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discussion

Loading Mechanisms in Thawed Permafrost Around Arctic Wells[1]

R. F. MITCHELL.[2] Dr. Goodman's review of permafrost loading mechanisms that influence well completion design is welcome and timely. This discussion will review some selected topics from this paper which might benefit from further analysis.

Phase Change Contraction. The loading mechanism called phase change contraction is associated with the thawing of excess ice. In this context, excess ice is bulk ice in the form of ice lenses and ice wedges. The change of phase from ice to water results in a 9 percent volume reduction along with the loss of the initial ice pressure. The volume change is claimed to be a determining factor in subsidence, for example, a 10-ft (3.1-m) lens causes 0.9 ft (0.3 m) of vertical subsidence. The analysis of subsidence due to the thaw of bulk ice is a more complex problem than this suggests.

For example, the thaw of near surface bulk ice at Prudhoe Bay generates casing loads which are not strain induced. At Prudhoe Bay, the near surface permafrost is an underconsolidated gravel with bulk ice found in the upper 100 ft (30.5 m). In the Arco/Exxon thaw-subsidence field test [1] this gravel sloughed very readily into voids created by the thaw of bulk ice. For similar situations, the thaw of a 10-ft (3.1-m) lens could produce 10 ft (3.1-m) of vertical subsidence. In extreme cases, the weight of the conductor casing and wellhead is no longer supported by the permafrost foundation. This weight would be carried by the surface casing and the more competent permafrost below 100 ft (30.5 m). The thaw-subsidence field test generated moderate compressive strain in the well casing in the upper 200 ft (6.1 m) of permafrost by this mechanism. The surface casing used for production wells at Prudhoe can easily carry these loads; however, routine gravel infill of surface voids maintains a good foundation and helps insure safe working conditions.

Fig. 1 sketches a possible boundary value problem for a buried ice lens with competent permafrost above and below the lens. An important feature of this problem is the reduced thaw radius at the lens. A competent permafrost is about 30 percent ice by volume, so a given quantity of heat will thaw about three times as much permafrost volume as bulk ice. The increased thaw radius above and below the lens produces the unusual pressure boundary conditions sketched in Fig. 1. The strongest pressure in this sketch, the ice pressure P_0, is trying to close the void radially, the vertical pressures are reduced by the pore pressure change ΔP in the permafrost. For slow strain rates, ice can be characterized as a viscous fluid, so for slow thaw rates and a lens of large radial extent, radial flow could be the dominant effect. The ice could flow into the thawed void, with relatively small vertical subsidence occuring over the life of the well.

The point of these two examples is that "phase change contraction" does produce subsidence loading but does not determine soil deformations and casing strains. The analysis of subsidence due to thaw of bulk ice is a very challenging problem, both in the characterization of the mechanical response of the materials involved and in the solution of the appropriate boundary value problems.

Stiffness Reduction. The concept of stiffness reduction has previously been recognized as "disturbance due to thaw" by Smith and Clegg [2] and as "a change in the initial effective stress upon thaw [that] would appear as an additional loading term" by Mitchell [3]. The result presented in this paper is an expression for this loading term based on the specific assumption that the soil matrix stress both before and after thaw is related linearly to the initial soil matrix strain. This seems to be a reasonable assumption for a consolidated permafrost, but to my knowledge this result has not been verified experimentally.

The expression for the body force $\underset{\sim}{L}$ is correct but the boundary conditions specified by equation A13 are not generally correct. This result can be seen by writing $\underset{\sim}{L}$ explicitly in terms of

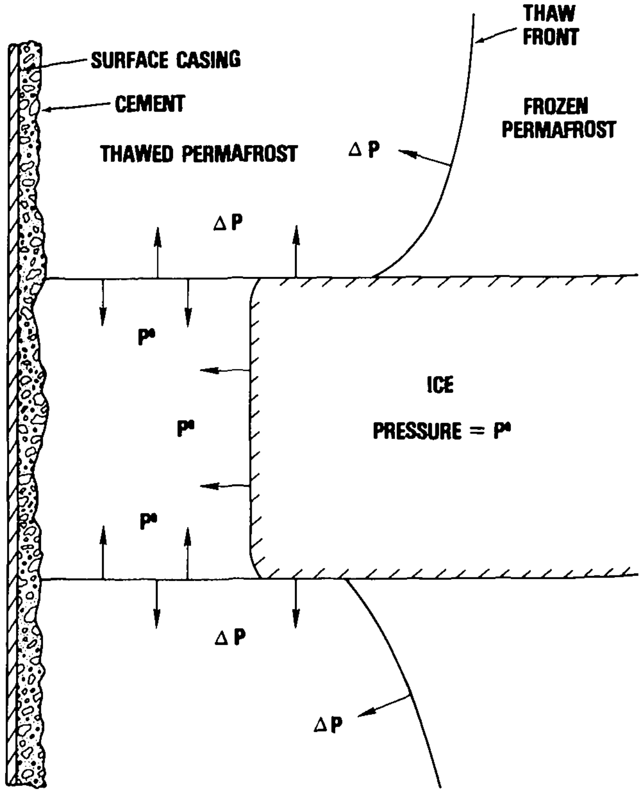

Fig. 1

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[1] By M. A. Goodman, published in the ASME Journal of Pressure Vessel Technology, Vol. 99, No. 4, Nov. 1977.

[2] Exxon Production Research Co., Houston, Tex.

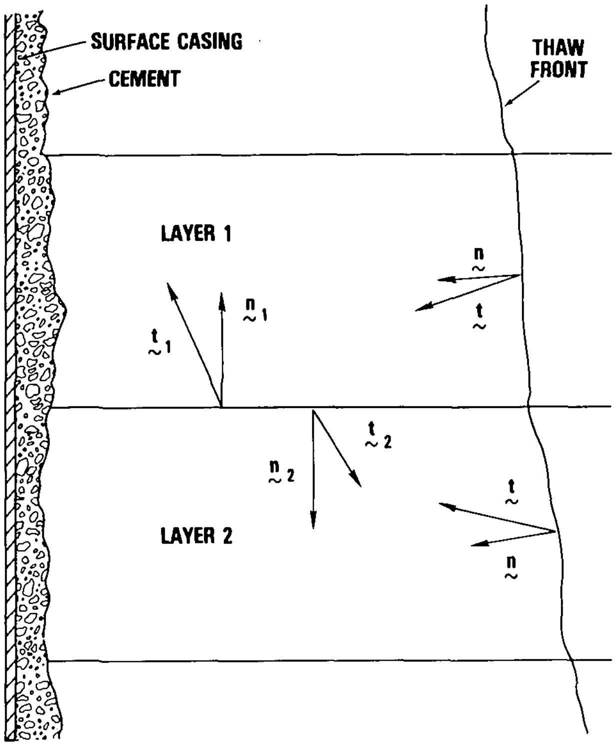

Fig. 2

the initial stress state:

$$\underset{\sim}{L} = \operatorname{div}\left\{-\left(\frac{\Delta G}{G} - \frac{\Delta k}{k}\right) N\underset{\sim}{I} + \left(\frac{\Delta G}{G}\right)\underset{\sim}{\sigma}\right\} + \operatorname{grad}(\Delta P)$$

using the notation given in the Appendix of the paper. At the thaw front, the boundary condition is the traction vector

$$\underset{\sim}{t} = -\left(\frac{\Delta G}{G} - \frac{\Delta k}{k}\right) N\,\mathbf{n} + \left(\frac{\Delta G}{G}\right)\underset{\sim}{\sigma}\ \mathbf{n} + (\Delta P)\mathbf{n}$$

where $\mathbf{n}$ is the unit vector normal to the thaw front and directed into the thawed zone. The surface traction $\underset{\sim}{t}$ is a combination of a pressure loading and a shear loading. The elastic problem with body force $\underset{\sim}{L}$ and boundary conditions $\underset{\sim}{t}$ is not equivalent to an isotropic thermal stress problem because the boundary condition may include a shear stress term which has no counterpart in isotropic thermoelasticity.

The appropriate boundary condition between layers is

$$\underset{\sim}{t}_{12} = \underset{\sim}{t}_1 + \underset{\sim}{t}_2$$

where $\mathbf{n}_1$ associated with $\underset{\sim}{t}_1$ points into layer from layer 2 and $\mathbf{n}_2$ associated with $\underset{\sim}{t}_2$ points into layer 2 from layer 1, as shown in Fig. 2. If the initial effective stress and pore pressure are continuous across the boundary, then

$$\begin{aligned}\underset{\sim}{t}_{12} = &-\left\{\left[\frac{\Delta G}{G} - \frac{\Delta k}{k}\right]_1 - \left[\frac{\Delta G}{G} - \frac{\Delta k}{k}\right]_2\right\} N\,\mathbf{n}_1 \\ &+ \left\{\left[\frac{\Delta G}{G}\right]_1 - \left[\frac{\Delta G}{G}\right]_2\right\}\underset{\sim}{\sigma}\ \mathbf{n}_1 \\ &+ [(\Delta P)_1 - (\Delta P)_2]\ \mathbf{n}_1\end{aligned}$$

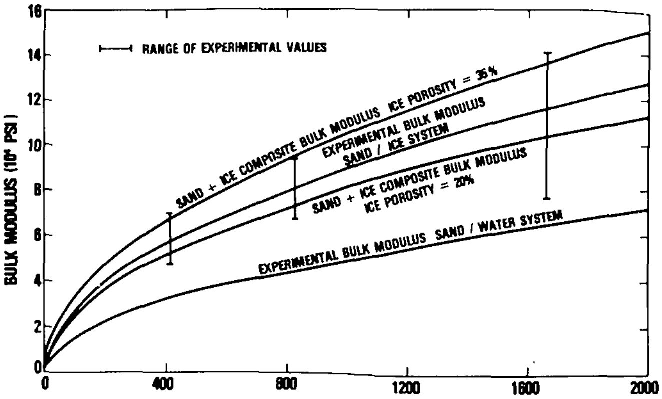

Fig. 3

The change in effective stress loads were not used in developing previous thaw-subsidence studies for two reasons. First, the subsidence model using only the pore pressure reduction mechanism proved adequate to model the thaw subsidence field test. It was recognized that the material properties used to model the field test were not the actual elastic moduli of the insitu permafrost. Instead, these moduli together with the assumed pore pressure variation implicitly accounted for the actual pore pressure distribution, the actual distribution of soil moduli, and the effects of effective stress change upon thaw.

The second reason these effects were not included was that experimental verification of this effect was not available. The results from Goodman's experimental studies [4] may be misleading because in the case of the sand-ice system, the Young's modulus measured is possibly influenced by the bulk modulus of the pore ice. In the case of the sand-water system, the much greater mobility of the water compared to the ice, combined with the free draining boundary condition, should give a result more characteristic of the sand matrix alone. As shown in Fig. 3 a composite bulk modulus for the sand-ice system, based on the sand-water matrix properties and the bulk modulus of fresh water ice, agrees with the sand-ice properties within experimental error. Changes in the soil matrix with thaw are certainly plausable, and this calculation does not prove that matrix changes did not take place in that experimental study. However, I believe that determination of soil matrix properties in frozen permafrost requires caution in the interpretation of experimental data.

References

1 Ruedrich, R. A., Perkins, T. K., Rochon, J. A., and Christman, S. A., "Casing Strain Resulting From Thawing of Prudhoe Bay Permafrost," SPE 6062 presented at SPE-AIME 51st Annual Technical Conference, New Orleans, 1976.

2 Smith, R. E., and Clegg, M. W., "Analysis and Design of Production Wells Through Thick Permafrost," *Proceeding of the 8th World Petroleum Congress*, Moscow, 1971.

3 Mitchell, R. F., "A Mechanical Model for Permafrost Thaw-Subsidence," ASME JOURNAL OF PRESSURE VESSEL TECHNOLOGY, Vol. 99, No. 1, Feb. 1977, pp. 183-186.

4 Goodman, M. A., "Mechanical Properties of Simulated Deep Permafrost," ASME *Journal of Engineering for Industry*, Vol. 97, No. 2, May 1975, pp. 417-425.