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The effect of variation of soil conditions along the pipeline in the fault-crossing zone

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ABSTRACT

In the paper, buried steel pipelines crossing strike-slip and normal-slip faults are considered within analytical and numerical approaches. The effect of variation of the backfill soil properties along the pipeline in the fault-crossing zone on the stress-strain state of the pipeline is analyzed.

The analytical model developed in the previous publications is substantially reworked to take into account the variation of soil conditions along the pipeline length and the effect of internal pressure on the deformed pipe geometry. A complete set of analytical solutions for the axial pipeline-soil interaction force taking into account two zones along the pipeline length with different soil conditions, plastic behavior of the pipeline and soil, initial stress in the pipeline has been derived and introduced into the model.

The effect of special (loose sand) backfill segment length on the pipeline response under strike-slip and normal-slip fault actions is studied. It is shown that the extension of the special backfill length has an advantageous effect in case of substantial axial fault displacement component. In this case, the reduction of soil constraining effect on a larger distance substantially reduces the maximal tensile strains in the pipeline. In contrast, under bending-dominant behavior of the pipeline, the elongation of the special backfill zone has no positive effect on the maximal strains.

1. Introduction

The methods of stress-strain analysis and strength verification for buried pipelines crossing active tectonic faults have been intensively developing during the last decades. These methods can be conditionally divided into analytical and numerical. The analytical models represent the pipeline at the fault crossing as a combination of segments which are analyzed according to beam-on-elastic foundation and beam theories [1–6]. In numerical models, the pipeline-soil system is considered within the finite-element methodology. In the beam-type models, the pipeline is represented as an assemblage of beam finite elements, and the soil is modeled by uniaxial nonlinear spring elements [7–13]. In more advanced shell-type models, the pipeline is considered as a shell structure surrounded by a three-dimensional inelastic continuum [14–19]. Within both approaches, a number of works has been published recently.

On the basis of the developed methods, various measures aimed at reducing the stress-strains state in the pipeline under the fault offset are being analyzed. Application of a soft soil backfill for minimization of the pipeline-soil interaction force is among the most widely used mitigating measures. Together with a soft soil backfill, special trench dimensions required for eliminating pipeline interaction with the surrounding native soil should be considered.

In [19], a special type of trench with shallow slopes and loose sand backfill is implemented within a three-dimensional finite-element model. The effect of trench backfill is studied. It is shown that the type of backfill substantially affects the stress-strain state in the pipeline, strain localization and the formation of local buckling.

The effect of trench dimensions has been addressed in [20–23] in case of lateral pipeline motion. For pipelines installed in sand-backfilled trenches, the trench dimensions sufficient to avoid interaction with the native soil are estimated. It is shown that, for a standard trench, the ultimate soil pressures and bending strains in the pipeline may be considerably magnified compared to the corresponding wide trench values.

Size and shape effects for trenches excavated in stiff soils and rocks are investigated in [23] by numerical simulation. It is shown that the width of trench and the inclination of the trench walls substantially affect the values of ultimate pressures and yield displacements.

In [12], a comparative review of various protection measures is presented. Based on numerical analyses, the assessment of the effectiveness of commonly used measures is performed. Among other measures, pipe-soil friction reduction by a special trench backfilling is considered. It is concluded that trench backfilling with a light-weighted

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pumice is a moderately effective way to protect the pipeline.

According to the published work, the effect of special backfill zone length has not been analyzed yet. Still, this is practically a very important issue, since the implementation of a special trench and backfill substantially affects the project cost.

In the present paper, the effect of special backfill zone length on the pipeline performance is studied on the basis of the analytical methodology developed in papers [4,5] and a numerical finite-element model. The analytical model takes into account the internal pressure and temperature variation ΔT (a difference between the operational temperature and the temperature of pipelay). The stress state in the pipe is considered as two-dimensional and is analyzed within an elastoplastic constitutive model.

In the paper, substantial refinements are made compared to the model of papers [4,5]:

- the effect of the internal pressure in the deformed state of the pipeline is introduced. This effect results in an additional axial force component in the equilibrium equation;
- analytical solutions of the equilibrium equation for the cases of tensile and compressive axial force in the pipeline are applied;
- the analytical solution for the axial pipeline-soil interaction force is constructed with account for two zones along the pipe length with different soil conditions, plastic behavior of pipeline and soil, and initial stress in the pipeline.

The paper is organized as follows. In Section 2, a structural model of the pipeline at a fault crossing is described. Special attention is given to a systematical treatment of the axial force entering the equation of equilibrium. Separate solutions for the cases of tensile and compressive axial force are obtained. In Section 3, the relations for the axial force in the pipeline are derived for the case of two zones along the pipeline length with different soil conditions. Comparison to a finite-element model is performed for varying lengths of soil zones, different pressure levels and temperatures. In Section 4, the results for strike-slip and normal-slip faults are presented and discussed in comparison to the finite-element results. In Section 5, a parametric analysis is performed. The effect of special backfill zone length is considered in relation to the fault-crossing angle.

2. Structural model of the pipeline at a fault crossing

2.1. Partitioning of the pipeline

In accordance with the papers [4,5], the pipeline at a fault crossing is partitioned into four segments (Fig. 1). The segments AB and BC of the lengths L_1 and L_2, correspondingly, represent the parts of the pipeline which absorb the main portion of the transverse fault displacements. The boundary points A and C are defined as the closest to the fault intersection points of the pipeline axis with zero transverse displacements. The segments AA' and CC' represents parts of the pipeline with relatively small transverse displacements attenuating with the distance from the fault.

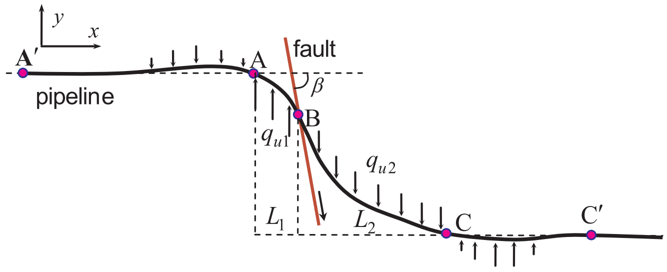

Fig. 1. Partitioning of the pipeline at a fault crossing.

In case of a strike-slip fault, taking into account that the ultimate soil resistance in either lateral direction is identical, $q_{u1} = q_{u2}$, the model becomes anti-symmetric relative to the fault intersection point. In the present model, this condition is not used, and the segments AB and BC are considered separately. Accordingly, the model can either be applied to a strike-slip or to a normal-slip fault.

2.2. Solution for the segments AA' and CC'

Taking into account that the pipeline displacements $w(x)$ relative to surrounding soil are small, and the ultimate soil resistance is not reached, a beam-on-elastic foundation is a suitable model for the segments AA' and CC'. The equilibrium equation has the form:

$$EI\frac{d^4w}{dx^4} + kw = 0, \tag{1}$$

where E is the elastic modulus, I is the moment of inertia of the cross-section, k is the elastic stiffness of soil for transverse pipe-soil displacements.

Under the assumption that the soil resistance is characterized by a bilinear diagram with the yield displacement w_u and the ultimate force q_u the stiffness is calculated as $k = q_u/w_u$.

A general solution of Eq. (1) subject to the boundary conditions $w = 0$ for $x = 0$ and $w \to 0$ for $x \to \infty$ is written as:

$$w(x) = Ce^{-\lambda x}\sin\lambda x, \tag{2}$$

where $\lambda = (k/4EI)^{1/4}$.

Next, standard relations between the displacement, bending moment $M(x)$ and transverse force $V(x)$ can be applied: $M(x) = EIw''(x)$ and $V(x) = EIw'''(x)$, where the notation $w' = dw/dx$ is used.

2.3. Refined solution for the segments AB and BC

The segments AB and BC are considered as beams subjected to bending and axial loads. The equilibrium of an infinitesimal element in the deformed configuration is shown in Fig. 2, a. The sources of the applied loads are listed in Table 1.

The intensity of the distributed load q corresponds to the limit value of the pipe-soil interaction force per unit length.

The intensity of the lateral force r can be found from the equilibrium of forces acting on the medium within a pipe element in the deformed state [24] (Fig. 2, b):

$$r = p\frac{\pi D_i^2}{4}\frac{d\varphi}{ds} \approx p\frac{\pi D_i^2}{4}\frac{d^2w}{dx^2}, \tag{3}$$

where D_i is the internal pipe diameter.

Calculation of the axial force F is considered in Section 3.

From the force and moment equilibrium conditions of the pipe element in Fig. 2, a the following equilibrium equation is obtained:

$$EI\frac{d^4w}{dx^4} - N\frac{d^2w}{dx^2} = q, \tag{4}$$

where the complete axial force N is given by the relation:

$$N = F - p\frac{\pi D_i^2}{4}. \tag{5}$$

The solution of Eq. (4) depends on the sign of N.

In case $N > 0$:

$$w(x) = w(0) + \phi(0)\frac{\sinh\alpha x}{\alpha} + \frac{M(0)}{EI\alpha^2}[\cosh\alpha x - 1] + \frac{V(0)}{EI\alpha^3}[\sinh\alpha x - \alpha x] + \frac{q}{N}[(\cosh\alpha x - 1)/\alpha^2 - x^2/2] \tag{6}$$

In case $N < 0$: