Loading Mechanisms in Thawed Permafrost Around Arctic Wells

M. A. GOODMAN
Enertech Engineering and Research Co.,
Houston, Tex. Assoc. Mem. ASME

Four permafrost thaw-subsidence loading mechanisms are described for inducing casing strain. Phase change contraction in ice rich soil and consolidation with fluid flow are more likely to occur in surface and near surface soils. Stiffness reduction and pore pressure reduction are important in deep permafrost and generate body force-type loads. The equations for stiffness reduction loading are presented in terms of an elastic model. The effects of lithology and thaw variations on casing loads are examined in the context of the four mechanisms.

Introduction

One of the first Arctic well completion problems identified at Prudhoe Bay and the Mackenzie Delta was the potential for thaw-subsidence which could generate soil movement and significant casing stresses. Until recently, the loading mechanisms for the thaw-subsidence problem were not well understood. Recent data from laboratory experiments [1, 2][1] and full-scale field tests [3, 4] and interpretations from model studies [4, 5, 6, 7] have demonstrated that various thaw-subsidence mechanisms can occur in different types of soils. In this paper, these mechanisms are classified into four categories:

1 phase change contraction,
2 consolidation with fluid flow,
3 stiffness reduction,
4 pore pressure reduction.

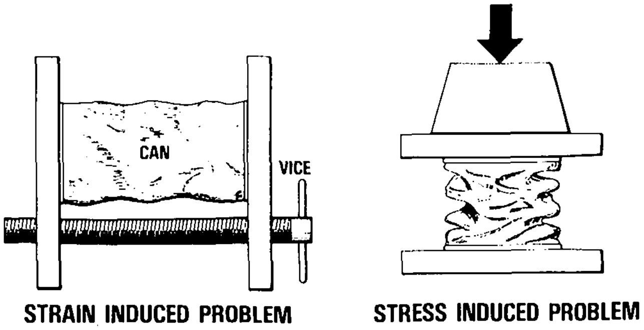
Any other mechanism can be identified with one or more of the foregoing categories. For example, underconsolidation of ice-rich soil can fall in category 3 or be a combination of 1 and 2.

The concept of casing strain as the measure of thaw-subsidence induced loads is discussed in the next section. The four basic mechanisms are then described, followed by an examination of special loading effects that can result. Conclusions are presented with emphasis on the relative magnitude and expected occurrence of the four mechanisms.

Casing Strain

The thaw-subsidence problem is one of casing strain and not casing stress. As the permafrost thaws and permafrost deformation occurs, strain is induced on the casing. The casing stress is only a consequence of the casing strain. The induced casing strain is controlled and bounded by the amount of permafrost deformation; the casing cannot strain any more than the permafrost allows it to.

The analogy of crushing a can in Fig. 1 illustrates the difference between a strain-induced and stress-induced problem for the casing/permafrost interaction. For the strain-induced problem, a tin can (analogous to the casing) is compressed in a vice (analogous to the permafrost). As long as the compression is less than the strain limit, the can does not fail. Other than thaw-subsidence, examples of strain-induced problems for well casing are subsidence due to reservoir fluid production and thermal contraction in steam stimulation. In the stress-induced problem, the tin can in Fig. 1 is loaded on top with weights and fails with large strain when the crushing weight is reached. Thaw subsidence is not a problem of this type. Examples of stress-induced problems on well casing are burst and collapse and hanging weight.



STRAIN INDUCED PROBLEM STRESS INDUCED PROBLEM

Fig. 1

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[1] Numbers in brackets designate References at end of paper.

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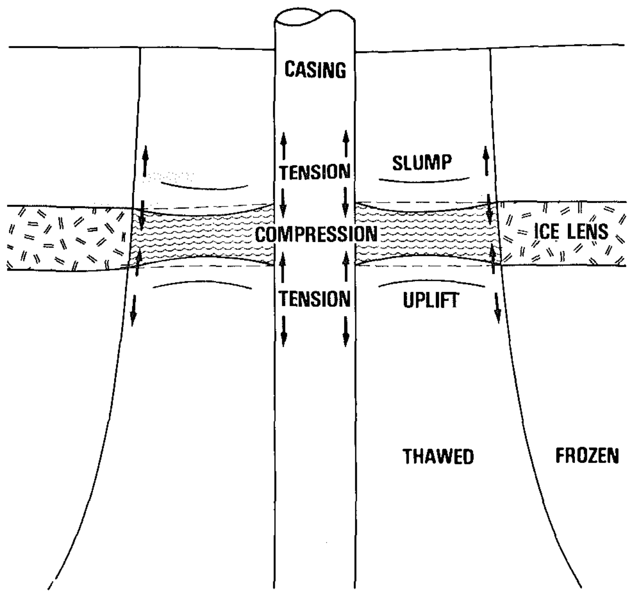

Fig. 2

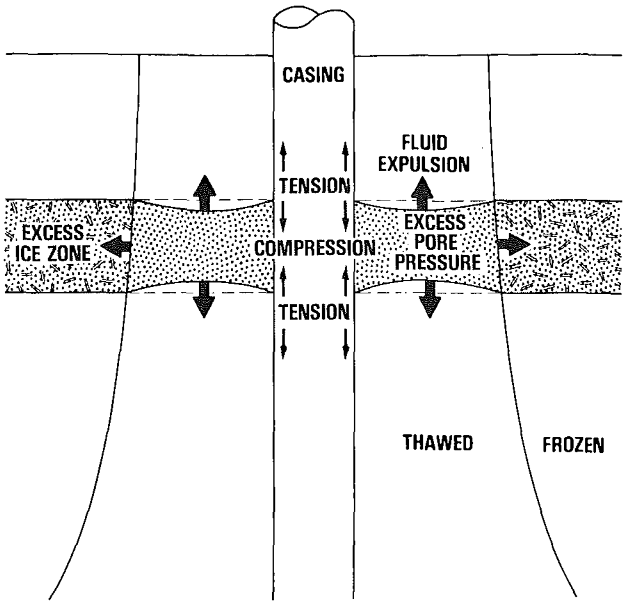

Fig. 3

Loading Mechanisms

The four thaw-subsidence loading mechanisms are discussed separately in this section.

Phase Change Contraction. The casing strain induced by phase change contraction is directly due to melting permafrost with excess ice, Fig. 2. The volumetric reduction of the ice (equivalent to 9 percent phase change contraction) creates a void in the ground. Slumping of the overlying soil (due to gravity) as well as uplifting of the underlying soil (due to stress reduction in the void) generates compression on the casing.

For large lateral extent of excess ice, the problem is one dimensional and the resulting vertical strain away from the casing corresponds to the 9 percent volumetric change, e.g., melting of a (10-ft) ice lens causes (0.9 ft) of vertical deformation. Near the casing, the strain is less due to the vertical shear support provided by the casing. Also, when the excess ice is not of large lateral extent or when the radial thaw is small compared to the thickness of the excess ice zone, the vertical shear support in the frozen soil and soil without excess ice can be significant. In this case the problem is two-dimensional and the casing strain is less than in the one-dimensional case. The mode of deformation associated with melting excess ice was one of the first considered for the thaw-subsidence problem [8] and although simple in concept, it is the most difficult to assess in the field. The problem reduces to that of determining the lithological ice content in the region of expected thaw around a well. At present, there is no known way to make a precise determination. Even coring is not absolute because of melting, creep, and rebound of cored material [1] as well as radial variations in ice content outward from the cored hole.

At Prudhoe Bay and the Mackenzie Delta, the various forms of excess ice are generally considered to be most common above (50 ft) [8, 9]. Statistical studies show that icy sediments in the Mackenzie Delta do occur down to (140 ft) and laboratory tests show that silty-clay-type soils can support excess ice at depth [10].

Consolidation With Fluid Flow. Thaw-consolidation shown in Fig. 3 is the mechanism whereby excess pressures are generated upon thaw, causing pore fluid to flow from the excess pore pressure zone and resulting in consolidation of the soil mass [5, 11, 12, 13]. By definition, this mechanism implies that the soil is underconsolidated in the frozen state or, equivalently, contains some amount of excess ice. In fact, the excess ice must be greater than 9 percent of the pore space, since otherwise upon thaw there would be a reduction, and not an excess of pore pressure. Consolidation with fluid flow is regarded as a followup to the phase change contraction mechanism; the total deformation is composed of two parts - phase change contraction of the excess ice followed by consolidation with fluid expulsion. Because of the requirement for excess ice and also a flow path, the thaw-consolidated mechanism is considered to be more likely in the near surface region than at depth.

The theory of thaw-consolidation is basically an extention of the soil mechanics theory of consolidation with appropriate boundary conditions at the thaw front - namely, that any flow from the thaw line is accommodated by a change in volume of the thawed soil. The flow is characterized by Darcy's Law.

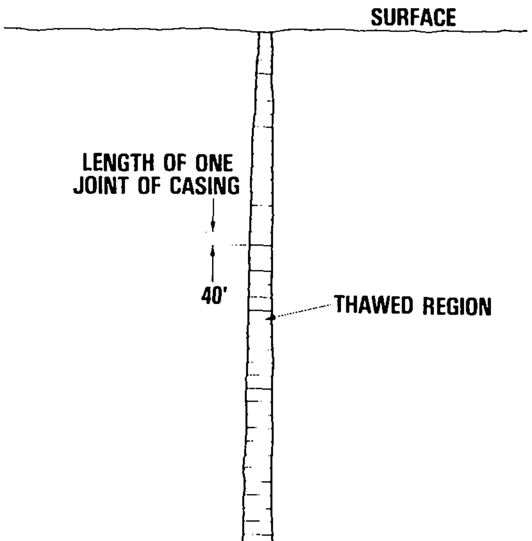

Fig. 4

Problem solutions are a function of the *thaw consolidation ratio*—a dimensionless parameter relating the thermal properties to the compressibility and permeability of the soil. This ratio expresses the interaction between rate of thaw and rate of fluid expulsion.

The theory in the literature at present is only one-dimensional. On the other hand the thaw-subsidence problem of a long thin vertical thaw zone (see Fig. 4) is two-dimensional. Examples of problems investigated with the theory of thaw-consolidation are pipeline settlement [13] and the effect of layers of different soil types [12]. Of interest is the dissipation of excess pore pressure with time and its effect on soil stability [11, 12]. Excess pore pressures imply decreased effective stresses in the soil and, hence, less shear support and bearing capacity.

For assessing the mechanism of thaw consolidation and excess pore pressures in deep permafrost, the freezeback and thaw-subsidence field tests at Prudhoe Bay provide data on measured downhole casing strains and thawed permafrost pore pressures [14, 4]. From a depth of (200 ft) to the base of the permafrost at (1850 ft), pressure transducers strapped to the outside of the casing indicated that there was no excess pore pressure during thaw. Moreover, measured casing strains were small, 0.13 percent [4], suggesting that large deformations due to melting excess ice followed by consolidation with fluid expulsion did not occur.

Stiffness Reduction. The mechanical properties of frozen and thawed permafrost are different [1, 2]. Upon thaw, there is a stiffness reduction of the soil. This change in stiffness coupled with the gravity field is a mechanism for deformation in the thaw-subsidence problem [6] as demonstrated in Fig. 5.

Physically, the stiffness reduction of thawed soil can be caused by the reduction of shear support of pore ice as it melts in normally consolidated permafrost and/or the melting of small amounts (<9 percent) of excess ice in underconsolidated permafrost. In the latter case, there is no excess pore pressure upon thaw to cause fluid expulsion, but there does exist the potential for deformation because of the underconsolidation.

If the thawed and frozen permafrost are considered to be elastic solids, the stiffness reduction is characterized by a change in the two elastic constants, the Young's modulus E and Poisson ratio ν (or, equivalently by relation (8) in the Appendix, the shear modulus G and the bulk modulus k). The derivation in the Appendix shows that the loading terms expressing the stiffness reduction appear in the equations of elasticity for force balance as

$$\frac{\Delta G}{G}(1/3\,\bar{\rho}g) + \frac{\Delta k}{k}(2/3\,\bar{\rho}g), \tag{1}$$

where G and k are the initial frozen moduli, ΔG and Δk are the reduction in moduli, g is the gravity field, and $\bar{\rho}$ is the effective permafrost density (bulk density less pore ice density). From the foregoing expression, it is seen that the loading due to stiffness reduction is like a body force released in the thawed zone; the material appears to have an *increase in weight* upon thaw. In addition, as shown in the Appendix, these terms also act laterally across the thawed-frozen interface (see Fig. 5). The reduction in stiffness across the interface causes a lateral loading that squeezes the interface inward. The magnitude of the pressure across the interface at a given depth z is

$$\frac{\Delta G}{G}(1/3\,\bar{\rho}gz) + \frac{\Delta k}{k}(2/3\,\bar{\rho}gz). \tag{2}$$

Both the vertical loading given by equation (1) and the lateral loading given by equation (2) must be considered together for the stiffness reduction mechanism in the thaw-subsidence problem. At the surface ($z = 0$) and at the permafrost base where $\Delta G = \Delta k = 0$, the contribution of the lateral loading is zero and, hence, the vertical loading mechanism dominates. However, in the central region, as well as in the region near the permafrost base, the lateral loading mechanism may dominate because of the dependence on depth z.

If only a reduction in Young's modulus E is considered without a change in the Poisson ratio ν, then

$$\frac{\Delta k}{k} = \frac{\Delta G}{G} = \frac{\Delta E}{E} \tag{3}$$

and the additional body force loading of expression (1) reduces to

$$\frac{\Delta E}{E}(\bar{\rho}g). \tag{4}$$

To gain insight into the magnitude of this additional loading, consider a permafrost bulk density of (130 lb/ft^3) and an ice density of (57 lb/ft^3) which gives an effective density $\bar{\rho} = 73$ lb/ft^3. From laboratory tests on frozen and thawed samples of simulated deep permafrost [2], the stiffness reduction is computed as $\Delta E/E = 0.35$. Hence, from equation (4) the body force release upon thaw for this case is (26 lb/ft^3). This means that the thawed permafrost appears 20 percent heavier than the initial frozen permafrost.

The stiffness reduction mechanism and body force release are considered important in underconsolidated permafrost, as well as in permafrost with varying lithology. Sands and clays can have different stiffness reductions upon thaw that lead to complex loadings across sand/clay interfaces.

Pore Pressure Reduction. The mechanism of pore pressure reduction upon thaw has been substantiated during initial thaw in freezeback field tests [14] and also in a full-scale thaw-subsidence field test [4, 7].

The pore pressure reduction is due directly to a shrinkage in volume of pore ice upon thaw. Assuming a hydrostatic head of ice before thaw and no influx of fluids after thaw, the pore pressure reduction Δp can be computed on the basis of a final pore pressure equal to zero (low vapor pressure in clays/silts and small hydrostatic head in gravels/sands) [7]. Hence,

$$\Delta p = \rho_i g z, \tag{5}$$

where ρ_i is the pore ice density. In the ARCO/Exxon thaw

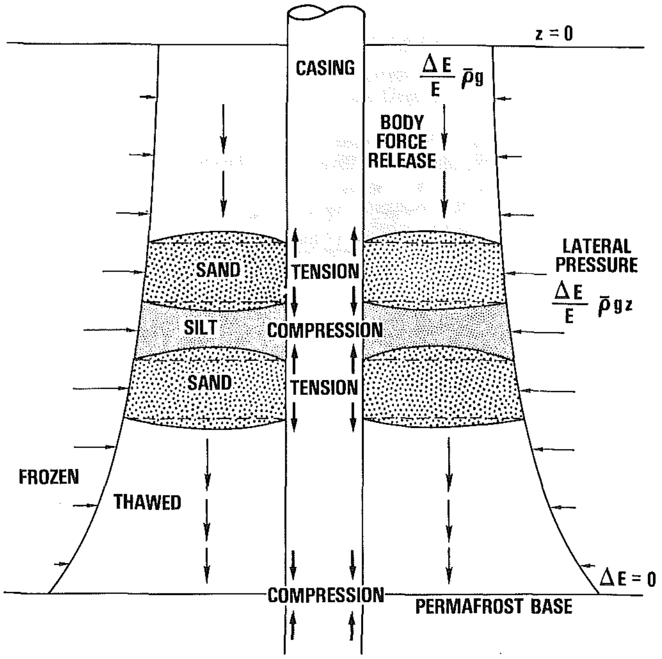

Fig. 5

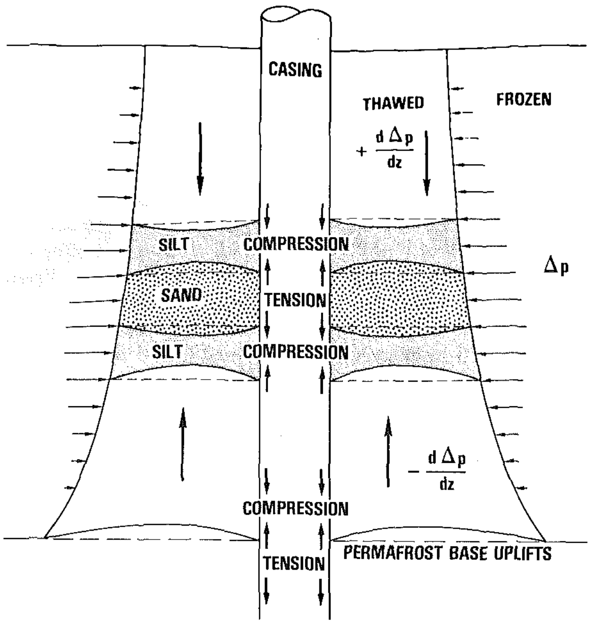

Fig. 6

subsidence field test, final pore pressures in the central region and near the permafrost base were measured to be nearly zero. For (1800 ft) of permafrost and ρ_i = (0.4 psi/ft), the maximum pore pressure reduction near the permafrost base is approximately 700 psi.

The pore pressure reduction loading, like the stiffness reduction loading, causes a pore pressure gradient in the vertical direction, (see Fig. 6)

$$\frac{d}{dz}\Delta p = \rho_i g, \qquad (6)$$

and also a loading in the horizontal direction given by (5). The horizontal pressure arises because of the unbalance of pore pressure across the thawed/frozen interface acting to squeeze the interface inward. Note that the vertical loading given by (6) is, again, like a body force. Taking ρ_i = (0.4 psi/ft) in (6) gives a body force density of (58 lb/ft^3).

The pore pressure reduction gradient defined by (6) is valid down to just above the permafrost base where the final pore pressure in the thawed zone is no longer zero but increases because of unfrozen water. At the permafrost base, the pore pressure returns to normal and, thus, there is no Δp at the base. The pore pressure reduction is, therefore, zero at the surface, increases to a maximum in the central region, and then decreases back to zero at the permafrost base. This turn around in Δp near the base causes a change in sign of the gradient in (6), indicating a reversal in the body force effect and causing an uplifting, and not subsidence, of the permafrost base.

Pore pressure reduction is important in normally compacted soils. Deep permafrost soils that were deposited and compacted before the onset of freezing can be expected to be normally consolidated. The presence of low permeability soils (silts and clays) will limit influx of water or flow of water between soils and, thus, create conditions for maximum pore pressure reduction. At Prudhoe Bay and the Mackenzie Delta, interspersed layers of silts, clays, or mudstone between sand and gravel layers act as natural fluid flow barriers.

Special Loadings

The nature of the horizontal and vertical forces due to the various thaw-subsidence mechanisms can generate special loadings associated with lithology and thaw geometry.

Alternating Casing Strains. The four mechanisms can induce casing strains that alternate between compression and tension. Phase change contraction and thaw consolidation in zones of excess ice will generate compression in the casing opposite these zones and tension above and below (see Figs. 2 and 3). Stiffness reduction and pore pressure reduction can cause alternating strains when the permafrost lithology is layered [4, 7]. Stiff sand layers next to soft silt layers will expand along the casing (tension) and compact soft silt layers (compression) due to the inward squeezing of the thawed/frozen interface, Figs. 5 and 6. Such casing strain behavior was demonstrated in the ARCO/Exxon thaw-subsidence field test at Prudhoe Bay.

Sloughing and Lateral Pressures. Lateral deformation of permafrost due to stiffness reduction and/or pore pressure reduction across a vertical thaw front can cause soil sloughing in an unsupported hole or generate lateral pressures on casing. In freezeback field tests with uncemented casing [14], pressure data immediately after thaw indicated numerous barriers to pressure communication along the casing, suggesting inward deformation and sloughing. Evidence of lateral pressure is provided by cement bond logs from two BP thaw-subsidence field tests [3] and the ARCO/Exxon field test, Fig. 7 [4]. The logs demonstrated better bonding in the central region (where the stiffness and pore pressure reduction are largest) and also increased bonding with duration of the tests.

Thaw Discontinuities. The geometry of the thaw zone can significantly effect the induced casing strains. If thaw discontinuities such as thaw bulbs are generated from sudden variations in permafrost thermal properties because of lithology or sudden variations in wellbore thermal properties because of insulation or refrigeration, then increased strains can result. The horizontal boundary associated with a thaw discontinuity allows for a stiffness and pore pressure reduction to act in the vertical direction. This creates a vertical squeeze or compression on the thaw zone and magnifies the casing strain.

A similar situation can occur in permafrost with unfrozen zones. Consider the case of a frozen zone overlain and underlain by unfrozen zones of normal pore pressure. A pore pressure reduction in the frozen zone upon thaw will generate compression in the thawed zone and tension in the unfrozen zones.

Conclusions

1 Four thaw-subsidence mechanisms can occur in perma-

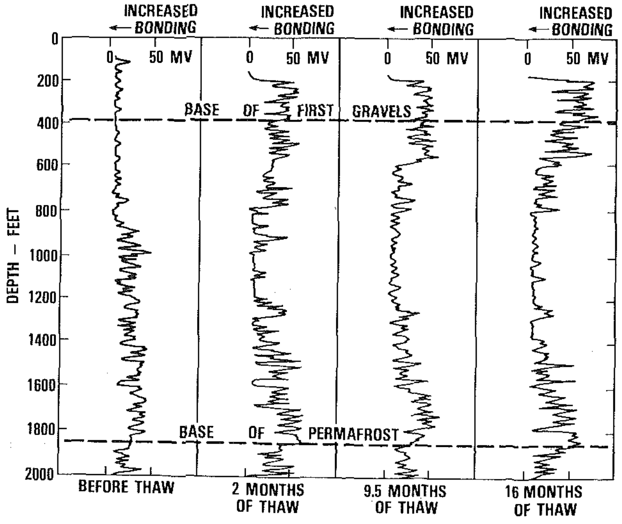

Fig. 7

frost. Phase change contraction and consolidation with fluid flow are most likely to occur in surface and near surface soils that are ice rich and underconsolidated. Stiffness reduction and pore pressure reduction are important in deep permafrost that is normally consolidated or slightly underconsolidated.

2 Stiffness reduction and pore pressure reduction generate vertical body force loads that cause the thawed soil to appear heavier and lateral loads across the thawed/frozen interface that squeeze the thawed soil inward.

3 The stiffness reduction and pore pressure reduction loads can be of the same order of magnitude. These body force loads can result in an apparent increase in soil weight by as much as 50 percent.

4 Lithology variations and thaw discontinuities can magnify the casing strains induced by thaw subsidence.

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APPENDIX

Stiffness Reduction Equations

The analysis presented here extends the analysis of Mitchell [7] to include changes in elastic moduli upon thaw.

Before thaw, the equations of elasticity are

$$G\frac{\partial^2 U}{\partial X^2} + \left(k + \frac{G}{3}\right)\frac{\partial e}{\partial X} = \rho g - \frac{\partial p}{\partial X} \qquad (7)$$

Where U is the displacement vector, e is the volumetric strain, p is the pore pressure, ρ is the bulk density, g is the gravity force vector, $\partial^2/\partial X^2$ is the Laplacian scalar and $\partial/\partial X$ is the gradient vector. The bulk modulus k and shear modulus G are related to the Youngs modulus E and Poisson ratio ν by

$$k = \frac{E}{3(1 - 2\nu)}, \; G = \frac{E}{2(1 + \nu)}. \qquad (8)$$

After thaw, the equations of elasticity have the same form

$$G'\frac{\partial U'}{\partial X^2} + \left(k' + \frac{G'}{3}\right)\frac{\partial e'}{\partial X} = \rho g - \frac{\partial p'}{\partial X}, \qquad (9)$$

where the superscript prime denotes values after thaw. Subtracting equation (7) from (9), one obtains after some manipulation

$$G'\frac{\partial^2}{\partial X^2}(\Delta U) + \left(k' + \frac{G'}{3}\right)\frac{\partial}{\partial X}(\Delta e) = L \qquad (10)$$

where the deformations are

$$\Delta U = U' - U, \; \Delta e = e' - e \qquad (11)$$

and the loading force L causing the deformation is given by

$$L = \frac{\partial \Delta p}{\partial X} + \frac{\Delta G}{G}\left[\rho g - \frac{\partial p}{\partial X} - \frac{\partial N}{\partial X}\right] + \frac{\Delta k}{k}\left[\frac{\partial N}{\partial X}\right] \qquad (12)$$

In expression (12), Δp is the pore pressure reduction upon thaw

$$\Delta p = p - p', \qquad (13)$$

ΔG and Δk are the change in moduli representing the stiffness reduction

$$\Delta G = G - G', \; \Delta k = k - k', \qquad (14)$$

and N is the mean effective stress in the permafrost before thaw

$$N = 1/3\,(\sigma_x + \sigma_y + \sigma_z) = ke \qquad (15)$$

The expression (12) for the loading force L can be simplified further if the initial pore pressure is taken as the ice hydrostatic pressure

$$p = \rho_i g z, \qquad (16)$$

and if the effective stresses are given by the usual relationship,

$$\sigma_x = \sigma_y = 1/2\sigma_z = 1/2\,(\rho - \rho_i)gz. \qquad (17)$$

In this case the relation (12) becomes

$$L = \frac{\partial}{\partial X}\Delta p + \frac{\Delta G}{G}(1/3\,\bar{\rho}g) + \frac{\Delta k}{k}(2/3\,\bar{\rho}g), \qquad (18)$$

where $\bar{\rho}$ is the effective density $(\rho - \rho_i)$.

With the loading term L in the elasticity equations (10), these equations are completely analogous to the equations of thermoelasticity; the changes Δp, ΔG, and Δk in (18) are analogous to a temperature change ΔT. The analogy for pore pressure changes was noted by Biot [15] and Lubinski [16] in the development of poro-elasticity theory. From this analogy it follows that the loading (18) also generates boundary loads (see Lubinski [16]) of the form

$$\Delta P + \frac{\Delta G}{G}(1/3\,\bar{\rho}gz) + \frac{\Delta k}{k}(2/3\,\bar{\rho}gz). \qquad (19)$$

For the thaw-subsidence problem, these boundary loads act across the thawed-frozen interface.