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PIPE-SOIL INTERACTION MODELS OF PIPELINE RESPONSE TO ACTIVE FAULTS AND BLOCKSLIDES ABRUPT DISPLACEMENTS

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Abstract

The similarity and the discrepancy of the impacts on pipeline caused by surface faulting and by activation of seismically triggered blockslides are analyzed. Both hazardous phenomena could produce significant (multi-meter) offsets concentrated within narrow zones that could rupture pipeline crossed by an active fault or by a blockslide boundary. Usually such sites should be avoided. However, trunk pipelines often have to cross them and it is critically important to ensure their safety either by special engineering measures or by rerouting. Similarity of the effects that both hazardous phenomena exert on the structure, up to some offset values (maximal single-event surface ruptures could reach 10-15 m; similar offsets are often observed at the blockslide boundaries), has been demonstrated that allows application of the similar pipe-soil interaction models for justification of the pipeline strength. Mechanisms of the pipe-soil interaction for displacements with different kinematics (normal, reverse, strike-slip) and different values (from 0.1 to 5 meters) were analyzed by the numerical modeling. Offsets with similar kinematics can be observed at the proximal, frontal and lateral boundaries of blockslides. To characterize pipe-soil interaction caused by the significant displacement of a pipe buried in a trench several numerical simulations were developed. We compared characteristics of pipe-soil interaction derived by the numerical simulation with those obtained by the traditional pipe-soil interaction models used in the engineering practice, and analyzed applicability of the traditional engineering models for pipeline displacements exceeding 0.5 m. Effect of the use of different soil models on the stress-strain state of pipelines has been estimated by examples of the Sakhalin pipelines prone both to active faulting and to landslides. Pipelines with different diameters, different trench shapes and different fault (landslide) kinematics were analyzed. These simulations by beam finite elements allow characterizing interaction of the pipeline and of the surrounding backfill when pipe moves laterally, downward or upward.

Keywords: pipe-soil interaction; active fault; blockslide; numerical modeling 5

1. Introduction

Oil and gas trunk pipeline routes often have to cross active faults and landslide-prone areas that cannot be bypassed. In such cases special measures must be undertaken to ensure pipeline safety. While some small shallow landslides can be passed beneath sliding surface or by use of the above-ground pipelining, same solutions might be technically impossible or too expensive for deeper and larges slides; besides, in landslide-prone regions new landslides can originate after pipeline construction at previously unexpected sites.

Case study of the Trans-Alaska pipeline that withstood almost 6-m offset along the 2002 M8 Denali fault earthquake surface rupture [1, 2] have proved that pipeline safety at its crossing with active fault can be achieved even when multi-meter surface faulting associated with large earthquake occur. At this crossing, however, the above-ground pipelining was used, while technical requirements for many other pipelines such as those of Sakhalin-1 and Sakhalin-2 projects claim subsurface pipelining [3].

For subsurface pipelining, both for landslide and active fault crossings, buried pipeline interacts with backfill and with natural soil where the trench has been excavated, and this interaction, along with the parameters of the ground displacement (offset value and kinematics) determines pipeline stress-strain state [4]. We compared characteristics of such interaction for displacements with different kinematics (normal, reverse, strike-slip) and values (from 0.1 to 5 meters) derived using numerical results for pipe-soil model with those obtained by the traditional models of pipe-soil interaction used in the engineering practice.

2. Basic input parameters and their accuracy

Despite significant difference of the two natural phenomena in question – surface faulting and landslides, their local, "point-scale" effects on buried pipeline are very similar from the mechanical point of view, especially for planar blockslide cases [5] where relative displacement between "passive" and "active" sides is concentrated just at the landslide boundaries and is kinematically similar to simple cases of fault displacements (Fig. 1). It allows uniform approach for the analysis of pipe-soil interaction models of pipeline response to abrupt displacements concentrated along some plane or within the narrow zone [6]. The proposed models cannot be applied for landslides that undergoes significant internal deformations of their bodies e.g. flow-like landslides.

Pipeline *I-I'* shown in Fig. 1 crosses lateral boundaries of a landslide with motion style similar to those of the strike-slip surface ruptures, while pipeline *II-II'* (ibid) undergoes deformations similar to normal faulting (vertical offset with some longitudinal extension) at the landslide crown and deformations similar to the thrust faulting at its front, also with vertical displacement but with significant compression and shortening. The main difference between such deformations associated with landslides and with surface faulting is that fault offsets during earthquakes are limited (analysis of the world-wide databases shows that they do not exceed ca. 10-18 m even during largest intracontinental earthquakes [7-9]), while displacements along or across landslide boundaries can exceed tens of meters and, thus, can be treated as unlimited. At the same time, in most of cases landslide bodies preserve their integrity at the initial stage of motion, before displacements increase significantly resulting in their disintegration and transformation of sliding of a block with well-defined boundaries into more flow-like motion. At this initial stage behavior of soil surrounding buried pipeline (both of natural soil and of the backfill) that crosses landslide should be similar to that at a pipeline - active fault crossing (see Fig. 1).

Movements associated with both surface faulting and blockslide boundaries can be localized with some accuracy and are characterized by displacement value and kinematics – 3-component slip direction that also can be determined with some scatter [see, e.g. 6]. Hereafter simple 2-component cases – pure strike-slip, normal and reverse (thrust) types of motion will be discussed to simplify the numerical models, while in nature real displacement can have all three components – vertical, lateral and transverse (compression or extension).

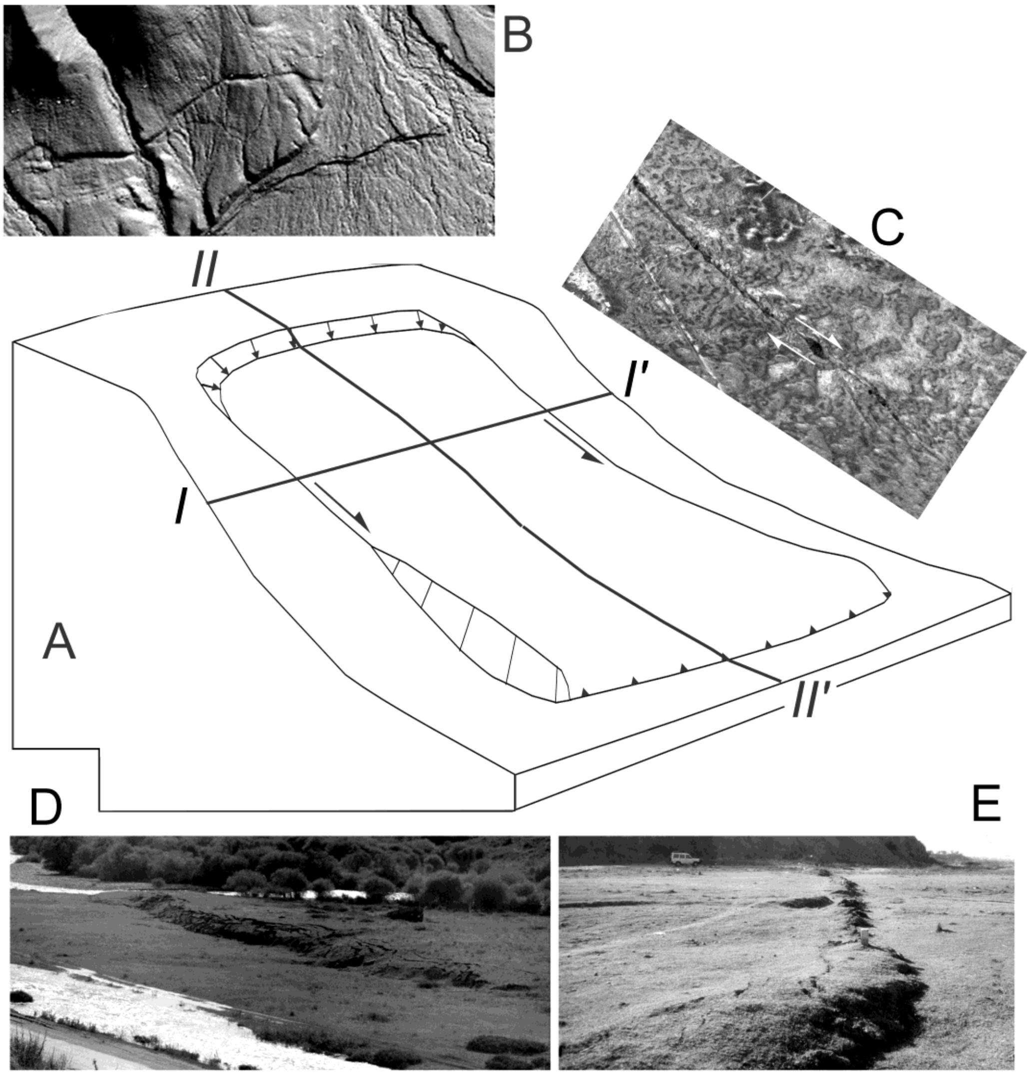
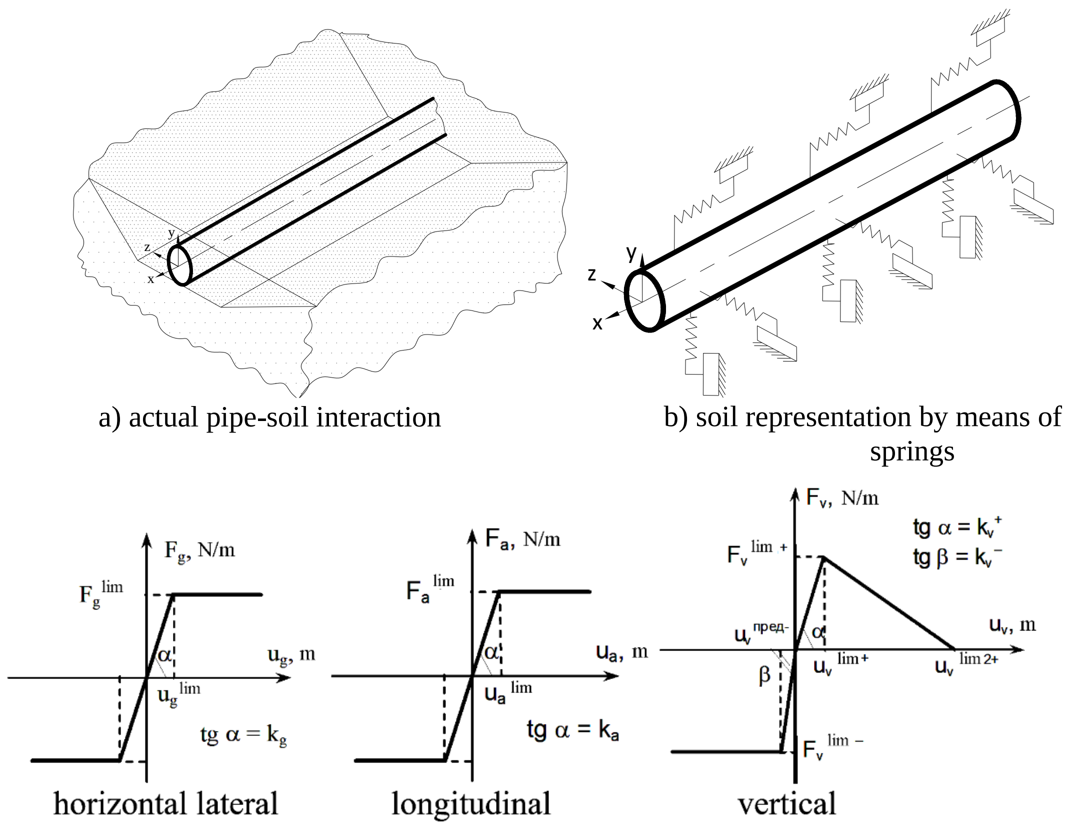


Fig. 1 – Kinematic similarity of blockslides and surface ruptures. A – scheme of a blockslide crossed by pipelines *I-I'* and *II-II'*; B – normal faults at the Baikal Rift Zone (shaded relief of the DEM made by aerial laser scanner) similar to the headscarp crown; C – strike-slip Lepse fault (Djungaria) with motion style similar to the blockslide lateral boundaries; D – thrust fault associated with 1992 Suusamyr earthquake (Central Tien Shan) whose kinematics is similar to that of the frontal boundary of the rotational landslide that originated in 2001 at the Himalayan foothills (E)

3. Mechanics of the pipe-soil interaction

In general, numerical modeling of a buried pipeline - soil interaction requires the multidisciplinary approach, since it has to include the 3-D pipeline model and the 3-D surrounding soil model (Fig. 2a). However, for most of the engineering problems that have to be solved by the design such approach is not used due to its labor-consuming nature and necessity of special knowledge and skills. That is why the approach that treats determination of soil stiffness during pipeline motion and of pipeline deformations separately is used traditionally. Pipeline-soil interaction is simulated in the engineering practice using special soil spring elements that transmit loads from soil to pipeline in axial (longitudinal), lateral horizontal and vertical (up and down) directions (Fig. 2b). Soil action in each direction (soil load applied to pipeline) is a nonlinear function of relative displacement in the pipe-soil contact. Pipe-soil interaction can be represented conditionally by a number of discrete springs with corresponding characteristics of resisting forces depending on pipeline relative displacements in pipe-soil system. These functions can be written in the form of F_g-u_g, F_a-u_a and F_v-u_v characteristics (Fig. 2c). Nonlinear characteristics of soil resistance versus relative displacement of pipeline gives more accurate description of the entire system. The bilinear characteristics of soils springs are utilized for buried pipeline calculations in most of cases. They are determined on the basis of physical-mechanical properties of undisturbed soil and backfill soil at such crossing using the soil model that were proposed by some researchers [10, 11]. For setting of soil resistance forces in finite element model the nodal forces F_g, F_a and F_v are used. If large relative displacements between pipeline and soil appear exceed u_g, u_a, and u_v, the soil forces reach constant maximal values F_g^{lim}, F_a^{lim} and F_v^{lim}. Pipeline is fixed by soil at both sides of fault or blockslide boundary axis when pipeline is forced by relative displacement. Thus at displacement of one side of the fault or blockslide relatively to the other one, the pipeline is exposed to cumulative action of the tree-component displacement.



c) pipe-soil springs characteristics

Fig. 2 – Pipe-soil interaction consideration by means of soil springs

Formulae used to determine soil springs characteristics have been confirmed by the experiments for relatively small offsets of buried pipeline [10, 11]. However, relative pipeline-soil displacements induced by active fault or blockslide motion can reach several meters and so large offsets have not been analyzed in [10, 11] when determining bilinear characteristics. It can be assumed that if pipeline displacement is comparable with trench dimensions or exceed them, the soil springs characteristics would differ from the bilinear significantly. Thus it is reasonable to calculate characteristics of pipeline-soil interaction for large displacements using modern numerical simulation methods. In our research we used the finite element method (FEM) that is one of main numerical techniques to solve the continuum mechanics problems. FEM, based on the matrix analytical methods is considered nowadays as an efficient way to solve problems described by the mathematical physics partial differential equations. Solution of the boundary value problem of the stress-strain state of the computational space can be reduced to calculation of the coupled equations:

$$[K]\{u\} = \{F\}, \qquad (1)$$

where: [K] – the stiffness matrix; {u} – the nodal displacement vector; {F} – load vector.

To solve the nonlinear problem of the deformed solid mechanics, set of equations is preset by the relationship:

$$F(\{\sigma\}, \{\varepsilon\}) = 0. \qquad (2)$$

In such case the solution is reduced to the input parameters $\{\varepsilon_0\}$ or $\{\sigma_0\}$ adjustment (by use of the initial strain or of the initial stress methods) that satisfies the equilibrium conditions of the computational space. Such parameters' adjustment is performed by the iterative methods. Set of physical relationships representing, in general, the numerical model of deformations is the most important part of any simulation. It is reasonable to consider these relationships within two interrelated aspects: equations describing stress-strain relationships and strength (or plasticity) criteria determining conditions of the soil limit state [12].

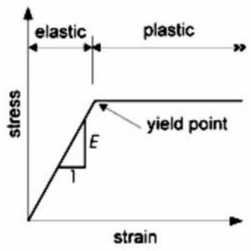
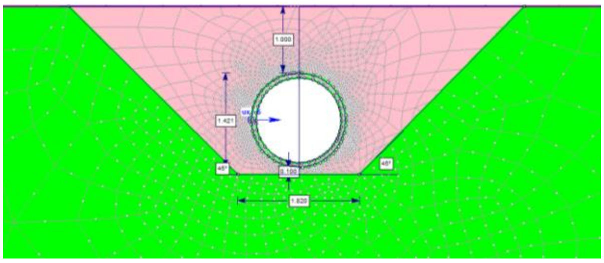


Fig. 3. The elastic – ideally plastic model of soil behavior

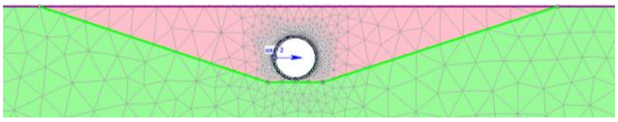
To describe links between stress and strain, we use the ideally plastic model with linear Mohr-Coulomb strength criterion. This model determines direction of the plastic deformations incremental vector in any point of the computational space if stress limited by the accepted loading surface. Stress-strain plot typical of such model is shown in Fig. 3. Stress is in the direct proportion to strain until it reaches the limit stress value. In case of the ideally plastic behavior beyond this point curve becomes horizontal [13] (GEO-SLOPE International Ltd., 2007). The stiffness matrix [K] in formulae (1) depends on the geometrical and mechanical parameters of the computational space in question and on the type of the stress state and of the finite elements in use. Boundary conditions (either kinematic or forceful) are determined to solve the assembled equations (1) and (2).

To simulate pipelines behavior for pipe outer diameters of 530 and 1420 mm in the trenches with 1:1 and 3:1 slopes (Figs. 4 a and 4b) soil springs properties were determined by use of the bilinear model [10] and finite element modeling. The mechanical properties of the natural and backfill soils are listed in Table 1. In case of pipe downward motion it affects the undisturbed natural soil mainly, while during upward motion – the backfill soil is affected. Vertical displacements of a pipeline practically do not depend on trench geometry. That is why the comparative analisys of the soil springs characteristics we performed calculations for the pipeline that moves in a trench laterally. When pipeline moves in a trench with 1:1 slopes (see Fig. 4a) the calculated displacements affect soil outside the trench limits (Fig. 4c), while same calculations for pipeline in a 3:1 trench (Fig. 4b) show that the entire area affected by non-zero soil deformations is located within the trench boundaries (Fig. 4d). It obviously influences the soil stiffness that is confirmed by calculated soil springs characteristics. We can notice the acceptable fit between bilinear soil springs characteristics and nonlinear characteristics provided by the numerical modelling for pipelines of both outer diameters that move through soil for up to 0.5 m (Fig. 5).

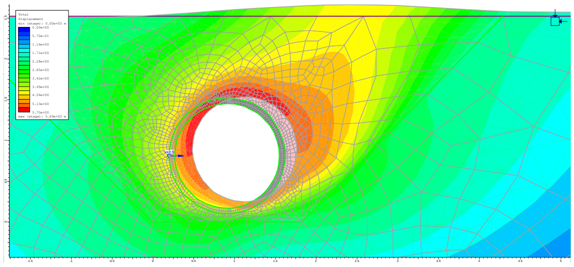
When displacements are larger, soil springs for the 3:1 trench undergo some hardening that provide loading 1.5-2 times larger than accepted for the bilinear character when pipeline motion increases up to 2 m. More significant hardening (up to 2.5-3 times larger than for the bilinear character) was obtained for calculated soil springs parameters in the 1:1 trench, which is governed by the involvement of the undisturbed soil in the deformation process when pipe moves up to 2 m. We did not get the convergence of the present-day numerical model for pipeline offset exceeding 2 m that requires further improvement of the finite element model. Effect of the difference of soil springs characteristics for the bilinear and finite element approaches on the stress-strain state of a pipeline subjected for strike-slip offset along active fault or landslide boundary should be analyzed.



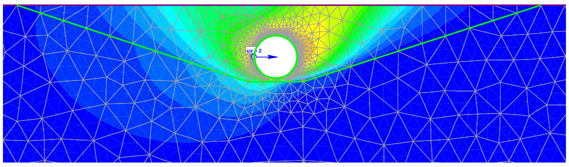
a) FEM of a pipeline in the 1:1 trench



b) FEM of a pipeline in the 3:1 trench

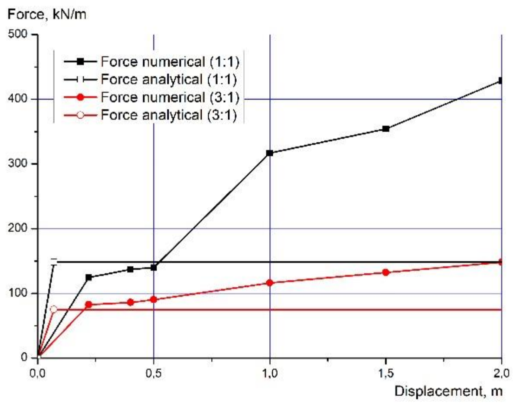


c) Net displacement distribution in the 1:1 trench

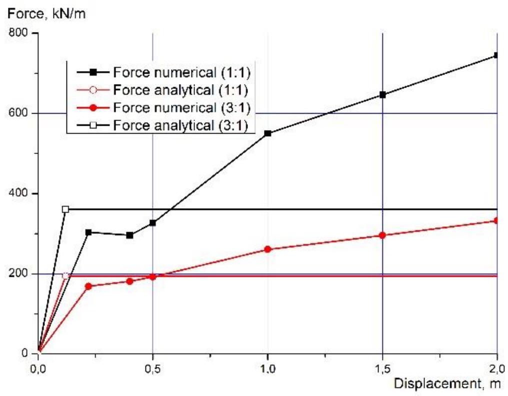


d) Net displacement distribution in the 3:1 trench

Fig. 4. Finite element modeling of the 1420 mm buried pipeline motion



a) 530 mm pipeline



b) 1420 mm pipeline

Fig. 5. Soil springs characteristics

Table 1 – Soil mechanical properties

Parameter	**Nomenclature**	**Value**	
Soil type		Fine (natural) sand	Loose sand (backfill)
Deformation modulus, MPa	E_{soil}	50	11.9
Unit weight, kN/m^3	γ_{soil}	16.0	16.6
Poisson ratio	μ_{soil}	0.25	0.25
Internal friction angle, degrees	φ_{soil}	40	31.0
Specific cohesion, MPa	C_{soil}	$3 \cdot 10^{-3}$	0.0
Generalized coefficient of tangential resistance, MPa/sm	C_{x0}	0.033	0.016
Bearing capacity, MPa	R_{soil}	0.5	0.152

4. Case studies of the influence of soil models on the pipeline stress-strain state for different fault (landslide boundary) motion kinematics

Beam model is used for pipeline calculations [4, 6, 14]. The 300 m long straight pipeline section is selected for numerical model (Fig. 6). Dead and movable sides contact at the middle of the selected pipeline section, so that pipeline have two sections 150 m long each at both sides of the border. Pipe beam element length chosen for calculation is equal to $1D_n$ (pipe outer diameter). Soil spring ends not attached to pipeline axis and located at dead fault side are fixed. Remaining pipeline section is located at movable side where the displacement is applied for soil springs ends that are not attached to pipeline axis. Soil springs fixation scheme by pipe finite element axes is shown in Fig. 2b. Loads from internal pressure, temperature drop and pipeline dead weight are applied in mathematical model. Calculations were performed for buried pipeline subjected to strike-slip offset; pipe diameters are 530 mm and 1420 mm. The elasto-plastic material model was used for pipeline calculations. More detailed description of the computational algorithm is described in [4].

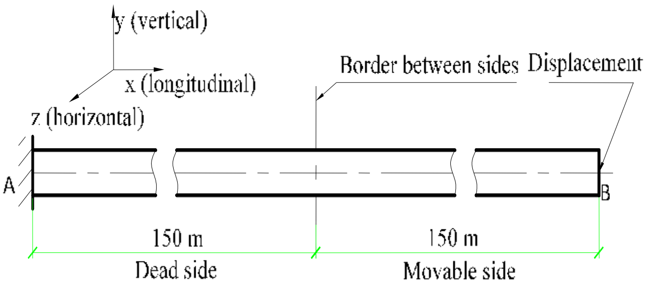
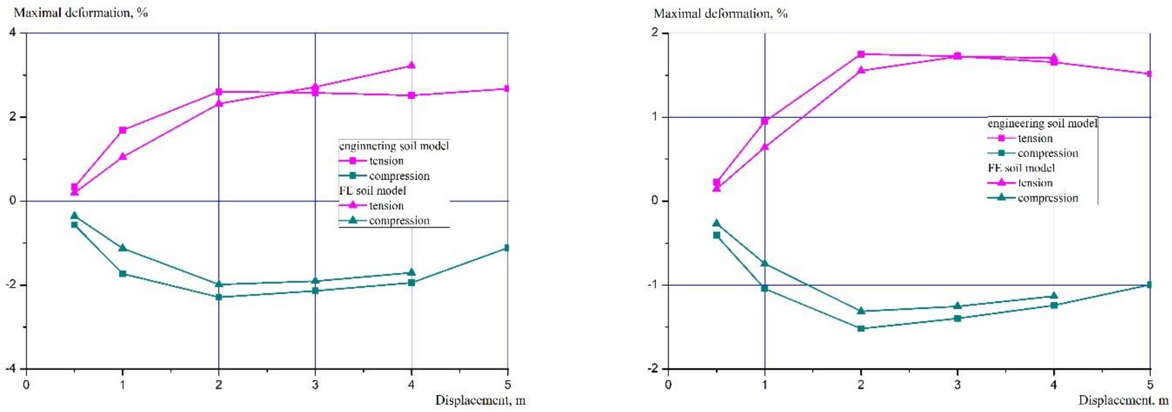


Fig. 6 – Pipe mathematical model

Results of the pipeline strain calculated for the bilinear and nonlinear soil springs characteristics are compared in Fig. 7. Maximal deformations of a pipeline in the 3:1 trench calculated according to the engineering and FEM approaches are in good accordance. Soil springs numerical modelling provides slightly lower stress level. It can be explained by smaller stiffness when displacements do not exceed 0.5 m that allows better compensation of such offset by pipeline.

Deformations of pipelines placed in 1:1 trench affected by 2 to 3 m offset are similar. Further increase of the displacement value results in a significant increase of tension strain in the finite element model caused by soil hardening at large fault (landslide) displacements. The applied soil model provided convergence of pipeline deformation modelling up to 4m offset only. We can assume that further increase of fault (landslide) displacement will cause higher difference between the bilinear and finite element soil models. Its proof, however requires additional work.



а) 1:1 trench　　б) 3:1 trench

Fig. 7. Maximal longitudinal strain in the 530 mm pipeline subjected to strike-slip offset e

5. Conclusions

The uniform approach describing active fault offset and blockslide motion on buried pipelines is presented. It was found that large relative pipe-soil displacements result in soil hardening that is especially significant when the natural soil outside the trench is involved in deformation. That is why the bilinear characteristics of soil springs are applicable for limited motion of a pipe in a trench only.

Deformations of a buried pipeline calculated with due regard to soil hardening that is derived from soils springs finite element modeling are larger than those derived from the bilinear soil springs model if fault (landslide) offset exceeds 2-3 m. More sophisticated numerical models have to be developed to get stable solution for larges displacements along active faults and blockslide boundaries

6. References

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