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INFLUENCE OF BACKFILL COMPACTION IN TIME ON BURIED TRUNK PIPELINE BEHAVIOR UNDER ACTIVE FAULT DISPLACEMENT

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Abstract

The usual design solution for buried trunk pipeline while crossing active fault zone is to make a trapezoid-like trench with flat slopes and using a backfill with special properties. The aim of this trapezoid-like trench is to reduce strains in pipeline under the action of active fault displacement by enhancing the pipeline capability for relatively free lateral and upward movement. Due to soft backfill these movements not limited to trench borders and gives pipeline a capability of free aboveground deformation. In most cases sand with special properties is used as backfill for the trapezoid-like trench in active fault zones. However, over the years backfill sand is compacting and its mechanical properties become closer to undisturbed soil. In current paper the investigation of pipe-soil interaction under active fault displacement for a number of pipeline lifetime periods were carried out. The influence of backfill properties changing on pipeline stress-strain state under the fault displacement action is shown. For simulation the special finite-element model of pipe-soil interaction is used. Pipeline was simulated by plastic finite elements. Pipe-soil interaction in trench was simulated by nonlinear spring finite elements.

Keywords: active fault, buried pipeline soil interaction, pipeline stress-strain state

1. Introduction

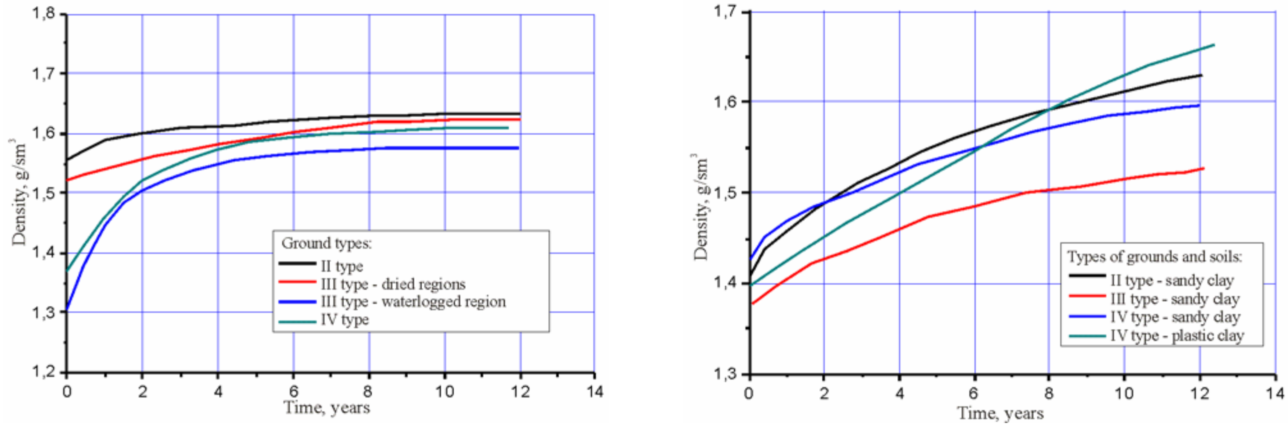
In present time pipelines are used to delivery oil and gas from infields in areas with high seismic activity. Pipelines are also supplying fuel for gas turbine units used in inaccessible regions for electricity generation. Safe operation of pipelines in areas of great seismic activity guarantees safety of hydrocarbons transmission to Clients and safe work of power plants. Conventional design solutions are not applicable at front-end engineering design (FEED) and constructions and installation works in the regions where pipelines cross active faults and other geological hazards. Fault displacements associated with large earthquakes provide a significant threat for pipelines safety. Active tectonic faults in the regions where they are intersected by pipelines need to be selected. Their activation leads to local kinematic action on pipeline by relative displacement of tectonic blocks and resulting to pipelines strains and may be a factor of pipeline fracture. The highest potential risk for pipeline appears from faults, which displacement may damage it and if fault activation can take place with sufficiently high probability at pipeline lifetime. Therefore, faults which activity appears in modern evolution stage in the form of significant single-event offsets associated with earthquakes need to be taken into consideration.

Design solution for pipeline intersection of active fault is based on capability of steel pipelines to compensate relative displacement of fault sides by means of displacements in widened trench with specially selected backfill material. Plastic strains that not leads to pipe leakage are allowed in pipeline at active fault displacement. Pipeline should be aligned in active fault zone intersection to make longitudinal tension and bending stresses prevail in pipe stress-strain state. This allows to decrease compression stresses because limit states for pipeline compression bearing capacity (local buckling or longitudinal stability loss) is usually characterized by lower values in comparison with tension stresses that leads to rupture.

Design and construction of pipeline sections intersecting active faults are performed in accordance with the Construction Code requirements and should correspond to special technical conditions requirements. Pipeline should bear without rupture the active fault displacement. In such case pipeline may have a sufficient damage resulted in operation termination. This damage could require repair works at one or several places. Fault displacement can cause strains in pipeline that sufficiently exceed elastic strains level corresponded to standard operational conditions. Therefore, design methodology supposed that pipe material will work in elastoplastic area assuming of development of comparably big plastic strains at active fault intersection that not leads to pipeline rupture and allows further repair works. Pipeline at active faults crossing stress-strain state is checked by the allowable strains criteria corresponding to rupture limit states.

Pipeline strains decreasing in the case of fault displacement are achieved by creation of conditions of its free motion in a trench. This achieved by applying of trapezoid-like trench with low slopes in regions of pipeline intersection of active tectonic fault. Pipeline backfilling is performed by dry, loose material that not disposed to self-packing during pipeline operation and allowed to pipeline free motion under the action of tectonic impacts. Applicable operation of buried pipeline in faults intersection regions depends upon possibility of preserving of easy deformable soil medium around the pipeline. To guarantee this the excessive backfill packing, mixture with other soils, overwetting or adfreezing. Excessive overwetting or adfreezing of soil may be presented by special measures. At that backfill soils self-packing in time is a natural physical process that not yielded to sufficient influence of a man.

Thesis of taking into account of backfill properties in pipeline calculations is not new. Such statements are discussed in studies [1-6]. To apply design solutions for pipeline laying in active tectonic faults regions the maximally precise information about physicomechanical properties of backfill material need to be known in addition to properties of undisturbed soils [7, 8]. With this requirement the important aspect of backfill soils behavior should be taken into account – backfill soils are exposed to self-packing and self-reinforcement processes. In comparison to maximal disintegration at the moment just after trench backfilling the soil passes through several stages. The fundamentals of such approach are presented in [9, 10]. For sands, sandy clays and plastic clays Nefedova [10] emphases three stages of the density changing: gravity reinforcement; reinforcement due to physicochemical interactions between particles; stabilization – the stage when density growth is negligible.



a) sands b) sandy clays and plastic clays

Fig. 1 – Backfill soils density changing in time (after Nefedova, 1986)
Ground types: II –thawed soils at smooth flat relief and with water table below 3 m;
III – the same with water table close to the daylight surface;
IV – frozen soils of various genesis and age overlaid by pit

Example of soils matrix density changing in time for sands, sandy clays and plastic clays applied as backfill soils are presented in Fig. 1 for different ground types. Analysis of soils density changing and as consequence its strength characteristics in time leads to conclusion that for design of pipeline intersection of active tectonic fault region it is insufficient to know only properties of undisturbed structure soils and backfill soils at time of trench refilling. Sufficient factors that have influence on pipe-soil interaction are backfill soils self-packing and self-reinforcement in time. For design of pipeline intersection of active tectonic faults, the loose backfill (primary homogeneous sand) is applied. Such backfill material have less resistance to pipeline motion in comparison with coherent backfill material. However even a sand soil has a sufficient self-packing gradient in time (Fig. 1a) and the backfill soil properties in time for whole period of pipeline lifetime need to be known for correct simulating of pipe-soil interaction.

2. Buried pipeline numerical model

Pipeline stress calculation at their intersection with active faults is carried out using pipe beam model taking into account its elastoplastic stress-strain state and nonlinear model of pipe-soil interaction. Pipeline operational characteristics are taken into account in the numerical model: internal pressure, pipeline dead weight, temperature of statically indeterminate structure fixation and filler temperature at considered sections. Pipe-soil nonlinear interaction is also considered in the overall numerical model. This soil model is used for simulation of tectonic fault offset during surface rupturing earthquake. The numerical model used for calculations is based on finite-element approach – both pipeline and soil are simulated by finite elements. Due to pipe material and soil mechanical properties nonlinearity and also because of large fault displacement the solving problem is deeply nonlinear. Its solution is carried out in large displacements using method of nonlinear equations solution with step-by-step loading.

Selected pipeline section at active fault intersection analyzed by finite element method and divided by straight and curved pipe finite elements. Pipeline section included in finite element model should have sufficient length for correct simulation of its behavior in fault zone. Pipeline model shall include points of actual fixation of pipeline in soil at both sides of fault (points where longitudinal soil resistance along pipeline axis is high enough to resist for axial forces appearing in pipeline at active fault displacement). Conditions of pipeline in soil fixation can be taken into account in more shorten models by setting of specific boundary conditions at the ends of selected pipeline section.

Pipe-soil interaction is simulated by means of discrete nonlinear springs in longitudinal axial, lateral horizontal and vertical (up and down) directions. Pipe material elastoplastic stress-strain state is taken into account by means of construction steel stress-strain nonlinear curve. Fault displacement are taken into account in numerical model as displacements of soil springs ends that are not connected to pipeline. These displacements are applied to soil springs at one side of the fault (on its moving side) as it shown in Fig. 2.

Finite elements analysis of pipeline stress-strain state at faults intersection is carried out by means of commercial finite element method program. It allows taking into account the model nonlinear geometrical characteristics, the nonlinear pipe material mechanical properties, the nonlinear properties of pipe-soil interaction and specific boundary conditions. It also allows solving problems in large displacements applying loads by parts in step process. For pipeline simulation the pipe beam elements with elastoplastic properties are used. For soil resistance interaction the spring elements with nonlinear stiffness are used.

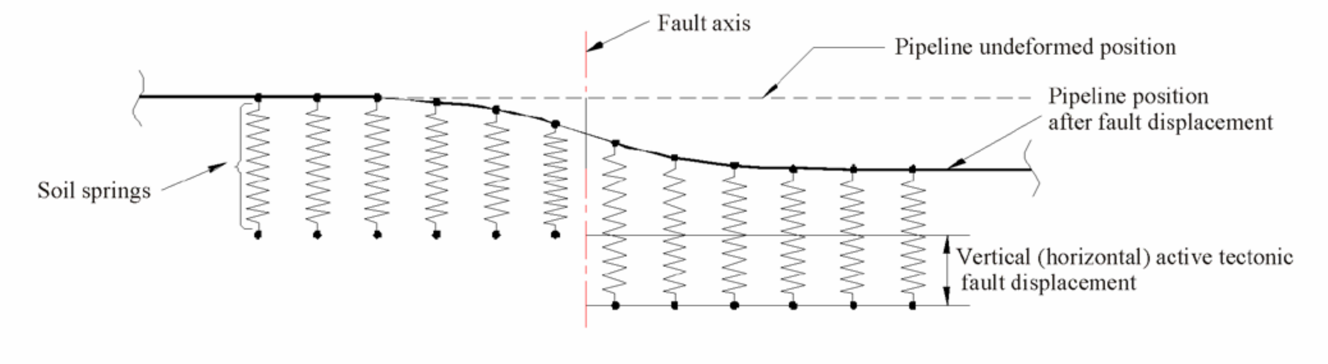


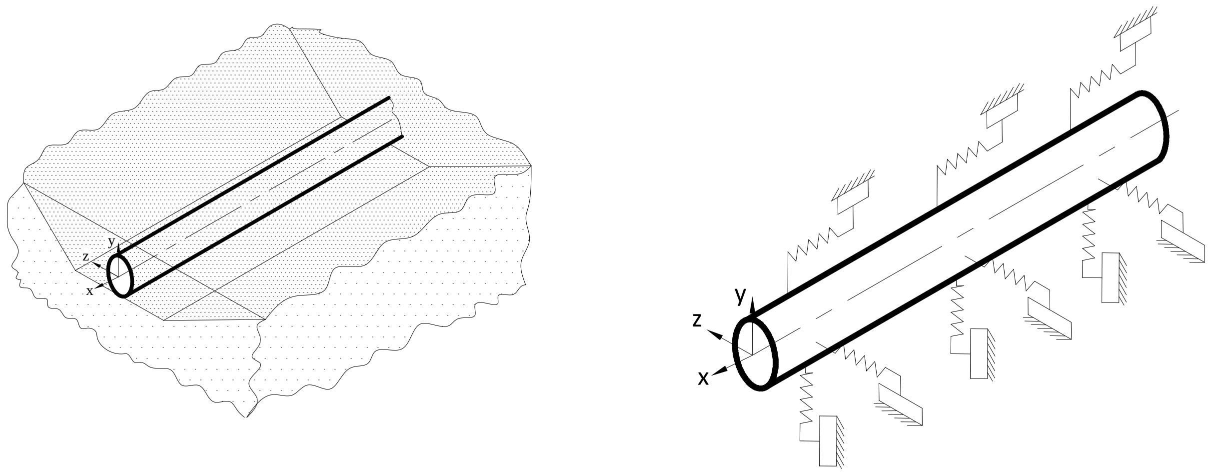
Fig. 2 – Active fault displacement consideration

3. Pipe - Soil interaction model

Pipeline and soil interaction is simulated using special soil spring elements that are transmitting loads from soil to pipeline in axial (longitudinal), lateral horizontal and vertical (up and down) directions. 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 upon pipeline relative displacements in pipe-soil system. These functions can be written in the form of t-x, q-y and p-z characteristics (Fig. 3). Nonlinear characteristics of soil resistance versus relative displacement of pipeline gives more accurate description of the entire system. However bilinear characteristics usually are sufficient for solution of pipeline large displacements problems which are occurred in active tectonic faults intersection regions.

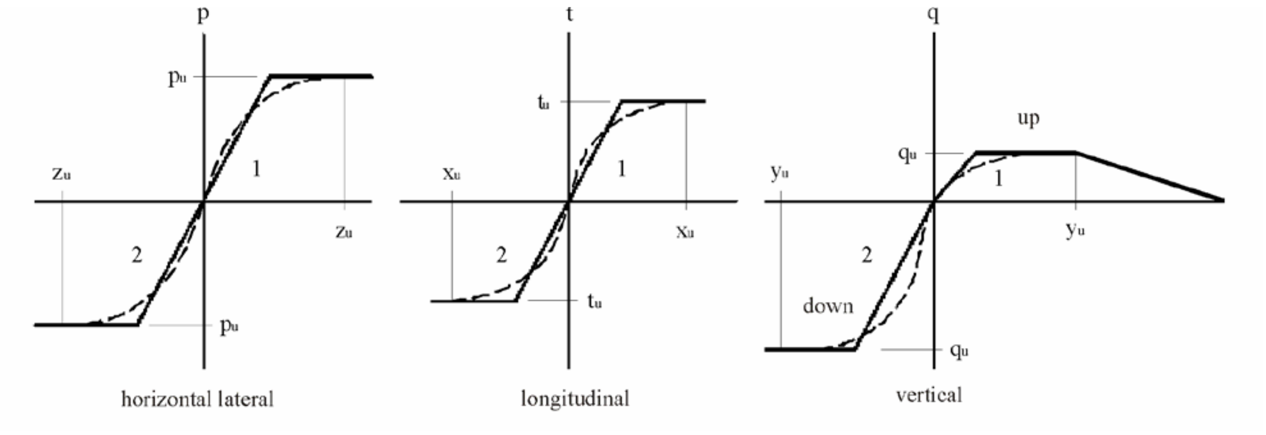
For setting of soil resistance forces in finite element model the nodal forces t, q and p are used. If large relative displacements are appearing between pipeline and soil (exceeding x_u, y_u, and z_u) the soil forces reaching constant maximal values t_u, q_u, и p_u. Pipeline is fixed by soils at both sides of fault axis when pipeline is forced by active fault displacement. Thus at displacement of one side of the fault relatively to the other one, the pipeline is exposed to cumulative action of the tree-component fault displacement.

Bilinear springs characteristics are determined on the basis of physicomechanical properties of undisturbed soil at active fault intersection and backfill soil using the soil model proposed by Ainbinder [1, 4].



a) actual pipe-soil interaction

b) soil representation by means of discrete springs



c) soil springs bilinear stiffness characteristics

Fig. 3 – Pipe-soil interaction consideration by means of soil springs

4. Pipe model

Beam model is used for pipeline calculations. The 300 m long straight pipeline section is selected for mathematical model (Fig. 4). Fault axis is located in the middle of the selected pipeline section. So pipeline have two sections 150 m each at both sides of the fault axis. Pipe beam element length chosen for calculation is equal to $1{\cdot}D_y$ or $0.5{\cdot}D_y$. Results obtained for two different pipe finite element length are in good correspondence. Soil

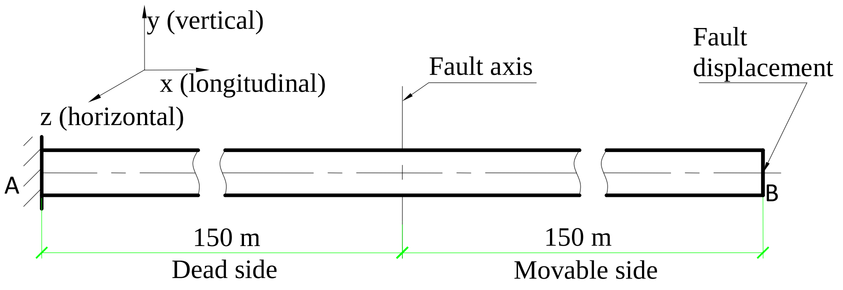


Fig. 4 – Pipe mathematical model

spring ends not attached to pipeline axis and located at dead fault side (150 m) are fixed. Remaining pipeline section is located at fault movable side where the fault displacement is applied for soil springs ends that are not attached to pipeline axis. Soil springs fixation scheme by pipe finite element axes are shown in Fig. 3b. Soil springs stiffness characteristics are assigned in form of bilinear curves received while taking into account soil mechanical properties (Fig. 3c). At the left side of pipeline in section A (Fig. 4) the rotation angles around axes x, y, z are prohibited and axial displacement received from neighboring pipeline section is applied. At right side in section B (Fig. 4) the rotation angles around axes x, y, z are prohibited and axial displacement received from neighboring pipeline section is applied. Loads from internal pressure, temperature drop and pipeline dead weight are applied in mathematical model. Pipeline characteristics used in calculation are shown in Table 1.

Table 1 – Pipeline characteristics

Pipe section		**Internal pressure, MPa**	**Δt, °C**	**Pipe steel characteristics**					
Outside diameter, mm	**Wall thickness, mm**			**Grade**	**Young modulus, MPa**	**Yield stress, MPa**	**Ultimate stress, MPa**	**Poisson ratio**	**Linear expansion factor**
1220	36	9.8	+40°	X60	$2\cdot10^5$	414	517	0.3	$1.2\cdot10^{-5}$

True stress – true strain behavior nonlinear diagram is simulated by means of stress versus strain power law:

$$\varepsilon = \frac{\sigma}{E}\cdot\left[1+A\cdot\left(\frac{\sigma}{\sigma_y}\right)^{n-1}\right] \qquad (1)$$

where:

n is a strengthen parameter, calculated as follows:

$$n = \frac{\log\left[\left(\varepsilon_u - \frac{\sigma_u}{E}\right)\Big/\left(\varepsilon_y - \frac{\sigma_y}{E}\right)\right]}{\log\left(\sigma_u / \sigma_y\right)} \qquad (2)$$

A calculated using formula:

$$A = \frac{\varepsilon_y \cdot E}{\sigma_y} - 1 \qquad (3)$$

σ_u is a minimal ultimate tension stress;

σ_y is a minimal Yield stress;

ε_y is a strain corresponded to Yield stress;

ε_u is a strain corresponded to ultimate tension stress.

Stress versus strain curve for grade X60 for minimal mechanical properties of pipe material [11] is presented in Fig. 5. In Table 2 the parameters that are used for stress versus strain curve are shown.

Table 2 – Parameters for stress versus strain curve for steel grade X60

Parameters	**Steel Grade according to API 5L**
	X60
Nominal Yield stress (MPa)	414
Nominal strain corresponded to nominal Yield stress	0,50%
Nominal ultimate tension stress (MPa)	517
Ultimate strain corresponded to ultimate tension stress	14,0%
Parameter A	1,47
Strengthen parameter n	10,6
Yield stress to ultimate tension stress ratio	0,8

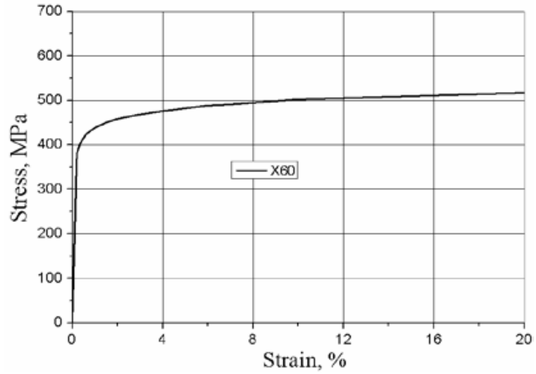


Fig. 5 – Stress-strain curve

Fine sand of average density is applied as surrounding soil for fault activation numerical model. For calculation of bilinear soil springs the values represented in Table 3 are used for the undisturbed and for the backfill soils. Using pipe-soil interaction model [1, 4] the soil spring characteristics are calculated using soil properties directly at the moment of backfilling and taking into account backfill soil self-packing during pipeline lifetime cycle. Other factors like backfill thickness, ballasting, etc. may be included in the model if any. Widened trench for pipeline as proposed in patent [12] is applied in calculations. All fault displacement components and full displacement vector value are presented in Table 4. Soil displacements in fault zone are translated to coordinate system adjusted to pipeline using data presented in Table 4 taking into account fault intersection angle by pipeline.

Pipeline calculation at fault displacement is carried out in two load steps. In the numerical model at the first load step the operational loads with safety coefficients according to SP 36.13330.2012 are applied: weight loads (pipeline weight and filler at maximal pressure weight), maximal internal pressure and maximal temperature drop, axial displacements of neighboring pipeline sections. In this load step the pipeline is restrained in the soil and both left and right fault sides are motionless. As result of calculation in this step the most loaded pipeline section stress-strain state is determined.

Fault displacement is taken into account in the second load step for pipeline that was already prestressed by operational loads using methodology of fault displacement application to soil springs as described above. For active fault displacement the substep process with finding of pipeline equilibrium position in soil for each substep fault displacement load up to maximal offset value is used. Loads combination at first load step may vary to determine worst combination. As example for each pipeline section of active tectonic fault intersection depends both upon factual temperature of pipeline fixation and upon filler temperature at active fault displacement.

Table 3 – Soil mechanical properties

Parameter	**Nomenclature**	**Value**	
Soil type		Fine sand, average density	Loose sand (backfill)
Poriness ratio	ε	0.63	0.75
Deformation modulus, MPa	E_{soil}	32	11.9
Unit weight, kN/m^3	γ_{soil}	16.9	16.6
Poisson ratio	μ_{soil}	0.25	0.25
Internal friction angle, degrees	φ_{soil}	35.6	31.0
Specific cohesion, MPa	C_{soil}	1.2·10-3	0.0
Generalized coefficient of tangential resistance, MPa/sm	C_{x0}	0.027	0.016
Bearing capacity, MPa	R_{soil}	0.4	0.152

Table 4 – Fault displacement

Fault type	**Fault strike azimuth, deg.**	**Slope angle, deg.**	**Fault design displacement, m**	**Fault displacement components, m (Fig. 6)**		
				Along fault strike	**Across fault strike (plus - tension, minus - compression)**	**Vertical (plus - up, minus - down)**
Upthrow shift fault	310	90	2.5	2	no	+1.5

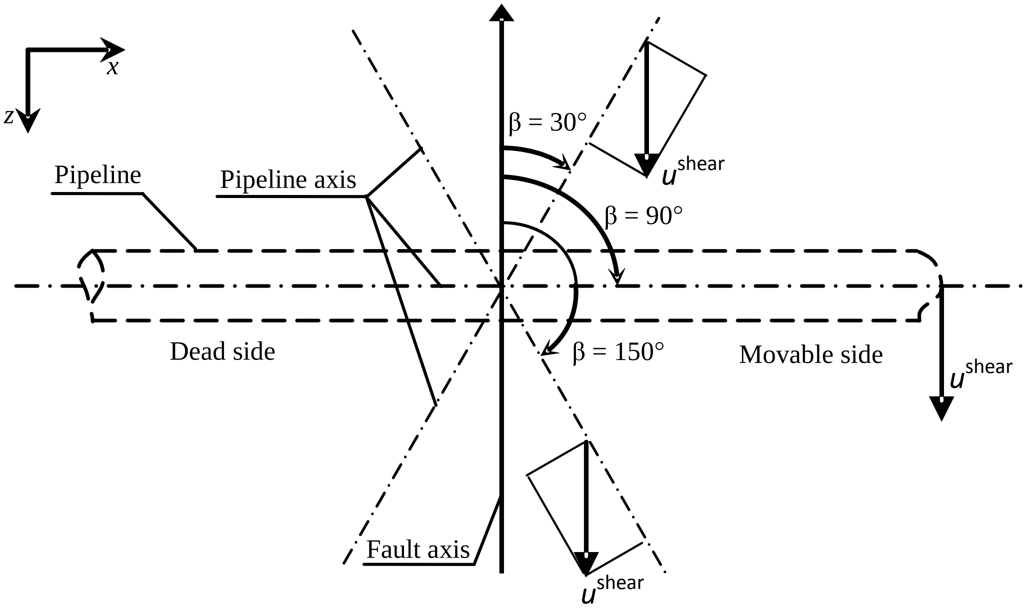


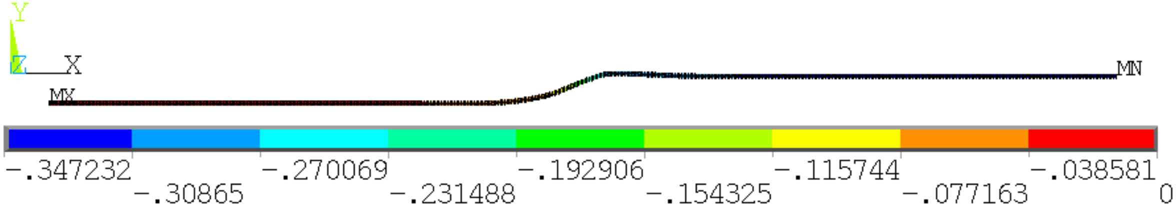
Fig. 6 – Fault displacement at pipeline axis projection scheme

5. Pipeline stress calculation at active fault displacement

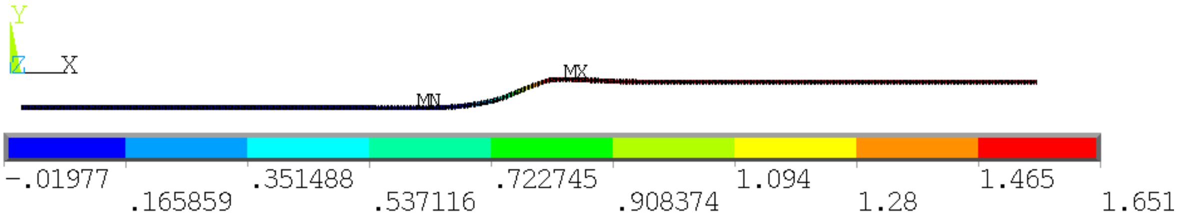
As mentioned above the pipeline calculation at active tectonic fault intersection sections need to be performed for different parameters. This is explained by necessity of determination of worst combination of operational loads and fault displacement. Main goal of the calculation is to check pipeline strains at fault crossing and worst possible operation conditions for criteria of maximal plastic tension and compression strains.

Pipeline calculation results at active fault / pipeline intersection are presented for three soil characteristics models: model 1 – backfill soil characteristics are taken for time state just after pipeline backfilling in a trench; model 2 – backfill soil characteristics are taken for self-packing time state after maximal period of pipeline lifetime (30 years); model 3 – backfill soil and surrounding soils characteristics are taken with regard to soils packing from possible influence of soil deformation rates in the pipe-soil system. For models wherein maximal strains occur, the calculations with positive temperature drop of 40 degrees Centigrade are carried out too.

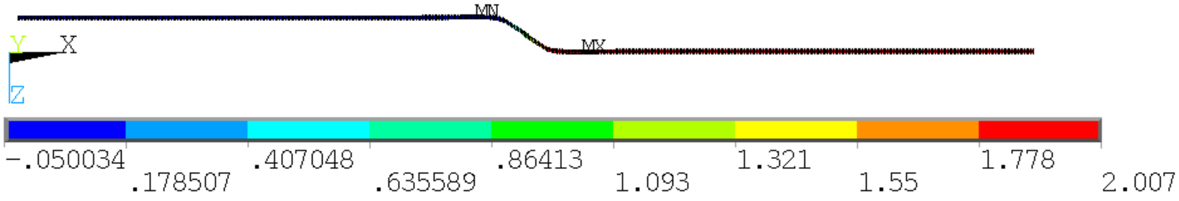
All results presented below are shown for different fault intersection angles by pipeline (β). Maximal strains are appearing in model 1 for active fault intersection angle of 80°. Graphic calculation results for model 1 are presented in Fig. 7-9. Distribution of pipeline displacement components along the coordinate axes are shown in Fig. 7. Distribution of maximal pipeline longitudinal compression strains are presented in Fig. 8. Similar results for maximal tension strains are shown in Fig. 9. Longitudinal and equivalent stresses in pipeline sections are also presented in Fig. 8 and Fig. 9. The results for maximal axial tension and compression strain curves in pipeline at fault section are shown in Fig. 10a in step-by-step form from zero to maximal fault displacement. The results for maximal axial tension and compression strains for different angles of fault intersection by pipeline also for models with temperature drop are shown in Fig. 10b.



a) u_x, m

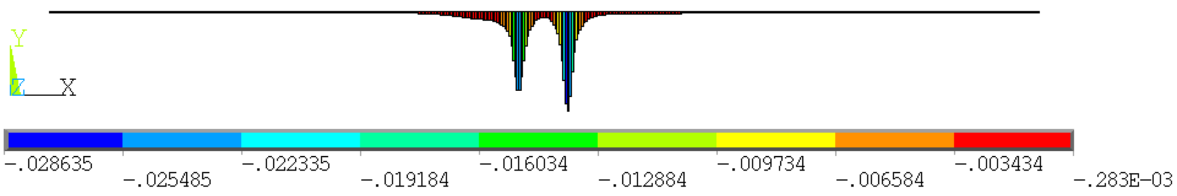


b) u_y, m

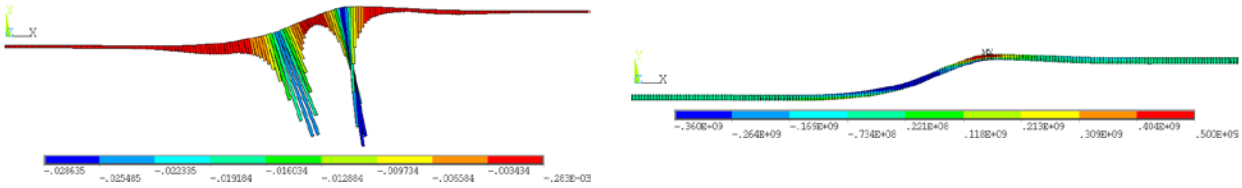


c) u_z, m

Fig. 7 – Distribution of pipeline displacement components along the coordinate axes for model 2 at fault intersection angle by pipeline β = 80°



a) maximal longitudinal compression strains

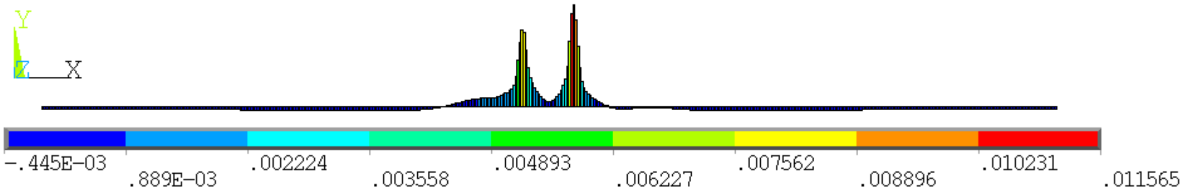


b) maximal longitudinal compression strains c) longitudinal stresses

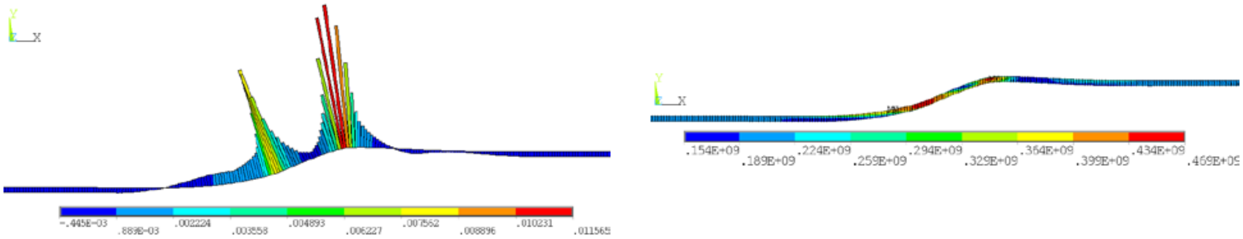
Fig. 8 – Distribution of pipeline longitudinal strains and stresses for model 2 at fault intersection angle by pipeline β = 80° at total fault displacement

Calculation results for models 1-3 demonstrates that fault intersection by pipeline with angle less than 90° causes compression stresses in pipeline sections. The big compression strains are appearing for all models. For two more rigid models # 2 and #3 (taking into account temperature drop) the compression strains are exceeding limit criteria for intersections angle of 80°. At that tension strains are not grow too much and not exceed of 1.5%. At the same time for intersection angles more than 90° the fault displacement causes pipeline tension strains. At that compression strains in pipeline decreases and absolutely disappear for intersection angle of 127° for all models.

Obtained results demonstrates that soil self-packing in time (models 1 and 2 in comparison) and possible soil packing at fast deformation (model 3 with temperature drop) leads to strains level increasing in pipeline for fault intersection angles less than 90°. For intersection angles more than 90° difference between all considered models are negligible.

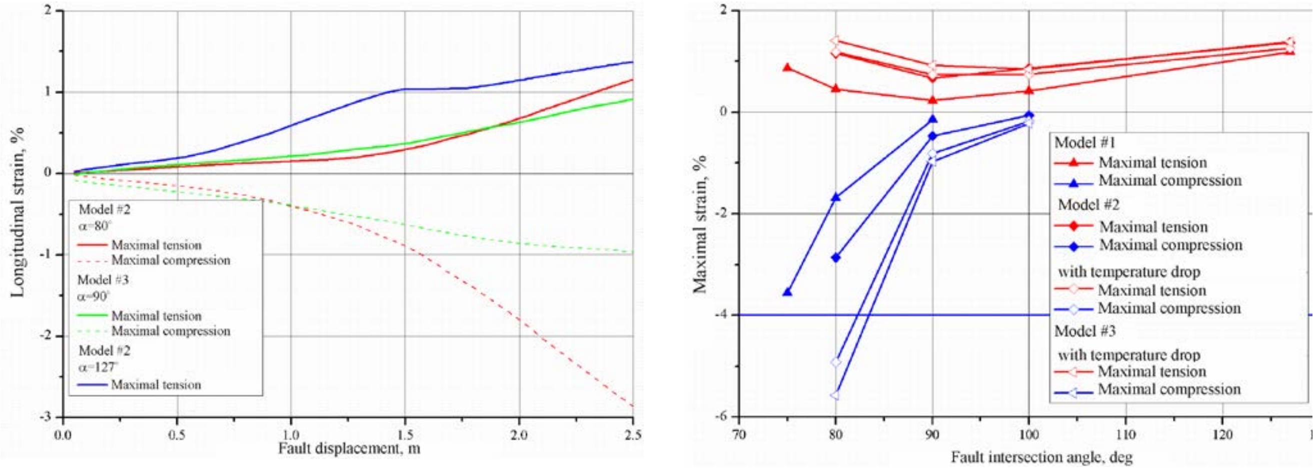


a) maximal longitudinal tension strains



b) maximal longitudinal tension strains c) equivalent stresses

Fig. 9 – Distribution of pipeline longitudinal strains and stresses for model 2 at fault intersection angle by pipeline β = 80° at total fault displacement



a) maximal longitudinal deformations versus to fault displacement applied step by step

b) maximal longitudinal deformations in pipeline versus to fault intersection angle (β) at total fault displacement

Fig. 10 – Calculation results for different fault intersection angles by pipeline

6. Conclusion

The numerical model of pipeline / active fault intersection is developed. This model allows analyzing stress-strain state in pipeline at operational loads and fault displacement for various soil conditions. Influence of the soil mechanical characteristics change due to long-term self-packing and packing caused by fast deformation at the pipeline stress-strain state are shown. Maximal influence of the soil self-packing around the pipeline on its stress-strain state are obtained for fault displacement that cause axial compression in the pipeline. Maximal compression strains associated with soil packing could exceed similar deformations for models with loose soil for 1.5 and more. Thus for the design of pipelines at active fault crossings it is required to elaborate a series of numerical models taking into account soil properties in different exploitation periods. This will allow setting an adequate margin that will guarantee pipeline section continuity in case of surface rupturing.

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