Tunnelling and Underground Space Technology 51 (2016) 291–300

Contents lists available at ScienceDirect

Tunnelling and Underground Space Technology

journal homepage: www.elsevier.com/locate/tust

# Parametric study of frost-induced bending moments in buried cast iron water pipes

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ARTICLE INFO

*Article history:*
Received 8 February 2013
Received in revised form 23 August 2014
Accepted 16 October 2015
Available online 11 November 2015

*Keywords:*
Buried pipes
Fracture
Cast iron pipe
Frost effects

ABSTRACT

While the features of frost susceptible soils have been examined in various studies, the mechanisms by which volume changes due to ground freezing can influence cast iron water pipes buried below the frost line have not been explained, and the hypothesis that frost-induced ground deformations can induce ring fractures due to longitudinal bending of these pipes has not been proven. Therefore, a parametric study employing three dimensional finite element analysis is reported, where the soil–pipe interaction associated with a pipe crossing under an intersection of a major arterial road with a residential street are examined. The arterial road is modeled as having non-frost susceptible sub-base and the local street is represented as having a lower grade pavement with frost susceptible sub-base. One specific frost loading case featuring both isotropic pore water expansion and orthotropic ice lens formation is modeled.

The analysis demonstrates how volume changes due to ground freezing in soil strata above the buried pipe can induce bending moments sufficient to cause ring fracture. Changes in the relative axial stiffness of the pipe were found to have only a small effect on pipe moments. Decreases in the relative flexural stiffness of the pipe resulting from reductions in pipe modulus also had only a small effect on pipe deflections and normalized moments. Changes due to soil modulus had a significant effect on deformations, but little influence on moments. Decreases in pavement stiffness decrease pipe deflections and moments. Trench backfill conditions greatly affect deflection and moment. Reduction in burial depth from 2 m to 1.5 m increases deflections, and increases moments beyond the failure capacity of the grey, cast iron pipe considered in the study, and this computational result is directly supported by field evidence.



## 1. Introduction

Seasonal frost penetration is a concern in Northern regions such as Ontario and Québec, Canada. It is very well known that cold weather events precipitate most of the ring fractures that develop in the small diameter cast iron pipes traditionally used for municipal water supply. However, these pipes are buried below the frost zone, and there have been no experimental or computational results to demonstrate how frost heave in the overlying soil can result in differential ground movements in the cast iron pipes buried below, or produce longitudinal bending moments large enough to cause ring fractures. Over time, municipal engineers have chosen to bury water pipes at ever-increasing depths below the frost-line (the depth of maximum frost penetration), because experience indicates that pipes still fracture even when the soil directly above the pipe does not freeze. A rational analysis capable of explaining how bending moments develop is therefore needed so that objective choices of burial depth can be made. Furthermore, an analysis of that kind can be used to examine suitable burial depths for the more flexible and ductile pipe materials currently employed in new water pipe construction like ductile iron and PVC, instead of continuing to choose water pipe depth based on experience with cast iron pipes.

One dimensional analysis is available to estimate the amount of frost heave resulting from ice-lens formation (Sheng et al., 1995) and the resource industry has funded extensive research on chilled gas pipelines which transition through ground of variable frost susceptibility e.g. Nixon et al. (1983), Selvadurai and Shinde (1993) and Selvadurai et al. (1999), however little work has been performed on the response of municipal pipe infrastructure to seasonal frost effects. Rajani and Zhan (1996) have developed simplified methods of estimating axial frost loads on buried water

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http://dx.doi.org/10.1016/j.tust.2015.10.028
0886-7798/

**Nomenclature**

*List of symbols*

| | |
|---|---|
| $\alpha_{il}$ | the orthotropic coefficient of thermal expansion modeling ice lens formation |
| $\alpha_{pw}$ | the isotropic coefficient of thermal expansion modeling pore water freezing |
| $v$ | Poisson's ratio for a material |
| $A$ | cross-sectional area of the pipe |
| $A_0$ | area bounded by the outer circumference of the pipe ($m^2$) |
| $b$ | beam width modeled in the analysis to represent the pipe (m) |
| $d$ | diameter of the circular pipe |
| $t$ | wall thickness of the circular pipe |
| $E$ | Young's modulus for a material |
| $E_f$ | Young's modulus of a frozen soil layer |
| $E_S$ | Young's modulus for a soil layer |
| $E_P$ | Young's modulus for the pipe |
| $h$ | height of the rectangular prism used to model the pipe (m) |
| $I$ | second moment of area of the pipe |
| $K$ | axial stiffness ratio of the pipe to the soil |
| $K_r$ | flexural stiffness ratio of the pipe to the soil |
| $L$ | length of the pipe (m) |
| $M_f$ | ultimate moment of the pipe in longitudinal bending (kN m) |

pipes by employing Winkler spring models. Unfortunately, the usefulness of the Winkler method for longitudinal pipe bending is limited by the fact that it characterizes soil pressures in terms of absolute pipe deflection, and it is challenging to model loading conditions which are not directly applied to the pipe (like volume changes in overlying soil materials).

A three dimensional finite element study of water pipes has been undertaken to investigate the hypothesis that the effect of frost is to generate differential ground movements along the pipeline large enough to produce bending moments that fracture the pipe. The work is used to assess the impact of varying problem geometry and material characteristics on pipe deflection, moment, and the potential for ring fracture under one well defined differential frost loading condition. The basis of the finite element analysis procedure is explained and the results of a parametric study are then presented. The investigation examines the material and geometrical factors influencing ring fracture in a pipe beneath a frost susceptible residential street, where it crosses under a non-frost susceptible arterial road. The study includes an examination of the influence of burial depth, so the potential for pipes at different depths to fracture as a result of excessive bending moments can be compared to field experience.

## 2. Problem statement and modeling

### 2.1. Cast iron water pipe failure

Cast iron water pipe failure may result from a variety of mechanisms such as circumferential or ring fractures due to longitudinal bending moments, longitudinal breaks (in the axial direction) resulting from circumferential tensions, joint failure, blowouts, or corrosion pits (Rajani et al., 1996). The failure mechanism of particular interest for the present parametric study is ring fracture resulting from longitudinal bending. Ring fractures may result from the axial tension which develops due to restraints on thermal contraction under temperature change (Rajani et al., 1996), flexural loading caused by inadequate bedding, or swelling of underlying materials. It may also result from the differential frost movements in overlying soil strata. The following parametric study investigates cast iron water pipe ring fracture as a result of differential frost action under varying geometrical and material conditions, to develop a better understanding of the factors affecting this failure mechanism and the longitudinal soil–pipe response.

### 2.2. Frost-related volume expansion

The two primary components of frost movement are incorporated into the analyses: isotropic pore water expansion and orthotropic ice lens formation. The first component is associated with the 9% volume increase of soil pore water as it freezes, while the second component relates to water migration from the unfrozen soil to the freezing front where ice lenses form. A three dimensional finite element procedure is employed, which captures the volumetric behavior associated with both pore water freezing and ice lens formation. The analysis does not attempt to model how heat and fluid flow lead to ground freezing and volume change. Instead, it uses coupled thermal-structural analysis as an artifice, where coefficients of volume increase are specified so a temperature increase of 1 °C applied to the frost heave zone leads to volumetric expansions. The three dimensional elastic analysis then accounts for the three dimensional response of the buried pipe as it passes from under frost-susceptible to frost-resistant roadways.

Fig. 1 illustrates volume changes induced by the artificial temperature increase employing two thermal expansion coefficients, $\alpha_{il}$ and $\alpha_{pw}$ for the frost-susceptible soil materials, producing the orthotropic expansion associated with ice lens formation or the isotropic expansion due to pore water freezing respectively. The specific values of the coefficients $\alpha_{il}$ and $\alpha_{pw}$ employed are as follows:

- Equal values of $\alpha_{pw}$ set to 1% are defined in the *x*, *y*, and *z* directions to simulate the effects of the 9% pore volume increase in the zone of pore water freezing as illustrated in Fig. 1b (these values could result from a 3% increase in total volume, where 90% of the pore water freezes and the soil has void ratio of 0.59); and
- For cases that also model the effect of ice lensing, a vertical coefficient in the zone of ice lensing $\alpha_{il}$ is selected to simulate a 25% increase in the height of the soil volume associated with the formation of ice lenses as illustrated in Fig. 1c (half the high value reported by Konrad et al., 1995, for frost susceptible sensitive clays). Coefficients in the two horizontal directions remain equal to the value associated with pore water freezing, 1%, since ice lensing effectively produces increases in the height of the zone affected, without additional increases in the horizontal dimensions.

Since the finite element analysis models the soil, pavement and pipe materials as elastic, analysis considering pore water freezing and then pore water freezing and ice lensing can be conducted separately using the coefficients of thermal expansion detailed above.

The 1 °C temperature change used in the analysis is a convenient (though arbitrary) value selected to impose the desired volume expansion. Any other temperature change could have been employed, provided that the thermal expansion coefficients were