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Seismic behavior of buried energy pipelines in northern permafrost regions

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ABSTRACT

Approximately one-third of Canada's marketable conventional resources of natural gas and recoverable light crude oil are found in the North. Pipelines, either above-ground or buried, are essential means of transporting this energy supply to refineries and various users. Beside common geohazards, such as river erosion and landslide, earthquake triggered geohazards including transient ground shaking and permanent ground displacement due to liquefaction can also jeopardize the integrity and safety of these pipelines. The main objective of the present study is to investigate the seismic behavior of buried pipelines in regions characterized with discontinuous permafrost conditions. To achieve this goal, the impacts of local soil conditions and the dynamic interaction of large portions of randomly distributed blocks of frozen soil surrounded by unfrozen soil on the ground motion have been considered. In addition, a simplified analysis has been developed to evaluate the seismic response of buried pipelines considering soil-pipe interaction, geometric nonlinearities and large deformations.

Introduction

Local site conditions can significantly influence ground surface motions. In northern climate regions, the site effects are compounded with the impacts of frozen soil conditions. In particular, discontinuous permafrost represents a challenge for the geotechnical earthquake engineering. Only a limited number of studies have evaluated the effects of permafrost on the free-field ground motion. Most of these studies were conducted recently in response to infrastructure developments in cold regions and only considered continuous permafrost. For example, Yang et al. (2011) applied one dimensional equivalent linear analysis of vertically propagating horizontal shear waves to study the effects of continuous permafrost on the seismic response of highway bridges in Alaska. It seems that the published literature is devoid of research on the seismic response of structures/infrastructure in discontinuous permafrost. Furthermore, the seismic response of buried pipelines is highly influenced by the nonlinear behavior of materials (soil and steel) as well as the geometric nonlinearities. To accurately evaluate the seismic response of buried pipelines, the analysis should be capable of simulating pipe cross-sectional deformations and soil cyclic behavior. The objective of this paper is to characterize the seismic site response under complex discontinuous permafrost conditions employing a simplified nonlinear analysis method. The calculated ground motions are then applied as input motion to a buried pipeline in order to evaluate its behavior.

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Discontinuous Permafrost

Permafrost or permanently frozen ground is a term used to describe the thermal condition of earth materials, such as soil and rock, with temperature continuously below 0°C for a number of years (Muller 2008). In a discontinuous permafrost zone, some parts are under permafrost conditions whereas others are not. The discontinuous permafrost represents a particular challenge for the geotechnical earthquake engineers since frozen soils have relatively high shear wave velocities (Vs=1000~2500 m/s) in comparison with unfrozen soils (generally $V_s \leq 360$ m/s). When located next to each other, the relatively high impedance contrast may contribute to important site effects.

The stratigraphy and geotechnical properties of soil profiles for this study are based on data extracted from the Alaska Highway geotechnical borehole database (Yukon Geological Survey, 2014). The soil deposits consist of saturated cohesionless soil layers with occasional thin layers of peat soil on top of frozen parts. Details of the considered soil profiles and layer properties are depicted in Figure 1. The first layer consists of unfrozen soils only due to seasonal thaw. The respective geotechnical properties of soil layers, including the shear wave velocity, V_s, the soil density, ρ, the shear modulus, G, Poisson's ratio, υ, the bulk modulus, K, the internal friction angle, ϕ, the dilation angle, ψ, the cohesion, c, the porosity, n and the relative density, D_r are provided in Table 1. The total thickness of the soil layers considered in the analysis was 40 m and the thickness of the frozen soils was assumed to be 50% of the total soil thickness.

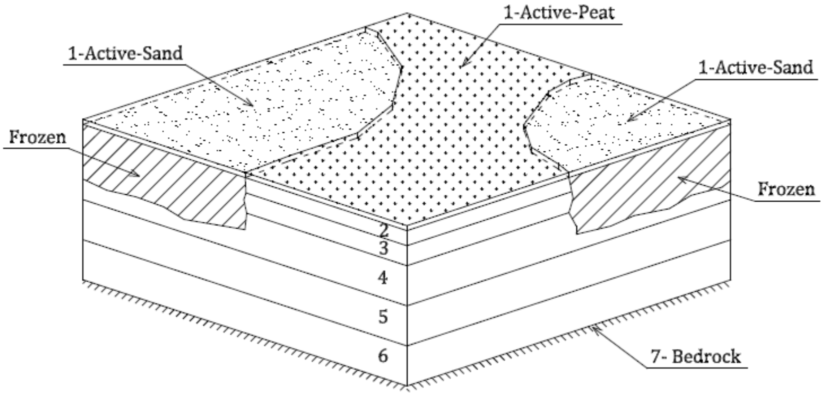


Figure 1. Vertical stratigraphy in a region with discontinuous permafrost.

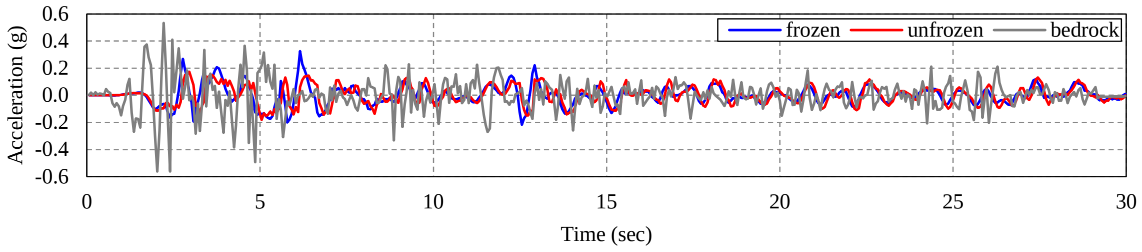
Table 1. Soil properties.

Layer	V_s (m/s)	ρ (kg/m^3)	G (MPa)	υ	K (MPa)	ϕ (°)	ψ (°)	c (Pa)	N	D_r (%)
Frozen	1500	2000	4500	0.26	7850	30	0	1000	-	-
1-Active-Peat	150	1900	43	0.35	129	1	0	1000	-	-
1-Active-Sand	160	1900	50	0.35	135	30	0	1000	-	-
2-Unfrozen	170	1900	55	0.35	165	30	0	1000	0.40	65
3-Unfrozen	170	1900	55	0.35	165	30	0	1000	0.35	65
4-Unfrozen	210	1900	84	0.35	252	35	5	1000	0.35	65
5-Unfrozen	260	1900	128	0.35	384	35	6	1000	0.35	82
6-Unfrozen	300	1900	171	0.35	513	35	7	1000	0.30	82
7- Bedrock	2500	---	---	---	---	---	---	---	---	---

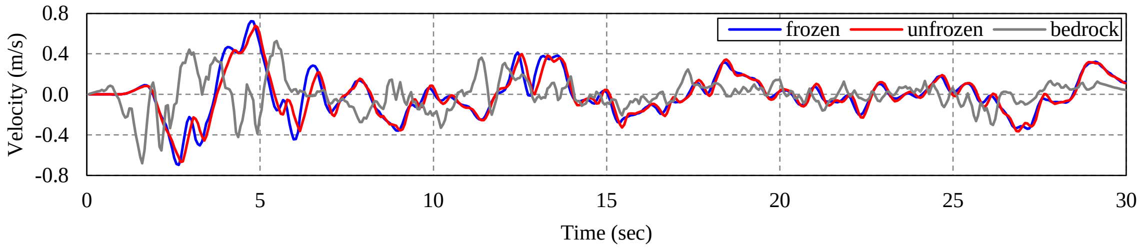
Seismic Site Response Analysis with FLAC

The computer program FLAC (Itasca Consulting Group Inc., 2002) was employed to conduct the seismic site response analysis. It applies an explicit finite difference scheme to solve the full equations of motion in continua and has capabilities that allow considering many aspects of the nonlinear behavior of the soil medium in the seismic analysis. Two-dimensional effective stress analysis was performed utilizing an appropriate built-in excess pore pressure model (Finn, 1982). Also, the stiffness degradation of frozen and unfrozen soils was considered in the analysis. The model included two embedded frozen blocks of width and thickness of 20 m that were spaced at 50 m apart. The developed model was subjected to the El Centro earthquake (1940) record scaled to PGA=0.58g and the free-field responses at the top of the frozen and unfrozen portions of the site were monitored throughout the analysis. Some of the results are shown in Figure 2.

(a) Time history of bedrock and free-field accelerations



(b) Time history of bedrock and free-field velocities



(c) Time history of bedrock and free-field displacements

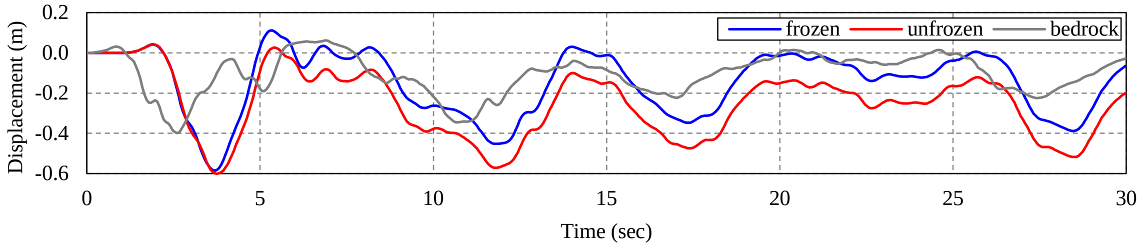


Figure 2. Time history of bedrock and free-field motions. The seismic input is the El Centro horizontal ground motion scaled at PGA=0.58g.

For the considered configuration and seismic input, the free-field acceleration time histories were mainly attenuated compared to that of bedrock motion (Figure 2a) but the respective free-field velocity and displacement responses were amplified slightly. This is an indication of nonlinear response in the unfrozen part and effect of excess pore pressure build-up on the stiffness degradation of the top layers. It can also be noted in Figures 2 that the free-field responses on top of the frozen and unfrozen soils are different. The peak ground acceleration (PGA) on top of the frozen soil is higher than that on top of the unfrozen soil (Figure 2a) and proportionally highest difference is observed for the free-field displacements (Figure 2c).

Seismic Analysis of Buried Pipelines in Discontinuous Permafrost

Formulation of the Problem

In the analysis of soil-structure interaction of pipelines, it is common to model the pipe employing frame finite elements and to simulate soil-pipe interaction with discrete elastoplastic springs in three perpendicular directions (Figure 3a). The soil spring force-displacement relationships suggested by the American Lifelines Alliance (ALA, 2005) are widely used in practice. In this study, ALA's springs were integrated into the "spring elements" and were combined with frame elements to form the structural model of the soil-pipeline system as indicated in Figure 3b.

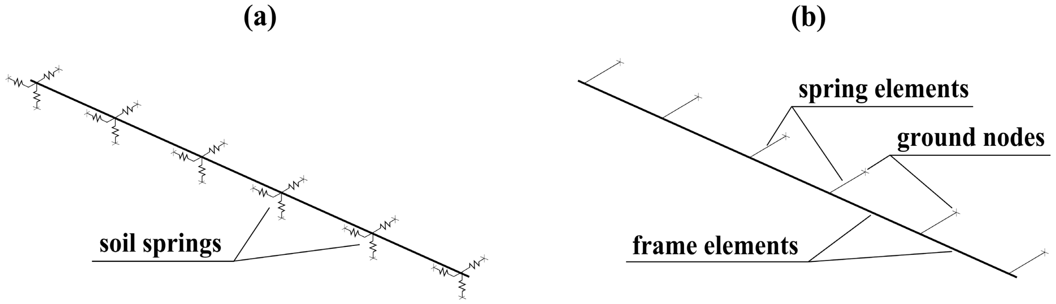


Figure 3. (a) ALA's soil spring representation and (b) soil-pipe interaction model of the present study.

Considering the site response analysis results, which show a difference in the response of frozen and unfrozen soils, the buried pipelines passing through the discontinuous permafrost are subject to multiple support excitations during earthquakes. The equation of dynamic equilibrium for the pipeline can be written as:

$$M\ddot{U} + C\dot{U} + KU = P(t) \tag{1}$$

where M, C and K are the mass, damping and stiffness matrices, U and its time derivatives are displacement, velocity and acceleration and P is the dynamic load. For a pipeline under multiple support excitations, Equation 1 can be expanded in a partition form as (Chopra, 2012):

$$\begin{bmatrix} m & m_g \\ m_g^T & m_{gg} \end{bmatrix} \begin{Bmatrix} \ddot{u}^t \\ \ddot{u}_g \end{Bmatrix} + \begin{bmatrix} c & c_g \\ c_g^T & c_{gg} \end{bmatrix} \begin{Bmatrix} \dot{u}^t \\ \dot{u}_g \end{Bmatrix} + \begin{bmatrix} k & k_g \\ k_g^T & k_{gg} \end{bmatrix} \begin{Bmatrix} u^t \\ u_g \end{Bmatrix} = \begin{Bmatrix} 0 \\ p_g(t) \end{Bmatrix} \tag{2}$$

in which the degrees of freedom (DOF) have been reordered in a way that the ones that are connected to the ground (Figure 3b) fall in the same partition and are denoted by subscript g. The rest of DOFs are indicated with superscript t and their response at each time instance has two parts: quasi-static and dynamic. The quasi-static response can be found by the following equation:

$$u^{qs} = -k^{-1} k_g u_g \tag{3}$$

And the dynamic response is obtained from:

$$m\ddot{u} + c\dot{u} + ku = p_{eff}(t) \tag{4}$$

where p_{eff} is defined as:

$$p_{eff}(t) = mk^{-1}k_g\ddot{u}_g(t) \tag{5}$$

Therefore, according to Equations 3 and 5, the time histories of ground displacement and acceleration are necessary to perform a dynamic analysis on a pipeline in discontinuous permafrost region. The Wilson's method (Chopra, 2012) was used to solve these equations.

Plastic Hinge Model for Buried Pipelines

Two types of nonlinearity exist in the structural analysis of a pipeline: material (soil and steel) and geometric (large deformations and cross-sectional ovalization) nonlinearities. Cross-sectional ovalization, caused by vertical components of tensile and compressive flexural stresses, is a geometric nonlinearity that changes the circular cross-section of a pipe to oval shape and results in reducing its bending capacity. In this study, the ovalization factor is defined as:

$$OV = \frac{\Delta D}{D} \tag{6}$$

where D is the pipe outer diameter and ΔD is the change of diameter in the plane of bending. Since excessive ovality of the cross-section can endanger pipeline integrity and serviceability, most of the codes limit the maximum ovality to 15%.

To deal with the mentioned nonlinearities, a plastic hinge model with fiber elements was developed. The cross-section of the pipe was divided into a number of longitudinal nonlinear inelastic fibers with constitutive relationship defined by the Ramberg-Osgood equation. The arrangement of the fibers in the hinge section could be changed according to an ovalization-curvature function to simulate the real behavior of a pipe under bending. A 16-fiber plastic hinge model was calibrated against the experimental data of Sherman (1983) for monotonic bending. The results are shown in Figure 4. The local buckling mode of collapse of two pipes with diameter to wall thickness ratio (D/t) of 36 and 96 was predicted satisfactorily by the model as demonstrated in Figure 4.

Shaw and Kyriakides (1985) conducted experimental studies on pipes subjected to bending moment and demonstrated that ovalization grows with number of loading cyclic. Therefore, a model was developed to simulate the cyclic behavior of the plastic hinge. The post-buckling behavior of the pipe was also included in the model to prevent structural instability during analysis. Figure 5 shows the calculated moment-curvature and ovalization-curvature diagrams for a pipe made of X65 steel (F_y=345 MPa) with D/t = 96 subjected to cyclic bending moment. The results show good agreement with the experimental results of Shaw and Kyriakides (1985).

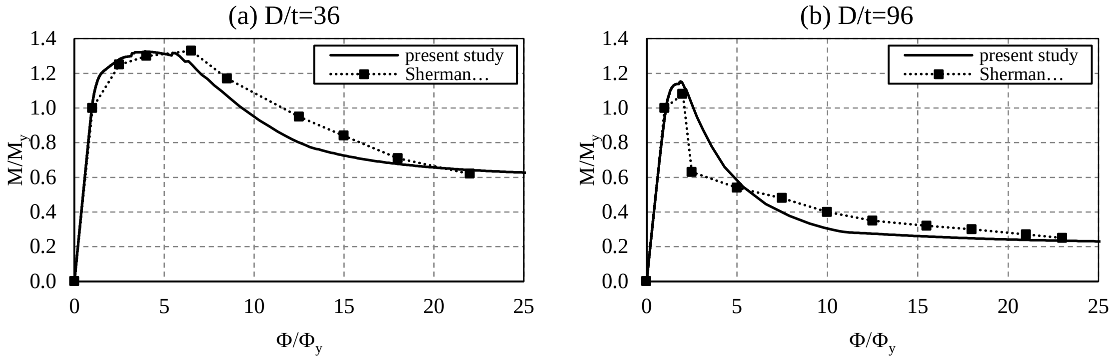


Figure 4. Numerical results of the present study compared to experimental results of Sherman (1983).

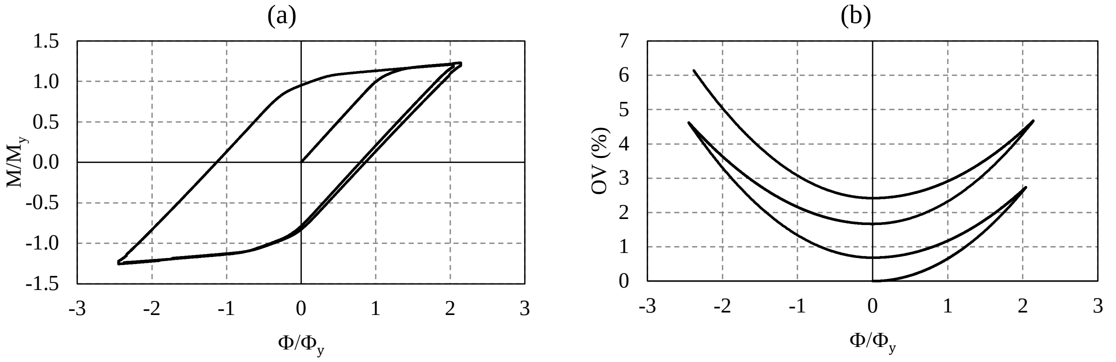


Figure 5. Numerical modelling of a pipe with D/t=96 under cyclic bending (a) moment-curvature and (b) ovalization-curvature.

Pipeline Seismic Response

In this section, the seismic response of a buried pipeline with length of 100 m, diameter of 0.5 m (D/t=96) made of X65 steel (F_y=345 MPa) was studied using the developed model. The layout of te pipeline and the soil profile configuration considered in that analysis are shown in Figure 6.

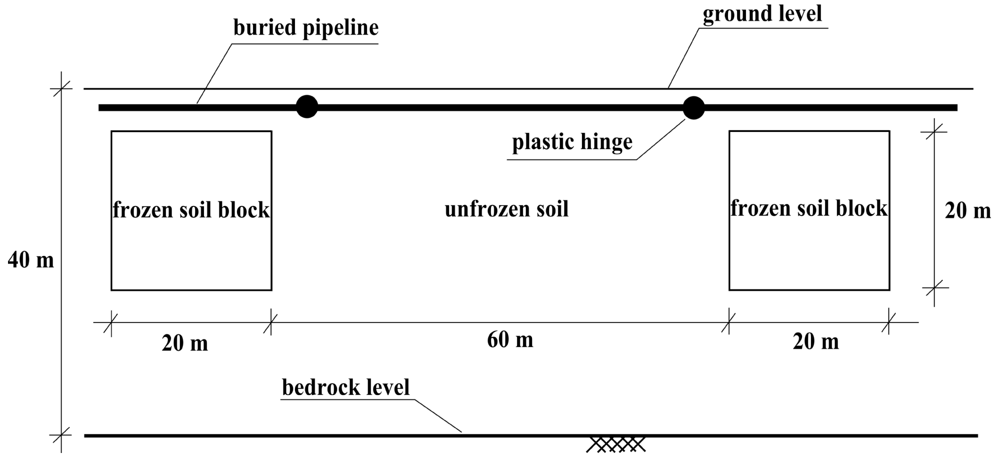


Figure 6. Schematic model of the studied pipeline.

The free-field motions obtained from the site response study were used as input motions (Figure 2). Parts of the pipeline that were on top of the frozen soil blocks were excited by the motions obtained from the top of the frozen parts in the FLAC model and the middle of the pipeline span was subjected to the ground motion that was recorded on top of the unfrozen soil. The results of the analysis are presented in Figure 7. As it can be seen in Figure 7a, the pipe yielded under the loading and experienced some inelastic cycles. Compared to the uniform support excitation case, in which no considerable moment is induced in the pipeline, the case of multiple support excitation induced large moment and permanent deformations (residual curvature) in the pipeline. According to Figure 7b, although the pipe has yielded, ovalization factor is still much smaller than the code suggested value of 15%.

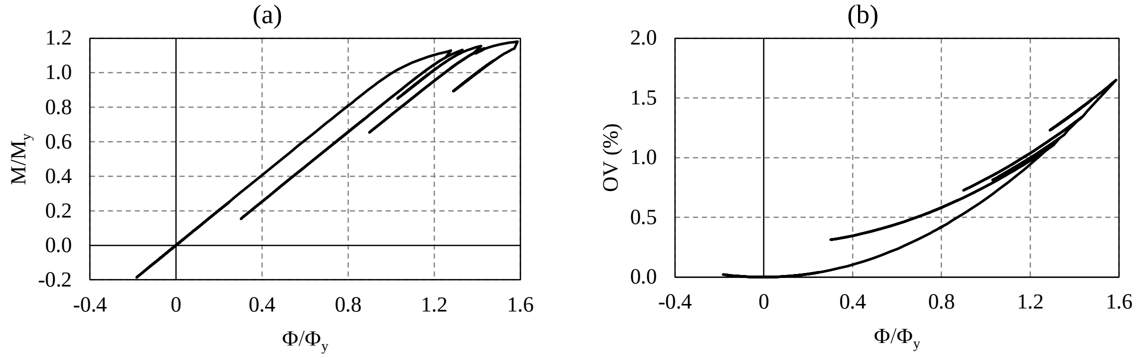


Figure 7. (a) Moment-curvature and (b) ovalization-curvature response of the plastic hinges of the studied pipeline subjected to multiple support excitation.

Conclusions

The seismic response of a site with discontinuous permafrost was studied using a 2D finite difference FLAC model. It was concluded that the free-field responses on top of the frozen parts of the site are larger than those above the unfrozen parts. This suggests that buried pipelines which traverse regions with discontinuous permafrost may experience multiple support excitations during earthquakes.

A plastic hinge model capable of simulation of cyclic behavior of the pipes was developed with nonlinear fiber elements and was successfully calibrated against experimental data.
The investigation of the behavior of a segment of a pipeline employing the developed model revealed that the multiple support excitation developed in a site with discontinuous permafrost can induce considerably larger stresses and strains in the pipeline compared to the case with uniform support excitations.

It can be assumed that more severe earthquakes may potentially cause collapse in the buried pipelines of discontinuous permafrost region. As well, more slender pipelines (with larger D/t) may suffer extensive damage in these regions.

The results of this study are important for the safety considerations of future pipeline projects and for seismic risk assessment of the existing pipelines. Additional analyses are, however, necessary to further determine the critical conditions under which a pipeline in a discontinuous permafrost region may be damaged under seismic loading.

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