

# Safety enhancement of oil trunk pipeline crossing active faults on Sakhalin Island

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**Abstract.** The article explores the issues concerning safety enhancement of pipeline active fault crossing on Sakhalin Island. Based on the complexity and analysis results, all the faults crossed by pipeline system are classified into five categories – from very simple faults to extremely complex ones. The pipeline fault crossing design is developed in accordance with the fault category. To enhance pipeline safety at fault crossing, a set of methods should be applied: use of pipes of different safety classes and special trench design in accordance with soil permeability characteristics.

## 1. Introduction

The TransSakhalin pipeline system passes through the areas characterized by complex geological setting and high natural risks. It stretches the areas of high seismic activity – up to 9-10 earthquake intensity (MSK). Besides vertical and horizontal surface displacements, the following adverse effects of seismic activity should be considered: soil liquefaction, landslide, seismic shaking and wave propagation [1]. When selecting pipeline route, it is not always possible to avoid active fault crossing. This presents a significant hazard, as earthquakes are more likely to occur along the faults, and displacements can be up to several meters. Therefore, it is of particular importance to develop a set of methods aimed at enhancing oil trunk pipeline safety, especially in those areas where it crosses the active faults [2].

Basically, active faults are those faults which have moved at least once over the past 10-11 thousand years. In addition, there are faults that can be evaluated as potentially active even if the movement has occurred over the past 500 thousand years. Thus, it can be stated that an active fault is a seismogenic fault that regularly rejuvenates, which, in its turn, constitutes a danger for the society [2, 3]. It is worth noting that the faults on Sakhalin Island occupy a zone with a width of a few kilometers [1].

Sakhalin Island is located along a diffuse plate boundary zone between the Eurasian tectonic plate and the Okhotsk microplate (North American plate). The Kuril trench that stretches northeastward from eastern Hokkaido is regarded as an eastern boundary of this zone. Three large N-S faults stretch along the whole Sakhalin Island: Western-Sakhalin, Central-Sakhalin (Tym-Poronaysk), and Hokkaido-Sakhalin (Northern Sakhalin).

The Sakhalin-II pipeline system crosses seismic zones of Central-Sakhalin and Hokkaido-Sakhalin faults. It passes through active faults that can lead to surface fault rupture. The pipeline system crosses a total of 10.5 km of faults [3]. There is one crossing of the Goromay fault and 18 crossings of the



Kliuchevskoy fault which stretches mainly along the pipeline route. In the course of pipeline design, several fault crossings were eliminated (faults №2 and №19). However, due to populated areas, roads and transport corridors, there is no further possibility to reduce the number of pipeline fault crossings. Active faults constitute a threat for the structural integrity of buried pipelines: in case of surface fault rupture during a seismic event, the pipeline is to accommodate significant differential ground displacement across the ruptured fault. The conventional buried pipelines are preferable for active fault crossings as there is possibility to avoid technical issues concerning a long run of unrestrained pipe; in addition, it reduces the risk of pipeline third-party damage. Crossing of active faults on Sakhalin II onshore pipeline route requires more complex engineering solutions [4].

## 2. Fault categories

The conventional engineering solution for active fault crossing is pipeline construction in a shallow, sloped-wall trench with loose backfill in order to provide pipeline flexibility within the trench. However, seasonal frost penetration on Sakhalin necessitates considering additional engineering solutions which are directly dependent on the category of the active fault [4].

The active faults that are crossed by the Sakhalin II onshore pipeline are divided into the following categories:

Category № 1 – very simple faults (4 faults). This category includes strike-slip faults with vertical and/or along the strike displacement up to 0.5 m [4].

Category № 2 – simple faults (4 faults). This category includes strike-slip faults with vertical and/or along the strike displacement exceeding 0.5 m.

Category № 3 – complex faults (1 fault). The category involves thrust faults with vertical and horizontal movements up to 0.7 m., where the orientation of the fault trace is such that the intersection angle of pipeline and fault can be easily adjusted perpendicularly (along - 20° N) to the horizontal fault displacement (along + 70° N) in order to control compression load on the pipe itself.

Category № 4 – very complex faults (3 faults). The category involves thrust faults with vertical and horizontal movements exceeding 0.7 m., where the orientation of the fault trace is such that the intersection angle of pipeline and fault can be easily adjusted perpendicularly (along - 20° N) to the horizontal fault displacement (along + 70° N) in order to control compression load on the pipe itself. In this case, the pipeline is subjected to relatively low compression loads. Pipeline expansion loops (bend offsets) are believed to reduce the risk of upheaval buckling.

Category № 5 – extremely complex faults (7 faults). The category involves thrust faults with vertical and horizontal movements exceeding 0.7 m., where the orientation of the fault trace is such that the intersection angle of pipeline and fault can be easily adjusted perpendicularly (along - 20° N) to the horizontal fault displacement (along + 70° N) in order to control compression load on the pipe itself. In this case, the pipeline is subjected to relatively high compression loads. Pipeline expansion loops (bend offsets) are believed to reduce the risk of upheaval buckling.

The above-described fault classification is based on the idea that pipeline should be oriented at fault crossing so that it is subjected to tension stress instead of compression loads. This is due to the fact that the stress which causes local bending and pipeline buckling is always less than tension stress that can result in pipeline rupture [5].

The calculations for fault 1 ALT are given as an example (table 1).

**Table 1.** 1 ALT fault parameters [6].

Parameters	Values
Pipeline band angle north upwards (degree)	-93.17
Fault line north upwards (degree)	-10
Vertical displacement (m)	1.00
Overthrust faulting (m)	0.13
Strike-slip faults (m)	5.40
Direction of fault movement	Westward

Table 2 compares the calculated strain values with the strain values allowable for earthquake-resistant pipes that are used at fault crossing 1 ALT.

**Table 2.** 1 ALT fault crossing [6].

Pipeline	Max. compression strain	Max. tensile stress
Oil pipeline	0.18% (<4.80%)	1.08% (<3.00%)
Gas pipeline	0.32% (<4.80%)	1.22% (<3.00%)

As evident from table 2, the calculated maximum values of compression strain and tensile stress both for oil and gas pipelines are less than the allowable values.

### 3. Measures aimed at enhancing pipeline safety

Let us consider the measures which are intended to ensure pipeline safety at active fault crossing on Sakhalin Island [4].

- Use of earthquake-resistant pipes in the fault trace zone taking into account the fault error.
- Perpendicular pipeline fault crossing (regarding fault horizontal movements) provides the control over the excessive compression loads, decreases the risk of buckling and excessive bending stresses and deformations.
- Use of bend offsets, i.e. combination of straight sections and pipe (lateral) bends, to accommodate compression loads.
- To provide additional safety, pipeline shutdown valves are installed on both sides of fault crossing.
- Implementation of seismic monitoring system that is intended for digital recording of ground shaking at sites and real-time processing of accelerograms.
- Establishment of pipeline emergency response and control center to make adequate decisions in accordance with the accidents (Pipeline Maintenance Depots).
- At pipeline fault crossing, the trench is dug along the entire width of the fault taking into account the fault errors. This decreases local bending stress caused by soil-pipe interaction forces (axial and transverse, lateral and vertical).
- Trench depth, insulation material at trench, backfill material (natural loose soil or artificial material, for example, expanded clay that can be put under pipeline or close to the pipeline at the fault) should be modified in accordance with pipeline operation conditions, soil characteristics, frost penetration depth, etc.

### 4. Special trench design concept

The concept of special trench design is based on the following principle: to facilitate displacement of the pipeline inside the trench without being damaged in response to earthquake activity. This means that pipeline accommodates the fault displacement by moving inside the trench without being subjected to significant stresses and deformations, which, in its turn, ensures structural integrity of the pipeline. To achieve this, backfill must be easily compressed and, by doing so, minimizes soil-pipe friction [6]. To guarantee that the pipeline behavior inside the trench corresponds to the stress analysis results, special trenches must not freeze, as ice formation alters the mechanical properties of the backfill. Besides, freeze-thaw cycles might result in undesired pipe deformations or local stresses. To avoid soil freezing, two essential factors must be considered: water entry and thermal equilibrium.

The first factor, i.e. water entry is controlled by constructing waterproof trenches, while the second – by installing insulation slabs above the pipe and inside the trench. To avoid water entry to the trench, the following three engineering solutions have been proposed considering hydrogeological and morphological conditions at each fault crossing:

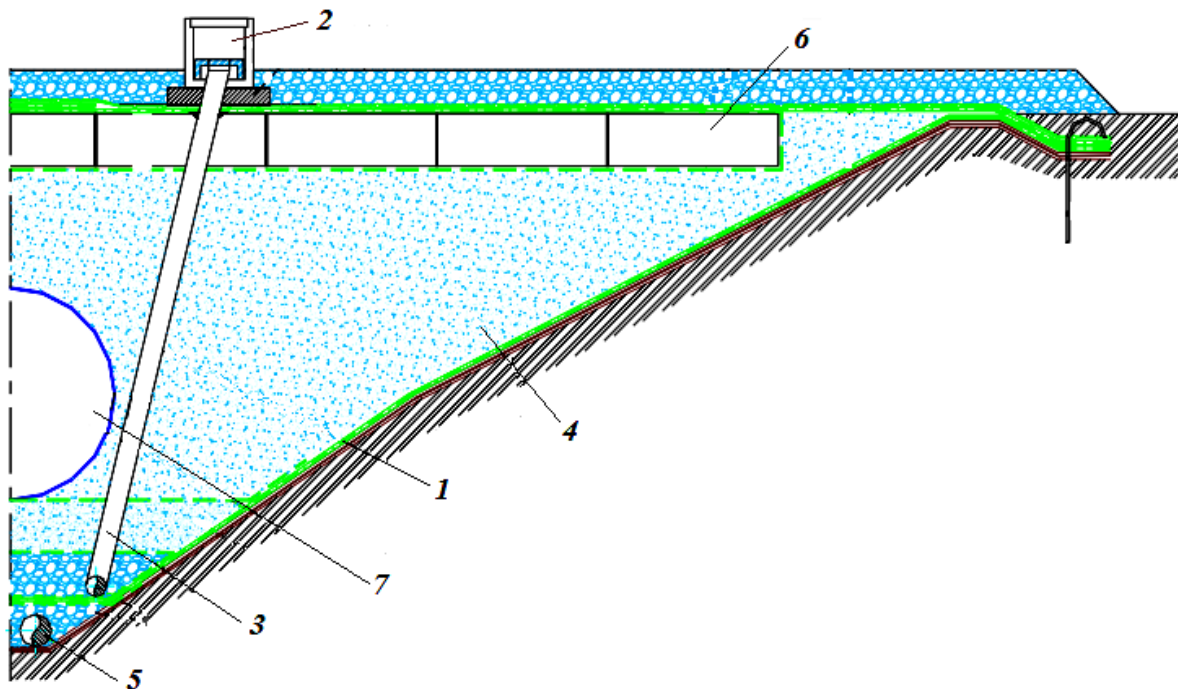
- draining trenches (at sites with high permeable soil);
- waterproof trenches (at sites with low permeable soil);

- waterproof trenches on embankments (when water drain is impossible due to landscape peculiarities).

The main objective of special drainage system (draining trenches) is to discharge water collected along the special trenches during the winter months when soil is frozen.

The special trench design is intended to ensure pipeline safety during the design earthquake. As an example, let us consider enlarged waterproof trench at fault crossing №1 Alt [7]. Sand or light material was chosen as a backfill.

The trench is sealed with the geomembrane (1) made from high-density polyethylene, with edges being welded (figure 1) [4]. Prior to geomembrane installation and welding, heavy nonwoven geotextile is placed to prevent geomembrane puncture. The sealed waterproof trench is fitted with inspection pits (2) to monitor water accumulation inside the trench. The inspection pits are connected with the trench bottom by means of non-perforated pipes (3) made of high-density polyethylene. This provides additional safety to the entire system since it is possible to control water ingress.



**Figure 1.** Waterproof trench design 1 – geomembrane; 2 – inspection pits; 3 – nonperforated pipe; 4 – light backfill material; 5 – perforated pipe; 6 – insulation slabs; 7 – pipeline.

Due to the possible sharp water level rise during the summer months, the drainage system for removing water through the high-density polyethylene perforated pipes (5) is installed at the trench bottom filled with the light backfill material (4). This decreases water stress on the trench walls and bottom. The length of waterproof trench ranges from 80 up to 100 m, which minimizes potential for pipeline damage and enables to localize the damaged section in case of waterproof barrier failure.

## 5. Conclusion

Thus, to provide the safety of pipeline fault crossing, the engineering solutions must be taken on the basis of the analysis results and, accordingly with the following principles:

- pipeline shall withstand a design strength level earthquake without any damages or with minimum damages. In addition, minimal interruption of normal operation can be required for insignificant pipeline repair;

- pipeline shall withstand the effect of ductility level earthquake without damages. In this case pipeline can be seriously damaged leading to pipeline shutdown for repair.

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