Underground Fastening of the Trunk Pipelines in Areas of Intermittent and Insular Permafrost

Kh Sh Shamilov¹, A K Gumerov¹, S M Sultanmagomedov¹
¹Department of Pipeline Transportation, Ufa State Petroleum Technological University (USPTU, FSBEI HE), 1 Kosmonavtov St., Ufa, 450062, Russia

E-mail: khiramagomed@mail.ru

Abstract. The paper is devoted to the development of methods for ensuring the design position for underground sections of gas trunk lines laid in areas of permafrost propagation at the risk of formation of frost mound at the areas of intersection of continuous ice lenses. It is proven the advantages of underground lining of separate potentially hazardous sections of the route of small length without thermal insulation, for which is proposed the way of local fastening using a specially developed underground support structure in the form of a pile base with pipe fastening by flexible links. Numerical studies of the stress-strain state of the underground fixed section of the pipeline and its underground support were carried out on the basis of the finite element model, during which the optimal laying parameters have been determined.

1. Introduction

Despite the existing world experience in laying linear objects in difficult engineering and geological conditions, the problems of a feasibility study of the pipeline laying method for sections of the route in the areas of permafrost spreading at the stage of pre-design investment project are of particular importance, mainly because of absence of initial data required (engineering surveys and geomonitoring data), especially taking into account the active development of the far northern and arctic regions [3,7, 11].

The basic requirements for ensuring stability and operational reliability are included in regulatory documents on engineering surveys and design [1-10], which do not provide comprehensive answers to all problematic issues, require a large amount of initial data, which can be obtained only by long-term monitoring or by the results of analysis of the operation of other similar objects in close conditions. For example, during the construction of the ESPO oil pipeline, a cheaper underground installation in a wider trench with shallow slopes and sand filling was adopted to compensate for seismic loads, but the risks of the formation of frost mound due to ice lenses in the areas of insular permafrost in individual regions were not taken into account. During the operation of the ESPO, numerous cases of exposure and subsidence of underground sections of the pipeline were identified, requiring the development of reliable effective solutions to recovery the design position of an existing pipeline.

The most common method of laying in permafrost soils, including solving the longitudinal movement of the pipeline, is the above-ground pipelining in thermal insulation on movable pile supports with thermal stabilization of the base soil.

It should be noted that such solutions differ in the directions of load compensation, depending on the design of the supports. For example, the technical solutions of the supports on the Vankor-Purpe
oil pipeline in permafrost sections can only compensate for longitudinal and transverse temperature movements of pipes, but will not withstand dynamic seismic loads. To reduce the estimated temperature difference and eliminate heat transfer of supports with the pipeline, it is mandatory to use thermal insulation, which significantly increases the cost of capital investments and complicates operation and maintenance.

To ensure reliability in seismically active areas on sections of above-ground laying, hinged support structures are used to compensate for both translational longitudinal and transverse, as well as bending and vibrational loads. The advantage of the method is the lack of need for thermal insulation.

Another solution that allows you to abandon the costly above-ground pipelining is the installation of wide trenches with gentle slopes and stuffing with soft soil. However the development of large volumes of frozen soils requires expensive equipment, while issues related to the delivery of soft imported soil and ballasting of the pipeline must also be resolved, which cannot always be technically and economically justified. As already mentioned, the experience of operating the ESPO has shown the ineffectiveness of such solutions in areas of insular permafrost propagation when frost mound are formed at the intersection of ice lenses.

Thus, at high risks of thawing of the bearing base soils, large temperature differences and potential seismic dynamic effects, the method of above-ground laying on hinged supports with thermal stabilization of soils does not have an alternative close in reliability, but at the same time it is the most expensive, both during construction and in subsequent operation. When building in areas with the spread of intermittent and insular permafrost, the selective above-ground laying of individual sections of an extended underground pipeline requires a serious technical and economic justification, and is often inexpedient, due to the local nature of the problems described, which may well be solved by the development of less costly effective methods of pinning subject to the expected stress-strain state of pipeline and safety requirements regulated by technical documents.

2. Concept
Unlike permafrost soils, the occurrence of continuous ice lenses and frost mounds in taliks in areas of intermittent (insular) permafrost is unpredictable in nature, and therefore, potentially dangerous zones cannot be identified during surveys at the pre-design stage. In contrast to the other cases that could be predicted, in area of insular permafrost the pipeline, on the contrary, will first experience the buoyant load of the formed frost mounds, and then under the influence of its own and external heat, the ice lens will thaw to form either thermokarst or an wet trench. Depending on the indicated process development options, the pipeline will experience completely different loads. The latter will largely depend on the diameter and weight of the underground section, in this case, thermal insulation, if available, will only increase non-design loads, both when surfacing and when the pipeline sags.

Quite effective in the conditions of insular permafrost to preserve the underground laying method, there may be solutions already developed for securing pipelines in weakly bearing soils. Container methods, due to less reliability in case of changes in the design position, and the need to bring mineral soil, in this case, are not recommended for use, although they can be used with a small depth of laying the route. The best solution would be to use pile structures from anchor supports in versions for frozen ground [12]. For the pinning of underground pipeline sections in the permafrost distribution zones, a pile foundation design was proposed (Fig.1).

Patents for a utility model and invention have been obtained. Piles are driven into frozen soils, at a distance from the predicted thawing areola, in the case of intense heat inflow to piles, it is also possible to supply a cooling agent for thermal stabilization of the soil of the pile foundation. The pipe is attached with clamps to flexible rods - cables, with a pre-adjusted amount of tension. The design allows you to win back both subsidence and ascent of the pipeline in a flooded trench [13-17].
1 - bored piles; 2 - steel cables; 3 - collar; 4 - hairpins; 5 loops; 6 - thermal stabilizers; 7 - embedded element; 8 - bolted connection; 9 - eye; 10 - lanyard; 11 - clamp.

**Figure 1.** Construction of the pile foundation of pipeline for underground laying in insular permafrost.

3. **Numerical studies**

To confirm the above arguments about the negative effect of thermal insulation, determine an optimal way of laying required, numerical studies of the stress-strain state of the pipeline in underground execution were carried out using the finite element method in the ANSYS software package.

**Figure 2.** Calculation of the stress-strain state (VAT) using the finite element method (FEM).

Fig. 2 shows the beam design, taken as a basis for the development of the underground locally fixed pipeline model in area of insular permafrost. When testing the model using analytical dependencies, high convergence was obtained, including when determining the location and magnitude of stresses in dangerous sections - at the points of fastening of the pipeline, adopted in the model in the form of underground anchor supports. Since gas pipelines, due to positive buoyancy,
belong to the most dangerous case, the results obtained for the DN1200 gas pipeline will be considered. Note that such dependencies will also be characteristic of oil pipelines. The calculation results of the loaded section of the underground gas pipeline in the formed thermokarst and in the wet trench are shown in Fig. 3. The initial span (step of the supports) was taken to be 100 m. The longitudinal stresses for the thermally insulated (250 mm) pipe section and the pipeline without thermal insulation are compared. As can be seen from the plots of the gas pipeline stresses, with the presence of thermal insulation, the greatest longitudinal stresses are observed on the upper generatrix of dangerous sections – in the places where the pipe is fastened with supports. Due to its lower weight, the non-insulated gas pipeline experiences less stress during sagging.

![Figure 3](image-url)

**Figure 3.** The results of calculating VAT in a dangerous section at a step of supports of 100 m (excluding loads from temperature deformations and elastic bending of the pipeline).

With a subsequent increase in span, the strength conditions are not met, even without thermal insulation, both for ascent surfacing and when the pipeline sags (Fig. 4).

![Figure 4](image-url)

**Figure 4.** The results of calculating VAT in a dangerous section with a step of supports of 100 m with thermal insulation thickness of 125 mm.

4. Discussion

Thus, longitudinal stresses were calculated with an increase in span from 10 to 150 m, for a thermally insulated pipeline and with insulation thicknesses of 125 and 250 mm. Note that in these calculations, additional design loads from the calculated temperature difference and the radius of the elastic bending of the pipeline have not yet been taken into account. As the results showed, the maximum allowable
step between the supports for a thermally insulated section is 110 m. The presence of thermal insulation, the permissible span is reduced to 100 m with a coating thickness of 125 mm, and up to 90 m with a thermal insulation of 250 mm.

Adding the calculated temperature difference to the model used for the conditions of the East Siberian climate sharply reduces the permissible span to 45-50 m. The limitation of the minimum installation temperature (joint of the last weld) is not lower than -25 °C, allows you to increase the span to 60-80 m, and thereby reduce the number of supports by a third (25-30%).

When laying with design elastic bending (at least 1000 DN) two options are possible. In the first case, even with a greater curvature of the bend of the route in the direction of the span boom (in both cases, ascent and sag), the pipeline experiences extreme loads significantly exceeding the strength conditions. Thus, if it is impossible to reliably predict the nature of thawing of frozen rocks (the formation of thawed lakes or thermokarst), the laying of underground sections by elastic bending, even significantly higher than the minimum allowable, can lead to unacceptable pipe deformations.

As in all the cases considered above, an even greater limitation of the minimum installation temperature (to -15 °C for the considered example) allows the laying to be used by elastic bending with a step of underground supports from 60 to 75 m. In this case, reducing the temperature difference, allows not only to save on the number of supports, but also to optimize the necessary volumes of land work. Similar results can also be obtained with a combination of limiting the minimum mounting temperature (to -25 °C) and doubling the radius of elastic bending (up to 2400 m). In this case, the step between the supports will be 50 m.

Much greater effect, as shown by the calculations of the model, can be achieved by laying the underground section by elastic bending in the direction of the backward flight arrow. So in cases where we reliably know which process development option should be expected when thawing frozen ground, even with a calculated temperature difference without limiting the installation temperature, the allowed radius of elastic bending (1000 DN) allows you to double the span between supports to 70-90 m (Fig. 5).

![Figure 5](image_url)

**Figure 5.** The results of calculating the VAT when laying with elastic bending in the opposite direction for span of arrow (installation at -55 °C).

5. **Conclusion**

It is important that in all cases considered, the presence of thermal insulation only worsened the loading conditions. In addition, it increases both the cost of the pipeline itself and the volume of land work. Supports and brackets for larger insulated pipes are also more expensive. Thus, as shown above, the results of modeling the VAT, even in cases of thawing of soils, it is possible to ensure secure fastening of the pipeline in the underground version, without resorting to expensive overhead laying in areas with intermittent or insular permafrost, which has a seasonal melting character.
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