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Influence of Ground Ice Variability on Settlement in Thawing Permafrost

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INTRODUCTION

The design of structures in areas of thawing permafrost is often controlled by the anticipated amount of thaw settlement. Differential settlements due to variations in the thawing mass result in uneven support and loading which impose high shear forces and moments on structures or otherwise lead to unacceptable strains. Since differential settlements are related to the spatial variation in total settlements, any rational basis leading to a reduction in forecast total thaw settlement will also lead to more economical engineering design.

The current design approach can be divided into geothermal, structural and geotechnical aspects. The geothermal aspect predicts the extent of thaw due to the operation of the structure, such as a warm oil pipeline, a building foundation or due to the surface modification associated with construction activity. The problem is highly non-linear due to latent heat effects, the moving thaw boundary and varying material properties, but there are powerful analytical capabilities in existence that provide results of sufficient accuracy. The geotechnical aspect is based on an extrapolation of one-dimensional thaw strain tests carried out on field samples. These tests can be conducted at ultimate overburden pressure to combine thaw strain and consolidation (Crory, 1973; Lusher and Afifi, 1973), extrapolated back to zero overburden for the thaw strain parameter, A_o (Tsytovitch, et al. 1965; Watson et al. 1973) or to a low nominal stress for high moisture soils (Nixon and Morgenstern, 1973). Speer, Watson, and Rowley (1973) suggested correlating thaw strain with the bulk frozen density to obtain a relationship between the two. The anticipated thaw settlement at a location is obtained by dividing the soil profile into homogeneous units and taking a weighted averaged of their thaw strains over the depth of thaw.

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The difficulty with this approach is the assumption that one-dimensional thaw strain tests can be summed in a one-dimensional manner to forecast the total thaw-settlement. No account is taken of the load transfer mechanisms within the soil, nor of the spatial variability of thaw strain in the ground mass which should result in a reduction of the magnitude and variability of surface thaw settlement. Experience indicates that actual settlements are usually less than those predicted in a one-dimensional manner.

This paper illustrates the influence of thaw strain variability on predicted surface settlements of thawing soil.

ANALYSIS OF VARIABILITY

In the following, thawing permafrost is treated as a non-homogeneous assemblage of uniform thaw-straining units. This population of thawing units is analysed statistically in terms of the thaw strain parameter, A_o, in order to quantify the variability of thaw strain. Variations of the resulting distribution are used in a numerical analysis to examine the effect of thaw-strain variability on surface thaw settlements.

The distribution selected to represent thaw strain is the beta (β) distribution because it allows for skewness, has realistic probabilities at all locations within the distribution, and can take on a variety of forms (Collins, 1987).

Data were obtained from laboratory thaw strain tests of permafrost from Norman Wells Site 1 (Speer, et al. 1973). All thaw strains were interpreted in terms of beta distribution, from which the representative values of thaw strain were subsequently generated for the analysis. This use of fictitious, but realistic, values had been used before for a related problem by Palmer (1972). In the work reported here, the fitted distribution was used to determine the representative, but finite number of thaw strain values used in the numerical analysis. The distributions of the original population, the generated beta curve and the ten representative values of thaw strain are shown in Figures 1 and 2.

NUMERICAL MODELS

Calculations were undertaken using the general-purpose finite element analysis program ADINA (Bathe, 1981). Thaw strain in an element was modelled by incrementally changing the stiffness of the element from a negligible stiffness (0.1 kPa) during the thaw phase to one that increased to 2000 kPa when the volumetric strain exceeded the element thaw strain, given by A_o.

Using the ten values of thaw strain, the soil was represented as a column of ten four-noded elements. A 10 kPa surface load was applied in small increments for the first part of the analysis in order to accommodate the sharp increases in stiffness as each material reached the thaw strain given by A_o. Subsequent load increments were larger. The resultant settlement of the 10m column was 2.53m. This procedure was repeated for a 10 x 10 mesh of 4-noded elements, consisting of layers of identical thaw strain parameter, with identical uniform settlements.

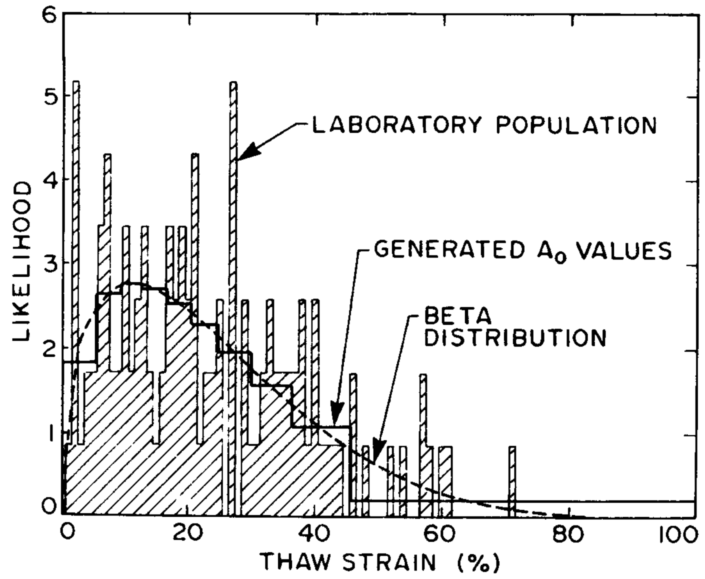

Figure 1. Beta Likelihood Distribution Functions

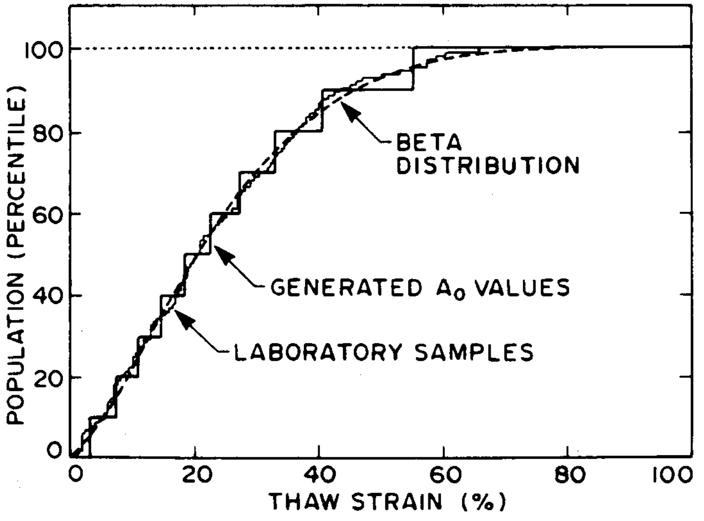

Figure 2. Cummulative Distribution of Thaw Strain

The analysis was repeated after randomly re-arranging the thaw-straining elements within the 10 x 10 mesh (Figure 3).

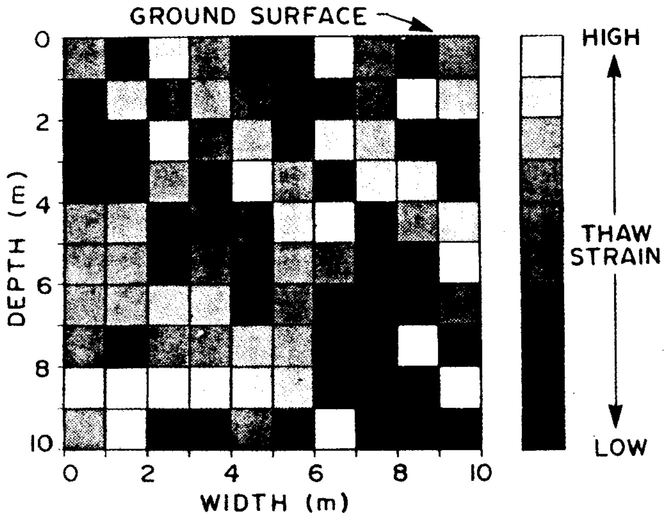

Figure 3. Randomly Distributed Elements

A settlement of 2.27m was calculated which is less than the 2.53m found from the layered analysis. As the smallest value of thaw strain was 17.8%, the absolute minimum settlement that could possibly be experienced by any configuration of randomly-arranged elements would be 1.78m. Using this value as a datum, the 2.27m settlement of the randomly arranged elements was a 35% improvement over the 2.53m settlement found in the layered analysis. This reduction in settlement was a result of soil arching that re-directed stresses around areas of high thaw strain.

The model was improved by using 8-noded elements, thereby permitting linear variations of strain within each element. Poisson's ratio, ν, was 0 during "thaw" and 1/3 afterwards. The bulk modulus was again negligible during thaw and increased to a constant value at the thaw strain for each of the ten materials. After gradually applying the loads on the random model, the average surface settlement was found to be 1.90m, representing a reduction of 81% relative to the 1.78m datum.

The deformed mesh and settlement profile are given in Figure 4. Elements with high thaw strains deformed to a greater extent than the other elements, with the low thaw strain elements supporting most of the load. At the surface, the irregular boundary resulted from application of a uniform pressure and reflected the local material variability.

The soil model consisting of a stepped bulk modulus at the thaw strain is a crude approximation to the actual behaviour. A refinement of this model can be made by assuming that post-thaw behaviour was modelled using the concept of residual stress.

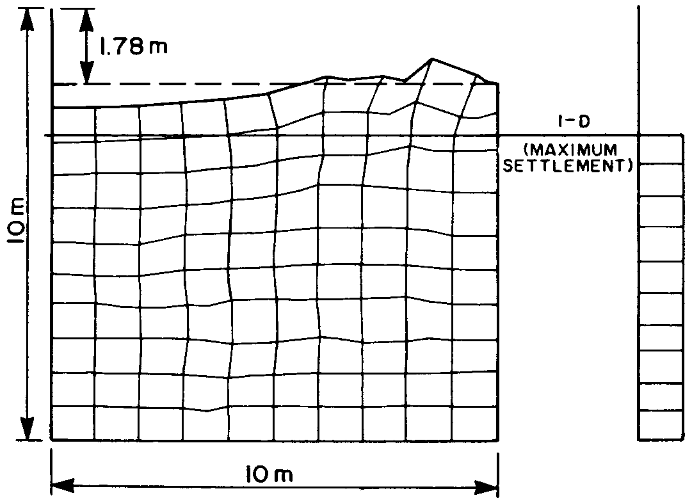

Figure 4. Final Deformations for the 8-Node Element Model

During freezing, soil differentiates into ice lenses and frozen soil peds (Nixon and Morgenstern, 1973). When thawed, some water is reabsorbed into the soil but some escapes, resulting in an overconsolidated soil. Furthermore, if the soil is re-loaded, there is no appreciable change in the void ratio until a specific stress level is reached, termed the "residual stress". (Roggensack, 1977) At this point, the soil compresses along a recompression line, as seen in Segment "C", Figure 5. This line represents the re-loading curve of a soil over-consolidated by freezing.

Values of the thawed undrained void ratio were obtained from the frozen bulk densities of the ten characteristic material. These void ratios were related to their residual stresses using a relationship for similar material (Roggensack, 1977).

The influence of the residual stress was implemented in the model as a step in the volumetric strain-bulk modulus curves over a 5% volumetric strain range immediately before the A_o value. Combining this with a gradual increase in loading ensured that the materials would not deform beyond the volumetric strain without first developing the residual stress in the soil. Materials with a higher thaw strain develop lower residual stresses. Stiffnesses beyond a strain of A_o were calculated using a compression index for the soil of $C_c = 0.16$ (Roggensack, 1977). The resulting curves can be seen in Figure 6.

It can be seen that the materials with a low thaw strain (Materials 1 and 2) will have an appreciably higher residual stress than those with high thaw strains (Materials 6 and 7). Extremely ice rich materials (8 to 10) had no residual stress.

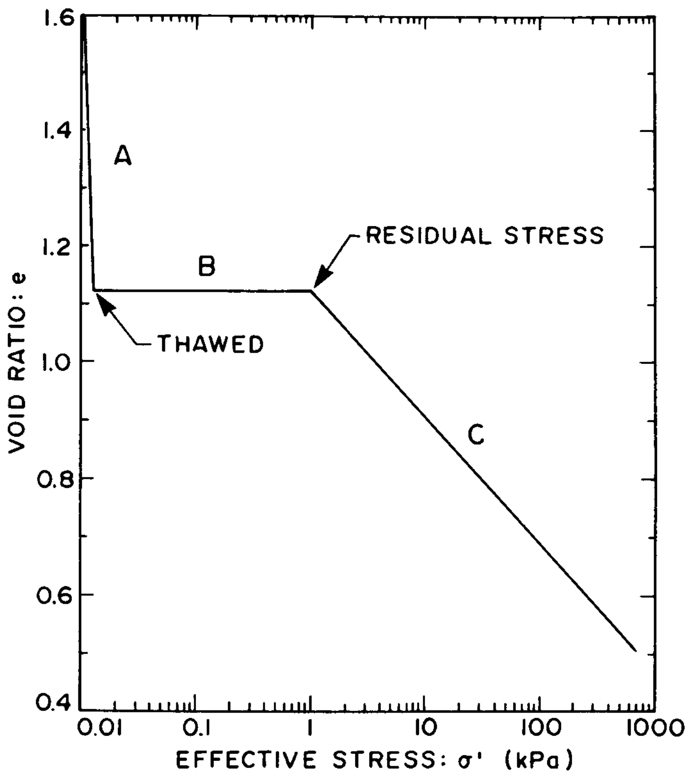

Figure 5. Idealized e-logσ' Curve for a Soil with Residual Stress

Again, an analysis of the layered materials was peformed to simulate a one-dimensional calculation. A 20 kPa surface load was applied incrementally followed by full gravity loading. The average surface settlement of 2.34 m was essentially identical to the settlement predicted using A_o values directly. Randomly mixing the materials and re-analysing produced a settlement of 2.15 m. The mechanism by which this reduction occurs is shown in Figure 7. At this point in the loading, a 9 kPa surface pressure had been applied. The mobilization of stress transfer as indicated on the diagram on the right coincides with the location of low A_o materials, as seen in Figure 3. Conversely, high A_o materials carried little or no load. The application of the full 20 kPa and gravity loads resulted in a more uniform stress distribution although the effect of soil arching around weaker materials was more pronounced.

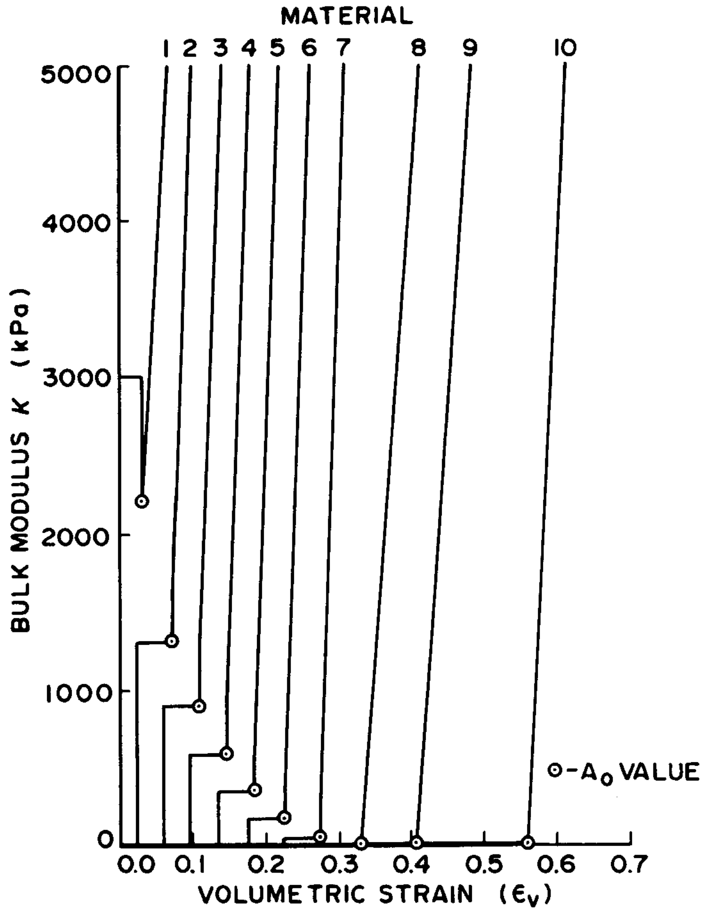

Figure 6. Thaw Strain-Compression with Residual Stress

INFLUENCE OF STATISTICAL VARIATION

Using the model with consideration of residual stress, the study was extended to examine to what extent the variation in A_o would affect settlements. Using the statistical parameters for the Normal Wells samples, new sets of ten A_o materials were generated by maintaining the same average value of 23.4% but altering the standard deviation of the A_o values. The resulting beta distributions in Figure 8 illustrate the variety of shapes with a common average A_o value.

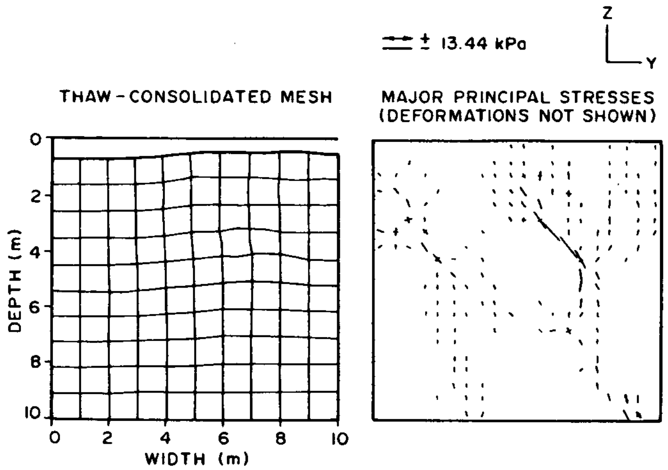

Figure 7. Stress Transfer in Randomized Medium

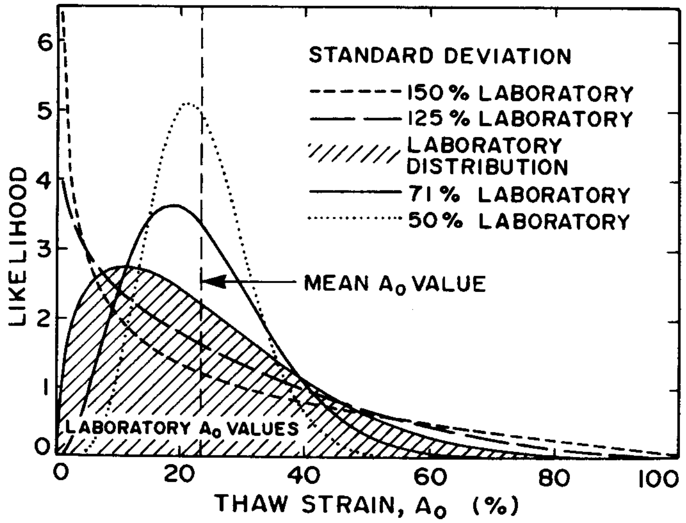

Figure 8. Beta Functions of Different Variances

The analysis of the random model was repeated for each of these distributions. As expected, the analyses using low standard deviations in A_o produced almost uniform stress fields and closely approximated the settlement predicted using conventional means. For the higher standard deviations, the analyses continued to show decreases in settlement due to load transfer through soil arching. A summary of the analyses in Figure 9 shows a significant reduction in settlement with increasing A_o variability.

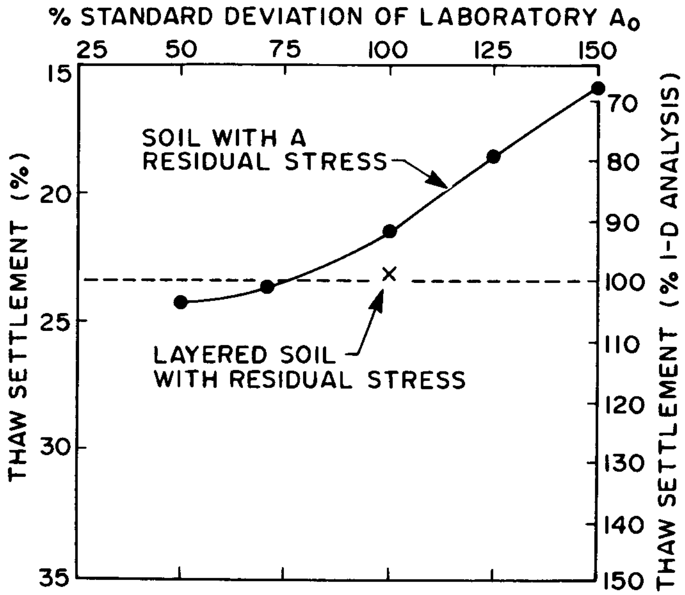

Figure 9. Average Surface Settlement as a Function of Thaw Strain Variability

At low values of standard deviation in A_o, the curve for computed settlement falls below the thaw settlement predicted in one-dimension. Clearly, this is not correct, given that a homogeneous soil having zero standard deviation in A_o should have a settlement identical to that from the one-dimensional analysis. The discrepancy is due to two factors. First, the data used to generate the β distribution were from samples tested at overburden pressures. As the raw data were unavailable for this analysis, the thaw strains were considered to be at zero stress. Therefore additional elastic and consolidation deformations are included in this analysis. Secondly, this analysis was carried out with a strain stiffening material using a numerical technique. Element stiffnesses for each load increment were calculated with the existing volumetric strain which would have underestimated the average stiffness for each increment. As a result, the system was less stiff and deformed more. This effect can be reduced by a finer discretization of the loading, at a commensurately higher cost.

The variation in A_o also affects the soil stresses. With increased variance in thaw strain, the maximum mesh stress also increases, as shown in Figure 10. This is due to the soil arching that redistributes the load to the stiffer materials.

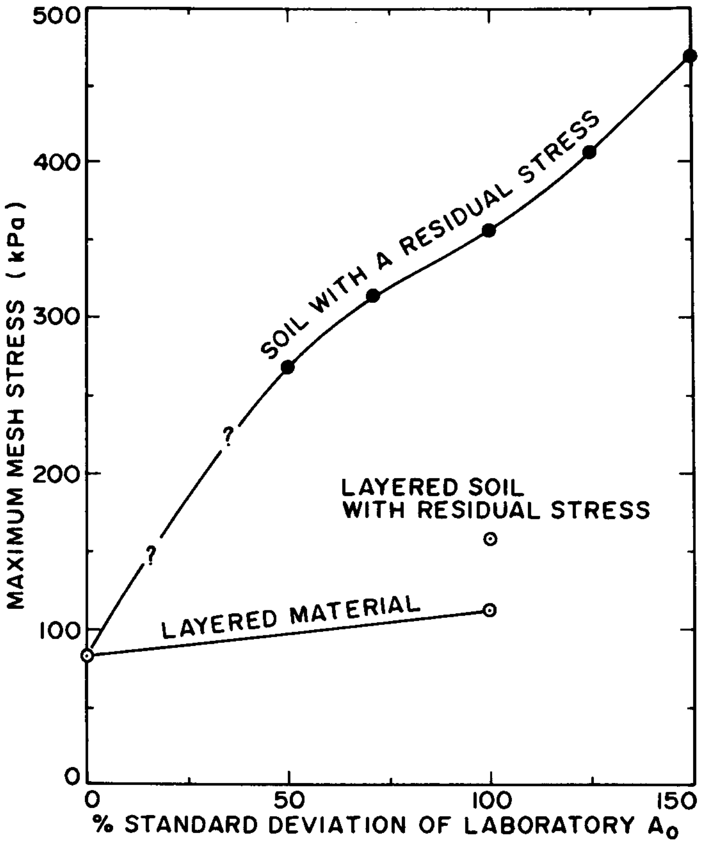

Figure 10. Maximum Mesh Stress as a Function of Thaw Strain Variability

CONCLUSIONS

The results of the analyses presented here reveal that consideration of thaw strain variability leads to a reduction in computed settlement when compared with commonly adopted one-dimensional procedures. This arises from the arching that develops during consolidation of a heterogenous thawing soil. The variability in thaw strain characteristics can be characterized by means of a beta distribution. Two constitutive formulations of the problem have been presented here and others are conceivable. To fully exploit the results of this study, field observations are needed to relate the difference between observed settlement and one-dimensional forecasts in terms of thaw strain variability.

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