Numerical Simulation of Frost Heave in Arctic Pipelines

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ABSTRACT

Pipeline strain due to frost heave is a main design concern for gas pipelines buried in the active layer of permafrost soil. The expansion of pore water upon freezing contributes to only a small portion of the overall frost heave, while the majority of soil heave is attributed to the moisture migration and formation of ice lenses. Driven by the increasing demand of burying chilled gas pipelines in the arctic environment, different models have been developed to predict the soil upheaval such as, rigid ice model, segregation potential model, and porosity rate function model, among others.

In this paper, a two-dimensional coupled thermal-mechanical finite element (FE) model based on the porosity rate function is developed using Abaqus. Using this model, the ice growth is described as the average increase in porosity of the soil rather than a separate ice lenses growth. The model computes the depth of active soil layer underlain by permafrost. Then, soil upheaval displacement due to chilled pipeline buried at 0.8m and 2.5m in various soil types is computed for summer and winter conditions. Model validation is carried out by comparisons with experimental data available in literature.

Based on a number of FE cases, empirical formulations are developed for prediction of frost heave under different pipe temperature, surface temperature, soil type, and burial depths. Once soil frost heave is predicted, the resulting pipe strain is determined by a simplified pipe soil interaction FE model. It is anticipated that the developed empirical relations be used at the conceptual design phase of arctic pipelines to predict pipe straining without the need for multiple numerical simulations, thus resulting in significant savings.

KEY WORDS: Arctic pipelines, FEA, frost heave, moisture migration, porosity rate function, permafrost, strain-based design

INTRODUCTION

Frost heave describes the phenomenon whereby soil freezing causes upwards motion due to the action of capillary suction that absorbs water from the unfrozen surrounding. The expansion of pore water upon freezing is called “in-situ” frost heave and generally contributes to a small part of the overall frost heave. The majority of the heave is due to the moisture migration and the formation of ice lenses, which is also identified as “secondary” heave.

Since the 1920’s, numerous efforts have been made to comprehend and explain the frost heave phenomenon, and various models have been developed accordingly to predict the frost heaving. Among them, rigid ice model (Holden, 1983; Miller, 1978; O’Neill et al., 1980), segregation potential (SP) model (Konrad et al., 1981; 1982; 1984), and porosity rate function (PRF) model (Michalowski, 1993; Michalowski et al., 2006) received the most attention. A literature review of these three models is performed by the authors in a separate publication (Xu et al., 2013). Due to the complex nature of the frost heave phenomenon, all models that predict the frost heave under field conditions are still under development or subject to improvement. No matter what model is adopted, reasonable assumptions and simplifications have to be made to achieve a methodology that is robust and practical for engineering purposes.

Upon a thorough evaluation, porosity rate function model is selected for the current study. The advantage of this approach over the other models is the use of a formulation consistent with continuum mechanics which allows the model to be generalized into arbitrary three-dimensional processes, and the standard numerical techniques to be used in practical problems. Moreover, the porosity rate function requires less laboratory testing efforts compared to the segregation potential model, which will be critical once a site-specific soil testing is required.

FINITE ELEMENT MODEL

In the current study, numerical analyses are carried out with three FE models; geothermal model to simulate heat transfer processes in soil, and the results provide guidance for the frost heave simulation domain; frost heave model is a fully coupled heat transfer and displacement model that predicts the transient frost heave with time; and finally, pipe-soil interaction model to calculate the pipe stress and strain due to differential soil heave. Brief descriptions of these three FE models are provided below, more details can be found in a separate paper by the authors (Xu et al., 2013).

Geothermal Model

The domain of the geothermal model is illustrated in Fig. 1. Only half of the pipeline and corresponding soil are modeled due to the geometry symmetry. The domain is defined as 25m wide and 50m deep. The left