The paper was published in the proceedings of the 7th International Conference on Earthquake Geotechnical Engineering and was edited by Francesco Silvestri, Nicola Moraci and Susanna Antonielli. The conference was held in Rome, Italy, 17 – 20 June 2019.

Earthquake Geotechnical Engineering for Protection and Development of Environment and Constructions – Silvestri & Moraci (Eds)
 ISBN 978-0-367-14328-2

Designers' requirements of surface rupture parameters determination accuracy at trunk pipelines/active fault crossings

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ABSTRACT: Stress-strain state of 530 mm and 1420 mm trunk pipelines that have to cross active faults with normal, reverse and strike-slip kinematics and with single-event offsets up to 5 m was analyzed. Pipeline sensitivity to displacement variation was investigated for two types of trenches (with slopes 1:1 and 3:1) and for different backfill properties. Deformations of pipeline depend on the directions of fault walls motion relative to pipeline axis. Influence of each displacement component on the pipeline that crosses fault at an optimal angle was studied and threshold offsets for different kinematic types of surface faulting were determined. Fault displacements with which the pipeline remains in the elastic state were determined for different trench shapes and backfill materials. Displacement ranges for which significant increase of pipeline plastic deformations is expected and ranges for which deformations stabilize and do not increase with displacement growth were determined too. The obtained results allow optimization of the construction codes' requirements. They also help focusing site investigations on more accurate assessment of those parameters that affect pipeline stress-strain state at a maximal extent.

1 INTRODUCTION

Some trunk pipelines have to cross active (causative) faults that, besides producing strong motions, can also produce surface ruptures with offsets up to several meters and variable slip along fault strike (Wells, Coppersmith, 1994; Strom, Nikonov, 1997, 2000; Chipizubov, 1998; Lunina, 2001). Unfortunately, designers often cannot bypass such faults and, thus, have to elaborate technically feasible and economically efficient protection measures. Reliability of such measures was proved by the Trans-Alaska pipeline (TAP) that withstood almost 6-m offset at its crossing with the 2002 M8 Denali fault earthquake surface rupture (Haeussler et al., 2004; Hall et al., 2003).

Surface faulting parameters that are used as input data for such design – the anticipated fault plane location, amount of possible net displacement, and its component's ratios are always determined with some uncertainty (Mattiozzi, Strom, 2008; Strom et al., 2009; Strom, 2017; Strom, Temis, 2018). Accuracy of surface rupture localization varies from meters to tens of meters, predetermining width of the "uncertainty zone" within which the anticipated rupture might occur. Considering complexity of the phenomenon in question, we postulate equal probability of rupturing at any part of the uncertainty zone that can be illustrated by the fact that the TAP was crossed by surface rupture close to the edge of the fault zone identified during site investigations (James McCalpin, personal communication). Besides, seismic surface ruptures are often characterized by significant variability of the amount of slip per event along rupture strike, and during successive rupturing events (McCalpin, 2009). Ratio between slip components can vary along rupture strike too (Strom, Nikonov, 2000).

Considering these uncertainties, it is important to analyze pipeline sensitivity to variations of the expected rupture location, fault kinematics, and single-event displacement value, both net and component-wise, namely vertical, across and along fault strike that can be recalculated as the offsets across and along pipeline route. Besides elaboration of the optimal pipeline/fault crossing design that includes choice of pipeline alignment, pipe types, size and shape of a trench, and backfill material for buried pipeline, results of such analysis help focusing engineering-geological investigations on more accurate assessment of those parameters that affect technical solutions at a maximal extent. Such analysis for relatively small (up to 2.5 m) offsets was presented in (Strom, Temis, 2018). Here we would like to expand it for pipeline-fault crossings with up to 5 m single-event displacement.

2 DEPENDENCE OF THE PIPELINE DESIGN ON ACTIVE FAULT PARAMETERS

Requirements of Technical Codes (e.g. American, 2005; Gazprom, 2009) allow sufficient deformations of pipeline that might be caused by active fault walls relative displacement. Pipeline could require repair after such event but should not be ruptured to avoid product leakage and environmental pollution. Design solutions should guarantee pipeline leak-proofness in the case of a maximal fault displacement.

Major fault parameters, determining design solutions for pipeline/fault crossing are: fault type (Figure 1); position of the possible fault line (axis of the fault zone) and width of the uncertainty zone where it is crossed by pipeline route (Figure 2); values of fault displacement components.

Special structural solutions required by Codes should be applied in such cases to compensate influence of fault walls relative motion by pipe movement in a trench and its elastoplastic deformation (O'Rourke, Liu, 1999). Special trench with inclined slopes and with backfill with low internal friction angle and reduced consolidation properties (coarse-grained sand in most of

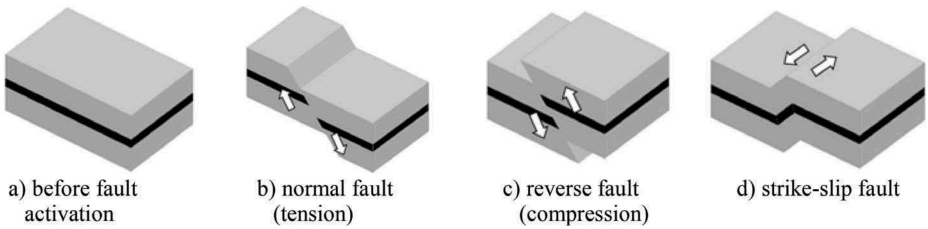

Figure 1. Basic types of fault displacement kinematics.

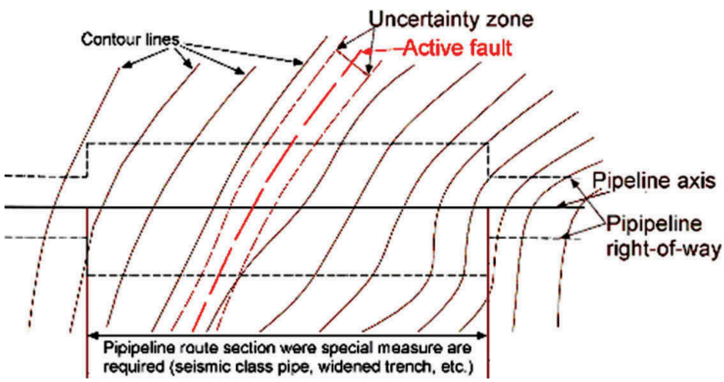

Figure 2. General scheme of fault/pipeline crossing.

cases) is used to provide relatively free pipeline displacement (Figure 3a). Slope angle β of such trench depends on the backfill internal friction angle (Figure 3b) and can be determined by numerical modeling. Since soil consolidation rate can vary in time significantly, soil mechanical properties and soil resistance rate for pipeline displacements can change (Temis, 2017). That is why special measures preventing soil freezing in cold period are undertaken (Liu et al, 2004). Use of seismic class pipes with high plastic deformations level before pipe wall rupture ensures pipeline elasto-plastic deformations with the 4% longitudinal strain as the allowable threshold value.

Russian Code (Gazprom, 2009) requires excavation of trench with inclined slopes and use of seismic class pipe across the entire fault uncertainty zone and for 150 meters in each side from its borders (see Figure 2). According to the Code, such requirements must be applied for all fault types regardless of the anticipated fault displacement and kinematic type. However, such uniform approach seems to be groundless and, sometimes, excessive. It ignores the fact that for some combinations of fault kinematics and displacement value pipeline integrity can be ensured without such measures or by their partial implementation.

It has been shown that various fault displacement kinematics and pipeline orientation at fault intersection causes different level of stresses in pipeline, and that 90 degrees intersection angle of the fault by pipeline is optimal (Strom, Temis, 2018). Here we analyze pipelines crossed by normal fault (see Figure 1b) reflecting tension across fault line, by reverse fault (see Figure 1c); reflecting compression across fault line, and by strike-slip (Figure 1d) when fault walls move in horizontal direction along shear plain. Combined fault kinematics are possible as well but we do not analyze such cases in this study.

To compensate pipeline displacements under the action of large strike-slip movements, use of special trench with inclined slopes is very efficient, while for pipelines crossed by faults with predominantly normal or reverse kinematics without significant strike-slip component efficiency of use of a trapezoid trench with flat slopes is not so obvious and its necessity should be tested by simulation of pipeline stress-strain state in normal (rectangular) and special (trapezoid) trenches. It can help to avoid unjustified increase of earthworks. Thus, the precise assessment of fault kinematics is critical.

Pipelines design is provided considering that fault rupture might occur at any time during pipeline lifetime. It requires analysis of the pipeline stress-strain state in the trench with consolidated backfill. Sometimes such consolidation makes the necessity of construction of the widened trapezoid trench questionable even for fault crossings with anticipated large strike-slip displacements, since difference in mechanical properties of the backfill in the normal and in widened trenches decreases with time. It also needs performing comparative simulation of the stress-strain state of pipeline in the normal and widened trenches that might experience large strike-slip offsets.

Special attention should be paid to fault displacements that do not cause plastic deformations in the pipeline. For such level of the loading use of an expensive seismic class pipe with high plasticity of the steel and of the widened trench seems to be questionable. If, according to the numerical modeling, the stress-strain level remains elastic even under worst loading conditions, the necessity of special measures such as seismic class pipe and widened trench is not so

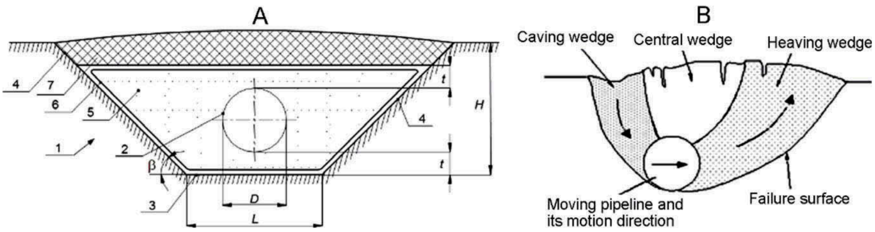

Figure 3. Measures for minimization of pipeline forcing by soil in case of fault activation. A) Schematic cross-section of the pipeline trench at its crossing with active fault: 1 – undisturbed soil; 2 – pipeline; 3 – trench bottom; 4 – trench slope; 5 – special backfill; 6 – waterproof casing; 7 – local backfill soil. B) Soil failure surface for pipe-soil relative lateral displacement.

obvious. Same reasoning can be applied also to small plastic deformations of the pipeline. The criterion according to which the plastic deformations can be considered as "small" should be derived and included in the new construction codes.

We will demonstrate effects of different trench types and of backfill consolidation on the 530 and the 1420 mm pipelines affected by pure strike-slip, normal or reverse fault displacements up to 5 m that were anticipated for buried pipelines of the Sakhalin-1 and Sakhalin-2 Projects (Mattiozzi, Strom, 2008).

3 NUMERICAL MODEL OF PIPELINE / FAULT CROSSING

Numerical simulation of the pipeline-soil interaction at active fault crossing has been performed by use of finite-element (FE) software. Pipeline was modeled by the Bernoulli beam FE representing pipe with the internal pressure and taking the elastoplastic properties of the pipe steel into account. Its interaction with soil is modeled by nonlinear soil springs connected to pipeline axis at the beam (pipe) FE nodes (Figure 4a). Soil springs are modeled by nonlinear uniaxial FE whose stiffness is set on depending on the character of pipe -soil interaction (Figure 4b). Pipe-soil interaction model allowing to calculate parameters of bilinear soil springs (F_g-k_g, F_a-k_a and F_v-k_v) provided by site investigations (Table 1) is presented in (Ainbinder, 1991). Fault active wall motion is modeled by the displacements of soil springs associated with FE nodes but not connected to pipeline. Calculations were performed considering both the geometrical (load are applied to deformed structure) and physical (elastoplastic deformations of pipeline) nonlinearities. Detailed description of this model of pipeline - soil interaction at active faults crossings was presented in (Temis, 2017).

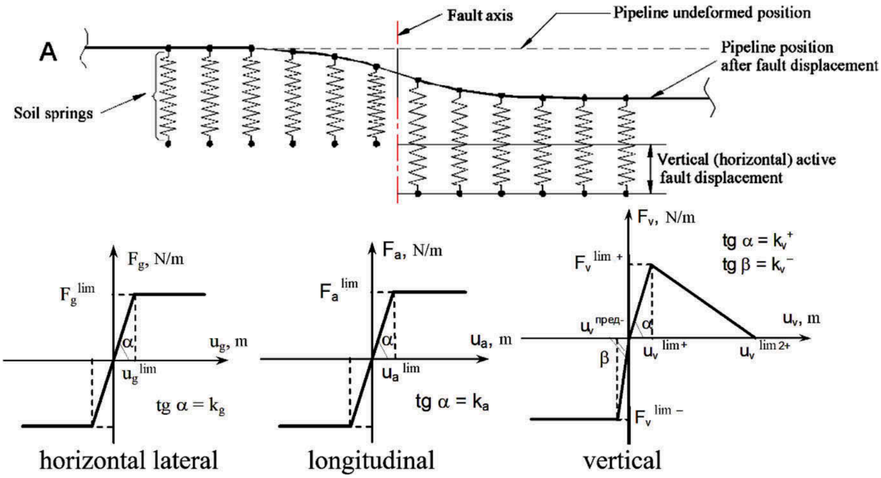

Figure 4. Pipe-soil interaction modelled by soil springs. A – model of active fault displacement; B – characteristics of the soil springs bilinear stiffness.

Table 1. Backfill soil properties

Backfill soil Parameter	Symbol	Imported soil (coarse-grained sand)	Soil excavated from a trench (medium-grained sand)
Modulus of deformation	E_{soil}	11.9 MPa	30 MPa
Angle of internal friction	φ_{soil}	31°	40°
Bearing capacity	R_{soil}	0.15 MPa	0.3 MPa

To analyze behavior of a pipeline affected by fault offsets (pure normal, reverse or strike-slip – see Figure 1) we modelled the 300 m long linear horizontal pipeline section (150 m at each side of the pipeline axis). The uncertainty zone was not considered to simplify the model. The K56 pipe steel with high plasticity properties allowing pipeline strain up to 4% was used as pipe material. The internal pressure is 9.8 MPa. The backfill soil was either the imported coarse-grained loose sand, or and native medium-grained sand excavated from the trench. Soil parameters were considered just after trench filling (Table 1) and after their compaction (soil strength increased by 1,67). This coefficient is derived considering that backfill soils properties are equal to 60% of their properties in undisturbed state. The upper limit of soil properties after compaction is taken as their properties in undisturbed state.

4 THE PARAMETRIC STUDY OF THE STRESS-STRAIN STATE OF A PIPELINE CROSSED BY ACTIVE FAULT

Different level of deformations can be assumed in the pipeline crossed by active fault depending on fault displacement kinematics and offset value. We simulated behavior of pipelines with outer diameter of 530 and 1420 mm crossed by active faults with normal, reverse and strike-slip displacements up to 5 m. Such diameters' range corresponds to the minimal and maximal diameters of trunk pipelines, allowing estimating effect of pipe stiffness on interaction with the surrounding soil. Geometry of the pipeline deformed by the reverse fault is shown in Figure 5 with von Mises stress distribution on pipeline surface. Stresses in Figure 5 were calculated for beam (pipe) FE size and shape corresponded to 1420×32 pipeline dimensions. Cumulative longitudinal compression and tension deformations of the 530 mm pipeline affected by fault displacements with different kinematics are presented in Figure 6 and the same for 1420 mm pipeline – in Figure 7. Such cumulative longitudinal deformations characterize pipeline strength and integrity. Results of the numerical modeling of the pipeline crossed by strike-slip fault are presented for two types of the trapezoid-shape trenches – with slopes' angle $\beta \approx 20°$ and with slopes' angle $\beta = 45°$. For pipelines crossed by normal and reverse faults, such comparison was not provided, since effect of the trench walls sloping in such cases is minimal and can be neglected.

Strain growth for the 530 mm pipeline is more intensive than for the 1420 mm one. Deformations of the 1420 mm pipeline for fault displacements up to 2-3 meters are less than those of the 530 mm pipeline (compare Figures 6 and 7). Further increase of fault displacement results in both cases in the appearance of the significant zones of plastic deformations, which level increases gradually with increasing fault offset. Maximal deformations for both diameters appear at reverse faults crossings (Figures 6d and 7d) that cause axial compression of pipeline due to shortening across fault strike (see Figure 1).

For 530 mm pipeline even 1 m reverse offset axial compression strain reaches the criterion threshold value of 4% almost at all models (see Figure 6d). For the 1420 mm pipeline the same threshold is reached for 2 m reverse offset (see Figure 7d). Practically in all other simulation cases for normal and strike-slip faults, regardless of the backfill soil properties, strains do not teach the threshold value of 4%. It proves that crossing of the pipeline by reverse active fault is the worst case. Thus, requirements for the assessment of reverse faults' kinematics and of the compression displacement value for such faults during site investigations should be most strict and that such estimates should be as precise as possible.

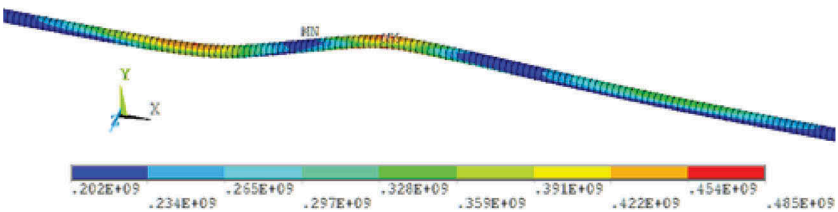

Figure 5. von Mises stress in the 1420×32 pipeline for the reverse fault displacement.

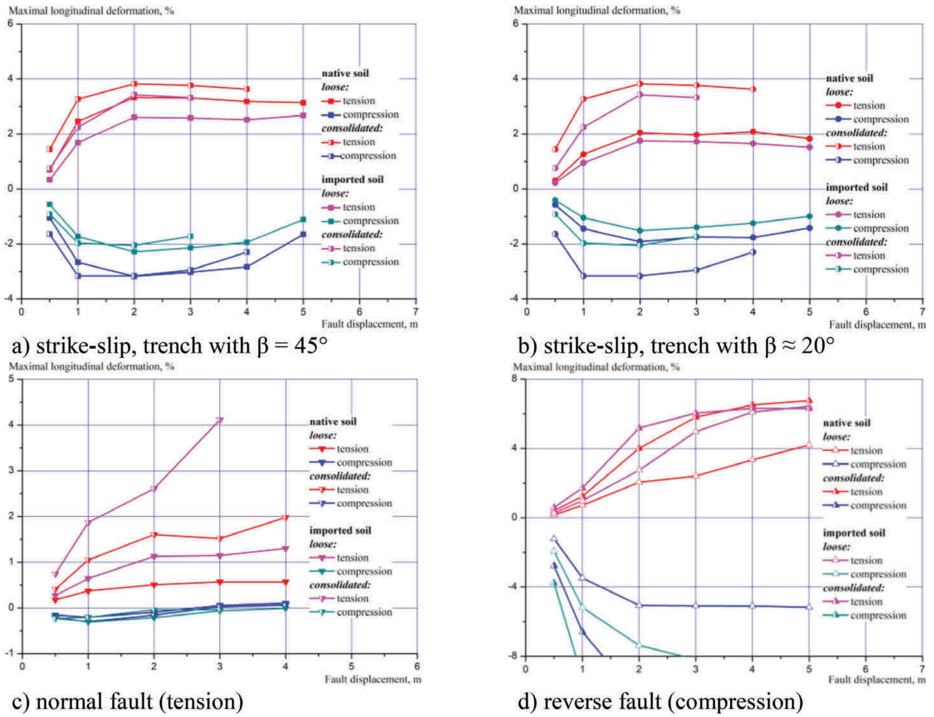

Figure 6. Maximal longitudinal strains in the 530×12 pipeline caused by fault activation.

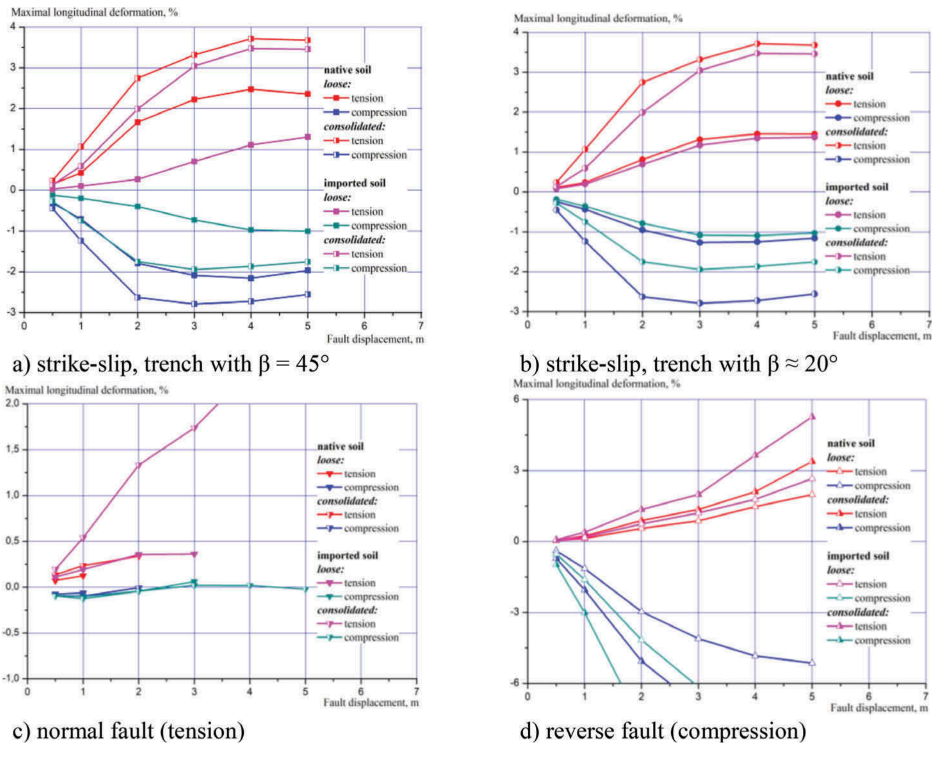

Figure 7. Maximal longitudinal strains in the 1420×32 pipeline caused by fault activation.

Deformations of buried pipeline with backfill of soil excavated from the trench that is crossed by the reverse fault were found to be less than of the similar pipeline buried by the imported sand, both immediately after backfilling and after backfill compaction. Pipeline compression by reverse faulting at some stage of loading results in its axial buckling failure. Unlike the traditional approach to the stability assessment, here the style of the stability failure depends on the character of pipeline-soil interaction. The simulation results demonstrate that it is possible to adjust soils properties and the backfilling depth to minimize pipeline deformations in case of reverse faulting. The traditional backfilling by loose soil might be not the optimal solution, since the pipeline deformations in the compacted soil are more than 1% higher than in loose soil just after backfilling.

Normal faulting (see Figure 1b) causes tension deformations of a pipeline mainly (Figures 6c and 7c). The compression strains for both pipeline diameters do not exceed 0.5% and are within the elastic zone mainly. Pipeline subjected to extension has smaller level of loading that is conditioned by prevailing tension loads.

Interaction with soil compacted after 30 years of operation results in soil deformations that are 0.5-1% larger than for soil just after backfilling (same results were obtained for reverse faulting case). Normal fault displacements up to 0.5 m for 530 mm pipeline and up to 1 m for 1420 mm pipeline produce deformations that do not exceed 0.5%. It raises a question on the necessity to use more expensive pipes with higher plasticity characteristics for such crossings. Requirements for accuracy of normal displacement assessment can be formulated considering the avoidance of pipeline plastic deformation as a criterion. It would be desirable to estimate this displacement value with an accuracy that is sufficient to understand if pipeline deformations caused by such offset are within elastic limit or exceed it.

For the 1420 pipeline in the conditions described herein such a displacement threshold value is 1.0 m. If it is larger it can be assessed with accuracy not better than ±0.5 m. This criterion for other pipeline diameters and for other pipeline laying conditions can be obtained by numerical modeling and should be included in the technical assignment for engineering-geological investigations.

Significant effect on deformation of pipeline crossed by strike-slip fault (see Figure 1d) is provided by the trench profile, especially if the backfill remains in loose state. For the 530 mm pipeline deformations are nearly similar both for trenches with $\beta = 45°$ and $\beta \approx 20°$, and are close to maximal values released when soil is compacted (see Figure 6a, b). It can be explained by similarity of the mechanical properties of the compacted backfill soil and of the original undisturbed soil that is almost independent from the trench geometry. For loose backfill the effect of the widened trench is obvious: deformation of the pipeline in the trench with $\beta \approx 20°$ is 0.5-1.0% less than in trench with $\beta = 45°$. Deformation of the 1420 mm pipeline in the trench with $\beta \approx 20°$ filled by loose soil (for both types of soil used as a backfill) does not exceed 1.5% (Figure 7a, b). If $\beta = 45°$, it does not exceed 1.5% when loose imported soil is used, while for native soil axial deformation reaches 2.5%. However, if the backfill soil properties are close to those of undisturbed soil, effect of trench slopes' angle is almost negligible. 530 mm pipeline affected by 0.5 m strike-slip fault displacement at some simulation cases experience axial strain exceeding 1% for both types of trenches. If displacement increases up to 1 m, deformation in 530 mm pipeline increases up to 3%. At the same time for the 1420 mm pipeline 0.5 m fault displacement results in deformation less than 0.5% and 1 m offsets for most of simulation models do not cause deformation larger than 1%.

Generally, effect of strike-slip faulting on pipeline deformations is smaller than that of the reverse faulting but lager than of the normal one. Pipeline deformations in case of strike-slip faulting are less in the trench with gently sloping walls filled by less consolidated soil. Therefore, designing pipelines that can be affected by active faults with strike-slip kinematics, special measures preventing soil consolidation should be undertaken and numerical modeling must be performed considering the expected properties of consolidated backfill soil. If we cannot prevent soil consolidation and large fault displacement values are anticipated, the comparative analysis of pipeline deformations in normal and in widened trenches must be performed. Necessity of widened trench excavation and of seismic class pipes is questionable for pipelines that are crossed by active faults with strike-slip offsets less than 0.5 m. If fault offsets exceed 0.5 m, pipeline safety can be guaranteed by use of either the widened trench or of the seismic class pipe. Use of seismic class pipe seems to be preferable from technical point of view since preservation of the backfill soil from its compaction is much more complicated task.

Displacement ranges for which accuracy of its assessment is critical for the design solutions and the construction cost can be proposed for the strike-slip cases similarly for normal faulting. Pipeline deformation will remain elastic, most likely, if strike-slip displacement will not exceed 0.5 m. Within the 0.5-2.0 m range pipeline deformations increase significantly, therefore in such cases it is desirable to estimate the design displacement value as precisely as possible to get more realistic level of pipeline strain. Such accuracy depends on many factors and can vary depending on particular situation. If strike-slip offset exceeds 2 meters, the rate of pipeline deformations growth stabilizes that is caused, most likely, by pipeline "escape" from the trench. Variation of pipeline deformations for 2-5 m strike-slip offsets does not exceed 0.5%. Thus, for such cases requirements for slip value assessment accuracy are not so strict.

5 CONCLUSIONS

Results of numerical modeling of pipeline-fault crossing presented herein demonstrate that sensitivity of the pipeline stress-strain state to the amount of displacement is quite variable depending on fault kinematics (normal, reverse, strike-slip), on trench shape (1:1; 3:1), backfill material, and on pipeline diameter. For strike-slip faulting some combinations of these characteristics result in the acceptable values of maximal deformations (<4%), regardless of the displacement (at least within the analyzed offset range). Reverse faulting leads to deformations exceeding this threshold value for smaller displacements that means that some additional engineering solutions are required to ensure pipeline safety. Normal faulting has smallest influence on pipeline deformations.

It was found that safety of pipelines crossed by active faults with small anticipated displacements can be ensured without applying all measures recommended by construction Codes that can cut down pipeline construction cost. These "small values" depends on pipe diameter, trench shape and backfill and should be estimated for each Project individually. However, the chance to use normal pipe in ordinary trench for such fault intersections will cover all additional design costs. Implementation of the recommended numerical simulation of pipelines crossed by active faults will allow reasonable and justified decrease of Codes' requirements to design solutions for such crossings and, thus, lower capital costs and duration of pipelines' construction.

Such analysis should be very useful for planning of the engineering-geological and seismotectonic investigations at the pipeline-fault crossing sites. Main focus should be paid on getting more detailed information on those parameters that influence the resultant strain at most, and on understanding if the assumed offset will exceed the critical value (with which strain will become inacceptable) or not. Further specification of the displacement value that requires long-term and expensive field studies can be skipped if it would not affect final engineering solution.

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