by a C_u value of 1.4, which resulted in a lack of variability in D_{50} and a biased conclusion about the effect of D_{50}.

Later studies used combinations of parameters obtained from grain size distribution and morphology to predict void ratios for various soil types, from natural gravel to sands, with varying percentages of fine content. Cubrinovski & Ishihara (2002) studied the impact of the ratio of small to large particles and the percentage of the fine particles in a binary packing on the minimum void ratio and proposed a model to evaluate the minimum and maximum void ratios and range based on data collected from 300 natural granular soils. Yilmaz (2009) studied the packing behaviour of more than 100 systematically prepared mixed-graded sand samples by means of their minimum and maximum void ratios obtained according to ASTM D 4253 and ASTM D 4254 standards. The test results showed that 3rd-degree polynomial equations as a function of packing material percentage were accurate predictors of the variation of the void ratios for the tested sand samples. Additionally, an error analysis of the index void ratios was conducted, which showed that the predictability of the maximum void ratio was more accurate than that of the minimum void ratio.

Bradley & Cubrinovski (2013) proposed an empirical, probability-based relationship between D_{50} and *FC* with void ratio limits and range for liquefaction triggering assessments. Chen & Kulhawy (2014) examined the relationship between several index properties of gravely soils, such as unit weight, void ratio (e_0, e_{max}, e_{min}), and porosity and factors affecting them using a database of 43 sandy and gravelly soils from 36 sites with 137 individual samples. Results indicated that these indices are largely a function of the soil gradation properties, geology, and age. Additionally, correlations were developed between these indices and several gradation properties (D_{50}, C_u, and angularity), but the accuracy of the proposed correlation was found to be low (R^2 = 56–58%).

Using a larger dataset, Zheng & Hryciw (2016) developed a model to calculate the index void ratios of sands. This model was improved over previous efforts by using a larger database of sand samples spanning a wide range of *R, Sph*, and C_u values, taking into account the combined and coupled effects of *R*, *Sph*, and C_u, and utilizing a computational geometry method on digital images to obtain precise values of R and *Sph* for a large number of particles. They concluded that particle shape parameters, along with C_u, were better input parameters for predicting void ratio.

Sarkar et al. (2019) examined the effects of particle size, distribution, and specific gravity on e_{max} and e_{min} and found that D_{50} and C_u were strongly correlated with void ratio limits for poorly graded glass beads but not for sands. However, it was shown that the accuracy was improved by considering the effect of specific gravity.

In the most recent effort for predicting limit void ratios, Cetin & Ilgac (2021) compiled a database of 636 cohesionless soils, including e_{max}, e_{min}, e_{max} - e_{min}, C_u, D_{50}, *FC, R* and *Sph* and soil type designation. Since not all the soils had complete input parameters, a methodology was proposed to accommodate incomplete datasets, a probabilistic approach was used, and the model parameters were evaluated using maximum likelihood methodology. Jointly regressed models were created, beginning with a simpler, single-input model and then progressing to more precise, multi-input models using combinations of C_u, *D50*, *FC*, *R* and *Sph*. These models are applicable for a wide range of granular soils.

4 METHODOLOGY

In this study, we predict the anticipated thaw strain of cohesionless soils using existing models for predicting index void ratios that rely on information such as grain size distribution, particle morphology, and soil fabric. As grain size analysis is among the most commonly reported data in geotechnical investigations and given the difficulty of characterizing the morphology and fabric of soils, this study focuses on models that only use parameters that can be obtained from grain size analysis. In this study, the application of models created by Bradley & Cubrinovski (2013) and Cetin & Ilgac (2021) for predicting void ratios will be examined, as these models only rely on parameters that can be obtained from grain size distribution and are based on fairly large datasets (Table 1). These models will be used to predict the void ratio of granular permafrost samples after thawing. This study is based on the premise that, regardless of the initial void ratio, samples with similar grain size distribution will achieve a similar thawed void ratio, given that drainage is possible and the applied pressure is similar.

4.1 The experimental data

Thaw settlement test results conducted and published by the Centre d'Études Nordiques were used to compare measured thaw strain with values predicted using index void ratios. These tests were conducted on intact permafrost samples obtained from boreholes located in different villages in Nunavik, northern Quebec. The extracted and digitalized data was summarized in a dataset containing 129 observations from different soil groups with parameters such as location, depth of the sample, water content, bulk density, grain size distribution, plasticity limits, and ground material description, along with thaw settlement test results (Allard et al., 2020a, 2020b, 2020c, 2020d, 2020e; L'Hérault et al., 2014). As this study focuses on coarse-grained samples, a subset containing all available coarse-grained samples, which had all required input parameters for predicting index void ratios. This subset contained 65 samples in total.

Table 1- models used in this study for predicting limit void ratios and their input variables. See cited sources for further details on the models.

Model name	C_u	D_{50}	FC
Bradley & Cubrinovski (2013)		•	•
Cetin & Ilgac (2021) -Model 1		•	
Cetin & Ilgac (2021) -Model 2		•	•
Cetin & Ilgac (2021) -Model 5	•		
Cetin & Ilgac (2021) -Model 8	•	•	
Cetin & Ilgac (2021) -Model 9	•	•	•

In these reports, the thaw settlement test consisted of thawing permafrost samples in a modified standard oedometer cell and measuring the observed settlement. An initial vertical stress of 25 kPa, equivalent to the average weight of a thawed active layer, was applied when the sample was subjected to thawing. After completion of thaw and consolidation, the stress was increased to 50 and then 100 kPa to simulate consolidation under the weight of a medium-sized embankment or building. Each load was applied for a minimum of 24 hours or until no more vertical settlement was observed, ensuring the completion of the consolidation process (L'Hérault et al., 2014).

5 RESULTS

5.1 Measured thaw strain

Using reported deformation readings for each loading step, we calculated the thaw strain at each pressure and plotted the thaw strain vs pressure curve for each sample. Then, we determined the thaw settlement parameter (A_0) and coefficient of compressibility (a_0) for each sample by fitting a linear regression between pressure and thaw strain, as shown in Figure 1. The distribution of A_0 and a_0 are shown in Figure 2, along with descriptive statistics in Table 2.

The test results showed that while A_0 has a broad range and can be as high as 68%, the a_0 parameter is generally small for coarse-grained samples. This indicates that thaw settlement for this type of sediment is mainly caused by the thaw strain that happens due to the release of excess water generated during the thawing process under low pressures, which is reflected by A_0 value.

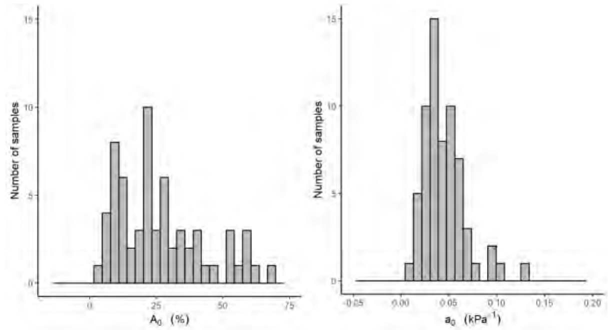

Figure 2- The distribution of the thaw settlement parameter (A_0) and coefficient of compressibility (a_0) obtained from thaw settlement test results.

Table 2- Descriptive statistics for A_0 and a_0 parameters obtained for samples from thaw settlement test results.

Parameter	Mean	Median	Std Dev	Range
A_0 (%)	26.58	22.35	16.55	2.03 - 68.24
a_0 (1/kPa)	0.045	0.039	0.022	0.009 - 0.131

5.2 Index void ratio calculation

Different models proposed by Bradley & Cubrinovski (2013) and Cetin & Ilgac (2021) were used to predict index void ratios based on the three main parameters available for the samples (D_{50}, C_u, and FC). Table 1 presents the models used and their corresponding input variables. Further details on the relationships employed in each model can be found in the cited sources.

To determine if the selected models could be applied to the existing dataset, the range of input variables in the validation dataset was compared to the specified limits for different models (Table 3). A plot of D_{50} and C_u for different fine content (Figure 3) revealed that the samples spanned a variety of input variables and were within limits for each model. This graph also indicated a correlation between D_{50} and C_u for different levels of fine content.

Table 3- Specified limits for the models used in this study.

Models from:	Input ranges
Bradley & Cubrinovski (2013)	Sandy and silty soils
Cetin & Ilgac (2021)	$0 \le FC$ (%) ≤ 100 $0.01 \le D_{50}$(mm) ≤ 25 $1.0 \le C_u \le 300$

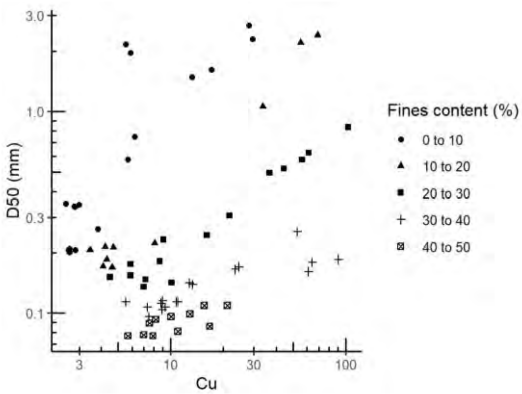

Figure 3-Mean grain size vs coefficient of uniformity for five different ranges of fine content for the permafrost samples within the validation dataset

5.3 Estimated thaw strain

After calculating the minimum and maximum void ratio for each sample using predictive models and assuming that the thawed void ratio will be within this range, it is possible to make an approximate estimate of the thawed void ratio value. The most conservative assumption is that the thawed void ratio will be close to the minimum void ratio, meaning that the maximum settlement can be expected when the thawed void ratio is equal to the minimum void ratio. The following equation was then used to calculate final thaw strain:

$$s = \frac{\Delta e}{1+e_0} = \frac{e_0 - e_{th}}{1+e_0} = \frac{e_0 - e_{min}}{1+e_0} \quad [2]$$

Where *s* (unitless) is the final thaw strain, e_0 is the initial void ratio, and e_{th} denotes the thawed void ratio.

Thaw consolidation tests on coarse-grained samples indicates that the a_0 parameter has a small magnitude and a narrow range (Table 2). The mean value of a_0 (0.045 kPa^{-1}) suggests that soil's compression under an applied pressure of about 100 kPa only accounts for 4.5% strain. Therefore, we decided to compare the estimated thaw strain using the minimum void ratio (equation 2) directly with the thaw settlement parameter obtained from laboratory measurements. Considering the uncertainty of the statistical analysis used for developing models for predicting minimum void ratios, the size of the validation dataset, and the level of accuracy required, we believe that excluding the a_0 term will not have a significant effect on the results. Additionally, using the A_0 parameter provides a basis for comparison with other existing methods that also use this as the main parameter characterizing the thaw strain.

The performance of six models in predicting A_0 was compared (Figure 4). The Root-Mean-Square Deviation (*RMSD*) was calculated for all models to provide a systematic basis for comparison. *RMSD* values for each model are shown in Table 4. The *RMSD* values for all the models developed by Cetin & Ilgac (2021) were similar, where Model 9 has the lowest *RMSD*, followed by Model 2. Comparing the *RMSD* for Model 2 and Model 1 shows that using *FC* as an extra input variable improved the thaw strain prediction to some extent. Similar results can be observed while comparing Model 8 and Model 9.

The Bradley & Cubrinovski model showed the largest deviation from the measured values. The relatively large number of negative values for the estimated A_0 may have contributed to this poor fit. This can be attributed to the dataset and test procedure used to measure the minimum void ratio for developing the correlations, which led to predicting higher minimum void ratios than the initial void ratios recorded for the samples.

In the evaluation and comparison of different e_{min} models by Cetin & Ilgac (2021), it was also demonstrated that Model 9 was one of the best-performing models. This model displayed the highest likelihood ratio and the lowest standard deviation, second only to a model that utilized *R* and D_{50} as inputs.

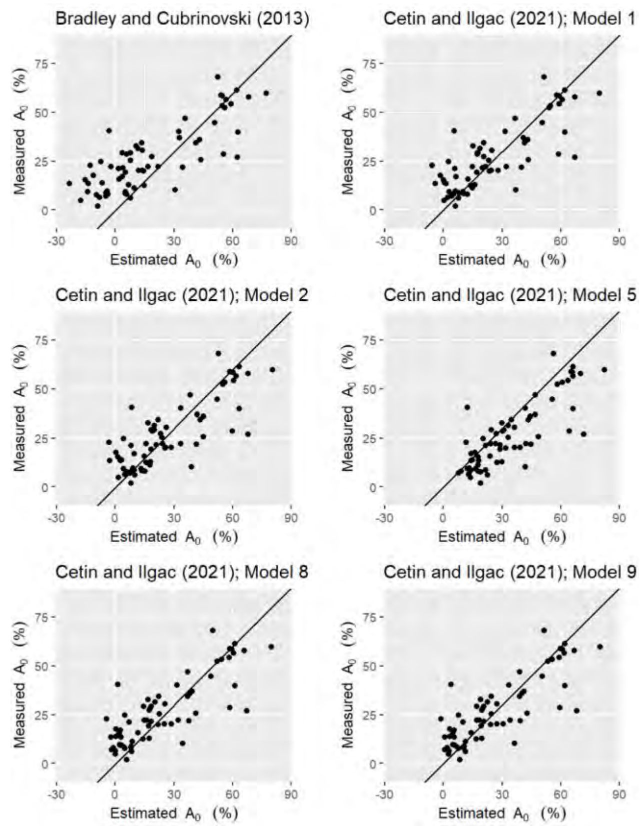

Figure 4- Comparison between measured vs estimated thaw settlement parameters obtained from six different models. The name of the model used for predicting the minimum void ratio used in calculating the estimated A_0 is shown above each graph. The black line indicates perfect prediction.

Table 4- RMSD for six different models of minimum void ratios used for predicting thaw settlement parameter.

Model	Root-mean-square deviation (***RMSD***)
Bradley & Cubrinovski (2013)	17.95
Cetin & Ilgac (2021) -Model 1	13.07
Cetin & Ilgac (2021) -Model 2	12.76
Cetin & Ilgac (2021) -Model 5	13.23
Cetin & Ilgac (2021) -Model 8	12.95
Cetin & Ilgac (2021) -Model 9	12.28

6 EXAMPLE CALCULATION

This section illustrates an example of how the approach proposed in this study can be used for thaw strain calculation. A permafrost sample from the database (WB-2017-F1-205-220) was used for this purpose. Following steps were taken to predict the thaw strain for this sample:

1. Required input parameters were obtained from the grain size curve and used to calculate the C_u value (Table 5).
2. The C_u, D_{50}, and *FC* values were then substituted into Model 9 (shown below) to calculate the minimum void ratio of the sample, which was 0.572. This value was used as thawed void ratio as well.

$$e_{min} = 0.391 \,.\, \exp(162.935 \,.\, [ln(D_{50} + 3.336]^{-0.005} - 163.2359) + 0.609 \,.\, \left(\frac{0.2767}{1+1.6302 \,.\left(\frac{C_u}{6.3352}\right)^{2.238}} + 0.3243\right) + (-0.0022 \,.\, (FC)^{0.0002} - 0.029) \rightarrow e_{min} = e_{th} = 0.572$$

3. The dimension of the frozen sample and its solid grain density (assuming 2.65 g/cm^3) were used to calculate the height of solids (given that diameter does not change), which was 35.81 mm. The initial void ratio was then calculated as:

$$e_0 = \frac{H_0 - H_s}{H_s} = \frac{140.54 - 35.81}{35.81} = 2.925$$

4. The initial void ratio and the thawed void ratio were then used to calculate the thaw strain of the sample as:

$$s = \frac{\Delta e}{1 + e_0} = \frac{2.925 - 0.572}{1 + 2.925} = 0.599$$

Finally, estimated thaw strain can be compared with measured thaw strains through settlement test (Table 6). The calculated thaw settlement parameter for this sample was 56.80%, which is close to the estimated value of 59.9%.

Table 5-reported data for WB-2017-F1-205-220 from the validation dataset

Grain Size Distribution	
Sample name	WB_2017_F1_205-220
D_{10} (mm)	0.031
D_{50} (mm)	0.181
D_{60} (mm)	0.269
FC (%)	22.7
C_u	8.68
Sample dimensions and mass	
Diameter (mm)	101.00
Ave. Height (mm)	140.54
Dry mass of sample (gram)	760.19
Height of solids (mm)	35.81

Table 6- thaw settlement test results for WB-2017-F1-205-220

Pressure (kPa)	Vertical displacement (mm)	Thaw strain (%)
25	80.35	57.17
50	82.4	58.63
100	83.43	59.36

7 DISCUSSION

The method proposed in this study for predicting thaw strain in coarse-grained soils is based on the comparison of the initial and thawed void ratios. The results of this approach were comparable to the measured thaw strain and provide an acceptable level of accuracy for rough estimation of thaw strain under minimal loadings. Additionally, the mean value for the coefficient of compressibility for coarse-grained soils proposed in this study can be used to calculate the compression component of the total settlement when significant load is anticipated after thawing.

The accuracy of the proposed thaw strain prediction method is largely dependent on the accuracy of the existing models used to predict the index void ratios. In this study, models developed using large datasets of experimental data were employed to predict thawed void ratio. A comparison of several models showed that the Cetin and Ilgac models outperformed the Bradley and Cubrinovski model, with Model 9 demonstrating the highest performance among all the models tested in this study. Comparing the performance of different models in predicting thaw strain revealed some variation between the results obtained by these models. This can be attributed to the data and variables used for the development of the models, as well as to the variability of the values obtained for the same soils when measuring index void ratios using different procedures.

The accuracy of the proposed method is also limited by the input data. The validation dataset used in this study was relatively small, and there was a lack of gravel samples. The impact of the presence of organic material or different types of ground ice on the settlement behaviour of the samples was also not considered. Moreover, the solid grain density of all samples was assumed to be 2.65 g/cm^3, which in the presence of organic material, this assumption can lead to some error in calculating the initial void ratio and, consequently, the thaw strain.

The methodology presented here informs users about the expected range of thaw strain given that permafrost thaws. To take full advantage of the proposed method, it should be integrated with thermal analysis that can provide the depth of degraded permafrost. Additionally, it should be noted that while the assumption that the thawed void ratio falls within the range of the minimum and maximum void ratio is reasonable, assuming that it tends to be biased towards the minimum void ratio can be conservative in certain situations..

8 CONCLUSION

This study has provided evidence that index void ratios can be used to draw conclusions about thawed void ratios of coarse-grained permafrost sediments. The proposed method for predicting the thaw settlement parameter, in combination with the typical average value suggested for the coefficient of compressibility, provides a reliable and cost-effective basis for engineers and planners to predict the magnitude of settlement when planning infrastructure development in permafrost regions. Future research will be conducted on comparing the accuracy of predictions made by this method with existing empirical methods. Additionally, existing experimental data on void ratio limits will be used to prescribe a unique value to the minimum void ratio of different groups of coarse-grained materials, which can be used in the absence of detailed grain size distribution data for predicting thaw strain.

9 ACKNOWLEDGEMENT

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