A Simplified Pipeline Strain Demand Model for Frost Heave

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ABSTRACT

Structural analysis methods used in the design of buried pipelines for the discontinuous permafrost regions need to handle the unique conditions that can arise; in particular thaw subsidence and frost heave. As a chilled gas pipeline traverses from a frost stable soil zone to a frost susceptible zone, frost bulbs are formed around the pipe and cause the pipeline to heave. If there is significant differential heave, pipe bending across the interface between these two zones could result in pipe strains exceeding design limits, or in extreme cases, buckling or tensile fracture.

For pipelines subjected to geotechnical hazards, characterization of strain demand is an integral part of the strain-based design process. This paper describes a simplified finite element model that was developed to predict compressive and tensile strain demand of gas pipelines subjected to frost heave. By using features that are typically available in general-purpose finite element analysis software, the proposed pipe-soil interaction model addressed issues that are essential for predicting pipeline strain demand. These issues include pressure-dependent heave displacement, and geometrically non-linear load-displacement response of steel pipe. The simplified model was validated by comparing model predictions to the Caen tests.

KEY WORDS: Pipeline; Design; Strain-Based Design; Finite Element Analysis; Frost Heave.

INTRODUCTION

Structural analysis methods used in the design of buried pipelines for the discontinuous permafrost regions of North America need to handle the unique conditions that can arise; in particular thaw subsidence and frost heave. As a chilled gas pipeline, operating at temperatures below 0°C, traverses from a frost stable soil zone to a frost susceptible zone, the soil in both zones starts to freeze, forming a frost bulb around the pipe. Volumetric expansion due to a phase change of water in the soil causes the pipeline to heave. In the frost susceptible soil, however, the migration of water to the freezing front results in the formation of ice lenses below the pipe which become part of the frost bulb, producing significantly larger heave displacements in that zone. If there is significant differential heave, pipe bending across the interface between these two zones could result in pipe strains exceeding design limits, or in extreme cases, buckling or tensile fracture.

Some analysis techniques used in this application treat the interaction of pipe and soil in a simplified manner. They generally assume that both the thermal and fluid flow responses of the soils surrounding the chilled gas pipeline are decoupled from the mechanical interaction of the soil and pipeline. At the time the work described here was conducted, there was a need to transfer academic research on coupled analyses into practical modeling techniques applicable to pipeline design.

A further simplification, involving the mechanics of pipe-soil interaction, is also normally made. Existing pipe-soil interaction analysis programs assume the pipeline behaves like a beam supported on a series of discrete non-linear springs (i.e., a non-linear “Winkler” foundation). In effect, this assumes that the soil can be regarded as a series of plane slices, perpendicular to the pipe, with no connection between the slices (resulting in the slices deforming independently of each other). It is reasoned that, if the bearing forces between pipe and soil vary gradually along the pipe, and if there are no sudden discontinuities in soil properties, this assumption is likely to be accurate. This method of analysis has been used to model pipe-soil interaction for many types of ground movement problems, including landslides, seismic faulting, frost heave and thaw subsidence (ASCE 1984).

Although soil-spring models have become an accepted method for analyzing pipe-soil interaction, little work has been undertaken to verify and calibrate such models for analyzing frost heave or thaw subsidence problems. It is possible that such models may in some cases be overly conservative, while in other cases be unconservative. For example, for the case of frost- heave of a pipeline in discontinuous permafrost, a sudden transition may occur at the frozen-unfrozen boundary. This violates the initial assumption that there are no sudden discontinuities, which could lead to inaccurate results. In addition, it can sometimes be difficult to determine an appropriate procedure for selecting soil-spring stiffness values that will accurately reflect the non-linear behaviour of the frozen and unfrozen soils in the regions of interest. In some cases, field data concerning soil properties are not readily available, and guessing at soil-spring coefficients based on standard approaches may produce misleading results.

It is expected that eventually more realistic assessments of the interaction between pipelines and heaving (or thawing) soils can be achieved through use of sophisticated finite element models that use three-dimensional continuum models for the soil and three-dimensional shell models for the pipe. Although such models can be developed, their complexity and size may render them impractical for routine