A systematic approach to developing measures for preventing and containing the consequences of accidents on oil pipelines in the Russian Federation’s Arctic zone

by Roman Y. Shestakov, Ilmar R. Aysmatullin, Vladislav N. Slepnev*, and Sergey A. Polovkov
Pipeline Transport Institute, Moscow, Russian Federation

The Zapolyarye - Purpe trunk oil pipeline runs through an area with an arctic climate (Yamalo-Nenets autonomous region), which is characterized by a prolonged, harsh, winter and relatively short but warm summer. In these conditions, the technology for transporting crude hydrocarbons necessarily includes preliminary heating to +60°C of the high-viscosity oil mix which is to be pumped. However, in the case of damage to the pipeline system, a ‘hot’ oil spill could cause the deformation of permafrost soils, as could subsequent actions to deal with the emergency situation and its consequences. This deformation would lead to irreparable damage to the Arctic environment and may result in more accidents on the trunk pipeline. In order to develop protective measures, the sections of the pipeline which are potentially most dangerous must be identified; the possible volume of an oil spill in the case of an accident should be calculated; and the route it would spread should be predicted.

This article examines the most dangerous possible incident, where the main factor affecting the spread and accumulation of spilled oil would be the topography of the area. A guillotine rupture of the pipeline was chosen as the event triggering the spill, because this type of failure would cause the greatest volume of transported liquid to be spilled. Modelling allows the furthest places where the liquid could drain and accumulate to be assessed. In order to exclude the threat of oil entering bodies of water, the necessity of constructing permanent barriers is indicated, which would prevent the spill from spreading. In order to save time in mobilizing technology and equipment to the site of the emergency situation, the creation of base stations is recommended: technically equipped bases, which would be located in the immediate vicinity of the most vulnerable sections of the pipeline route.

The systematic approach described in this article allows us to obtain the fullest and most realistic picture of events in the case of an accident on the trunk pipeline. These results may be used to develop protective measures aimed at minimising damage and at reducing as much as possible the impact of a possible oil spill on the fragile natural balance of the Arctic. The results may also be relevant when planning new trunk pipelines and reconstructing existing pipelines, and for setting-up a system of protective structures.

Introduction

In January 2017, the Zapolyarye - Purpe trunk oil pipeline was brought into operation - the northernmost pipeline in the Transneft system. The geographical location of the pipeline is shown in Fig 1. The pipeline’s operating conditions significantly limit the possibility of eliminating the consequences of a possible...
accident in the system and, among other issues, they greatly complicate the process of containing the oil spill.

The Zapolyarye – Purpe trunk pipeline runs through an area with an arctic climate, whose features include an extended harsh winter and relatively short, but warm summer. The overall direction of the route is from North to South. The region where the pipeline is constructed is distinguished by its extremely difficult geology: more than 50% of the area is made up of permafrost soils, 70% of which are boggy and waterlogged.

The crude blend designated for pumping has high viscosity and a pour-point of +17°C. Accordingly, specially equipped heating stations are placed along the route in order that it may be heated to +60°C [1].

If an emergency situation, the impact of ‘hot’ crude and the oil spill containment works could cause deformation to the permafrost soils of the Arctic, which would not only disturb the delicate balance of the unique climate system and cause irreversible damage to the natural environment of the region, but could also lead to further accidents on the pipeline.

Consequently, issues connected with preventing accidents and minimizing their consequences are of paramount importance, starting from the climatic conditions and the topography of the area: evaluating the risk of damage to the pipeline occurring; selecting and developing methods of the spill containment; and erecting protective structures with this aim in mind.

The above-mentioned points testify to the necessity of forming a systematic approach to forecasting accidents on the trunk pipeline in the Arctic zone of the Russian Federation, and preparing to put in place optimum measures to reduce the possible area of oil contamination and, correspondingly, to minimize damage to the environment.

Research methods

The Zapolyarye - Purpe pipeline was constructed using mainly above-ground methods. This choice can be explained because, among other reasons, when using underground methods to build a trunk line designed for transporting hot oil, at sections where permafrost soils are widespread, circular thawing zones will form around the pipeline, leading to the development of extended waterlogged zones along the pipe. This in turn provokes the active development of erosional processes leading to soil deformation, which may trigger non-uniform displacements of the pipeline, and thus threaten its integrity. As such, an emergency situation may arise. Similar processes may also be caused by an accidental spill of hot oil. Moreover, soil deformation can be caused by works carried out for the oil-spill containment and elimination, and for oil-contaminated soil remediation.

In forming a systematic approach to
forecasting accidents on trunk pipelines in the Arctic zone, it is advisable to begin by identifying sections of the pipeline which are potentially at risk from accidents. In the context of this article, the procedure for evaluating the risk of an accident arising has been used in order to solve this task. However, it is first worth describing the most likely incidents on an oil pipeline which could have the consequence of an oil spill.

Toward this end, 107 incidents were analysed on the linear sections of trunk pipelines in the period from 1998 to 2010, including such sections of trunk pipeline as underwater crossings and joints at the position of air valves, shut-off and control valves, and launching and receiving stations for cleaning and diagnostic devices (utility and intelligent pigs). Of these, 97 incidents were connected to oil leaks in the linear sections of the oil pipelines, and seven incidents were linked to oil leaks in the areas where features of the trunk pipeline were located (joints at the position of air valves, shut-off, and control valves, and pig launching/receiving stations); three incidents were linked with oil leaks at underwater crossings of the trunk pipeline (Fig.2).

In the majority of the incidents examined, (87%) the oil spill did not lead to ignition. In 14 cases (13%) ignition of the liquid being transported did occur. Of these, ignition took place most often during scheduled or repair work at the linear
sections of trunk pipeline, including joints at the position of air-valves, shut-off and control valves, and pig launching/receiving stations (Fig.3).

Casualties were avoided in almost all - 104 out of 107 - of the incidents examined (Fig.4).

Based on these data, to evaluate the risk of an accident arising at a pipeline, a hypothetical scenario will be examined where oil ignition does not occur and there are no human casualties (supposing, for example, the area where the trunk pipeline is located to be sparsely populated). In this case the greatest damage to the environment would be caused exactly by oil contamination.

Risk is a combination (product) of the probability (or frequency) of damage being inflicted, and the severity of that damage [2]. In a general form, the formula for risk can be presented as:

\[ R = \sum_{i=1}^{N} p_i U_i \]

where

- \( R \) - risk;
- \( N \) - the quantity of discrete values of possible damages (of one type, one dimension) or groups combining them;
- \( U_i \) - the discrete value of the damage (severity of the damage) to the health and life of the worker;
- \( P_i \) - the probability that this value of damage will occur (be inflicted).

In order to calculate the degree of damage an accident at a trunk pipeline may cause, two specific (per the unit of the pipeline length) indicators are taken as characteristic:

- specific expected losses of oil in the case of an accident;
- specific expected environmental damage from the accident.

Risk evaluation was carried out using the software Toxi+Risc version 4.4.1, and damage was evaluated in accordance with methodological recommendations [3].

Based on the results of the risk evaluation, all sections of the trunk pipeline (the design length of one section is 1 km) were characterized as having a low or, more rarely, a medium relative degree of danger of failure. The medium degree was determined by the probability of oil ingress into a body of water. Moreover, it is worth noting in particular that it was impossible to identify by using risk evaluation the most dangerous section of the pipeline, which can be explained by the use of the newest methods and innovative technologies in constructing the Zapolyarye - Purpe trunk pipeline, as well as by stringent quality requirements for the works. Therefore, it was decided to carry out further modelling of the pipeline section located in conditions with numerous bodies of water in close proximity to the oil trunk line route.

For the modelling, a guillotine rupture in the pipeline was chosen as the accident situation, causing the largest oil spill into the surrounding environment. The length of the experimental section of the pipeline was 11 km, and points of possible outflow were set at every 500 m. Depending on the purpose of modelling, the interval between points could be reduced, and their number increased. Only the accuracy of the initial topography data was limited. The total volume of spilled oil can be estimated using the formula:

\[ V = V_1 + V_2 + V_3 \]

where:

- \( V_1 \) - the volume of oil (or oil-product) leaked in a pressure flow, i.e. from the moment when damage occurs to the pumping stop, cu m;
- \( V_2 \) - the volume of oil (or oil-product) leaked in a pressureless flow, i.e. from the moment of the pumping stop to the closure of the pipeline valves, cu m;
- \( V_3 \) - the volume of oil (or oil-product) leaked from the moment of the pipeline valves closure to the
leakage stop (until the moment emergency response team arrives and the leak is eliminated, or until the total emptying of the isolated section of the trunk pipeline), in cu m.

The volume of oil leaked from each point was calculated taking into account the time needed to close valves and the topography in accordance with guidelines [4], as well as with the programme Risk - oil - pipeline, approved by the letter of the Gosgortekhnadzor [the Federal Mining and Industrial Inspectorate] of Russia on 07.07.1999 No 10-03/418. The volume of possible oil leaks is presented in Table 1.

Modelling was carried out using the module Oil-product spill (onshore) in the software complex ArcGIS (hereinafter - Module). The results of laser scanning of the area along the pipeline route were taken as initial data for the topography. Using contour lines and elevations, and ArcGIS processing, a regular topography grid was obtained (in GRID format). The topography conversion is shown in Fig.5.

However, the topography obtained in the process of modelling does not represent many particular features of the area through which the pipeline runs. An understanding of these can be gained from real photos of the route (for example, in Fig.6).

In order to adjust the relief model, information from satellite images and maps was used, which is freely available in the Internet. Bodies of water located in close proximity to the pipeline route were plotted on the terrain map. The module used enables modelling under the condition of oil reaching a hard surface. Therefore, in the examined case of the area being significantly water-logged, the following assumption was used: upon reaching a body of water, oil would not flow out of its limits. For that, bodies of water are presented on the terrain as depressions in the ground. The process of topography adjusting is presented in Fig.7.

For visual clarity, the final version of the topography is presented in 3D format (Fig.8). Satellite images can be used as the mount instead of a map (Fig.9).

The procedure of the Express-evaluation module was used for modelling, as it helps to identify the furthest places from the pipeline route where the oil could drain and accumulate.

The following assumptions were made in this method of modelling [5]:

- oil flows down in the terrain in the direction of the steepest descent;

<table>
<thead>
<tr>
<th>Point no.</th>
<th>Volume of oil leak in the case of a guillotine rupture, in cu m</th>
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<tr>
<td>1</td>
<td>1576</td>
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<tr>
<td>2</td>
<td>2346</td>
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<tr>
<td>3</td>
<td>2825</td>
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<td>4</td>
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<td>21</td>
<td>1581</td>
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<td>22</td>
<td>1541</td>
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</table>

Table 1. The volume of possible oil leakage in the case of a guillotine rupture in the pipeline.
• where the oil reaches a local depression, it will fill up to the spillover point;

• where the capacity of the local depression is insufficient to contain the volume of the spill, the minimum height at the edge of the basin of the local depression is calculated. Further calculation continues according to point 1, where the remaining volume of oil is defined as the difference between the initial volume and the capacity of the local depression;

• if the capacity of the local depression is sufficient to hold the volume of spilled oil, the total volume of the spill is calculated by adding the volumes contained in separate cells of the terrain (neighbouring cells) up to the spillover moment;

• processes of evaporation and infiltration of the oil product are not considered here.

Research results

The modelling results are presented in Fig.10.

Places where it would be possible for an oil spill to enter bodies of water are circled in red. In the conditions examined here, these are the zones should be protected as a priority, and are in maximum need of the development and installation of protective measures and structures.

In order to exclude the possibility of oil reaching bodies of water, it is necessary to construct permanent barriers, which would prevent a spill from spreading. Considering the distinctive features of the environment in the Arctic zone of the Russian Federation, such barriers would have to be erected with minimal earthworks, and where possible without them entirely. In this article, two options for such structures are demonstrated as proposals for technical improvement:

Protective embankments (Fig.11) – the structure consists of a foundation laid on weak soil (bog of the first or second type). The foundation is made of logs firmly fastened to each other. Non-woven synthetic material (NSM) is used to cover the foundation, and sand ballast is spread on this, and it is subsequently sewn up with synthetic thread.

Geoweb could serve as an alternative option for protective structures (this is often used in Arctic zone conditions in the Russian Federation when constructing temporary
roads). Cells of the web are filled with soil proper to the area. Depending on the necessary change in the topography elevation the Geoweb can be laid down in one or in several layers. An example overview of this protective structure is shown in Fig.12.

These suggestions should not be taken as a definitive solution to the issue of protective structures at the pipeline sections with high risk of accident.
However, they may serve as a starting point for further studies.

Moreover, in order to save time when mobilizing machines and equipment to the site of an emergency situation, it is proposed to establish the base stations—technically equipped bases located in the immediate vicinity of the most vulnerable sections of the pipeline route, and which in the case of an accident would allow a quick and full oil spill response.

In order to check the effectiveness of suggestions to set up additional protective facilities at accident-prone sections of the pipeline, remodelling was performed with 0.5-m high protective structures plotted on the route. The result of remodelling is shown in Fig.13 and a 3D projection is shown in Fig.14.

Discussion

An evaluation of the damage caused by an oil spill was carried out according to guidelines [3]. Overall, the damage from an accident at a dangerous production facility can be expressed in the formula:

$$ P_a = P_{p+p} + P_{l+is} + P_{is} + P_{m} + P_{e} + P_{s+t+p} $$

where:
Fig. 11. Structural concept of the protective embankment
1 - foundation made of firmly fastened logs;
2 - synthetic material;
3 - sand ballast;
4 - synthetic threads.

Fig. 12. Overview of Geoweb.

\[ P_a = \text{the total damage from the accident, in roubles;} \]
\[ P_p = \text{the direct losses to the organisation running the dangerous production facility, in roubles;} \]
\[ P_l = \text{the expense of containing and eliminating the incident, and investigating it, in roubles;} \]
\[ P_s = \text{the social-economic losses (expenses as a result of deaths and injury to people), in roubles;} \]
\[ P_n = \text{the indirect damage, in roubles;} \]
\[ P_{eco} = \text{the ecological damage (caused to features of the surrounding environment), in roubles;} \]
\[ P_{vtp} = \text{losses from the decrease of labour resources as a result of people’s deaths or disability in roubles.} \]
The economic effect of the measures described in the article has been estimated approximately by comparing the magnitude of damage from oil reaching bodies of water and the size of expenditure for installing protective structures.

Considering the design documentation and the conditions of use of the Zapolyarye - Purpe trunk pipeline, the maximum mass of a possible spill at the pipeline would be 3,734 t. The mass of oil entering the water is taken to be 75% of the mass of the possible spill and therefore equals 2,800 t.

The potential damage from contaminating...
the environment as a result of an accident at bodies of water would be in the region of 16.5 billion roubles. The cost of works to construct a containment boundary at a distance of 1 km would be approximately 5 million roubles. Taking into account the area topography, the required reserve of protective facilities would be 20 km. Total expenses for setting up protective structures would be around 100 million roubles.

It can thus be seen that, if the protective measures described in this article are put into place, and if their implementation successfully prevents oil from reaching bodies of water, the economic effect of setting up these protective structures in areas where there is a high risk of damage to pipelines located in the Arctic zone of the Russian Federation, would total approximately 16.4 billion roubles.

Conclusions

The approach described in the article has a methodical character and allows the fullest and most realistic picture to be obtained of events’ escalation in the case of an accident at a trunk pipeline. The results obtained may be used to develop protective measures aimed at minimising damage and reducing the impact of a possible oil spill on the fragile natural balance of the Arctic. They may also be relevant when planning new trunk pipelines and when reconstructing pipelines currently in use, and when setting up systems of protective structures.

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References

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