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Potential failure analysis of thawing-pipeline interaction at fault crossing in permafrost

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ABSTRACT

Fault slippage threatens the structural integrity of buried pipelines. In this work, we adopted a 3D thermo-hydro-mechanical coupling numerical model for investigation of a warm steel pipeline crossing active tectonic fault in permafrost, focusing on two pipeline-soil interactions: fault slippage in the course of the thawing of the permafrost and pipeline mechanical behavior. Effects of pipeline fluid temperature, thawed soil permeability as well as faulting regime to longitudinal strain along the pipeline were examined. This study shows that the relatively warm pipeline heats the surrounding soil-ice bonded permafrost, thawing of the permafrost leads to diffusion of the pore fluid surrounding the warm pipeline, and the accumulated pore water near the impermeable freezing front could cause a drastic pore pressure change, which would affect the destabilization of previously stable faults in critically stressed regime. The fault slippage and the corresponding longitudinal strain along the pipeline increase with pipeline fluid temperature and thawed soil permeability, while a relatively larger longitudinal strain takes place in the strike-slip faulting regime.

1. Introduction

Long distance buried pipelines system is one of the most important transportation means of natural gas and oil [1]. At present, buried pipelines are often constructed in permafrost region [2], such as the Roman Well pipeline in Canada [3], the Far East pipeline in Siberia [4], the Alyeska hot oil pipeline in North America [5], and China 's pipeline network in cold region. In geohazard region, buried pipelines could be subjected to hidden faults [6,7]. Fault displacement, even micro-fault slippage has the potential to induce severe strains and ruptures of the pipeline wall, which could result in pipeline damage, and cause irrecoverable ecological disasters [8]. When a relatively warm pipeline penetrates a fault in the permafrost, the pipeline wall would heat the surrounding soil-ice bonded permafrost, leading to the gradually thawing of the permafrost and phase change of the pore fluid [9]. Therefore, the heat released from the pipeline may create a permafrost thaw bulb within the surrounding permafrost, and generally reduce the load carrying capacity of the soil. The permafrost thaw bulb would in turn lead to significant excess pore-water pressures, as well as excessive stress and strain on the pipeline which cause its eventual damage [10]. Heat transfer process together with the phase change of the pore fluid would result in significant excess pore-water pressure on the fault wall around the pipeline [11], especially when the thawing take place around the pipeline, the impermeable permafrost accumulates the fluid flow and enhances the pore pressure. The maximum pore pressure changes can also be correlated to net volume changes of the soils subsequent to thawing [12]. Consequently, the pore pressure change on the fault plane can reach a significant level.

Faults are discontinuous planes in geological formations across where relative displacement of adjacent layers would take place [13,14]. On the fault plane, change in pore pressure usually affects the in-situ stress field in critically stressed regime [15–17]. Pore pressure increase shifts the Mohr circle to left, destabilization of previously stable faults occurs when the Mohr circle intersects the failure envelop, which is equal to coefficient of friction [18,19], and subsequently fault slippage occurs along pre-existing fault plane [20]. A large number of investigations on pipeline-fault crossing have been well performed [21–24]. Regarding fault displacement, analytical approaches such as the Newmark-Hall approach [25], the Kennedy et al. approach [6] and the Wang-Yeh approach [26] were conducted. However, as average strain is usually considered as a failure criterion in analytical approaches, the neglected pipe axial stress on pipe bending stiffness leads

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to overestimate the tolerable fault movement for pipelines, resulting in the inapplicability of these methods for pipelines under compression [7]. Later, based on the performance of gas and water pipes during the San Fernando earthquake, Desmond et al. [22] studied the stress and strain development in buried pipes crossing faults, considering the pipe as a beam on elastic foundation. With respect to material nonlinearities, Karamitros et al. [27] introduced refinements in former analytical methodologies to calculate the maximum design strain, the pipeline bending moment and axial force can be obtained through elastic-beam theory and beam-on-elastic-foundation.

Other than analytical approaches, in recently years numerically approaches based on finite element techniques in application to the buried pipelines fault crossing problem are actively developing [28–30]. Beam-type models are introduced based on the representation of the pipeline by ensemble of beam elements to simulate global bending and axial deformations of the pipe [31]. One advantage of the beam-type modelling is that the large displacements and strains can be included in this formulation. Kokavessis and Anagnostidis [32] presented a finite element methodology (FEM) using contact elements to describe buried pipeline-soil behavior. With the similar model geometry to Kokavessis, Liu et al. [33] presented their numerical simulation through a shell finite element model and reported results for axial strain distribution along the pipeline. Considering the elastoplastic behavior of soil, Vazouras et al. [23] introduced a 3D continuous soil representation, and examined the effect of both cohesive and non-cohesive soil conditions on the response behavior of the pipeline crossing fault with sensitivity analysis.

In the present work, we adopted a three-dimensional thermo-hydro-mechanical coupling numerical model of a buried steel pipeline crossing active tectonic fault, focusing to two pipeline-soil interact behaviors: fault slippage in the course of the thawing of the permafrost and pipeline mechanical behavior. In Section 2 we presented the governing equations of thermo-hydro-mechanical (THM) coupling process in porous media. Then we described the three- dimensional numerical model we adopt in Section 3. Numerical results were presented in terms of the fault slippage evolution and pipeline mechanical behavior, and parametric analysis of the pipeline fluid temperature, thawed soil permeability and faulting regimes were performed in Section 4.

2. Theoretical background

Based on the principle of virtual work [34], stress field equilibrium equation could be described as:

$$\int_V \sigma : \delta\varepsilon dV = \int_s f_s \bullet \delta v dS + \int_V f \bullet \delta v dV + \int_V sn\rho_w g\delta v dV \tag{1}$$

where $\delta\varepsilon$ and δv are the virtual strain and virtual displacement, f_s is the face force per unit area and f is the volume force, the fluid weight $f_w = sn\rho_w g$ with s is the soil saturation and n is the soil porosity.

For spatial integration, a shape function N^N is introduced and thus the virtual displacement δv could be presented by a function of the virtual displacement on the nodes of one element:

$$\delta v = N^N \delta v^N \tag{2}$$

β^N is introduced to bridge the relationship between δv^N and the virtual strain $\delta\varepsilon$ of the elements:

$$\delta\varepsilon = \beta^N \delta v^N \tag{3}$$

Thus, the discreted stress field equilibrium equation could be presented as:

$$\delta v^N \int_V \beta^N : \sigma dV = \delta v^N \left(\int_s f_s \bullet N^N dS + \int_V N^N \bullet f dV + \int_V sn\rho_w g N^N dV \right) \tag{4}$$

According to the principle of conservation of mass [35], the continuous equation of motion of the fluid in a porous medium can be expressed by a continuous equation as follows:

$$\int_V \frac{1}{J}\frac{d}{dt}(J\rho_w n_w) dV = -\int_S \rho_w n_w \cap \bullet v_w dS \tag{5}$$

$$J \stackrel{\text{def}}{=} \left| \frac{dV}{dV^0} \right| \tag{6}$$

Here the v_w is the average flow rate of the flow relative to the solid particles, $\cap$ is the outward normal direction of the surface, J is the change of soil volume. Assuming the flow direction, according to the finite element discretization principle the continuous equation can be expressed as:

$$\frac{1}{J}\frac{d}{dt}(J\rho_w n_w) + \frac{d}{dx}(\rho_w n_w v_w) = 0 \tag{7}$$

Variation of pore water pressure δu_w is introduced according to the variational principle [36], now the differential equations of seepage field could be described as:

$$\int_V \frac{1}{J}\frac{d}{dt}(J\rho_w n_w) dV + \int_v \delta u_w \frac{d}{dx}\left[\rho_w \left(-k\frac{\partial\phi}{\partial x}\right)\right] dV = 0 \tag{8}$$

Heat transfer due to conduction in the pore fluid and soil skeleton, as well as convection in the pore fluid [37], can be governed by thermal equilibrium equation for a continuum in which a fluid is flowing with velocity υ:

$$\int \delta \left\{ \rho c \left[\frac{\partial\theta}{\partial t} + \upsilon \bullet \frac{\partial\theta}{\partial x} \right] - \frac{\partial}{\partial x}\left[k \bullet \frac{\partial\theta}{\partial x} \right] - q \right\} dV + \int_{Sq} \frac{\partial\theta}{\partial x} \left[n \bullet k \bullet \frac{\partial\theta}{\partial x} - q_s \right] dS = 0 \tag{9}$$

where n is the outward normal to the surface, x is spatial position, and t is time, $\theta(x, t)$ is the temperature at point x, $\rho(\theta)$ is the fluid density, $c(\theta)$ is the fluids specific heat, $k(\theta)$ is the conductivity of the fluid, q is the heat added per unit volume from external sources, q_s is the heat flowing into the volume across the surface on which temperature is not prescribed. Therefore, the boundary term in the thermal equilibrium equation can be defined as:

$$q_s = -n \bullet k \bullet \frac{\partial\theta}{\partial x} \tag{10}$$

With respect to position, the above equations are discretized by first order isoparametric elements, the fluid velocity υ is computed from the density of the fluid and the mass flow rate. The discrete time generates the solution at time $t + \Delta t$ from the previous time t. Thus, the interpolation for the temperature $\theta(x, t)$ could be defined over a time increment Δt as:

$$\theta(x, t) = N^N(x) A^n(t) \theta^{(N,n)}, \quad N = 1, 2, ..., \quad n = t, \quad t+\Delta t \tag{11}$$

where the N^N are standard isoparametric functions and A^n is the time interpolation:

$$A^n = 1 - \frac{\tau}{\Delta t}, \quad A^{t+\Delta t} = \frac{\tau}{\Delta t} \tag{12}$$

The Petrov-Galerkin discretization [38] couples this linear interpolation A^n with the weighting functions:

$$\delta\theta = \left[N^N \overline{A} + \frac{h}{2}\left(\alpha\overline{A} + \beta\frac{\Delta t \bullet d\overline{A}}{2dt} \right) \frac{v}{|v|} \bullet \frac{\partial N^N}{\partial x} \right] \delta\theta^N \tag{13}$$

$$\overline{A} = 6\frac{\tau}{\Delta t^2}(1 - A^{t+\Delta t}) \tag{14}$$

h is a characteristic element length measure, α is the introduced parameter to eliminate artificial diffusion of the solution, while β is introduced to avoid numerical dispersion, γ is the local Péclet number in an element and C is the local Courant number defined as: