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by D.A. Neganov 1, O. I. Filippov 2, I. I. Mikhaylov* 1, A. V. Gelt 4, P. S. Golosov 3

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ABSTRACT

During construction, reconstruction and technical inspection of vertical steel tanks (VST), all wall butt welds are subjected to ultrasonic testing (UT) to detect internal defects or flaws. The considerable length of examined welds (it can exceed 3,000 m) necessitates the development and implementation of mechanized and automated inspection systems that can increase the rate of testing and documentation of results.

Systems of mechanized and automated ultrasonic echo-testing do not support the detection of all defect types and reliable determination of their geometric parameters. The Time-of-Flight Diffraction (TOFD) technique makes it possible to estimate the height of the defect regardless of its type and orientation. However, the application of TOFD technique for welds with non-equal wall thickness is complicated by the fact that the standard software of flaw detectors (‘depth calculator’) does not consider this non-uniformity. The authors have developed the testing procedure to overcome this limitation and to determine the depth of defects in the welds with non-equal wall thickness by TOFD technique using the standard ‘depth calculator’.

An experimental verification of this technology confirmed the correctness of the calculations. The inspection scheme and calculation of the depth of discontinuity boundaries using the TOFD technique were tested using the example of the welded joint of the walls with non-equal thickness of the 10,000-m3 tank under construction. The thickness of the walls was 12 and 14 mm; 8 and 10 mm. The inspection of the real facility has confirmed good detection of defects and high reliability of the results.

Key words: Melded joint, inspection of welded joints, TOFD, vertical steel tank, weld joints with non-equal thickness, ultrasonic testing.

INTRODUCTION

During construction, reconstruction and technical inspection of vertical steel tanks, all wall butt welds are subjected to ultrasonic testing (UT) to detect internal defects. The considerable length of examined welds (it can exceed 3,000 m) necessitates the development and implementation of mechanized and automated inspection systems that can increase the rate of testing and documentation of results.

Fig. 1 shows one of the options for beveling. Such beveling leads to frequent omissions of defects in the plane of the lower edge (incomplete penetration, lack of fusion) and makes it difficult to find horizontally located defects (cracks, incomplete penetration in the root face, slag inclusions). UT is complicated by the presence of a bevel in the lower part of the weld. Bevel length can attain 10 mm or more; it does not allow to bring the sensor to the edge of the weld, decreasing the testing range in the ‘straight beam’ mode. Similar difficulties arise in tests using the ultrasonic phased arrays operating in the sectorial scanning mode.

The solution in this case can be the use of the TOFD technique in combination with other UT methods in automated or mechanized inspection. The TOFD technique is effective for testing welds of equal thickness (e.g. vertical welds). This technique is described in detail in the regulatory documents [1, 3, 4] and in open publications [1–4].

However, the standard software of flaw detectors designed to calculate the depth and height of defects (let’s call it the ‘depth calculator’) does not consider the possible non-equal wall thickness that makes it extremely difficult to inspect, for example, horizontal welds. In this case, the inspection of welded joints with non-equal wall thickness is possible if conducted from the inside of the tank (when the wall surfaces are on the same line). But access to the inner surface of VST is limited due to the fact that the facility is in operation. The use of the ‘depth calculator’ for inspection from the outer surface (when the wall surfaces are not on the same line) is difficult.

There are publications describing the use of the TOFD technique to inspect the complex-shaped products [5–7]. Its use in the inspection of welds with non-equal thickness is also permitted by the document of the Chinese Classification Society [8].

Another challenge in using the TOFD technique is due to the presence of corrosion-resistant coating of the tank. Experiments have shown that the repeated reflection of ultrasonic signals in the coating leads to an increase in their duration and, consequently, to a decrease in the method and to an increase in the ‘dead zones’ size. However, this issue is beyond the scope of this work and requires detailed study in the future.

The proposed solution

To test the possibility of determining the defect depth in a welded joint with non-equal thickness using the signal arrival time, a ‘calculator’ was modeled that implements computations in accordance to TOFD technique principle shown in Fig. 2.

The signal travel time from the emitter to the receiver without considering the delay time in prisms will be equal to:

\[
T = \sqrt{\frac{L_1^2 + (H-W_{tn}+W_{th})^2}{V_{mn}}} + \sqrt{\frac{L_2^2 + H^2}{V_{mn}}},
\]

where

\[\begin{align*}
W_{tn} & \text{ - the thin and thick wall thickness, respectively;} \\
W_{th} & \text{ - the distance from the piezoelectric transducer (TOFD) input points to the weld axis for thin and thick wall, respectively;} \\
L_1 & \text{ - flaw depth;} \\
V_{mn} & \text{ - velocity of longitudinal wave in the metal.}
\end{align*}\]

Since the software installed in general-purpose flaw detectors (built-in ‘depth calculator’) does not support the resolution for welding joints with non-equal thickness, the depth and height of the defect in this case was determined using Excel program.

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*Guidelines for combined inspection of time-of-flight diffraction (TOFD) technique and phased array ultrasonic testing (PAUT) for marine thick plate welds (effective from January 1, 2017)
TOFD technique application to examine welded joints with non-equal wall thickness of the vertical steel tanks

by D.A. Neganov 1, O. I. Filippov 2, I. I. Mikhaylov 1, A. V. Gelt 1, P. S. Golosov 1

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Systems of mechanized and automated ultrasonic echo-testing do not support the detection of all defect types and reliable determination of their geometric parameters. The Time-of-Flight Diffraction (TOFD) technique makes it possible to estimate the height of the defect regardless of its type and orientation. However, the application of TOFD technique for welds with non-equal wall thickness is complicated by the fact that the standard software of flaw detectors (‘depth calculator’) does not consider this non-uniformity. The authors have developed the testing procedure to overcome this limitation and to determine the depth of defects in the welds with non-equal wall thickness by TOFD technique using the standard ‘depth calculator’. An experimental verification of this technology confirmed the correctness of the calculations. The inspection scheme and calculation of the depth of discontinuity boundaries using the TOFD technique were tested using the example of the welded joint of the walls with non-equal thickness of the 10,000 m³ tank under construction. The thickness of the walls was 12 and 14 mm; 8 and 10 mm. The inspection of the real facility has confirmed good detection of defects and high reliability of the results.

Key words: Melded joint, inspection of welded joints, TOFD, vertical steel tank, welded joints with non-equal thickness, ultrasonic testing.

ABSTRACT

The TOFD technique is effective for testing welds of equal thickness (e.g. vertical welds). This technique is described in detail in the regulatory documents 1, 2, 3 and in open publications [1–4]. However, the standard software of flaw detectors designed to calculate the depth and height of defects (let’s call it the ‘depth calculator’) does not consider the possible non-equal wall thickness that makes it extremely difficult to inspect, for example, horizontal welds. In this case, the inspection of welded joints with non-equal wall thickness is possible if conducted from the inside of the tank (when the wall surfaces are on the same line). But access to the inner surface of VST is limited due to the fact that the facility is in operation. The use of the ‘depth calculator’ for inspection from the outer surface (when the wall surfaces are not on the same line) is difficult.

There are publications describing the use of the TOFD technique to inspect the complex-shaped products [5–7]. Its use in the inspection of welds with non-equal thickness is also permitted by the document of the Chinese Classification Society [8]. Another challenge in using the TOFD technique is due to the presence of corrosion-resistant coating of the tank. Experiments have shown that the repeated reflection of ultrasonic signals in the coating leads to an increase in their duration and, consequently, to a decrease in the sensitivity of the method and to an increase in the ‘dead zones’ size. However, this issue is beyond the scope of this work and requires detailed study in the future.

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The signal travel time from the emitter to the receiver without considering the delay time in prisms will be equal to:

$$T = \sqrt{\frac{L}{V_{ms}}} + \frac{H - W_{th} + W_{th}}{V_{ms}} \sqrt{\frac{L}{V_{ms}} + \frac{W_{th}}{V_{ms}}}$$

where

- $W_{th}$ and $W_{th}$ – the thin and thick wall thickness, respectively;
- $L_1$ and $L_2$ – the distance from the piezoelectric transducer (TOFD) input points to the weld axis for thin and thick wall, respectively;
- $H$ – flaw depth;
- $V_{ms}$ – velocity of longitudinal wave in the metal.

Since the software installed in general-purpose flaw detectors (built-in ‘depth calculator’) does not support the direct calculation for welded joints with non-equal thickness, the depth and height of the defect in this case was determined using Excel program.
Calculations were made for walls 12 and 16 mm thick (Fig. 3) and for input angle 60°. The depth $d/2$ was selected as the cross-point of the directional pattern axes, which corresponds to the selection of the intersection point for the welded joint with equal thickness according to the EN 10863 recommendations on the TOFD configuration selection.

The curves in Fig. 4 show the change in the depth of the defect depending on the UT signal arrival time. The estimated time does not consider the time of the signal passing through TOFD sensor prisms.

The deep-blue curve shows the values calculated using formula (1) for the diagram in Fig. 3. Only those are shown that correspond to the parameters from 4 to 16 mm of the thick wall thickness, since the arrival time of the signals from defects located above the level of the thin wall (from 0 to 4 mm of the thick wall thickness) cannot be determined unambiguously. This is due to the fact that the signal propagates along the wall surface (side wave LW), and the shape of the outer surface has variations.

The red curve is the estimation trend obtained by the formula from EN 583-6 (standard ‘calculator’ of the flaw detector). Since different distances from TOFD probes input point to the weld axis and different wall thickness are not allowed in this case, the following assumptions were made in further calculations:

- the distance from each TOFD probe input point to the weld axis: $L = \frac{L_w + L_t}{2}$ (2)
- the wall thickness $WT = \frac{W_{t1} + W_{t2}}{2}$ (3)
- when determining the depth of the defect obtained by the formula from EN 583-6, WT shall be increased by the following value: $WT' = \frac{W_{t1} - W_{t2}}{2}$ (4)

The green curve with correction (4) is shown in Fig. 4.

Fig. 4 shows that the calculation results are almost identical in the range of wall thickness from 6 to 16 mm (green and blue curves). The ultrasonic signal duration when using the TOFD technique is about 2-2.5 oscillation periods (0.40 µs for 5 MHz frequency), which corresponds to the curve to 6...7 mm (the ‘dead zone’). This value almost completely covers the curve from 4 to 7...7.5 mm along the ordinate axis; there is a slight discrepancy (from 0.1 to 0.7 mm) in the calculation results. Due to the fact that the arrival time of the signal that passed along the upper surface of the weld depends on many factors, the authors allow the depth of the defect measuring relative to the lower surface of the weld joint.

**Experimental verification**

As part of the verification of the proposed solution, two samples were made that simulate welded joints with non-equal thickness: the first with a stepped configuration, the second with a smooth beveled transition from one wall to another (Fig. 5). The minimum wall thickness of the samples was 12 mm, the maximum, 16 mm. A 20 mm deep lateral hole was drilled in the stepped sample. The hole diameter was 2 mm, its center was located at 7 mm from the bottom surface.

The following equipment was used: flaw detector ‘Omniscan MX2’, TOFD probes with 5 MHz operating frequency and prisms with a longitudinal wave input angle of 60° as TOFD sensors.

The following parameters were tested during the experiments:

1. the distance between the TOFD sensor input points – 39 (15 + 24) mm,
2. wall thickness – 14 (12 + 16) / 2 mm,
3. UT signal propagation velocity in metal – 5.94 mm/µs.

Subject to the assumption (4), the correction for the depth of the defect determination is 2 mm: (16 – 12) / 2.

According to the data, the ‘calculator’ showed the distance 2 mm to the front (contact) wall, and 14.1 mm to the rear wall (Fig. 9a). Based on the taken assumption (4), this distance to the front surface corresponds to the depth 4 mm (2 + 2), to the rear surface – 16.1 mm (14.1 + 2.0).

After TOFD sensors were installed in the zone with lateral hole, the signal depth was determined from the upper surface of the hole (6.3 mm) and from its lower surface (8.2 mm), Fig. 9b. Subject to the assumption (4), the depth of the defect to the upper surface of the hole was 8.3 mm (6.3 + 2.0), to the lower surface – 10.2 mm (8.2 + 2.0).

Thus, the measurement data determined that the center of the hole lies at a depth of 9.25 mm (8.3 + 10.2 / 2) that with an error of 0.25 mm coincides with its real position – 9 mm from the upper surface of the thick wall of the sample or 7 mm from its lower surface.
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The red curve is the estimation trend obtained by the 'calculator'. Since in all these calculations, 2/3 of the thin wall thickness – 4 mm, its center was located at 7 mm from the bottom surface. The ultrasonic signal duration when using the TOFD technique is about 2–2.5 oscillation periods (40 µs for 5 MHz frequency), which corresponds on the ordinate axis; there is a slight discrepancy (from 0.1 to 0.7 mm) in the calculation results. Due to the fact that the arrival time of the signal that passed along the upper surface of the weld depends on many factors, the authors allow the depth of the defect measuring relative to the lower surface of the weld joint.

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- correctness of the defect height and depth determination.

Experiments have shown the following:

1. Results of the tests carried out on both samples were similar (Fig. 6). At that, the signals from the stepped sample look ‘clearer’, because there are fewer echoes in the subsurface zone to generate ‘phantoms’ that duplicate the main LW-signal.
2. Changing the TOFD probes position does not have a significant impact on the practical result of the test.

Fig. 7 and 8 show A-scans and TOFD-scans considering the change of the emitter and receiver positions (Fig. 8 – sample with smooth transition in the zone without drilling, Fig. 9 – same sample in the zone with lateral drilling). As one can see from the figures, the scans are almost identical in both cases.

Similar results are obtained for the stepped sample.

3. The stepped sample with lateral hole was used to check the possibility of measuring the defect depth using the built-in ‘depth calculator’.

Since in all these calculations, 2/3 of the thin wall thickness was adopted as the depth of cross-point of TOFD sensors directional pattern, the input angle was 60° and the sample wall thickness was 12 and 16 mm, the calculated distances between the sensor input points and the weld axis were 15 and 24 mm. In accordance with the assumptions (2) and (3), the following input parameters were set in the flaw detector ‘calculator’:
- the distance between the TOFD sensor input points 39 / (15 + 24) mm;
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Thus, the measurement data determined that the center of the hole lies at a depth of 9.25 mm (8.3 + 10.2) / 2 that with an error of 0.25 mm coincides with its real position – 9 mm from the upper surface of the thick wall of the sample or 7 mm from its lower surface.
Application example

The proposed configuration of the weld inspection scheme and calculation of the defect depth using the TOFD probes technique was applied for horizontal welding joints of the walls of 10,000 m³ tank under construction. The wall thickness was 12 and 14 mm; 8 and 10 mm. There was no coating in the area of inspected welds.

The following equipment was used: 'Harfang VEO' flaw detector, TOFD with operating frequency of 10MHz and prisms with longitudinal wave input angle of 70° as TOFD sensors.

The estimated depth of the defect depending on the UT signal arrival time for the welded joint of 12–14 mm walls is shown in Fig. 10; for the welded joint of 8–10 mm walls in Fig. 11. All calculations were made considering the delay time of the UT signal in the prisms of TOFD sensors.

Examples of inspection results

Fig. 12a illustrates the TOFD-scan of the welded joint section with thickness of the welded elements 12 and 14 mm. These defects were confirmed by an ultrasonic hand scanner with two 16-element ultrasonic phased arrays with an operating frequency of 5 MHz, located to the left and right of the weld (Fig. 12b). The scan, obtained using phased arrays, is acquired with a sensitivity of 6 dB higher than the rejection level set at a control reflector with an equivalent area of 7 mm².

Findings:
1. The TOFD technique can be used to inspect welded joints with equal and non-equal thickness from the outside of the tank wall.
2. The area between the upper surface of the thick wall and the upper surface of the thin wall cannot be accurately inspected due to the inability to describe exactly the surface profile throughout the weld.
3. To calculate the depth and height of defects, the
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The TOFD data fragment (Fig. 13a) has indications with coordinates 5,570, 5,595, 5,620 and 5,640 mm. The presence of these indications is confirmed by a manual UT scanner (Fig. 13b). The scan, obtained using phased arrays is acquired with a sensitivity of 8 dB higher than the rejection level set at a control reflector with an equivalent area of 7 mm².

Findings:
1. The TOFD technique can be used to inspect welded joints with equal and non-equal thickness from the outside of the tank wall.
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standard ‘depth calculator’ program (included in the software package of flaw detectors that support TOFD) can be used, provided that the following requirements and assumptions are met:

a. TOFD sensors are installed so that the cross-
point of the directional pattern axes is located
at a depth of 2/3 of the thickness of the thin
wall from its outer surface;

b. the average distance between the TOFD input
points and the weld axis for the thin and
thick walls of the welded joint is taken as the
distance from the input point of each TOFD
to the weld axis set in the ‘depth calculator’
parameters;

c. the wall thickness in the ‘depth calculator’
is the average thickness of the thin and thick
walls of the welded joint;

d. in order to obtain real values, it is necessary to
add half of the delta in the wall thickness of the
welded joint to the depth value obtained using
the ‘depth calculator’.

Competing interests
The authors declare that there is no competing interest
regarding the publication of this paper.

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INTEGRITY ANALYSIS OF DENTED PIPELINES USING ARTIFICIAL NEURAL NETWORKS

by Janine Woo1, Muntaseer Kainat1, Chike Okoloekwe1, Sherif Hassanien1, and Samer Adeeb3

1 Enbridge Inc., Alberta, Canada
2 Stantec, Alberta, Canada
3 University of Alberta, Alberta, Canada

ABSTRACT

The repair of dents in oil or gas pipelines is mandated based on depth and interaction with stress risers, according to pipeline regulations in Canada and the United States. However, there have been cases where dents that did not meet the regulatory repair criteria have ended up failing, leading to operator need for an accurate assessment method for dents in order to maintain safety. While there is no agreed-upon method currently available in industry, conservative techniques employed by operators have led to poor dig efficiency. Recent research in industry has focused on strain- and fatigue-based techniques to assess the severity of dents and prioritize them for excavation and repair. Finite element analysis has been highlighted as an accurate method to evaluate strains and stresses within dented regions of pipe, although the significant computational time required for this method makes it inefficient for system-wide analysis. In this paper, the results from hundreds of finite element analysis models are used to train artificial neural networks. Subsequently, the artificial neural networks output accurate stresses and strains, that would be obtained using finite element analysis, when presented with input dent and pipe information. As a result, the artificial neural networks harness the accurate results that can be obtained from finite element analysis while results can be obtained efficiently for applicability to a pipeline system.

Key words: Pipelines, dents, finite element analysis, artificial neural networks, pipeline integrity, deformation.

INTRODUCTION

Potential threats to the integrity of an oil or gas pipeline include metal loss, cracking, dents, or the interaction of any of these. Dents, which are permanent inward plastic deformations, are common occurrences along pipelines and can be formed due to pipe contact with external forces such as rocks or construction equipment [1]. The dent can cause coating damage and accelerate the potential for or growth of existing corrosion or cause the pipe to become more susceptible to cracking in the deformed area [2]. In-line inspection (ILI) tools can take readings of the inner diameter of the pipe and indicate the location, shape, and size of dents.

Current industry regulations in Canada and the United States require repair of dents primarily based on depth, while there is minimal industry agreement on a suitable fitness-for-purpose approach for dents. The Canadian Standards Association (CSA) Standard Z662 specifies that plain dents greater than 6% of the nominal pipe diameter should be excavated and repaired [3]. CSA also recommends the repair of dents interacting with welds and dents interacting with stress concentrators (such as corrosion, stress corrosion cracks, other cracks, or gouges). There is room for improvement of the dent repair regulations, however, as there have been instances in the past where plain dents smaller than 6% of the outer diameter (OD) in depth, thereby acceptable per the CSA criteria, have failed [4]. In 2009, two separate dent failures occurred: one dent was 0.51% of OD and the other was 2.7% of OD [5]. After failure investigation, it was determined that each dent had led to the initiation of a crack, which then propagated due to pressure cycle induced fatigue until the crack reached through-wall and the pipe leaked. The failures prompted the NEB to issue an advisory in 2010 pertaining to shallow dents due to pressure cycle induced fatigue until the crack reached through-wall and the pipe leaked. The failures prompted the NEB to issue an advisory in 2010 pertaining to shallow dents.
**RESEARCH PAPER**

**Integrity Analysis of Dented Pipelines using Artificial Neural Networks**

by Janine Woo, Muntaseer Kainat, Chike Okoloekwe, Sherif Hassanien, and Samer Aadeeb

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The repair of dents in oil or gas pipelines is mandated based on depth and interaction with stress risers, according to pipeline regulations in Canada and the United States. However, there have been cases where dents that did not meet the regulatory repair criteria have ended up failing, leading to operator need for an accurate assessment method for dents in order to maintain safety. While there is no agreed-upon method currently available in industry, conservative techniques employed by operators have led to poor dig efficiency. Recent research in industry has focused on strain- and fatigue-based techniques to assess the severity of dents and prioritize them for excavation and repair. Finite element analysis has been highlighted as an accurate method to evaluate strains and stresses within dented regions of pipe, although the significant computational time required for this method makes it inefficient for system-wide analysis. In this paper, the results from hundreds of finite element analysis models are used to train artificial neural networks. Subsequently, the artificial neural networks output accurate stresses and strains, that would be obtained using finite element analysis, when presented with input dent and pipe information. As a result, the artificial neural networks harness the accurate results that can be obtained from finite element analysis while results can be obtained efficiently for applicability to a pipeline system.

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Due to the many different variables that affect the severity of a dent (including size, shape, interacting features, and the pipe's operating conditions), a universal equation or model to assess the integrity of a dent does not exist in industry [14]. Although FEA has proven accurate in providing the stresses and strains within a dented region, FEA is inefficient for analyzing a large number of dents as each model is computationally expensive [2]. Therefore, FEA is impractical from a time and resource perspective for system-wide dent analysis.

A method that can handle a complex problem with a large number of inputs, such as this, is an artificial neural network (ANN). ANNs imitate the architecture and concept of neural networks in the human brain by learning from samples of data to detect complex relationships, where a simple formula cannot be used to connect inputs and outputs [16, 17]. The database of samples used to train the neural network can be based on numerical analyses.

The objective of this paper is to demonstrate the feasibility of using artificial neural networks to efficiently and accurately estimate the strains and stresses of a dented region given only the input pipe properties and the ILI profile of the dent. This would be the only information available to an operator during system-wide analysis of dents. In this paper, two case studies will be used to demonstrate the proposed methodology, where the ANNs will be trained using the results of hundreds of FEA models. This would remove the need for modelling each dent.
with FEA but would harness the accurate results that can be obtained from FEA. The results from the ANNs will be compared to the results that could be obtained directly from FEA as well as to the results from other analysis techniques proposed in industry.

Methods

The FEA for this paper was performed using the software package, Abaqus Version 6.14. First, a deformable, 3D part was created in the modelling environment to represent a segment of the pipeline structure. The outer diameter and length of the pipe section were specified at this stage. Next, another part was created, separate from the pipe part, to represent the indenter. The indenter part was a 3D, analytical rigid body. The indenter shape used in this study was a torus indenter, which is pictured in Fig. 1. The reason for the selection of this indenter shape was for its simplicity, and the ease with which its aspect ratio could be adjusted by changing the major and minor radii. The indenter was then positioned in relation to the pipe so that it was just in contact with the outer surface of the pipe and was centered in the middle of the length of the pipe segment.

Only two-dimensional ILI profiles through the most significant point (MSP), or deepest point of the dent, will be considered in this study based on demonstration by a previous study that the 2D profiles provide sufficient representation for simple dent shapes [18]. Example ILI profiles in the longitudinal and circumferential directions are shown in Fig. 2 and Fig. 3, respectively. The major radius of the torus indenter aligns with the direction of the dent profile that is flatter and thus requires a major radius to affect the dent shape in the circumferential direction and a change in the minor radius will affect the dent shape in the longitudinal direction of the pipe. In this case, the profile is flatter in the circumferential direction than the longitudinal direction. For simplicity, the radii of the indenter aligned with each of the directions of the pipe will be referred to as the circumferential and longitudinal radii of the indenter.

Table 1. Pipe properties for FEA models.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Outside diameter (mm)</td>
<td>863.6</td>
</tr>
<tr>
<td>Wall thickness (mm)</td>
<td>7.14</td>
</tr>
<tr>
<td>Length of section (mm)</td>
<td>3000</td>
</tr>
<tr>
<td>Pipe grade X52 (359 MPa)</td>
<td></td>
</tr>
<tr>
<td>Maximum operating pressure (MPa)</td>
<td>4.74</td>
</tr>
</tbody>
</table>

Table 2. List of different indenter radii used in FEA models.

<table>
<thead>
<tr>
<th>Indenter Radius in the Longitudinal Direction (mm)</th>
<th>Number of Hidden Neurons</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>1</td>
</tr>
<tr>
<td>50</td>
<td>2</td>
</tr>
<tr>
<td>100</td>
<td>3</td>
</tr>
<tr>
<td>250</td>
<td>4</td>
</tr>
<tr>
<td>500</td>
<td>5</td>
</tr>
<tr>
<td>1000</td>
<td>6</td>
</tr>
<tr>
<td>2000</td>
<td>7</td>
</tr>
<tr>
<td>5</td>
<td>8</td>
</tr>
</tbody>
</table>

Table 3. Percentage of depth increments and X values used to train ANNs (example).

<table>
<thead>
<tr>
<th>Depth (mm)</th>
<th>X value (used to train ANNs) (mm)</th>
<th>% of Depth</th>
</tr>
</thead>
<tbody>
<tr>
<td>95</td>
<td>-32.8</td>
<td>13</td>
</tr>
<tr>
<td>90</td>
<td>-31.1</td>
<td>19</td>
</tr>
<tr>
<td>80</td>
<td>-27.6</td>
<td>29</td>
</tr>
<tr>
<td>75</td>
<td>-24.2</td>
<td>40</td>
</tr>
<tr>
<td>60</td>
<td>-20.7</td>
<td>51</td>
</tr>
<tr>
<td>50</td>
<td>-17.3</td>
<td>65</td>
</tr>
<tr>
<td>40</td>
<td>-13.8</td>
<td>80</td>
</tr>
<tr>
<td>30</td>
<td>-10.4</td>
<td>98</td>
</tr>
<tr>
<td>20</td>
<td>-6.91</td>
<td>117</td>
</tr>
<tr>
<td>10</td>
<td>-3.45</td>
<td>141</td>
</tr>
<tr>
<td>5</td>
<td>-1.73</td>
<td>157</td>
</tr>
</tbody>
</table>

True stress-true strain curve approximation for X52 grade steel.

Figure 5. True stress-true strain curve approximation for X52 grade steel.

Figure 6. Boundary conditions for FEA pipe model.

Table 4. Variation of error for differing numbers of hidden neurons.

<table>
<thead>
<tr>
<th>Number of Hidden Neurons</th>
<th>MSE</th>
<th>$R^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>326.4</td>
<td>0.9965</td>
</tr>
<tr>
<td>2</td>
<td>79.0</td>
<td>0.9991</td>
</tr>
<tr>
<td>3</td>
<td>63.6</td>
<td>0.9993</td>
</tr>
<tr>
<td>4</td>
<td>73.8</td>
<td>0.9991</td>
</tr>
<tr>
<td>5</td>
<td>73.5</td>
<td>0.9992</td>
</tr>
<tr>
<td>6</td>
<td>75.2</td>
<td>0.9992</td>
</tr>
<tr>
<td>7</td>
<td>74.4</td>
<td>0.9991</td>
</tr>
<tr>
<td>8</td>
<td>69.4</td>
<td>0.9993</td>
</tr>
</tbody>
</table>

Figure 7. Example of points on FEA profile used to train ANNs.

ANNs (example).

The next step in the FEA modelling was to create a partition in the area closest to the point on the pipe that the indenter was first in contact with. This was to section off a portion of the model and allow the area of the pipe closest to the MSP of the dent to have a fine, structured mesh. The fine seed size could be defined on the partition edges. In the area outside of the partition, the mesh becomes coarser further away from the point of indentation. In dents, the areas further away from the MSP have relatively small deformations that can adequately be captured by coarser mesh. FEA methodology described in literature typically follows this mesh configuration [13,19].

Once the geometries of the two parts were set up, the elastic and plastic material properties of the pipe were defined. The elastic behavior was assumed to be linear and isotropic, while uniaxial stress strain curves defined the plastic behavior of the material. The plastic hardening was assumed to be isotropic. In CSA Z662, the stress-strain relationship can be estimated for steel pipe using the Ramberg-Osgood model (1), shown below [3].

\[
\varepsilon = \frac{\sigma}{E_t} + \left(0.005 \cdot \frac{\sigma}{E_t} \right)^n
\]

where \(\varepsilon\) is the strain, \(\sigma\) is the stress, \(E_t\) is the modulus of elasticity of steel pipe, \(F_s\) is the specified minimum yield strength, and \(n\) is the strain hardening parameter.

For the models in this paper, the value of yield strength was taken as the specified minimum yield strength (SMYS) of API X52 grade material. Fig. 5 shows the resulting true stress-true strain curve for the material, which was based on research done by Lin [20] and approximated using (1) with \(E_t\) assumed to be 210 GPa [3], \(F_s\) equal to 359 MPa, and \(n\) equal to 12. The resulting values of yield stress versus plastic strain were input in the FEA software as the plastic properties of the material.

Surface-to-surface interaction between the rigid body indenter and the pipe was set up in the FEA software. The interaction properties included ‘penalty’ friction formulation for tangential behavior, with a standard friction coefficient of 0.5, and ‘hard contact’ for normal behavior.

The initial boundary conditions were set up such that a reference point at the center of each end of the pipe was fixed and a coupling condition was applied to the end of the pipes to restrict the pipe from movement except in the radial direction. This was to simulate real-life pipe conditions: the pipe cannot move vertically or laterally (due to restriction by soil), but can expand (due to internal pressure). In addition, symmetry boundary conditions were used and only a quarter...
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The major radius of the torus indenter aligns with the direction of the dent profile that is flatter and thus requires a larger radius than the other side. For example, in Fig. 4, the torus indenter is oriented in Abaqus such that a change in the major radius will affect the dent shape in the circumferential direction and a change in the minor radius will affect the dent shape in the longitudinal direction of the pipe. In this case, the profile is flatter in the circumferential direction than the longitudinal direction. For simplicity, the radii of the indenter aligned with each of the directions of the pipe will be referred to as the circumferential and longitudinal radii of the indenter.

### Results

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\[
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\]

where \( \varepsilon \) is the strain, \( \sigma \) is the stress, \( F_y \) is the modulus of elasticity of steel pipe, and \( n \) is the specified minimum yield strength.

\( F_y \) is the yield stress, which is defined as being the stress at which the material begins to deform plastically, i.e., the stress at the onset of non-recoverable deformation. The plastic hardening parameter \( n \) is the strain hardening parameter.

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of the pipe was modelled in order to reduce computational efforts. Symmetry boundary conditions for the pipe are only applicable when the dent shape is symmetrical in both the longitudinal and circumferential directions. This is the scenario that will be considered throughout this research. The boundary conditions are shown in Fig. 6.

There are several scenarios that can lead to dent formation that can be reflected in the FEA model by modifying the load sequence. For this research, the consistent loading sequence of indentation, and then a pressure cycle was applied in the FEA model by translating the indenter vertically downward (operation dent) [11]. The indentation step was applied in the longitudinal and then a pressure cycle was applied in the circumferential direction versus pressure cycle then indentation of the dent component in the pipe (in the respective direction) due to one pressure cycle. These outputs provide deterministic representations of the stress-strain state of the deformed pipe and the results can be used to prioritize dents in terms of either strain or fatigue.

**Artificial Neural Networks: Case Study 1**

**Methodology**

**Building Database**

The first step required to develop the artificial neural networks was to collect the data required for training. A total of 63 FEA models were run, where the pipe properties were held constant at the values shown in Table 1.

To build the database of information for the ANN, the indenter radius was adjusted 7 times in the longitudinal direction and 9 times in the circumferential direction; Table 2 shows the different values used. After the FEA models were run, the 2-dimensional displacement profiles were extracted, through the MSP of the dent in the longitudinal and circumferential directions. As the

<table>
<thead>
<tr>
<th>Number of Inputs</th>
<th>Inputs</th>
<th>Number of Hidden Neurons</th>
<th>Number of Outputs</th>
<th>Output</th>
</tr>
</thead>
<tbody>
<tr>
<td>11</td>
<td>Points along displacement profile in longitudinal direction</td>
<td>3</td>
<td>1</td>
<td>Indenter radius in longitudinal direction</td>
</tr>
<tr>
<td>11</td>
<td>Points along displacement profile in circumferential direction</td>
<td>8</td>
<td>1</td>
<td>Indenter radius in circumferential direction</td>
</tr>
<tr>
<td>2</td>
<td>Indenter radius in both directions</td>
<td>8</td>
<td>1</td>
<td>Indenter radius in circumferential direction</td>
</tr>
<tr>
<td>2</td>
<td>Indenter radius in both directions</td>
<td>8</td>
<td>1</td>
<td>Indenter radius in circumferential direction</td>
</tr>
<tr>
<td>2</td>
<td>Indenter radius in both directions</td>
<td>5</td>
<td>1</td>
<td>Indenter radius in longitudinal direction</td>
</tr>
<tr>
<td>2</td>
<td>Indenter radius in both directions</td>
<td>6</td>
<td>1</td>
<td>Indenter radius in longitudinal direction</td>
</tr>
</tbody>
</table>

**Table 6. Inputs, Hidden Neurons and Outputs for the ANNs.**
Indenter radius in both directions 8 1

### Table 5. Variation of error for different training algorithms.

<table>
<thead>
<tr>
<th>Training Algorithm</th>
<th>MSE</th>
<th>R</th>
</tr>
</thead>
<tbody>
<tr>
<td>Levenberg-Marquardt</td>
<td>150.3</td>
<td>0.9984</td>
</tr>
<tr>
<td>Bayesian Regularization</td>
<td>63.6</td>
<td>0.9993</td>
</tr>
<tr>
<td>Scaled Conjugate Gradient</td>
<td>388.1</td>
<td>0.9996</td>
</tr>
</tbody>
</table>

The boundary conditions are shown in Fig. 6. For the mesh, four-node, reduced integration, shell elements were used with linear geometric order. The size of the mesh within the partition was 2 mm and the mesh grew coarser outside of the partition, far away from the indentation (the area of interest). Five integration points were used in the thickness direction of the shell elements. The desired outputs from the FEA models were \( \sigma_{h hoop} \) and \( \sigma_{h axial} \), where \( \sigma_{h hoop} \) is the maximum equivalent plastic strain, \( \sigma_{h axial} \) is the maximum delta sigma in the hoop direction, and \( \Delta \sigma_{h hoop} \) is the maximum delta sigma in the axial direction. Delta sigma refers to the maximum difference in the stress component in the pipe (in the respective direction) due to one pressure cycle. These outputs provide deterministic representations of the stress-strain state of the dented pipe and the results can be used to prioritize dents in terms of either strain or fatigue.

### Table 6. Inputs, Hidden Neurons and Outputs for the ANNs.

<table>
<thead>
<tr>
<th>Number of Inputs</th>
<th>Inputs</th>
<th>Number of Hidden Neurons</th>
<th>Number of Outputs</th>
<th>Output</th>
</tr>
</thead>
<tbody>
<tr>
<td>11</td>
<td>Points along displacement profile in longitudinal direction</td>
<td>3</td>
<td>1</td>
<td>Indenter radius in longitudinal direction</td>
</tr>
<tr>
<td>11</td>
<td>Points along displacement profile in circumferential direction</td>
<td>8</td>
<td>1</td>
<td>Indenter radius in circumferential direction</td>
</tr>
<tr>
<td>2</td>
<td>Indenter radius in both directions</td>
<td>8</td>
<td>1</td>
<td>( \Delta \sigma_{h hoop} )</td>
</tr>
<tr>
<td>2</td>
<td>Indenter radius in both directions</td>
<td>5</td>
<td>1</td>
<td>( \Delta \sigma_{h axial} )</td>
</tr>
<tr>
<td>2</td>
<td>Indenter radius in both directions</td>
<td>6</td>
<td>1</td>
<td>( \Delta \sigma_{h hoop} )</td>
</tr>
</tbody>
</table>

### Table 7. Summary of inputs and outputs for each step of ANN development process.

<table>
<thead>
<tr>
<th>Step</th>
<th>Analysis Mechanism</th>
<th>Inputs</th>
<th>Outputs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Building Database</td>
<td></td>
<td>FEA</td>
<td>Displacement profile ( \sigma_{h hoop} ) and ( \sigma_{h axial} )</td>
</tr>
<tr>
<td>Creating and Training the ANNs (using Abaqus)</td>
<td></td>
<td>Training algorithm</td>
<td>Indenter radius in longitudinal direction ( \sigma_{h hoop} ) and ( \sigma_{h axial} )</td>
</tr>
<tr>
<td>Creating and Training the ANNs (using MATLAB)</td>
<td>Training algorithm</td>
<td>Input Data (to present to network)</td>
<td>Indenter radius in circumferential direction ( \Delta \sigma_{h hoop} ) and ( \Delta \sigma_{h axial} )</td>
</tr>
<tr>
<td>Creating and Training the ANNs (using MATLAB)</td>
<td>Training algorithm</td>
<td>Input Data (to present to network)</td>
<td>Indenter radius in circumferential direction ( \Delta \sigma_{h hoop} ) and ( \Delta \sigma_{h axial} )</td>
</tr>
<tr>
<td>Creating and Training the ANNs (using MATLAB)</td>
<td>Training algorithm</td>
<td>Input Data (to present to network)</td>
<td>Indenter radius in longitudinal direction ( \Delta \sigma_{h hoop} ) and ( \Delta \sigma_{h axial} )</td>
</tr>
<tr>
<td>Creating and Training the ANNs (using MATLAB)</td>
<td>Training algorithm</td>
<td>Input Data (to present to network)</td>
<td>Indenter radius in circumferential direction ( \Delta \sigma_{h hoop} ) and ( \Delta \sigma_{h axial} )</td>
</tr>
<tr>
<td>Creating and Training the ANNs (using MATLAB)</td>
<td>Training algorithm</td>
<td>Input Data (to present to network)</td>
<td>Indenter radius in circumferential direction ( \Delta \sigma_{h hoop} ) and ( \Delta \sigma_{h axial} )</td>
</tr>
<tr>
<td>Creating and Training the ANNs (using MATLAB)</td>
<td>Training algorithm</td>
<td>Input Data (to present to network)</td>
<td>Indenter radius in circumferential direction ( \Delta \sigma_{h hoop} ) and ( \Delta \sigma_{h axial} )</td>
</tr>
</tbody>
</table>

Artificial Neural Networks: Case Study 1

### Methodology

#### Building Database

The first step required to develop the artificial neural networks was to collect the data required for training. A total of 63 FEA models were run, where the pipe properties were held constant at the values shown in Table 1. To build the database of information for the ANNs, the indentor radius was adjusted 7 times in the longitudinal direction and 9 times in the circumferential direction; Table 2 shows the different values used. After the FEA models were run, the 2-dimensional displacement profiles were extracted, through the MSP of the dent in the longitudinal and circumferential directions. As the

\[ P = \frac{80S}{D} \]

\[ D = 0.05 \times \frac{2S}{F} \]

\[ S = \text{the specified minimum yield strength of the pipe (in MPa)} \]

\[ r = \text{the wall thickness (in mm)} \]

\[ D = \text{the outer diameter of the pipe (in mm)} \]
profiles would need to be used in a consistent format to train the ANNs, the horizontal distances (i.e., the indenter radius in the longitudinal direction) from the MSP to the profile at 11 different depth increments were recorded. For example, the extracted points are shown as the red diamonds in Fig. 7 and bolded in Table 3. The percentage of depth increments were held constant across the different FEA models.

Therefore, the inputs to training the neural networks to find the indenter radius in each direction were the 11 consistent points along the displacement profiles (i.e., the red diamonds shown in Fig. 7). The maximum $\Delta r$, $\Delta \sigma_{\text{req}}$, and $\Delta \sigma_{\text{curv}}$ were also recorded from each FEA model.

Creating and training the ANNs

Five separate neural networks were trained using MATLAB Version R2018a, with the desired outputs of: the indenter radius in the longitudinal direction, the indenter radius in the circumferential direction, $\Delta r$, $\Delta \sigma_{\text{req}}$, and $\Delta \sigma_{\text{curv}}$. The Neural Net Fitting application within MATLAB was used to create and train the ANNs as well as evaluate their performance.

The type of ANN created using the software was a two-layer feed-forward network designed to fit multi-dimensional mapping problems [21]. The tool randomly divides the input samples into three groups: training, validation, and testing. The training group has been set to use 80% of the total samples into three groups: training, validation, and testing.

The number of hidden neurons affects the performance of the network, but the optimal value varies for different applications [21]. For this study, the optimal number of hidden neurons was determined by trial and error, where the number of hidden neurons that resulted in the lowest error was chosen for the network (as indicated by the lowest Mean Squared Error (MSE) value and closest $R^2$ value to 1, where the MSE represents the average squared difference between the outputs and targets and $R^2$ measures the correlation between the outputs and targets). An example of this process for the longitudinal indenter radius network is summarized in Table 4, where 3 hidden neurons were chosen for the network, due to having the smallest MSE and $R^2$ values.

There are three options provided in the software for the training algorithm: Levenberg-Marquardt, which is recommended for most problems, Bayesian Regularization, which is recommended for noisy or small problems, and Scaled Conjugate Gradient, which is recommended for large problems. The three algorithm options were tested and the algorithm that resulted in the smallest errors was chosen for the network. For the longitudinal indenter radius network, a comparison between the three training algorithms is shown in Table 5; the Bayesian Regularization algorithm was found to be most suitable for this network.

A diagram of the neural network architecture for the longitudinal indenter radius network is shown in Fig. 8, which shows that the network is a feed-forward network with 11 inputs (the 11 displacement profile points), 3 hidden neurons in the 1 hidden layer, 1 output layer, and 1 output variable (the indenter radius in the longitudinal direction). The default transfer functions built into the MATLAB toolbox were used, which were a sigmoid transfer function in the hidden layer and a linear transfer function in the output layer [21]. The number of inputs, hidden neurons, and outputs for the 5 different ANNs is shown in Table 6. The Bayesian Regularization training algorithm was found to result in the least error for all 5 ANNs.

After being given a certain input, an ANN is trained by comparing the output to the given target. If the network output does not match the target, the weights, or connections, between the neurons of the network is adjusted. This process is repeated until the error on the network outputs is minimal (i.e. the error fails to decrease over several subsequent iterations). The MATLAB Neural Net Fitting toolbox has been programmed to automatically iterate through this process, which is demonstrated by Fig. 9 [21].
profiles would need to be used in a consistent format to train the ANNs, the horizontal distances (in either the longitudinal or circumferential direction) from the MSP to the profile at 11 different depth increments were recorded. For example, the extracted points are shown as the red diamonds in Fig. 7 and bolded in Table 3. The percentage of depth increments were held constant across the different FEA models.

Therefore, the inputs to training the neural networks to find the indenter radius in each direction were the 11 consistent points along the displacement profiles (i.e. the red diamonds shown in Fig. 7). The maximum \( \mathcal{E}_\text{max} \), \( \Delta \mathcal{E}_\text{max} \) and \( \Delta \sigma_\text{max} \) were also recorded from each FEA model.

Creating and training the ANNs

Five separate neural networks were trained using MATLAB Version R2018a, with the desired outputs of: the indenter radius in the longitudinal direction, the indenter radius in the circumferential direction, \( \mathcal{E}_\text{max}, \Delta \mathcal{E}_\text{max} \) and \( \Delta \sigma_\text{max} \). The Neural Net Fitting application within MATLAB was used to create and train the ANNs as well as evaluate their performance.

The type of ANN created using the software was a two-hidden-layer feed-forward network designed to fit multi-dimensional mapping problems [21]. The tool randomly divides the input samples into three groups: training, validation, and testing. The training group has been set to use 80% of the total number of samples, where the network’s weights and biases are adjusted based on this group. The validation group uses 15% of the samples and the error on this group is monitored during training. In the initial phase of training, the error on the training and validation sets typically decreases until a certain point when the error on the validation set starts to increase. This behavior during neural network training is called overfitting. Significant overfitting can be avoided by having a large enough sample size to train the network, although the definition of an adequate size varies for different applications and is difficult to predict before training of the network begins [21]. Training will cease when the error begins increasing; however, the network weights and biases from the point of minimum error will be saved in the network. Only 5% of the sample was set aside for testing. This is because independent tests will be conducted outside of the MATLAB toolbox in this study, and the testing set has no effect on network training.

The next step in setting up the network architecture is to set the number of neurons in the network’s hidden layer. The number of hidden neurons affects the performance of the network, but the optimal value varies for different applications [21]. For this study, the optimal number of hidden neurons was determined by trial and error, where the number of hidden neurons that resulted in the lowest error was chosen for the network (as indicated by the lowest Mean Squared Error (MSE) value and closest \( R^2 \) value to 1, where the MSE represents the average squared difference between the outputs and targets and \( R^2 \) measures the correlation between the outputs and targets). An example of this process for the longitudinal indenter radius network is summarized in Table 4, where 3 hidden neurons were chosen for the network, due to having the smallest MSE and \( R^2 \) values.

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After being given a certain input, an ANN is trained by comparing the output to the given target. If the network output does not match the target, the weights, or connections, between the neurons of the network are adjusted. This process is repeated until the error on the network outputs is minimal (i.e. the error fails to decrease over several subsequent iterations). The MATLAB Neural Net Fitting toolbox has been programmed to automatically iterate through this process, which is demonstrated by Fig. 9 [21].

### Table 8. List of different indenter properties used in FEA models to train ANNs.

<table>
<thead>
<tr>
<th>Indenter Radius in the Longitudinal Direction (mm)</th>
<th>Indenter Radius in the Circumferential Direction (mm)</th>
<th>Indentation Depth (%OD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>75</td>
<td>2</td>
</tr>
<tr>
<td>75</td>
<td>100</td>
<td>3</td>
</tr>
<tr>
<td>250</td>
<td>350</td>
<td>4</td>
</tr>
<tr>
<td>500</td>
<td>500</td>
<td>5</td>
</tr>
<tr>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Table 9. Constant pipe properties for FEA models to train ANNs.

<table>
<thead>
<tr>
<th>Outside diameter (mm)</th>
<th>812.8</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wall thickness (mm)</td>
<td>7.14</td>
</tr>
<tr>
<td>Length of section (mm)</td>
<td>1000</td>
</tr>
<tr>
<td>Pipe grade</td>
<td>X52 (359 MPa)</td>
</tr>
<tr>
<td>Maximum operating pressure (MPa)</td>
<td>5.04</td>
</tr>
</tbody>
</table>

### Table 10. Comparison of \( \mathcal{E}_\text{max} \) from ASME B31.8 and from ANN versus \( \mathcal{E}_\text{max} \) from FEA.

<table>
<thead>
<tr>
<th>Outside diameter (mm)</th>
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</tr>
</thead>
<tbody>
<tr>
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</tr>
<tr>
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</tr>
<tr>
<td>Pipe grade</td>
<td>X52 (359 MPa)</td>
</tr>
<tr>
<td>Maximum operating pressure (MPa)</td>
<td>5.04</td>
</tr>
</tbody>
</table>

### Table 11. Circumferential indenter radius predicted by ANN versus radii used in FEA.

<table>
<thead>
<tr>
<th>Outside diameter (mm)</th>
<th>812.8</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wall thickness (mm)</td>
<td>7.14</td>
</tr>
<tr>
<td>Length of section (mm)</td>
<td>1000</td>
</tr>
<tr>
<td>Pipe grade</td>
<td>X52 (359 MPa)</td>
</tr>
<tr>
<td>Maximum operating pressure (MPa)</td>
<td>5.04</td>
</tr>
</tbody>
</table>

### Table 12. Comparison of \( \mathcal{E}_\text{max} \) from ASME B31.8 and from ANN versus \( \mathcal{E}_\text{max} \) from FEA.

<table>
<thead>
<tr>
<th>Outside diameter (mm)</th>
<th>812.8</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wall thickness (mm)</td>
<td>7.14</td>
</tr>
<tr>
<td>Length of section (mm)</td>
<td>1000</td>
</tr>
<tr>
<td>Pipe grade</td>
<td>X52 (359 MPa)</td>
</tr>
<tr>
<td>Maximum operating pressure (MPa)</td>
<td>5.04</td>
</tr>
</tbody>
</table>

### Table 13. Circumferential indenter radius predicted by ANN versus radii used in FEA.

<table>
<thead>
<tr>
<th>Outside diameter (mm)</th>
<th>812.8</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wall thickness (mm)</td>
<td>7.14</td>
</tr>
<tr>
<td>Length of section (mm)</td>
<td>1000</td>
</tr>
<tr>
<td>Pipe grade</td>
<td>X52 (359 MPa)</td>
</tr>
<tr>
<td>Maximum operating pressure (MPa)</td>
<td>5.04</td>
</tr>
</tbody>
</table>

### Table 14. \( \Delta \mathcal{E}_\text{max} \) results from ANN versus results from FEA.

<table>
<thead>
<tr>
<th>Outside diameter (mm)</th>
<th>812.8</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wall thickness (mm)</td>
<td>7.14</td>
</tr>
<tr>
<td>Length of section (mm)</td>
<td>1000</td>
</tr>
<tr>
<td>Pipe grade</td>
<td>X52 (359 MPa)</td>
</tr>
<tr>
<td>Maximum operating pressure (MPa)</td>
<td>5.04</td>
</tr>
</tbody>
</table>

### Table 15. \( \Delta \mathcal{E}_\text{max} \) results from ANN versus results from FEA.

<table>
<thead>
<tr>
<th>Outside diameter (mm)</th>
<th>812.8</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wall thickness (mm)</td>
<td>7.14</td>
</tr>
<tr>
<td>Length of section (mm)</td>
<td>1000</td>
</tr>
<tr>
<td>Pipe grade</td>
<td>X52 (359 MPa)</td>
</tr>
<tr>
<td>Maximum operating pressure (MPa)</td>
<td>5.04</td>
</tr>
</tbody>
</table>

### Table 16. \( \Delta \mathcal{E}_\text{max} \) results from ANN versus results from FEA.

<table>
<thead>
<tr>
<th>Outside diameter (mm)</th>
<th>812.8</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wall thickness (mm)</td>
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</tr>
<tr>
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<td>1000</td>
</tr>
<tr>
<td>Pipe grade</td>
<td>X52 (359 MPa)</td>
</tr>
<tr>
<td>Maximum operating pressure (MPa)</td>
<td>5.04</td>
</tr>
</tbody>
</table>
After the networks were trained, independent testing was performed by feeding the inputs from 21 separate FEA models into the networks and comparing the outputs from the networks to the indenter radii \(\delta r\), \(\Delta \sigma_{\text{long}}\), and \(\Delta \sigma_{\text{circ}}\) from FEA. The 21 validation models had different indenter radii values than were used to train the ANNs, although the values were within the bounds of the training range (i.e. the validation set had indenter radii ranging from 25 mm to 550 mm, while the training set had indenter radii ranging from 10 mm to 2.000 mm). The separate validation data set was used to test if the ANNs could predict accurate results when presented with new data. It was attempted to directly predict the \(\delta r\) and stresses from the displacement profiles (without creating separate ANNs to find the indenter radii), but this resulted in a poor comparison between the ANN-predicted results and the FEA-produced results. This was likely due to the high number of inputs and outputs that the neural network would have had to fit between, and this would have required creating separate ANNs to find the indenter radii, but this resulted in a poor comparison between the ANN-predicted results and the FEA-produced results. This was likely due to the high number of inputs and outputs that the neural network would have had to fit between, and this would have required a much larger training sample size for accurate results.

The overall process described in this section (including building the database, training the ANNs, and validating the ANNs), is summarized in Table 7. In the table, symbols are used to show where the same values are used. For example, the dark red dash shows that the known indenter radius values used in the FEA models were used as the Targets to train the ANN where the desired network output is the indenter radius. On the contrary, the yellow triangle pointed to the right shows that the known indenter radius values used in the FEA models were used as the Targets to train the ANN where the desired output was the longitudinal radius.

### Results

The points from the displacement profiles of the 21 validation models were given as inputs to the ANNs where the desired outputs were the indenter radii in the longitudinal and circumferential directions. This process is used to imitate the real-life scenario where the ILL-reported dent profile is known, but the indenter radius required to model the feature in FEA is unknown. The outputs from the ANNs were then compared against the true indenter radii used to achieve the displacement profiles in FEA and the results are shown in the plots in Fig. 10 and Fig. 11.

Once the indenter radii were predicted using the ANNs, the radii were then used as inputs to 3 other ANNs to predict the \(\delta r\), \(\Delta \sigma_{\text{long}}\), and \(\Delta \sigma_{\text{circ}}\). For comparison, the analytical equations recommended in ASME B31.8 Appendix R were used with the FEA profiles and pipe properties of the 21 models created in this study. Fig. 12 shows the maximum \(\delta r\) predicted from the ANN and the \(\delta r\) predicted using the ASME B31.8 equations plotted against the \(\delta r\) found using FEA. In Fig. 12, the \(\delta r\) from the alternative method is plotted on the y-axis, while the \(\delta r\) from FEA is plotted on the x-axis, with the dashed black line through the center of the plot indicating that the points on the x- and y-axis are equal. As the blue diamonds, which represent the comparison between the \(\delta r\) found from the ANNs against the \(\delta r\) from FEA, are much closer to the dashed black line than the red diamonds (comparison between ASME B31.8 and FEA), this indicates that the ANNs were more accurate than the ASME B31.8 equations in predicting \(\delta r\), with the FEA \(\delta r\) used as the benchmark for accuracy.

In Fig. 13 and Fig. 14, the maximum \(\Delta \sigma_{\text{long}}\) and maximum \(\Delta \sigma_{\text{circ}}\) respectively, are shown, where the results from ANN are compared against the results from FEA. As the points are all close to the dashed unity line down the center of the plot, this indicates that the results predicted by the ANNs were close to the results found from FEA.

<table>
<thead>
<tr>
<th>Number of Inputs</th>
<th>Inputs</th>
<th>Number of Hidden Neurons</th>
<th>Number of Outputs</th>
<th>Output</th>
</tr>
</thead>
<tbody>
<tr>
<td>12</td>
<td>Points along displacement profile in longitudinal direction and indentation depth</td>
<td>10</td>
<td>1</td>
<td>Indenter radius in longitudinal direction</td>
</tr>
<tr>
<td>12</td>
<td>Points along displacement profile in circumferential direction and indentation depth</td>
<td>20</td>
<td>1</td>
<td>Indenter radius in circumferential direction</td>
</tr>
<tr>
<td>3</td>
<td>Indenter radius in both directions and indentation depth</td>
<td>20</td>
<td>1</td>
<td>(\delta r)</td>
</tr>
<tr>
<td>3</td>
<td>Indenter radius in both directions and indentation depth</td>
<td>35</td>
<td>1</td>
<td>(\Delta \sigma_{\text{long}})</td>
</tr>
<tr>
<td>3</td>
<td>Indenter radius in both directions and indentation depth</td>
<td>35</td>
<td>1</td>
<td>(\Delta \sigma_{\text{circ}})</td>
</tr>
</tbody>
</table>

Table 10. Inputs, hidden neurons, and outputs for the ANNs in Case Study 2.

<table>
<thead>
<tr>
<th>Task</th>
<th>FEA and ANN</th>
<th>FEA Only</th>
</tr>
</thead>
<tbody>
<tr>
<td>Training the Database</td>
<td>18 hours</td>
<td>N/A</td>
</tr>
<tr>
<td>Obtaining Results</td>
<td>1 minute</td>
<td>50 hours</td>
</tr>
<tr>
<td>Total Time</td>
<td>18 hours</td>
<td>50 hours</td>
</tr>
</tbody>
</table>

Table 11. Comparison of time between using FEA and ANN versus FEA only.
After the networks were trained, independent testing was performed by feeding the inputs from 21 separate FEA models into the networks and comparing the outputs from the networks to the indenter radii, $\epsilon_l$, $\sigma_{\text{avg}}$, and $\Delta \sigma_{\text{avg}}$ from FEA. The 21 validation models had different indenter radii values than were used to train the ANNs, although the values were within the bounds of the training range (i.e. the validation set had indenter radii ranging from 2.5 mm to 550 mm, while the training set had indenter radii ranging from 10 mm to 2,000 mm). The separate validation data set was used to test if the ANNs could predict accurate results when presented with new data. It was attempted to directly predict the $\epsilon_l$ and stresses from the displacement profiles (without creating separate ANNs to find the indenter radii), but this resulted in a poor comparison between the ANN-predicted results and the FEA-produced results. This was likely due to the high number of inputs and outputs that the neural network would have had to fit between, and this would have required a much larger training sample size for accurate results.

The overall process described in this section (including building the database, training the ANNs, and validating the ANNs), is summarized in Table 7. In the table, symbols are used to show where the same values are used. For example, the dark red dash shows that points from the displacement profiles in FEA used as input data to train the ANN where the desired network output is the indenter radius. On the contrary, the yellow triangle pointed to the right shows that the known indenter radius values used in the FEA models were used as the Targets to train the ANN where the desired output was the longitudinal radius.

Results

The points from the displacement profiles of the 21 validation models were given as inputs to the ANNs where the desired outputs were the indenter radii in the longitudinal and circumferential directions. This process is used to imitate the real-life scenario where the ILI-reported dent profile is known, but the indenter radius required to model the feature in FEA is unknown. The outputs from the ANNs were then compared against the true indenter radii used to achieve the displacement profiles in FEA and the results are shown in the plots in Fig. 10 and Fig. 11.

Once the indenter radii were predicted using the ANNs, the radii were then used as inputs to 3 other ANNs to predict the $\epsilon_l$, $\sigma_{\text{avg}}$, and $\Delta \sigma_{\text{avg}}$.

For comparison, the analytical equations recommended in ASME B31.8 were used with the FEA profiles and pipe properties of the 21 models created in this study. Fig. 12 shows the maximum $\epsilon_l$ predicted from the ANNs and the $\epsilon_l$ predicted using the ASME B31.8 equations plotted against the $\epsilon_l$ found using FEA. In Fig. 12, the $\epsilon_l$ from the alternative method is plotted on the y-axis, while the $\epsilon_l$ from FEA is plotted on the x-axis, with the dashed black line through the center of the plot indicating that the points on the x- and y-axis are equal. As the blue diamonds, which represent the comparison between the $\epsilon_l$ found from the ANNs against the $\epsilon_l$ from FEA, are much closer to the dashed black line than the red diamonds (comparison between ASME B31.8 and FEA), this indicates that the ANNs were more accurate than the ASME B31.8 equations at predicting $\epsilon_l$ with the FEA $\epsilon_l$ used as the benchmark for accuracy.

In Fig. 13 and Fig. 14, the maximum $\sigma_{\text{avg}}$ and maximum $\Delta \sigma_{\text{avg}}$, respectively, are shown, where the results from ANN are compared against the results from FEA. As the points are all close to the dashed unity line down the center of the plot, this indicates that the results predicted by the ANNs were close to the results found from FEA.
Artificial Neural Networks: Case Study 2

Methodology
The process described in the methodology of the first case study was repeated in this section but with a larger training dataset where an additional variable, the indentation depth, was also modified. The properties that were held constant across the models is shown in Table 8, while the properties that were adjusted is shown in Table 9. The true-stress-true-strain curve approximation for X52 steel was shown in Fig. 5 and the MOP shown in Table 8 is equal to 80% of SMYS calculated using Equation 2. As the indenter radius was modified 6 times in both the longitudinal and circumferential directions and the indentation depth was modified 6 times, a total of 216 models were used to train the ANNs.

Using trial and error, the Bayesian Regularization training algorithm was found to result in the least error for all 5 ANNs. A summary of the number of inputs, hidden neurons, and outputs for each of the trained ANNs for Case Study 2 is shown in Table 10.

For validation, 100 models were generated where the indenter radii in both directions and the indentation depth were randomly selected between the bounds of the training set (i.e., the indenter radius in each direction was randomized between 50 mm and 500 mm and the indentation depth was randomized between 1% OD and 6% OD). The pipe properties of the validation set were the same as the training set, as presented in Table 8.

Results
The results predicted from the ANNs were plotted against the results obtained from FEA for the randomized validation set of 100 models. The comparisons for the longitudinal and circumferential indenter radius are shown in Fig. 15 and Fig. 16, respectively. In the figures, the results predicted by the ANN are plotted on the y-axis, while the results from FEA are plotted on the x-axis; data points along the diagonal line indicate equal values from the two methods.

In Fig. 17, the \( \varepsilon_f \) results estimated by the ANN are plotted against the \( \varepsilon_f \) values extracted from FEA. For the same dataset of 100 models, the \( \varepsilon_f \) was also determined using the analytical equations in ASME B31.8, as well as using the analytical methodology described by Okoloekwe [8] and are plotted against the \( \varepsilon_f \) from FEA in Fig. 17. The maximum \( \Delta \sigma_{fl} \) and maximum \( \Delta \sigma_{fu} \) results are shown, respectively, in Fig. 18 and Fig. 19. In terms of time required for this process, the FEA models used to train the ANNs in this paper took, on average, 5 minutes of computational time to complete. For Case Study 2, the computational time required to run all 216 training models was roughly 18 hours. Once the 100 validation models needed to be analyzed, however, the ANNs provided results in less than 1 minute.

For a typical dent analysis using FEA, the displacement profile obtained from FEA must first be aligned to the dent profile reported by ILI. To achieve this, a trial and error profile matching process is required, whereby the indenter radius is adjusted in each direction in FEA until the resulting profile aligns with the ILI profile [18]. However, this process is time consuming due to it being iterative, as well as subjective, due to the absence of a set criteria for an acceptable match. The amount of time required for this process is difficult to quantify accurately as it is subjective, however, an accurate profile match for one dent took approximately 30 minutes to achieve (including both computational time of running the models and user time to assess that the match was not close enough and another method was required). The time-consuming process of profile matching is running the large number of FEA models needed to train the ANNs. However, if automation techniques for model generation and results extraction are used, then the models would require minimal user intervention and would simply require extensive computational time. In addition, the ANNs would only have to be trained once to cover all pipe properties and potential dent properties that could be seen on a pipeline system. Any new features that are reported could then be analyzed using the already trained ANNs. Thus, the time investment required to train the ANNs, while initially significant, would pay off over time as future analyses could be performed instantly. The time comparison between the two processes summarized in Table 11 shows that the use of FEA and ANNs is far more efficient than using FEA alone.

The effect would be even more dramatic if applied to a larger dataset of features requiring analysis, for example, all dent features across an entire pipeline system. However, although the ANNs from Case Study 1 proved to be accurate, the ANN results in Case Study 2 were even closer to their FEA counterparts and almost equivalent in most cases. This demonstrates that a large training set that adequately covers the full range of input variables is required for accurate results. In addition, the indentation depth was modified for Case Study 2 but kept constant for Case Study 1. This demonstrates that the modification of additional variables that were held constant in previous studies, such as dent diameter and wall thickness, should not affect the accuracy of the results if a sufficient number of training models is used.

Conclusion
In this paper, artificial neural networks (ANNs) were trained to predict the indenter radius in both the longitudinal and circumferential directions, the maximum equivalent plastic strain (\( \varepsilon_f \)), \( \Delta \sigma_{fl} \), and \( \Delta \sigma_{fu} \). These ANNs were trained using FEA models to harness the accuracy that can be obtained using FEA but can produce results in far less time. In the first case study in this chapter, the indenter radii were modified while all other properties were held constant and an independent data set was used to validate the indenter radii. In Case Study 2, the indenter radii were modified while all other properties were held constant and an independent data set was used to validate the indenter depth were the only properties modified, and the ANN results were compared against 100 FEA models with randomly generated input variables.

These results show that ANNs can be used to predict the maximum strains and stresses in dented regions with similar accuracy to what is achieved using FEA, which has already been proven to be an accepted method of analyzing injudicious dents by other researchers. The use of ANNs creates the added benefit of achieving results in far less time than using FEA alone and could be feasible for system-wide application from a time and resource perspective.

Acknowledgements
The authors would like to thank Doug Langer for his technical support and contributions to the initial development of the research described in this paper.

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Competing interests
The authors declare that there is no competing interest regarding the publication of this paper.

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Numerical simulation of thermal-hydraulic effect of wall-boundary layer of oil deposits In oil trunk pipelines

by R. Z. Sungatullin 1, R. M. Karimov* 2, R. R. Tashbulatov 2, B. N. Mastobayev 2,
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ABSTRACT
The paper presents the results of numerical studies of the effect of the wall-boundary layer of oil deposits formed on the inner surface of oil trunk pipelines. The possibility to reduce the hydraulic drag and to increase the throughput capacity of pipelines due to the thermal insulating and surface-smoothing properties of the asphalt-resin-wax oil deposits layer is mathematically proved. Numerical experiments proved the efficiency of the wall-boundary layer of deposits with various thickness both in isothermal and ‘hot’ oil pipelines. The effect is due to lower roughness of the inner surface of the pipes and higher flow temperature. The latter in non-isothermal sections of hot pumping leads to the lower average viscosity of the pumped oil. In case of isothermal pumping, the deposit layer is efficient only in developed turbulent flow conditions. Moreover, in large diameter pipelines, the effect of the deposit layer is maintained even at its considerable thickness, despite a high reduction in the inner pipeline diameter.

Key words: asphalt-resin-wax deposits, oil pipeline, thermal insulation, surface roughness, hydraulic drag, thermal-hydraulic conditions, viscosity, optimal thickness of the wall-boundary layer.

FUNDING INFORMATION
The study was supported by the Russian Foundation for Basic Research as part of Research Project № 17-48-020721 p_a.

INTRODUCTION
Oil deposits on the inner surface of pipelines, consisting of a mixture of organic compounds of oil (resins, wax, asphaltelanes) and inorganic impurities (sand, water), decrease the effective diameter and, consequently, increase the hydraulic drag. Because of that, the focus in the oil trunk pipeline transport is in the periodic cleaning of the inner cavity to maintain the throughput capacity of the pipes both to maintain the throughput capacity and to prepare the sections for in-line inspection. While using the ultrasonic inspection pigs, this procedure is a mandatory requirement, but the need for frequent periodic cleaning of the inner surface after using various techniques. Quite high anti-corrosive and heat-insulating effect of the layer is confirmed, so that one can speak about the possibility of using deposits as functional internal coatings of operating oil pipelines. In this case, the indirect economic effect is achieved by optimizing the frequency of cleaning the inner cavity of the pipes. Using the data obtained in the above works regarding the deposits effect on the roughness and the wall heat transfer coefficients, let’s conduct numerical studies of the thermal-hydraulic effect of the wall-boundary layer of heavy oil deposits, for which we simulate the operation conditions of variable-diameter oil pipelines at different thickness of asphalt-resin-wax oil deposit layer. 

Methods
First, let’s estimate the maximum possible loss of throughput capacity caused by the effect of deposits on the inner diameter of the pipeline, for which the Leibenzon equation is applied that explicitly expresses the head loss versus the flow rate:

\[ Q = \frac{P_2 - P_1}{\rho g} + \frac{Z_2 - Z_1}{B} + \frac{1}{B^2} \left( \frac{D^2}{4} \right) \frac{\Delta P}{\Delta T} \frac{v_m}{2} \frac{m}{2} \frac{m}{2}. \]  

(1)

After differentiating (1) with respect to the inner diameter, the expression is obtained as follows:

\[ \frac{dQ}{Q} = \frac{5}{2} \frac{m}{2} \frac{m}{2} \frac{dD}{D}. \]  

(2)

Switching to finite-difference values, the following dependences are obtained for the flow rate drop versus the residual diameter of the oil pipeline covered with a uniformly distributed layer of heavy oil deposits:

\[ \frac{\Delta Q}{Q} = -4 \frac{\Delta D}{D}; \]  

(3)

– at the laminar flow:

\[ \frac{\Delta Q}{Q} = -2.7 \frac{\Delta D}{D}; \]  

(4)

– at the turbulent flow in the zone of hydraulically smooth pipes:

\[ \frac{\Delta Q}{Q} = -2.3 \frac{\Delta D}{D}; \]  

(5)

– at the turbulent flow in the zone of mixed friction:

\[ \frac{\Delta Q}{Q} = -2.5 \frac{\Delta D}{D}; \]  

(6)

Thus, the magnitude of the pipeline section throughput

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Table 1. Initial data for the calculation of modes of oil pipelines.
Numerical simulation of thermal-hydraulic effect of wall-boundary layer of oil deposits in oil trunk pipelines

by R. Z. Sungatullin 1, R. M. Karimov* 2, R. R. Tashbulatov 2, B. N. Mastobayev 2,
1 Pipeline Transport Institute, LLC, Moscow, Russian Federation
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The paper presents the results of numerical studies of the effect of the wall-boundary layer of oil deposits formed on the inner surface of oil trunk pipelines. The possibility to reduce the hydraulic drag and to increase the throughput capacity of pipelines due to the thermal insulating and surface-smoothing properties of the asphalt-resin-wax oil deposits layer is mathematically proved. Numerical experiments proved the efficiency of the wall-boundary layer of deposits with various thickness both in isothermal and 'hot' oil pipelines. The effect is due to lower roughness of the inner surface of the pipes and higher flow temperature. The latter in non-isothermal sections of hot pumping leads to the lower average viscosity of the pumped oil. In case of isothermal pumping, the deposit layer is efficient only in developed turbulent flow conditions. Moreover, in large diameter pipelines, the effect of the deposit layer is maintained even at its considerable thickness, despite a high reduction in the inner pipeline diameter.

Key words: asphalt-resin-wax deposits, oil pipeline, thermal insulation, surface roughness, hydraulic drag, thermal-hydraulic conditions, viscosity, optimal thickness of the wall-boundary layer.

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The primary arguments in favor of the positive effect of the deposit layer on the operation of oil pipelines are given in [1, 5, 6–7]. Later, experimental laboratory studies into the properties of oil deposits taken from long-operated oil pipelines were carried out [3, 8–10] to confirm the assumptions. For example, the smoothing ability of the deposit layer was experimentally proved in the work [10], which allows to smooth the roughness of the inner wall by 40% compared to the steel pipe clean new surface or cleaned surface after using various techniques. Quite high anti-corrosive and heat-insulating effect of the layer is confirmed, so that one can speak about the possibility of using deposits as functional internal coatings of operating oil pipelines. In this case, the indirect economic effect is achieved by optimizing the frequency of cleaning the inner cavity of the pipes. Using the data obtained in the above works regarding the deposits effect on the roughness and the wall heat transfer coefficient dependencies are obtained for the flow rate drop versus the residual diameter of the oil pipeline covered with a uniformly distributed layer of heavy oil deposits:

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<td>λ_m</td>
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<td>W/(m·K)</td>
</tr>
<tr>
<td>Thermal conductivity of coating</td>
<td>λ_c</td>
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<td>W/(m·K)</td>
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<tr>
<td>Coating thickness</td>
<td>δ_i</td>
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<tr>
<td>Thermal conductivity of deposits</td>
<td>λ_d</td>
<td>0.15</td>
<td>W/(m·K)</td>
</tr>
</tbody>
</table>
Table 2. The results of calculating thermal-hydraulic modes for 'hot' transportation in non-isothermal oil pipeline sections.

<table>
<thead>
<tr>
<th>Diameter DN, mm</th>
<th>Flow rate Q, m³/h</th>
<th>Hydraulic drag variation</th>
<th>% at wall-boundary layer thickness δ, mm</th>
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<tbody>
<tr>
<td></td>
<td></td>
<td>at turbulent flow in the zone of quadratic friction</td>
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<td>at the turbulent flow in the zone of mixed friction</td>
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<td>-6.6</td>
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Table 3. The results of the process modes calculation for isothermal oil pipelines.

<table>
<thead>
<tr>
<th>DN, mm</th>
<th>3 × 1.1M Q-H (D)</th>
<th>Throughput capacity variation</th>
<th>% at wall-boundary layer thickness δ, mm</th>
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</thead>
<tbody>
<tr>
<td>530</td>
<td>1250-260 (1.0 D)</td>
<td>1256-260 (1.1 D)</td>
<td>0.5</td>
</tr>
<tr>
<td>720</td>
<td>5000-210 (0.7 D)</td>
<td>5000-210 (1.0 D)</td>
<td>1.0</td>
</tr>
<tr>
<td>1020</td>
<td>7000-210 (1.25 D)</td>
<td>7000-210 (1.0 D)</td>
<td>2.4</td>
</tr>
<tr>
<td>1220</td>
<td>10000-210 (1.0 D)</td>
<td>10000-210 (1.1 D)</td>
<td>2.1</td>
</tr>
</tbody>
</table>

capacity drop can theoretically vary in the range of 2.5–4% of the relative change in the inner diameter, while the impact of even thicker deposit layer (15 mm) decreases with the increase in the pipe diameter.

In the case of non-isothermal or 'hot' pumping of high-viscous and congealing oils under conditions of high temperature gradient at the interface of the steel wall of non-insulated pipes, the viscosity changes over a wide range as the flow temperature drops along the length of the section. The explicit expression of the similar flow dependence regarding the non-isothermal process correction is rather complicated, so let’s estimate the change in thermal-hydraulic regime using the mean value of the flow kinematic viscosity. For that, we will use again equation (1), differentiate it on oil viscosity, and also move on to finite-difference values:

\[
\frac{\Delta Q}{Q} = \frac{m}{2} \frac{\Delta v}{v},
\]

– at the laminar flow:

\[
\frac{\Delta Q}{Q} = \frac{1}{15} \frac{\Delta v}{v},
\]

– at the turbulent flow in the zone of hydraulically smooth pipes:

\[
\frac{\Delta Q}{Q} = \frac{1}{15} \frac{\Delta v}{v},
\]

– at the turbulent flow in the zone of mixed friction:

\[
\frac{\Delta Q}{Q} = \frac{0}{2} \frac{\Delta v}{v},
\]

As can be seen from (7–11), the change in the throughput capacity of the section ranges from 7 to 14% of the relative change in the kinematic viscosity of oil under turbulent flow conditions (in zones of mixed friction and hydraulically smooth pipes) to a directly proportional relationship in the laminar flow zone.

The analysis of differential equations (1–11) showed that heavy oil deposits on the inner surface of the wall can have both positive and negative thermal-hydraulic effect. On the one hand, the thermal insulation properties of sufficiently thick deposit layer contribute to an increase in the average flow temperature and to a drop in the oil kinematic viscosity. On the other hand, a decrease in the effective diameter leads to an increase in hydraulic drag. It is important to note that the assessment did not consider the effect of deposits on the roughness of the inner surface of the pipes, and therefore the presented results do not reflect the real picture, since in developed turbulent conditions, the inertia forces significantly prevail over the friction forces. For large diameter pipes, this may be a more determining factor. In the subsequent numerical simulation, we use the properties of oil deposits obtained from laboratory tests data in [10]. In particular, the thermal conductivity factor of the deposits is 0.15 W/m*K and the smoothing capacity is 40%. Thermal insulation properties of oil deposits are considered when calculating the total heat transfer coefficient. Smoothing ability predetermines the roughness of the inner surface in the presence of heavy oil deposits.

Results

Calculations of transportation modes were performed for both isothermal and non-isothermal 'hot' 530–1,220 mm diameter underground oil pipeline. Initial data for the calculations are summarized in Table 1. The calculation results are presented in Tables 2 and 3.

In calculating thermal and hydraulic modes for non-isothermal 'hot' transportation (Table 2), the wall surface roughness is adopted as for the new pipe (k = 0.2 mm). The obtained results demonstrate that the effective use of the deposit layer is possible for DN 720–1,220 oil pipelines in developed turbulent operational conditions.

Results of modeling the process conditions for isothermal oil pipelines (Table 3) confirmed the effectiveness of the deposit layer for large diameter pipes DN 1,020–1,220. Permissible layer thickness is in the range of 1–4 mm for new pipes and up to 10–12 mm for old steel pipelines (k = 0.4 mm).

Findings

As the results of numerical simulation have shown, in some cases the wall-boundary layer of heavy oil deposits to a certain thickness does not increase the hydraulic drag, but contrary assists to decrease the friction losses and to increase the throughput capacity of pipes. This positive effect is due to the smoothing ability of the deposit layer, resulting in the reduced more than twice roughness of the inner surface of the pipeline. This effect in developed turbulent conditions is enhanced by increasing the diameter of the pipeline, where the inertia forces prevail over the friction forces. The most effective wall-boundary deposits layer is observed in the old pipes with high roughness. In cases of non-isothermal hot-oil transportation, the wall-boundary deposit layer not only has the roughness smoothing ability, but at a certain thickness can have a significant insulating effect that provides an increase in the average temperature of the flow, decrease in oil viscosity and in thermal impact on the surrounding soil of the pipeline. The latter is applicable to large-diameter infield pipelines with laminar flow, where the thermal insulation effect is sharply reduced at increased diameter and increased turbulence of the flow.

Competing interests

The authors declare that there is no competing interest regarding the publication of this paper.

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\[ \frac{\Delta Q}{Q} = \frac{\Delta m}{m} \cdot \frac{\Delta \nu}{\nu}, \]

– at the laminar flow:

\[ \frac{\Delta Q}{Q} = \frac{\Delta \nu}{\nu}, \]

– at the turbulent flow in the zone of hydrodynamically smooth pipes:

\[ \frac{\Delta Q}{Q} = \frac{1}{15} \frac{\Delta \nu}{\nu}, \]

– at the turbulent flow in the zone of mixed friction:

\[ \frac{\Delta Q}{Q} = \frac{1}{15} \frac{\Delta \nu}{\nu}, \]

– at the turbulent flow in the zone of quadratic friction:

\[ \frac{\Delta Q}{Q} = \frac{0}{2} \frac{\Delta \nu}{\nu}. \]

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**Table 2. The results of calculating thermal-hydraulic modes for ‘hot’ transportation in non-isothermal oil pipeline sections.**

<table>
<thead>
<tr>
<th>Diameter DN, mm</th>
<th>Flow rate Q, m³/h</th>
<th>Throughput capacity variation [ΔQ/Q] % at wall-boundary layer thickness δ, mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>530</td>
<td>650</td>
<td>0.2</td>
</tr>
<tr>
<td>950</td>
<td>1.8</td>
<td>3.7</td>
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<td>-7.2</td>
<td>-6.6</td>
</tr>
</tbody>
</table>

**Table 3. The results of the process modes calculation for isothermal oil pipelines.**

<table>
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</thead>
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<td>1250</td>
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<tr>
<td>720</td>
<td>5000-210 (0.7 D)</td>
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<td>1020</td>
<td>7000-210 (1.25 D)</td>
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</tr>
<tr>
<td>1220</td>
<td>10000-210 (1.0 D)</td>
<td>0.1</td>
</tr>
</tbody>
</table>

**Findings**

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**Competing interests**

The authors declare that there is no competing interest regarding the publication of this paper.

**References**


RESEARCH PAPER

Optimizing the desktop processing of the terrestrial laser scanning data in assessing the stress-strain state of tanks

by G. G. Vasiliev 1, A. P. Salnikov 1, A. A. Katanov* 2, M. V. Likhovtsev 2, E. G. Ilyin 2

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ABSTRACT

This paper deals with optimizing the desktop processing of the tanks’ terrestrial laser scanning data in assessing their stress-strain state (SSS). The basic concepts to optimize the desktop processing are established and analyzed, thus providing the means to reduce the spent resources and time of PC work without losses to the final result of the tanks’ SSS assessment.

Key words: vertical steel tank (VST), terrestrial laser scanning, stress-strain state (SSS).

INTRODUCTION

When determining the residual service life of the tank, strength analysis of its structural elements is performed. Such analysis is recommended to be carried out by 3D-simulation using software products that use the finite element method 1, 2. In order to improve the monitoring efficiency of engineering structures’ technical condition, the terrestrial laser scanning technology is used for more than 12 years in domestic and international practice [1].

The terrestrial laser scanning is a logical continuation of the electronic tachometer’s development and enables the operator to obtain in the automated mode the complete information about the surface of the scanned object [2, 3]. By their main purpose, terrestrial laser scanners are purely topographic devices. However, the accuracy of the point coordinates measurement and the high resolution of the latest generations of terrestrial laser scanners open the potential for their wide application as inspection instruments in assessing the technical condition of storage tanks for oil and petroleum products 1, 3, 4.

The data obtained as a result of the terrestrial laser scanning (hereinafter – laser scanning), generate the basis for constructing the 3D model of the tank surface, with regard to its real geometric shape, suitable for the analysis of its stress-strain state (SSS) using specialized software packages employing the finite element method [4]. The results of such analysis reflect the real picture of the tank’s SSS, since the original 3D model is constructed with regard to the actual geometric shape and spatial position of the tank [5-8].

At the same time, optimization of methods for desktop processing of the tank laser scanning data to obtain its 3D model becomes actual. This is explained by the need to allocate significant resources and time of the personal computer, spent on the desktop processing of the entire array of data obtained by laser scanning of the tank. Thus, depending on the selected method of scanning and the resolution of the laser scanner, the total point cloud of the 20,000 m³ tank surface may consist of more than 20 million points. Moreover, higher laser scanning resolution multiplies the arrayed data and necessitates the use of much more powerful personal computers [5].

In order to solve the issue of optimizing the desktop processing method of tanks’ laser scanning data, it is necessary to review the main steps of the tank point model

Table 1. Data for work in GeomagicStudio.

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Table 2. Data for estimation in Ansys.

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<th>Triangle height h, mm</th>
<th>Triangle area, m²</th>
<th>Required number of triangles</th>
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*Corresponding author: Alexey A. Katanov, e-mail: KatanovAA@niitnn.transneft.ru
http://dx.doi.org/10.28999/2514-541X-2019-3-2-112-117
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</table>
Optimizing the desktop processing of the terrestrial laser scanning data in assessing the stress-strain state of tanks

by G. G. Vasilyev 1, A. P. Salnikov 1, A. A. Katanov* 2, M. V. Likhovtsev 2, E. G. Ilyin 2

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INTRODUCTION

When determining the residual service life of the tank, strength analysis of its structural elements is performed. Such analysis is recommended to be carried out by 3D-simulation using software products that use the finite element method 1, 2. In order to improve the monitoring efficiency of engineering structures technical condition, the terrestrial laser scanning technology is used for more than 12 years in domestic and international practice [1].

The terrestrial laser scanning is a logical continuation of the electronic tacheometer’s development and enables the operator to obtain in the automated mode the complete information about the surface of the scanned object [2, 3]. By their main purpose, terrestrial laser scanners are purely topographic devices. However, the accuracy of the point coordinates measurement and the high resolution of the latest generations of terrestrial laser scanners open the potential for their wide application as inspection instruments in assessing the technical condition of storage tanks for oil and petroleum products 1, 2, 3.

The data obtained as a result of the terrestrial laser scanning (hereinafter – laser scanning), generate the basis for constructing the 3D model of the tank surface, with regard to its real geometric shape, suitable for the analysis of its stress-strain state (SSS) using specialized software packages employing the finite element method [4]. The results of such analysis reflect the real picture of the tank’s SSS, since the original 3D model is constructed with regard to the actual geometric shape and spatial position of the tank [5-8].

At the same time, optimization of methods for desktop processing of the tank laser scanning data to obtain its 3D model becomes actual. This is explained by the need to allocate significant resources and time of the personal computer, spent on the desktop processing of the entire array of data obtained by laser scanning of the tank. Thus, depending on the selected method of scanning and the resolution of the laser scanner, the total point cloud of the 20,000 m³ tank surface may consist of more than 20 million points. Moreover, higher laser scanning resolution multiplies the arrayed data and necessitates the use of much more powerful personal computers [5].

In order to solve the issue of optimizing the desktop processing method of tanks’ laser scanning data, it is necessary to review the main steps of the tank point model generating procedure and indicate the most time-consuming and resource-intensive stages. The paper deals with optimizing the desktop processing of the tanks’ terrestrial laser scanning data in assessing their stress-strain state (SSS). The basic concepts to optimize the desktop processing are established and analyzed, thus providing the means to reduce the spent resources and time of PC work without losses to the final result of the tanks’ SSS assessment.

Key words: vertical steel tank (VST), terrestrial laser scanning, stress-strain state (SSS).

ABSTRACT

The paper deals with optimizing the desktop processing of the tanks’ terrestrial laser scanning data in assessing their stress-strain state (SSS). The basic concepts to optimize the desktop processing are established and analyzed, thus providing the means to reduce the spent resources and time of PC work without losses to the final result of the tanks’ SSS assessment.

Table 1. Data for work in Geomagic Studio.

<table>
<thead>
<tr>
<th>Tank</th>
<th>Belt #</th>
<th>Actual plate thickness, mm</th>
<th>Height of belts, m</th>
<th>Tank image level, m</th>
<th>Roof weight, kg</th>
<th>Product density, kg/m³</th>
<th>Steel density, kg/m³</th>
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<td></td>
</tr>
</tbody>
</table>

Table 2. Data for estimation in Ansys.

<table>
<thead>
<tr>
<th>Tank</th>
<th>Triangle height h, mm</th>
<th>Triangle area, mm²</th>
<th>Required number of triangles</th>
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<tr>
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<td>200</td>
<td>23094</td>
<td>148557</td>
</tr>
</tbody>
</table>
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At the same time, such a step can lead to the polygonal model (i.e., using smaller number of triangular polygons to build a polygonal model than their theoretically necessary resolution of the tank SSS assessment). The concept was accepted that the polygonal model can be approximated by the identical equilateral triangles. The height of triangles $h$ was considered as the evaluation factor of their size (and, as a consequence, of their number).

This height $h$ also enables to judge on the minimum necessary resolution of the tank surface laser scanning for its SSS assessment. Potentially, it will not only optimize the process of desktop data processing, but also can reduce the time of field work when scanning the tank surface.

Surface modeling and further estimation of SSS were carried out at different values of the approximating triangles height $h$ ($h = 15, 25, 50, 100, 150, 200$ mm) for the walls of two tanks: VSTP-20000 with significant geometric defects, and VSTP-50000, without significant geometric defects. For the example considered in this paper, the terrestrial laser scanning results were desktop-processed using the non-linear geometric approximation of tank surfaces point models was the nature and magnitude of changes of the effective midplane and surface stresses in selected zones (three zones were considered for each type of stress: zones $1-3$ and $4-6$ in VSTP-20000 for midplane and surface stresses; zones $7-9$ and $10-12$ in VSTP-50000, respectively).

The choice of equivalent von Mises stress as a criterion for analysis of changes in tank’s SSS is explained by the fact that this stress is the most suitable for the assessment of complex stress state of tank wall with regard to the deviations of its geometry from cylindrical shape (in the form of dents, bulges, angularity) and the deviation of its spatial position from the design. In this case, the equivalent von Mises stresses are determined by the formula:

\[
\sigma_{eq} = \sqrt{\frac{1}{2} \left( (\sigma_1 - \sigma_2)^2 + (\sigma_1 - \sigma_3)^2 + (\sigma_2 - \sigma_3)^2 \right)},
\]

where $\sigma_1, \sigma_2, \sigma_3$ - principal stresses.

The selection of individual zones to analyze changes in the effective midplane and surface stresses at different heights $h$ of the approximating triangles was carried out on the basis of the following criteria:

1. The maximum stress of this type is acting in the zone at $h = 15$ mm;
2. There are major tank geometry defects in the zone (dents, bulges, angularity, etc.).
3. The result of the measurement to simulate the work of the upper part of the wall [10].

SSS estimation was performed in the non-linear geometric setting.

### Criteria for comparison and analysis of the simulation results

The main evaluation criterion for comparison and analysis of the simulation results for 3D models of tank surfaces with different number of triangles used in the polygonal approximation of point models was the nature and magnitude of changes in SSS of tanks.

Comparison of the simulation results and analysis of the changes in SSS of the tank wall was carried out for midplane and surface equivalent (von Mises) stresses compared to the surface model at $h = 15$ mm, with regard to:

- changes in the overall picture of the effective stress distribution in the wall of tanks at various $h$;
- changes of the effective midplane and surface stresses in selected zones (three zones were considered for each type of stress: zones $1-3$ and $4-6$ in VSTP-20000 for midplane and surface stresses; zones $7-9$ and $10-12$ in VSTP-50000, respectively).

### Simulation in Ansys software

Ansys Workbench software was used to calculate SSS. Additional processing of tank models in Ansys was not carried out, except for the walls breakdown into rings. When calculating the wall’s SSS, the following loads were considered (Table 2):

- the hydrostatic pressure of the product;
- the net weight of the wall (using the actually measured thicknesses according to the results of technical inspection);
- the roof weight (the weight of the roof was transferred to the wall in the form of a distributed load; the roof is not shown in the figures for clarity).

Shell 181 was used as the finite element (maximum size of the finite elements is $10$ cm). The thrust block was considered as an anchor, and $20\times20$ cm square beam was used as a stiffness element to simulate the work of the upper part of the wall [10].

SSS estimation was performed in the non-linear geometric setting.

### Figure 2. Zones selected for the analysis of changes in surface equivalent stress of VSTP-20000 tank.

<table>
<thead>
<tr>
<th>Zone</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Zone 1</td>
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<td>Zone 2</td>
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<td>5</td>
<td>Zone 5</td>
</tr>
<tr>
<td>6</td>
<td>Zone 6</td>
</tr>
</tbody>
</table>

The initial data for tanks SSS calculation in Ansys software are shown in the Table 2.

### Simulation in Geomagic Studio software

At all steps of simulation, point models of the tanks VSTP-20000 and VSTP-50000 were subjected to the same desktop processing.

The difference was only in the number of triangles used in the polygonal approximation of tank surfaces point models that was taken according to Table 1.

Parameters of additional processing of tanks’ polygonal models and also the parameters of polygonal model’s transformation into shell surfaces (NURBS-surfaces) are presented in the Table 3 in a sequence of the processing performed.

The resulting shell models of tank surfaces were exported to Ansys software in the .igs format. The selection of this format for export is due to the fact that it was specifically designed to exchange 3D-models between various CAD/CAE – systems and is the most common [3].

### Simulation results

An example of the results for midplane equivalent stress evaluation in VSTP-20000 tank wall at $h = 15$ mm and $h = 200$ mm is shown in Fig. 3 and 4.

As a result of the simulation, it was found that the increase in the size of the triangles used in the polygonal approximation of the tank point model (decrease in the number of triangles) leads to the following:

1. Gradual decrease in the overall level of the midplane and surface stress acting in the tank wall, which is explained by the model’s geometry gradual approaching to the cylindrical shape as and when the number of approximating triangles decreases. This can be seen in zones 1, 3, 7, 8 (Fig. 5) and 5, 6, 11, 12 (Fig. 6);
2. Gradual increase of the maximum stress zone size in the tank first-ring wall is explained not only by a...
A pipeline tank is a critical component in many industrial applications, and ensuring its structural integrity is crucial. This process involves the conversion of a point model into a 3D model suitable for analysis of SSS (structural safety assessment).

### Initial Concepts and Data for Simulation

To evaluate the number of triangle polygons (hereinafter - triangles) needed for polygonal approximation of the tank wall surface point model without 'damage' to final results of SSS assessment, the concept was accepted that the point model can be approximated by the identical equilateral triangles. The height of triangles $h$ was considered as the evaluation factor of their size (and, as a consequence, of their number).

This height $h$ also enables to judge on the minimum necessary resolution of the tank surface laser scanning for its SSS assessment. Potentially, it will not only optimize the process of desktop data processing, but also can reduce the time of field work when scanning the tank surface.

### Simulation in Ansys software

**Ansys Workbench** was used to calculate SSS. Additional processing of tank models in Ansys was not carried out, except for the walls breakdown into rings. When calculating the wall’s SSS, the following loads were considered (Table 2):

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- the net weight of the wall (using the actually measured thicknesses according to the results of technical inspection);
- the roof weight (the weight of the roof was transferred to the wall in the form of a distributed load; the roof is not shown in the figures for clarity).

Shell 181 was used as the finite element (maximum size of the finite elements is 10 cm). The thrust block was considered as an anchorage, and 20х20 cm square beam was used. The element to simulate the work of the upper part of the wall [10]. SSS estimation was performed in the non-linear geometric setting.

### Criteria for Comparison and Analysis of the Simulation Results

The main evaluation criterion for comparison and analysis of the simulation results for 3D models of tank surfaces with different number of triangles used in the polygonal approximation of point models was the nature and magnitude of changes in SSS of tanks.

Comparison of the simulation results and analysis of the changes in SSS of the tank wall was carried out for midplane and surface equivalent (von Mises) stresses compared to the surface model at $h = 15$ mm, with regard to:

- changes in the overall picture of the effective stress distribution in the wall of tanks at various $h$;
- changes of the effective midplane and surface stresses in selected zones (three zones were considered for each type of stress: zones 1–3 and 4–6 in VSTP-20000 for midplane and surface stresses; zones 7–9 and 10–12 in VSTPA-50000, respectively).

The choice of equivalent von Mises stress as a criterion for analysis of changes in tank’s SSS is explained by the fact that this stress is the most suitable for the assessment of complex stress state in the tank wall with regard to the deviations of its geometry from cylindrical shape (in the form of dents, bulges, angularity) and the deviation of its spatial position from the design. In this case, the equivalent von Mises stresses are determined by the formula:

$$
\sigma_{eq} = \frac{1}{\sqrt{2}} \left( (\sigma_x - \sigma_y)^2 + (\sigma_y - \sigma_z)^2 + (\sigma_z - \sigma_x)^2 \right),
$$

where $\sigma_x, \sigma_y, \sigma_z$ - principal stresses.

The selection of individual zones to analyze changes in the effective midplane and surface stresses at different heights $h$ of the approximating triangles was carried out on the basis of the following criteria:

- the maximum stress of this type is acting in the zone at $h = 15$ mm;
- there are major tank geometry defects in the zone (dents, bulges, angularity, etc.).

In particular, Fig. 2 shows zones 4, 5 and 6 of VSTP-20000 tank selected for the analysis of changes in surface equivalent stress. These areas correspond to the maximum local deviations of the tank surface from the correct geometric shape.

### Simulation Results

An example of the results for midplane equivalent stress evaluation in VSTP-20000 tank wall at $h = 15$ mm and $h = 200$ mm is shown in Fig. 3 and 4.

As a result of the simulation, it was found that the increase in the size of the triangles used in the polygonal approximation of the tank point model (decrease in the number of triangles) leads to the following:

1. Gradual decrease in the overall level of the midplane and surface stress acting in the tank wall, which is explained by the model's geometry gradual approaching to the cylindrical shape as and when the number of approximating triangles decreases. This can be seen in zones 1, 3, 7, 8 (Fig. 5) and 5, 6, 10, 11, 12 (Fig. 6).
2. Gradual increase of the maximum stress zone size in the tank first-ring wall is explained not only by a
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**Table 3.** Additional models processing in Geomagic Studio package.

<table>
<thead>
<tr>
<th>Carcass defects removal</th>
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<tr>
<td>Surface detail</td>
<td>Maximum</td>
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<tr>
<td>Custom tolerance</td>
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</tbody>
</table>

The dimensions of approximating surface elements in other software packages for processing the laser scanning results and preparing data to calculate SSS of civil engineering structures.

### Competing interests

The authors declare that there is no competing interest regarding the publication of this paper.

### References


decrease in the values limiting the zone of maximum stress (visual component of the simulation results presentation), but also by a slight increase of stress in certain zones compared to the initial values. Thus, at $h = 200$ mm the action point of the maximum midplane stress shifts to a new region and the stress increases by 4 MPa in VSTPA-50000 tank; increase by 4 MPa in VSTPA-50000 tank; when passing from the point model to the polygonal approximation of the tank wall surface, the most optimal equilateral triangle, in terms of the personal computer resource and time of operation, has the height $h$ from 50 to 100 mm.

### Findings
Based on the results of the simulation, the following conclusions can be drawn:
1. When passing from the point model to the polygonal approximation of the tank wall surface, the most optimal equilateral triangle, in terms of the personal computer resource and time of operation, has the height $h$ from 50 to 100 mm.
2. The results of this study can be used to determine

### References
[1] Averaged triangle height, mm

### Table 3. Additional models processing in Geomagic Studio package

<table>
<thead>
<tr>
<th>Triangle area, mm$^2$</th>
<th>Triangle height $h$, mm</th>
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<tr>
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<td>Priority of curvature</td>
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<td>Maximum</td>
</tr>
<tr>
<td>Custom tolerance</td>
<td>0.001 mm</td>
</tr>
</tbody>
</table>

### Figure 3. Midplane equivalent stress in VSTP-20000 tank wall at $h = 15$ mm.

### Figure 4. Midplane equivalent stress in VSTP-20000 tank wall at $h = 200$ mm.

### Figure 5. Relative change of the midplane stress in the tank wall (stress at $h = 15$ mm is taken equal to 1).

### Figure 6. Relative change of the surface stress in the tank wall (stress at $h = 15$ mm is taken equal to 1).
Numerical method of pipeline hydraulics identification at turbulent flow of viscous liquids

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1 Azerbaijan State Oil and Industry University (ASIOU), Baku, Azerbaijan

ABSTRACT

A mathematical model for the process of incompressible viscous liquid unsteady turbulent flow in a pipeline is proposed, based on the semi-empirical theory of Prandtl turbulence. As part of this model, the problem of identifying the pipeline hydraulics is formulated. It is assumed that slippage of the flow on the pipeline wall meets the condition of Navier law. This problem belongs to the class of inverse problems related to the restoration of the parabolic equations right parts’ dependence on time. Next, a difference analogue of the formulated problem is constructed, and a special representation associated with the solution of two linear difference problems of the second order is proposed to solve the obtained difference problem. The result is an explicit formula to determine the approximate value of the differential pressure along the length of the pipeline for each discrete value of the time variable. On the basis of the proposed computational algorithm, numerical experiments for model problems were carried out.

Key words: pipeline transport, turbulent conditions, hydraulics, semi-empirical theory of turbulence, non-local integral condition, inverse problem.

INTRODUCTION

Currently, trunk pipelines are the key transport of various liquids, including oil and petroleum products. In their design, the required flow rate, which serves as the main characteristic of the pipeline performance, and the positions of its start and end points are usually specified. One of the key tasks is to identify the hydraulics of the pipeline, that is to determine the differential pressure required for a given liquid flow rate. In practice, when solving this problem, the fluid flow in the pipeline is stationary and the Darcy – Weisbach formula [1–3] is used for calculations:

\[ \Delta P = \lambda \frac{L}{d} \left( \frac{u}{2g} \right)^2 \]  

where \( \Delta P \) – differential pressure in the pipeline section with length \( L \); \( d \) – pipeline diameter; \( \lambda \) – drag coefficient;

\( u \) – average velocity in the pipeline cross-section.

Formula (1) is used in the case of both turbulent and laminar flow, the difference is only in the values of the drag coefficient \( \lambda \). This formula, as well as an explicit expression for the drag coefficient can be obtained only for the stationary laminar flow of homogeneous incompressible liquids through the pipeline at the appropriate rheological laws. As a boundary condition on the pipeline wall, the so-called no-slip condition is used, according to which the velocity of the liquid on the pipeline wall is assumed to be zero. So, there is a known parabolic velocity profile of viscous liquids stationary flow caused by a differential pressure. However, for the turbulent flow regime, due to the extreme complexity of the analytical study of its mathematical models, it is not possible to obtain formula (1), so its acceptability is only postulated.

The experimental values of drag coefficient \( \lambda \) are used in practical calculations of turbulent flow in liquids. For its definition, there are many empirical and semi-empirical formulas [1–3]. Meanwhile, despite numerous theoretical and experimental work carried out by various researchers, a unified approach to determining the drag coefficient does not exist. In addition, another very important circumstance regarding the boundary condition on the pipeline wall should be noted. On the basis of molecular concepts, some authors concluded that instead of the liquid no-slip condition on the solid wall of a pipeline, there is a slip condition in fact [4, 5]. The author [6] has established by numerical experiments, as part of the incompressible viscous liquid flow model in a pipeline, that the slip condition can be fulfilled at certain ratios between the liquid flow rate and the differential pressure on the wall.

In the literature, three models of liquid interaction with a solid wall are considered; they correspond to the following boundary conditions: no-slip, slip according to Navier law and slip with ultimate stress [4, 5, 7]. According to the Navier slip model, the flow velocity on the pipeline wall is proportional to the tangential stress:

\[ w = \frac{\mu}{\eta} \frac{\partial \tau}{\partial y} \]

where \( w \) means the liquid flow velocity parallel to the pipeline axis; \( \mu \) means the liquid dynamic viscosity; \( \eta \) means the friction coefficient. At \( \tau = 0 \), the given boundary condition is reduced to the classic no-slip condition.

The problem of pipeline hydraulics identification for unsteady flow of viscous liquids based on the no-slip model is studied in [8]. However, it is obvious that the no-slip model is a special case of the Navier model. In this context, it is very important in the pipeline transport practice to develop methods for identifying the pipeline hydraulics in the unsteady flow of viscous liquids based on the Navier model. This paper deals with the problem of the pipeline hydraulics identification in the unsteady turbulent flow of viscous liquids, which is based on the semi-empirical Prandtl theory of turbulence and anticipates the satisfaction of slippage condition by Navier law on the wall of the pipeline.

Problem formulation

Given a horizontally located pipeline with stiff walls, length \( l \), radius \( R \), and an incompressible viscous liquid pumped through it under the turbulent conditions. It is assumed that the axis \( Oz \), as well as the flow, is directed along the axis of the pipeline, and the only one \( u \), remains of three velocity components \( (u, v, w) \), but \( u \) and \( w \) are equal to zero. Assuming that the turbulent flow of incompressible viscous fluid in the pipeline is single-layered and axisymmetric, the mathematical model of this process may be presented as follows [3, 9]:

\[ \frac{\partial u}{\partial t} + \frac{1}{R} \frac{\partial}{\partial r} \left( r u \right) + \frac{1}{R^2} \frac{\partial}{\partial z} \left( R^2 v \right) = - \frac{1}{\rho} \left( \frac{\partial P}{\partial r} \right) + \nu \left( \frac{\partial^2 u}{\partial r^2} + \frac{1}{r} \frac{\partial u}{\partial r} \right) \]

where \( u \) – the liquid flow velocity component parallel to the pipeline axis;

\[ P \] – pressure;

\( \rho \) – liquid density;

\( \tau \) – tangential friction stress.

It is known that during the liquid turbulent flow in the pipeline, much more energy is spent than in the case of the laminar flow, where the energy is spent only to overcome the internal friction forces between the adjacent layers of liquid moving at different velocities. While in the turbulent mode, much energy is also spent on the mixing process, causing additional tangential stresses in the liquid. In this regard, the total tangential friction stress \( \tau \) arising in a turbulent flow is defined as the sum of two stresses [3, 9]:

\[ \tau = \tau_t + \tau_s \]

where \( \tau_t \) – tangential internal friction stress; \( \tau_s \) – tangential stress of the turbulent friction, caused by the turbulent mixing of the liquid. The viscous component of the total tangential stress \( \tau_s \) is determined by Newton formula:

\[ \tau_s = \frac{1}{2} \rho u^2 \]

We use the Prandtl turbulent friction formula for the tangential stress of turbulent friction:

\[ \tau_t = \frac{1}{2} \rho u^2 + \frac{1}{2} \rho \nu \frac{\partial u}{\partial r} \frac{\partial v}{\partial z} \]

where \( y \) – the length of the mixing path, which, according to Prandtl’s semiempirical theory of turbulence, increases with the distance from the stiff wall surface, while the linearity of \( y \) changes is postulated:

\[ y = \kappa (R-r) \]

where \( \kappa \) – Karman universal constant. Hence, the total tangential friction stress \( \tau \) can be represented as:

\[ \tau = \mu \left( \kappa + \nu \kappa (R-r) \right) \left( \frac{\partial u}{\partial r} \right) \frac{\partial v}{\partial z} \]

It follows from the second equation of the system (2) that \( \nu \) is the function of only \( r \) and \( \tau \) and two last equations demonstrate the pressure \( P \) independence of \( r \) and \( \rho \). It means that \( \frac{\partial P}{\partial z} \) is the function of the time only. Supposing that...
Numerical method of pipeline hydraulics identification at turbulent flow of viscous liquids

by Kh. M. Gamzaev*

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INTRODUCTION

A mathematical model for the process of incompressible viscous liquid unsteady turbulent flow in a pipeline is proposed, based on the semi-empirical theory of Prandtl turbulence. As part of this model, the problem of identifying the pipeline hydraulics is formulated. It is assumed that slippage of the flow on the pipeline wall meets the condition of Navier law. This problem belongs to the class of inverse problems related to the restoration of the parabolic equations right parts’ dependence on time. Next, a difference analogue of the formulated problem is constructed, and a special representation associated with the solution of two linear difference problems of the second order is proposed to solve the obtained difference problem. The result is an explicit formula to determine the approximate value of the differential pressure along the length of the pipeline for each discrete value of the time variable. On the basis of the proposed computational algorithm, numerical experiments for model problems were carried out.

Key words: pipeline transport, turbulent conditions, hydraulics, semi-empirical theory of turbulence, non-local integral condition, inverse problem.

RESEARCH PAPER

ABSTRACT

It is known that during the liquid turbulent flow in the pipeline, much more energy is spent than in the case of the laminar flow, where the energy is spent only to overcome the internal friction forces between the adjacent layers of liquid moving at different velocities. While in the turbulent mode, much energy is also spent on the mixing process, causing additional tangential stresses in the liquid. In this regard, the total tangential friction stress \( \tau \) arising in a turbulent flow is defined as the sum of two stresses [3, 9]:

\[
\tau = \tau_\text{f} + \tau_\text{t},
\]

where \( \tau_\text{f} \) – tangential internal friction stress; \( \tau_\text{t} \) – tangential stress of the turbulent friction, caused by the turbulent mixing of the liquid. The viscous component of the total tangential stress \( \tau_\text{f} \) is determined by Newton formula:

\[
\tau_\text{f} = \mu \frac{\partial u}{\partial y},
\]

where \( \mu \) – liquid dynamic viscosity; \( y \) means the liquid flow velocity parallel to the pipeline axis; \( \frac{\partial u}{\partial y} \) means the liquid flow velocity component perpendicular to the pipeline axis.

We use the Prandtl turbulent friction formula for the tangential stress of turbulent friction:

\[
\tau_\text{t} = \rho \nu \frac{\partial^2 u}{\partial y^2},
\]

where \( \nu \) – the length of the mixing path, which, according to Prandtl’s semiempirical theory of turbulence, increases with the distance from the stiff wall surface, while the linearity of \( y \) changes is postulated:

\[
y \sim \kappa (R - r),
\]

where \( \kappa \) – Karman universal constant. Hence, the total tangential friction stress \( \tau \) can be represented as:

\[
\tau = \left( \mu + \nu \kappa \right) \left( R - r \right) \left| \frac{\partial u}{\partial y} \right| \frac{\partial u}{\partial y}.
\]

It follows from the second equation of the system (2) that \( u_r \) is the function of only \( r \) and \( \tau \), and two last equations demonstrate the pressure \( P \) independence of \( r \) and \( \phi \). It means that \( \frac{\partial P}{\partial \phi} = 0 \) is the function of the time only. Supposing that...
are studied in works [8, 10–13].

The recovery of the right parts of partial differential equations as well as numerical methods for solving inverse problems for local condition for equation (4). The issues of formulation, as the additional condition (8) in this problem is not a classical class of inverse problems associated with the recovery of the right parts of partial differential equations [10]. However, the problem of identifying the pipeline hydraulics problems (4–8) may be written as follows:

\[ \frac{\partial u}{\partial t} + \frac{1}{r} \frac{\partial}{\partial r} \left( r \frac{\partial u}{\partial r} \right) + \frac{\partial u}{\partial t} = 0, \]

where \( u \) is the volumetric flow rate of the liquid, \( P \) – differential pressure along the pipeline length in the flow direction.

Let be known for equation (4):

\[ Q = \int Q \, \mathrm{d}t, \]

\[ P = \int P \, \mathrm{d}r, \]

where \( \gamma = \mu / \rho \) – kinematic viscosity of the liquid; \( \Delta P = P - P^0 \) – variation versus time \( \Delta P(t) \) and having solved the direct problem (4) – (7), one can find the volumetric flow rate of the liquid in the pipeline.

First, let's represent equation (4) and conditions (5–8) as a system of linear algebraic equations, where the approximate values of the sought-for functions \( u(r, t) \) and \( P(r, t) \) are defined by the following quadrature formula:

\[ Q' = \sum_{j=1}^{m} w_j u_j, \]

where \( Q - \int Q \, \mathrm{d}t \), \( w_j \) – the quadrature formula’s coefficients.

Thus, the computational algorithm for solving the problem (4) – (7) is as follows:

1. Define the time step \( \Delta t \) and the spatial step \( \Delta r \).
2. Choose the quadrature formula for \( Q \) and \( P \).
3. Formulate the system of linear algebraic equations for the initial conditions (5–8) and the boundary condition (9).
4. Solve the system of linear algebraic equations using a suitable method (e.g., Thomas algorithm).
5. Calculate the approximate values of the sought-for functions \( u(r, t) \) and \( P(r, t) \) for the next time step using the obtained solution.
6. Repeat steps 3–5 until the desired time interval is reached.

The obtained difference problems (20–22) and (23–25) at every fixed value \( j \), \( i \), and \( \mathbf{a}_j \) are a system of linear algebraic equations with a tridiagonal matrix, and the solutions of these systems irrespective of \( \Delta \) may be found by Thomas method [10].

And, substituting the representation (19) into (17), we have

\[ Q' = \sum_{j=1}^{m} w_j u_j, \]

where \( Q' = \int Q \, \mathrm{d}t \), \( w_j \) – the quadrature formula’s coefficients.

From here, one can determine the approximate value of the sought-for function \( P(t) \) at \( t = i \), i.e. \( \Delta P(t) \):

\[ P(t) = \int P \, \mathrm{d}t, \]

Thus, the computational algorithm for solving the difference problem (14–18) to define \( w_j \) at \( i = 0, \ldots, m \) and \( \mathbf{a}_j \) at every fixed value \( j = 1, \ldots, m \) it is based on the solution of two linear difference problems of the second order (20–22) and (23–25) with respect to auxiliary variables \( x_j \), \( y_j \), \( i = \mathbf{a}_j \) determination of \( \Delta \) from (26) and use of the representation (19) for \( w_j \) at \( i = 0, \ldots, m \).

Results of numerical calculations

The numerical experiments were carried out for model problems on the basis of the proposed computational algorithm. The procedure of the numerical experiment is
Solving method

First, let's represent equation (4) and conditions (5–8) in a dimensionless format. This will enable us to select the range of dimensionless variables changes so as to improve the problem casualty. Let's introduce the following dimensionless variables:

\[
\begin{align*}
\tau &= T^* \frac{T}{R} \\
\xi &= \frac{r}{R} \\
\eta &= \frac{t}{T} \\
\phi &= \frac{\phi^*}{\nu} \\
\psi &= \frac{\psi^*}{R^2} \\
\Delta &= \frac{\Delta P^*}{P^*} \\
\end{align*}
\]

where \(\gamma = \frac{\nu}{\rho} - \) kinematic viscosity of the liquid;

\(\Delta P(t)\) – differential pressure along the pipeline length in the flow direction.

Let be known for equation (4):

\[u_{\text{in}} = 0\]

the initial boundary condition

\[
\frac{\partial u}{\partial r} \bigg|_{r=0} = 0
\]

the natural boundary condition at \(r = 0\)

\[
\frac{\partial u}{\partial r} \bigg|_{r=R} = 0
\]

and the boundary condition of slipping on the pipeline wall according to Navier law

\[
\tau \frac{\partial u}{\partial r} + \Gamma u = 0
\]

where \(\gamma = \frac{\nu}{R}\) - slipping length.

Apparently, by setting the law of differential pressure variation versus time \(\Delta P(t)\) and having solved the direct problem (4) – (7), one can find the volumetric flow rate of the given liquid flow rate in the pipeline.

\[
\frac{\partial Q}{\partial t} = \frac{\partial \Delta P}{\partial r}
\]

(8)

Now, let's assume that the volumetric liquid flow rate variation law \(Q(t)\) is known, and it is required to find the variation of the dimensionless differential pressure \(\Delta P(t)\) needed for a given liquid flow rate in the pipeline.

Thus, the problem of identifying the pipeline hydraulics is to determine the functions \(u(r,t)\) and \(\Delta P(t)\) that satisfy the equation (4) and conditions (5–8). This problem belongs to the class of inverse problems associated with the recovery of the right parts of partial differential equations [10]. However, the additional condition (8) in this problem is not a classical local condition for equation (4). The issues of formulation, as well as numerical methods for solving inverse problems for local condition for equation (4), were studied in works [8, 10–13].
The first set of calculations was performed using undisturbed input data, the desired function $ΔP(t)$ is restored exactly for all calculated grids in time (Table 1, column 3).

From Table 2 it follows that when the slip length increases from $γ = 0$ to $γ = 0.032$, the differential pressure, which would ensure the given liquid flow in the pipeline, decreases by about 2-fold.

Table 1. Results of numerical calculations.

<table>
<thead>
<tr>
<th>t, s</th>
<th>Exact $\times 10^{-5}$ Pa</th>
<th>Calculated $\delta=0$</th>
<th>$\delta=10^{-6}$</th>
<th>$\delta=5\times10^{-4}$</th>
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<td>3.062</td>
<td>3.062</td>
<td>3.063</td>
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<td>1.772</td>
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<td>4.725</td>
<td>4.725</td>
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</table>

Numerical calculations were performed using a space-time difference grid with increments $Δt=0.01$, $Δx=10^{-5}$. The results of a numerical experiment performed for the case $v=3\times10^{-4}$ m/s; $ρ=1000$ kg/m$^3$; $R=0.6$ m; $ΔP(t)$ for $μ=μ_{\text{min}}$; $ω=4.5\times10^{-2}$ Pa/s; $γ=2\times10^{-3}$ m; $ΔP(t)=μ=0$, $L=1000$ m using undisturbed and disturbed input data are presented in Table 1.

Results of the numerical experiment show that with undisturbed input data, the desired function $ΔP(t)$ is restored exactly for all calculated grids in time (Table 1, column 3). And when using perturbed input data, where the error has a fluctuating character, the desired function $ΔP(t)$ is recovered with an error. In this case, the maximum relative error for the recovered values of the sought-for function $ΔP(t)$ does not exceed 1.3% and 2.2%, respectively.

Numerical experiments were carried out to study the effect of the wall boundary slip condition on the pipeline hydraulics. The results of numerical calculations for the case $v=3\times10^{-4}$ m/s; $ρ=1000$ kg/m$^3$; $L=1000$ m using undisturbed and disturbed input data are presented in Table 1.

It should be noted that the proposed model is not applicable for the calculation of transient pumping modes in the case of significant role of wave processes. For this purpose, one can use a mathematical model of turbulent flow, built with regard to the compressibility of the pumped liquid.

Findings

The problem to identify the pipeline hydraulics at unsteady turbulent flow of viscous liquids was considered, taking into account slipping on the pipeline wall according to Navier law.

The developed numerical method based on the problem discretization in time and space, and a special representation for the separation of the sought-for variables. The proposed method allows to determine the differential pressure and the flow velocity distribution over the pipeline cross-section in each time layer. The results of numerical experiments carried out for the models show that ensuring slip conditions on the pipeline wall can decrease the cost of pumping viscous liquids in the turbulent mode.

The work was performed with the financial support of the “University Grant” of the Azerbaijan State Oil and Industry University (grant No. ADNSU-2018-1-01).

Competing interests

The authors declare that there is no competing interest regarding the publication of this paper.

References


data, \( \delta = 10 \times 10^{-5} \) Pa

Then, the found relationship is taken as the equation

\[ \frac{\partial \Delta P}{\partial r} = 0 \]

Results of numerical calculations for the case \( Q = 3 \) m\(^3\) s\(^{-1}\), \( \gamma = 0 \) and \( \gamma = 0.002 \).

From Table 2 it follows that when the slip length increases from \( \gamma = 0 \) to \( \gamma = 0.032 \), the further 4-fold increase in the slip length from \( \gamma = 0.008 \) to \( \gamma = 0.032 \) leads to an increase in the slip length from \( \gamma = 0.008 \) to \( \gamma = 0.032 \) leads to about 2.7 times, and also unevenly. The 4-fold increase in the slip length from \( \gamma = 0.008 \) to \( \gamma = 0.032 \) leads to about 2-fold decrease in the differential pressure. For this purpose, one can use a mathematical model of turbulent flow, built with regard to the compressibility of the pumped liquid.

### Findings

The work was performed with the financial support of the “University Grant” of the Azerbaijan State Oil and Industry University (grant No. ADNSU-2018-1-01).

### Competing interests

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### References


[4] Boundary slip in Newtonian liquids: a review of the numerical experiments carried out for the models show that ensuring slip conditions on the pipeline wall can decrease the cost of pumping viscous liquids in the turbulent mode.

### Table 1. Results of numerical calculations.

<table>
<thead>
<tr>
<th>( t \times 10^{-2} ) s</th>
<th>Exact ( \Delta P(t) \times 10^{-5} ) Pa</th>
<th>Calculated ( \Delta P(t) \times 10^{-5} ) Pa</th>
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### Table 2. Pipeline’s hydraulics determination.

<table>
<thead>
<tr>
<th>( Q ) m(^3) s(^{-1})</th>
<th>( \gamma = 0 )</th>
<th>( \gamma = 0.002 )</th>
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### Table 3. The flow velocity distribution over the pipeline cross section.

<table>
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<tr>
<th>( r, m )</th>
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</table>


INTRODUCTION

The paper outlines the ways to increase the operational reliability of trunk pipelines in the permafrost zone by increasing the soil bearing capacity through the use of technology and technical means to control their physical and chemical properties. The example analyzing the permafrost-soil conditions of the North-East of the Russian part of Russia proves that the problem of the foundation soil stabilization occurs almost everywhere and requires a solution for a wide range of soils and temperatures. In this regard, the task of improving the operational reliability of trunk pipelines laid in the permafrost zone, using technology and technical means of controlling the physical and chemical properties of soils is a topical subject for studies both from a scientific and practical point of view. The development of new methods for manufacturing composite materials based on cryogels with controlled physical and chemical properties will assist to solve important tasks in permafrost conditions. Operational and technical measures include experimental studies of cryogels for effective soil stabilization, as well as drafting provisions for using cryogels in the construction and operation of facilities in the permafrost zone.

Key words: permafrost, geocryological subzone, permafrost zone, trunk pipeline, stress-strain state, cryogel, cryotropic polymer compositions with controlled hydrophobic properties.

ABSTRACT

Ensuring the failure-free transport of hydrocarbons is one of the key tasks of the companies – pipelines operators. Currently, this task becomes more challenging as the potential of the Russian Federation fuel-and-energy complex is associated with establishing the hydrocarbon production centers in the Arctic and other territories of the country having quite complicated subsurface conditions in the permafrost areas. Organizational and technical measures include experimental studies of cryogels for effective soil stabilization, as well as drafting provisions for using cryogels in the construction and operation of facilities in the permafrost zone. Stabilization of the foundation soil and strengthening of the tunnels along the pipeline route through areas with uneven subsidence and deformation under loads, including waterflooded zones, is the topical problem of the pipeline transport, particularly in the permafrost zone of the North-East of the European part of the country, Eastern Siberia and Far East. Analysis of the combined work of the engineering facility and soil massive as well as consideration of temperature variations are important issues in the design of the pipeline systems. Any technogenic pressing in the permafrost zone inevitably leads to disturbance of the hydro-thermal regime of the permafrost rocks. The lessons learned in construction and operation of the northern pipelines showed that in many cases the balance in the litho-technical system ‘pipeline – foundation soil’ is disturbed as a result of thermal and mechanical interference of pipelines with the environment leading to substantial changes in the natural terrain and to the activation of negative geocryological processes that result in pipeline distortions, loss of their design position, and frequently lead to emergencies. The underground trunk pipelines exert the highest impact on the permafrost, because at shallow and medium depths of seasonal thawing (0.4–1.2 m), when the maximum soil wetting is observed in the lower part of the seasonal-thawed layer (STL) and in the zone adjacent to that upper part of permafrost, pipes are laid somewhat below STL – in the layer of the potential seasonal thawing. The least thermal impact on the frozen rocks is observed at above-ground pipeline laying. The pipeline thermal impact on the enclosing frozen rocks, specifics of forming seasonal and multi-year thawing envelopes of frozen rocks is determined by the temperature of the transported product, which may be positive and/or negative. Depending on the particular temperature regime and physical state of the soil (thawed or frozen), the envelopes of seasonal or multi-year freezing and/or thawing of the foundation soil are formed along the pipeline route.

Temperature measurement in the litho-technical system is the key factor of geocryological processes activation. Thus, in operation of underground pipelines with positive temperature of the transported fluids, thawing envelopes are formed, and unwanted cryogenic processes are manifested, primary soil subsidence and thawing (due to changes in the surface run-off conditions), also thermo-karst and thermal erosion is often progressing in the trenches [1].

When designing bases and foundations of the linear-type facilities in the permafrost areas, the following factors shall be considered:

- route passage through areas with various engineering – geocryological conditions, including boundaries of thawed and frozen zones, subsiding and non-subsiding soil;
- manifestation of negative soil and permafrost processes and events: frost blisters, thermo-karst, ice buildups, landslides, solifluction, thawing of bedded and repeated-wedge ice;
- disturbance of water-and-heat balance and difficulty of surface and over-permafrost waters run-off, etc.

Methods

Field and remote surveys were the key methods in this study. The materials for geocryological conditions of the territories were obtained mainly in diachronous field works, the basis of which were the results of permafrost engineering-geological surveys (1:25000). The following field works were performed: drilling wells, pilot trenching, temperature measurements, thawing depth measurements, route surveys. Drilling wells (total number – about 3000, diameter – mainly 140 mm) was accompanied by core description, sampling, temperature readings. Also, sounding wells were drilled without sampling and temperature readings. During pilot trenching, samples were taken to study soils and cryogenic processes for better understanding of the studied upper horizon (the seasonal freezing/thawing layer). Totally, about 2000 trenches were excavated, their depth 1–2.5 m was determined by the tasks of studies. For temperature measurements, time-bound ‘lazy’ thermometers, ETC-0.1/10 instrument, TK-10/10 multi-sensor cable/thermal chain and DS89210 temperature data logger (Thermochron) were used during various time periods. At the desktop stage, the set of large-scale maps was composed, including the landscape and engineering-geological permafrost maps. In order to provide the terrain-permafrost data for the studies, the information was analyzed for 27 key areas from 100 to 1000 km², located in various types of terrain. The total coverage was about 20000 km². The diachronous remote studies were performed using the data of airborne and space photography: V-3.2, ArcGIS-9.2, GlobalMapper-11, IDRISI software packages. Decoding was performed manually and automatically. Zonal images Landsat-7 ETM+ with 30-m spatial resolution were used as remote sensing data for thematically-oriented RGB-synthesis to obtain colored images in pseudo-colors, and color-synthesized Aster/Terra photos with 15-m resolution. When processing the geocryological studies data, the original technique was used based on determining the quantitative parameters of the terrain morphological structure [2]. When designing the underground structures, it is necessary to assess the stress-strain state (SSS) of the soil adjacent to the pipeline at certain depth from the surface. For the majority cases, SSS assessment consists in the search of solution for the elastic boundary value problem in the plain-strain case. Finite elements method (FEM) is used for this case; its advantages are in the minimum requirements to the initial data and in the optimal format of the results.

Figure 1. The process of cytotropic gel formation: a) initial sample; b) frozen sample; c) cryogel: 1 – polymer precursor; 2 – solvent; 3 – low-molecular substances or monomer precursor; 4 – polycrystals of the frozen solvent; 5 – non-frozen liquid microphase; 6 – polymer lattice of gel phase in the heterogeneous cryogel; 7 – macropores; 8 – solvent.
Organizational-technical measures for cryogels application to increase the soil bearing capacity in the construction and operation of the pipeline transport facilities

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INTRODUCTION

The paper outlines the ways to increase the operational reliability of trunk pipelines in the permafrost zone by increasing the soil bearing capacity through the use of technology and technical means to control their physical and chemical properties. The example analyzing the permafrost-soil conditions of the North-East of the European part of Russia proves that the problem of the foundation soil stabilization occurs almost everywhere and requires a solution for a wide range of soils and temperatures. In this regard, the task of improving the operational reliability of trunk pipelines laid in the permafrost zone, using technology and technical means of controlling the physical and chemical properties of soils is a topical subject for studies both from a scientific and practical point of view. The development of new methods for manufacturing composite materials based on cryogels with controlled physical and chemical properties will assist to solve important tasks in permafrost conditions. Organizational and technical measures include experimental studies of cryogels for effective soil stabilization, as well as drafting provisions for using cryogels in the construction and operation of facilities in the permafrost zone.

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INTRODUCTION

Ensuring the failure-free transport of hydrocarbons is one of the key tasks of the companies – pipelines operators. Currently, this task becomes more challenging as the potential of the Russian Federation fuel-and-energy complex is associated with establishing the hydrocarbon production centers in the Arctic and other territories of the country having quite complicated subsurface conditions including areal distribution of permafrost. Strategic projects for energy resources transportation are oriented on the search of innovative technological and cost-effective integrated solutions, e.g. new approaches to construction of stable foundations in the permafrost zone. Stabilization of the foundation soil and strength enhancement of the soils in the areas with uneven subsidence and deformation under loads, including waterflooded zones, is the topical problem of the pipeline transport, particularly in the permafrost zone of the North-East of the European part of the country, Eastern Siberia and Far East.

Analysis of the combined work of the engineering facility and soil massive as well as consideration of temperature variations are important issues in the design of the pipeline systems. Any technogenic pressing in the permafrost zone inevitably leads to disturbance of the hydro-thermal regime of the permafrost rocks. The lessons learned in construction and operation of the northern pipelines showed that in many cases the balance in the litho-technical system ‘pipeline – foundation soil’ is disturbed as a result of thermal and mechanical interference of pipelines with the environment leading to the substantial changes in the natural terrain and to the activation of negative geocryological processes that result in pipeline distortions, loss of their design position, and frequently lead to emergencies.

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The least thermal impact on the frozen rocks is observed at above-ground pipeline laying. The pipeline thermal impact on the enclosing frozen rocks, specifics of forming seasonal and multi-year thawing envelopes of frozen rocks is determined by the temperature of the transported product, which may be positive and/or negative. Depending on the particular temperature regime and physical state of the soil (thawed or frozen), the envelopes of seasonal or multi-year freezing and/or thawing of the foundation soil are formed along the pipeline laying route.

Temperature measurement in the litho-technical system is the key factor of geocryological processes activation. Thus, in operation of underground pipelines with positive temperature of the transported fluid, thawing envelopes are formed, and unwanted cryogenic processes are manifested, primary soil subsidence and swamping (due to changes in the surface runoff-off conditions), also thermo-karst and thermal erosion is often progressing in the trenches [1].

When designing bases and foundations of the linear-type facilities in the permafrost areas, the following factors shall be considered:

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Assessment of the pipeline structures' SSS based on the strength of materials data and civil engineering methods also enables to perform the adequate analysis of the oil-and-gas pipeline strength with acceptable accuracy, and in some cases can provide the qualitative picture of the structure's SSS. Currently, FEM is the real global standard for strength and other types of structures' design; its versatility enables to analyze any structure with various material properties in unified approach. The information obtained as a result of the pipeline SSS assessment enables to determine pipeline sections in the pre-failure state (including prior to occurrence of defects) and to take necessary remedial measures, thus improving the pipeline system reliability [3]. Calculations assume on the absence of winter loads and temperature impact on the pipeline. The analysis of oil pipeline section (pipe) was performed using well-known energy methods of civil engineering.

Results

Permafrost conditions in the zone of interaction with pipeline transport facilities (using permafrost zone of the European North-East of Russia as an example)

The problem of ensuring the load-carrying capacity of foundation soils at construction and operation of the oil-and-gas industry facilities in the permafrost zone persists to be relevant. Particularly, the permafrost zone in the North-East of Russia is characterized by high-degree mosaic structure that extremely complicates the civil engineering projects in permafrost areas. With increasing distances from the thawed soils can be replaced by frozen ones, while the latter are characterized by highly variable temperatures. For example, the situation, when the thawed state changes into the frozen one within the distance of 100–150 m (in loams) or 50 m (in peats) is quite common, and high-temperature soils with temperature –2...–3 °C are replaced by more stable soils with temperature –2...–7 °C and below [2].

The cryogenic soils are represented in the region – continuous, sporadic, massive insular and inner permafrost that consistently change each other from north to south in a sub-lateral order [4–6].

Continuous permafrost subzone is confined to tundra. Here, permafrost covers more than 90% of the area, not always on the surface, but can occur at the depth between 10–20 m (open taliks of various genesis are 10–40 m wide). So, within the limits of ‘block-trenched tundra’, unstable (in terms of soil usage for foundations) thawed areas and high-temperature permafrost areas (with average temperature above –1 ... –2 °C) may cover up to 20% of the territory, and they shall be thermally stabilized (as other areas with average temperature above –2 °C). The areas confined to the central parts of blocks or polygons as a rule do not need thermal stabilization.

Areas without taliks are built on top by organogenic soils (peats): plain-bumpy and polygonal peatlands; thermokarst topographic lowlands are the second most common natural sites. Permafrost temperatures here attain –3.5 °C, but can exceed –1 °C (unstable foundation soil). Due to the presence of underground lode ice, polygonal peatlands should be bypassed by construction, but due to their significant occurrence, this is often not possible. In this case, it is recommended to construct only aboveground pipelines with careful preliminary survey of the lode ice location.

Occasionally, polygonal, near-valley and hilly tundra occur, its surface is formed with sand. Permafrost temperatures here also vary widely (0 ... –3.5 °C). At temperatures above –1 °C, the foundation soils are unstable, besides that, areas with sands are subject to erosion and deflation. Mineral soils of the coastal tundra strip are mostly saline, permafrost temperatures are relatively low; it is necessary to perform works to stabilize the foundation soil in such territories.

Discontinuous permafrost subzone is confined to the Northern forest tundra. Permafrost covers 50–90 % of the area and prevails in peatlands and ‘block tundra’ zones, occasionally occurring in forests and in areas of undulating tundra plains. It is characterized by the complex combination of merging and non-merging permafrost. Despite the fact that in the baseline natural sites (tundra, peatlands) the permafrost temperature can retain –2 ... –2.5 °C, almost half of the area with permafrost are characterized by semi-stable foundation soils (loam, peat), requiring actions to stabilize them. In undulating tundra and in woodlands, permafrost has a limited occurring; its high-temperature areas are stable, therefore underground laying of pipelines is possible here. There are large swamps in the subzone, where permafrost is absent, but the surface is waterlogged. Natural sites (tundra, peatlands), areas with sands are extremely rare, they are mostly in a thawed state and in general are potentially hazardous regarding the erosion development.

Massive island permafrost subzone is confined to the southern forest tundra. The permafrost area (mainly of merging type) covers 10–50% of the territory. There are no natural sites with pervasive permafrost here, high degree of mosaic natural characteristics is observed, and thawed areas alternate every 5–50 m. Mainly, permafrost is specific for peatlands, less often – for undulating tundra and rarely – for forests. Permafrost is absent in swamps and in forest lands composed by sands. High-temperature permafrost prevails in this subzone. The risk of permafrost thawing is high during the underground pipeline's construction in areas with frozen loams on the surface, but this should not lead to significant deformations as the soils are low-iced. When crossing the plain peatlands, aboveground pipeline construction technology shall be used, and soil-stabilizing actions shall be dominant component of the soil profile in its upper part is loam, and thixotropic loams predominate. Peat type of profile is also quite common. These are the least stable foundation soils, and additionally the peat has high ice content in the frozen state and often contain repeated-wedge ice. Sands are the least common, but these areas are characterized by the development of erosion processes (including deflation).

The most ‘challenging’ temperature interval for permafrost is 0 ... –2 °C. Such high-temperature permafrost exists in all geologically subzones. Obviously, the principles of construction in the permafrost zone of the region cannot be unified. Thermal stabilizers [7–11] are widely used in order to provide the necessary bearing capacity of foundation soils in high-temperature permafrost conditions; in some cases, the alternative to them are cryotropic polymer compositions with controlled properties – cryogels. Their application will lead to creation of a litho-technical system with new properties that ensure its stability. It is worth noting that for the considered region, characterized by high complexity and diversity of permafrost-soil conditions, no field surveys and pilot projects data are available regarding technologies and technical means of controlling physical and chemical properties of soils. The authors consider such controlling methods as the most appropriate and effective ways of engineering protection of pipelines and ensuring the bearing capacity of foundations of buildings and structures in the permafrost zone. Thus, the solution of the problem of improving the operational reliability of trunk pipelines in the permafrost zone using the technology and technical means of controlling physical and chemical properties of soils is a relevant topic of studies both from scientific and practical points of view. For the first time in the Russian Federation, the technology of stabilizing the foundation soils of trunk transport facilities using cryogels, depending on the soil’s composition and external conditions, will be developed on the basis of theoretical and experimental studies.

Organizational – technical measures involve experimental studies of cryogels for effective soil stabilization in various conditions of the permafrost zone and drafting requirements to soil stabilization using cryogels in construction and operation of the facilities in the permafrost zone.

Development of scientific basis of soil physical and chemical properties management

One of the contemporary ways to control soil properties is the use of cryogel. For the first time, the ability of the polyvinyl alcohol (PVA) solutions to form gels after solutions’ freezing/thawing was discovered by Inoue [12]. In the scientific literature, a direct indication of such gelation was made in [13]. The authors noted that in the case of aqueous PVA solutions (M = 80000) with concentration of more than 3 g/dL, cryolitic freeze/thaw cycles lead not only to an increase in viscosity [14–16], but also to jelling. When the system is frozen, the partial crystallization of pure water causes an increase of the macromolecules concentration in the unfrozen part of the water and, consequently, a closer ‘approach’ of polymer chains. After thawing, the system retains some of the original structural macromolecular formations that arose during cooling and freezing of the solution and have a sufficiently long-time life [12, 16–18].

Thus, it is widely believed that the processes leading to the formation of cryogels on the surface of soil PVA solution during freezing. Authors of works [19–20] described the possibility to control the PVA structure by changing both the rate of cross-linking and the supramolecular structure. Control of the PVA structure through changing the time of cryo-concentration on its aqueous solutions in the process of film formation at the temperature ~18 °C, as well as control of cryolitic transformations were carried out by introducing different amounts of stable free radicals into these solutions. When the PVA solution freezes, a pure solvent crystallizes the PVA first (Fig. 1b), and the dissolved substance is concentrated in the yet liquid part of the sample [12]. Such cryo-concentration significantly enhances the ‘polymer-polymer’ interaction, which leads to the formation of stable nodes in the cryogel spatial lattice. Since these processes occur in a heterogeneous system, a heterogeneous gel is obtained after its thawing. Under the effect of frozen solid crystals, pores of different size and geometry are formed in it. Thus, the solvent acts...
Assessment of the pipeline structures’ SSS based on the strength of materials data and civil engineering methods also enables to perform the adequate analysis of the oil-and-gas pipeline strength with acceptable accuracy, and in some cases can provide the qualitative picture of the structure’s SSS. Currently, FEM is the real global standard for strength and other types of structures’ design; its versatility enables to analyze any structure with various material properties in unified approach. The information obtained as a result of the pipeline SSS assessment enables to determine pipeline sections in the pre-failure state (including prior to occurrence of defects) and to take necessary remedial measures, thus improving the pipeline system reliability [3]. Calculations assume on the absence of winter loads and temperature impact on the pipeline. The analysis of oil pipeline section (pipe) was performed using well-known energy methods of civil engineering.

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Cryogenic transformations of these soils are represented in the region – continuous, sporadic, massive insular and insular permafrost that consistently change each other from north to south in a sub-lateral order [4-6].

Discontinuous permafrost subzone is confined to the Northern forest tundra. Permafrost covers 50-90 % of the area and prevails in peatlands and ‘block tundra’ zones, occasionally occurring in forests and in areas of undulating tundra plains. It is characterized by the complex combination of merging and non-merging permafrost. Despite the fact that in the baseline natural sites (tundra, peatlands) the permafrost temperature can range –2...–2,5 °С, almost half of the area with permafrost are characterized by semi-stable foundation soils (loam, peat), requiring actions to stabilize them. In undulating tundra and in woodlands, permafrost has a high-temperature occurrence, with high-temperature temperatures are relatively low; it is necessary to perform works to stabilize the foundation soil in such territories.

Continuous permafrost subzone is confined to the central parts of blocks or polygons as a rule do not need thermal stabilization. Areas without taliks are built on top by organogenic soils (peats): plain-bumpy and polygonal peatlands; thermokarst topographic lowlands are the second most common natural sites. Permafrost temperatures here attain –3.5 °С, but can exceed –1 °С (unstable foundation soil). Due to the presence of underground lode ice, polygonal peatlands should be bypassed by construction, but due to their significant occurrence, this is often not possible. In this case, it is recommended to construct only aboveground pipelines with careful preliminary survey of the lode ice location.

Ocasionally, polygonal, near-valley and hilly tundra occur, its surface is formed with sand. Permafrost temperatures here also vary widely (0 ... –3.5 °С). At temperatures above –1 °С, the foundation soils are unstable, besides, that, areas with sands are subject to erosion and deflation. Mineral soils of the coastal tundra strip are partially saline, permafrost temperatures are relatively low; it is necessary to perform works to stabilize the foundation soil in such territories.

Permafrost temperature –2...–3 °С and below [2].

Insular permafrost subzone is confined to the most northern taiga. The permafrost covers no more than 10% of the area and prevails in peatlands and ‘block tundra’ zones, occasionally occurring in forests and in areas of undulating tundra plains. It is characterized by the complex combination of merging and non-merging permafrost. Despite the fact that in the baseline natural sites (tundra, peatlands) the permafrost temperature can range –2...–2,5 °С, almost half of the area with permafrost are characterized by semi-stable foundation soils (loam, peat), requiring actions to stabilize them. In undulating tundra and in woodlands, permafrost has a high-temperature occurrence, with high-temperature temperatures are relatively low; it is necessary to perform works to stabilize the foundation soil in such territories.

Watering at the trench base level

The analytical model of pipeline vertical movement in the soil environment.

Figure 1. Watering at the trench base level

Figure 2. Theoretical model of pipeline vertical movement in the soil environment.

Figure 3. The analytical model of pipeline vertical movement in the soil environment.
as a porogen. Melting or dissolving of these porogens after thawing leaves cavities in the cryogel mass filled with the melted solvent, and the surface tension forces of the gel phase itself bend the macroscopic wall of the cryogel, which takes a rounded shape (Fig. 1c) instead of the faceted shape, characteristic for crystalline porogen particles. At that, the wall material has its own (gel) porosity. Since the formation of such a gel occurs at high concentrations of precursors, the resulting polymer own (gel) porosity. Since the formation of such a gel occurs at high concentrations of precursors, the resulting polymer

The results of the calculations show the validity and 

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Competing interests

The authors declare that there is no competing interest regarding the publication of this paper.

References


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Currently, there are lessons learned in cryogel applications, but they are not relevant for the North-East of the European part of Russia. Tomsk Polytechnic University (TPU), Tomsk State University of Architecture and Civil Engineering, and Institute of Petroleum Chemistry (IPC SB RAS) SB RAS are involved in active R&D works to establish the fundamental relationships between soil, gel and pipeline as well as regularities of their changes with manufacturing technology and impact of operational conditions in the Arctic. Also, the scientific basis of technological solutions is being developed. This approach is principally new in the minerals extraction and formation of the subsurface setting of TPU and IPC SB RAS are the leaders of R&D in this area and for several years are working in order to find approaches to develop principally new technologies of design and creation a new type of the construction gel [21]. The methods being developed can be implemented into practice using the standard equipment and machinery. The improved structural and mechanical properties of these structures compared to those of gels based on two-component cryogels shall provide the innovative component of the methods. The compositions of cryogel-based materials, methods of their production and applications are patentable.

Development of new production methods for cryogel-based composite materials, controlled physical and chemical properties shall be helpful in solving important technical problems in the permafrost environment.

Various deviations, including significant ones, of SSS from the design may occur during the pipeline operation. Changes in the spatial position may lead to a substantial change in SSS. Such deviations occur as a result of the soil subsidence after filling the cavities left; soil compaction due to excess water removal or due to the weight of the pipeline and soil fill (Fig. 2). As a result, pipeline defects appear: substantial pipe bending, over-stress, pipeline compaction due to excess water removal or due to the weight of the pipeline without soil stabilization by cryogel, thus substantial change in SSS. Such deviations occur as a result from the design may occur during the pipeline operation.

Stress (strength) calculations were performed to study SSS, stress diagrams, variation range, numerical characteristics of the processes that affect the deformations in the pipeline subsidence. The model of pipeline section (pipe) was generated using well-known energy methods of the structural engineering. The model parameters were as follows: outer diameter – 373 mm; wall thickness – 11 mm; length – 50 m; operating pressure – 8.0 MPa. Oil pipeline material – steel 17GCrMo (17MnSi) with mechanical properties: ultimate strength σU = 490 MPa; yield strength σS = 350 MPa. The assumptions corresponding to the simplest case of pipeline interaction with soil were taken: anchorage of pipe ends is used in the model to prevent movement along the x-axis at the beginning and the end of the pipe section; the upward soil pressure qP is provided by a light sandy loam with compression strength 490 kPa under long-term load action [22–24]. The pipe geometry changes due to temperature variations were taken into account. The compression strength of the proposed model with base stabilization by cryogel under long-term loading is 19 MPa, elastic module is 250 kPa, Poisson ratio is 0.33.

Equivalent stress diagrams are obtained. Maximum bending stress is observed in the middle of the pipe and attains approximately 300 MPa, i.e. it is close to the yield stress for residual strain of the pipeline material, which is absolutely unacceptable in terms of pipeline operation under given conditions and loads. Also, maximum bending stress is observed at the pipeline ends, where limit conditions are applied. When the proposed model of the pipeline base stabilization using the cryogel was applied, the bending stress in the middle of the pipe decreased from 300 MPa to 124 MPa.

Maximum deformations at given loads in the middle part of the pipeline without soil stabilization by cryogel attain 1,000 mm, and with stabilization by cryogel – 196 mm. Bending stress and pipeline deformation in the studied case of the possible soil subsidence showed more acceptable SSS with the pipeline soil base stabilized by cryogel, thus indicating a potential for its application. It is worth noting that this model describes the complete picture of cryogel soil interaction and requires a more detailed study of the pipeline stabilization with regard to all physical and mechanical properties of the soil.

Findings

1. The analysis of thermal and mechanical interaction of pipelines with permafrost in the North-East of the European part of Russia is performed taking into account the emergent properties of litho-technical system. The most problematic combinations of permafrost-soil parameters are determined, which require special studies aimed at improving the operational reliability of linear and area facilities in the permafrost zone.

2. The relevant scientific and technical problem is solving a new type of cryogel, which consists of the development of cryotropic polymer compositions with controlled properties that have high elasticity and good adhesion to the soil for use in permafrost areas, where the construction of pipeline transport facilities is planned.

3. The method of improving the operational reliability of trunk pipelines in permafrost zone is proposed based on the application of technology and technical means to control the physical and chemical properties of soils.

4. The results of the calculations show the validity and the potential of cryogels application to increase the bearing capacity of the pipeline foundation soils and dictate the need for laboratory and field tests of cryotropic compositions with various types of soils.

Acknowledgments

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Competing interests

The authors declare that there is no competing interest regarding the publication of this paper.

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The cross-disciplinary approach to analysis and forecast of operational damage tolerance of the oil pipeline system – part 1

by Sergei S. Sherbakov* 1, 2

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INTRODUCTION

The paper presents the cross-disciplinary approach to the analysis of the oil pipeline system based on the methodologies of tribo-fatigue and mechanothermodynamics. The pipeline section is analyzed as a complex system pipe-soil-flow of liquid subject to the set of mechanical, thermal and friction loads. It is shown that these loads are mainly repeatedly-alternated, and the pipe metal works in the multi-cycle fatigue conditions. The procedure of resonance accelerated fatigue tests is proposed, and their results are presented. Also, the unorthodox method of integrated wear-fatigue tests of the pipeline steel was proposed with the model of simultaneous pressure and wall friction actions. The presented field test results of pipes subject to the long-term operation showed that their fracture may occur not only in the near-weld zone, but also in the vicinity of internal corrosion damages. New models of three-dimensional stress-strain state and volumetric damage tolerance for the system pipe-soil-flow liquid were developed. These models were applied with regard to the pipe internal corrosion damages, defined using the inline inspection technique. A new efficient method to describe static and cyclic elastic-plastic fracture of the pipe steel with crack using the transverse strain is proposed and tested. Results of the computer-simulated propagation of the crack-like damage are based upon the model of deformed solid with dangerous volume. The new model is proposed for risk and safety assessment with regard to the ultrasonic inspection data. The algorithm of the ‘oil line pipe’ problem solution is presented for drafting a short-term plan of particular R&D actions.

Key words: oil pipeline, tribo-fatigue, mechanothermodynamics, damage, stress-strain state, safety, mechanical fatigue, field tests, crack resistance, management.

ABSTRACT

The problem of ‘oil line pipe’ is cross-disciplinary. Really, such scientific disciplines as hydraulics and hydraulic mechanics, thermodynamics, mechanics of deformable solids, mechanics of materials, elasticity theory, strength theory, linear and non-linear fracture mechanics, metal science, damage theory, corrosion theory, etc. are used to solve the problem of the line pipe performance capability assessment and improvement. As it is known, individual sciences enable us to receive answers only to partial questions, while the ‘oil line pipe’ problem is an integrated one. Thus, the cross-disciplinary approach is needed to assess the operational reliability of oil lines. This approach may be based on the contemporary achievements of tribo-fatigue (new chapter of mechanics of materials) and mechanothermodynamics (new chapter of physics) [1-5] (Fig. 1) and mechanothermodynamics (new chapter of physics) [6-9].

Therefore, this paper formulates (in the first approximation, of course) and justifies the R&D activities in the area of ‘oil line pipe’ (OLP) with regard to well-known problems [3, 11]: fundamental studies and updating of the theories of pipeline operational damage tolerance, mathematical models of its interaction with the environment, including soil, oil streams, mass, mechanical fatigue, lifetime, reliability, and safe operating time, development and implementation of the resource management methods based on the assessment of integrated quality of the linear part of the pipeline. The innovative algorithm to the problem solution is proposed in Fig. 2 for discussion. Surely, its detailed and full analysis is outside of this paper scope, but the formulation of the most relevant, in the author’s opinion, problems is briefly discussed below.

This is a sort of concept outline of the algorithm: the pipe as a tribo-fatigue system – the role of the wall friction – the necessity to consider the stage of dispersed damages based on the stress-strain state (SSS) analysis in the vicinity of many small and large defects, including the soil pressure component – formation of dangerous volumes as integrated assessment of dispersed damages tolerance level – use of ILI results to analyze the multiple damages level and assessment of its possible progress – transition to the stage of concentrated (local) cracks and analysis of their propagation risk – aging processes – multiplier factor of the limit state – integrated assessment of the system quality, risk and operational safety – resource optimization based upon integrated technical-economic studies.

For practical implementation of this algorithm (OLP), development of methods (including rights to inventions) and correct laboratory tests for experimental determining the service properties (ε_{cr}, K_{cr}, ..., ) of the material and pipe components under conditions close to operational and with regard to aging and damaging processes is very important.

The key objective of the OLP-algorithm shown in Fig. 2 is to improve the assessment and forecast accuracy for the mechanical states of oil pipeline systems during their operation in various conditions based on the achievements of the contemporary science. These states shall be understood as SSS, dispersed and local damages, risk/safety, ageing criteria, limit state and, in integrated term, the quality state. Thus, the optimal resource management of the oil pipeline systems and their individual sections is provided with certain economic effect.

The development of the package of software and regulatory documents including State standards will enable, in our opinion, to implement and support a non-contradictory unified organizational, technological and regulatory policy in the oil transport industry in order to ensure the

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The development of the package of software and regulatory documents including State standards will enable, in our opinion, to implement and support a non-contradictory unified organizational, methodological and technological policy in the oil transport industry in order to ensure the...
required operational reliability of the oil pipeline system with the expected economic effect – reduction of material, labor, money expenditures, etc. The following briefly describes the key provisions of OLP algorithm shown in Fig. 2.

**Pipe as the tribo-fatigue system**

As known, the tribo-fatigue describes the integrated approach to the analysis of the mechanical systems’ serviceability, where the processes of load application and friction are acting simultaneously (Fig. 1). It can be shown that the oil pipeline shall be considered as the tribo-fatigue system pipe-soil-flow of liquid (Fig. 3), because it demonstrates the repeatedly-alternated internal pressure $p(t)$, which may lead to the fatigue damage in the pipe inner surface, and wall friction of the oil flow with velocity $v_j$, which initiates its hydro-erosion under tangential stress $\tau$. So, the general case shall describe the integrated wear-fatigue damages of the inner surface of the oil line pipe that is additionally complicated by the effect of temperature $T$ and possible corrosion damage ($\chi_j$). Thus, the pipe operation lifetime or its resource $R$ is determined at least by four indicated features of the damage tolerance, caused by the relevant loads (re. Fig. 3):

$$R = R\left[p(t), T, \chi_j, A_j, m_j, \ldots\right], \quad \text{(1)}$$

where $m_j$ means the set of properties and conditions of the pipe steel material. According to the tribo-fatigue concept [1–5], the indicated damages dialectically interact ($\varphi_2$) with each other. The principle of such interaction (parameters $A_j$) is shown in Fig. 3. Let identify the pressure component $p(t)$ from formula (1) and briefly analyze it.

Until recent time, the internal pressure was considered as a static load $p_{cont}$ in design, estimation and analysis of pipeline serviceability. But at the end of the last century, many scientists have postulated in their works that the internal pressure $p(t)$ has the low-cycle behavior. Early in the beginning of this century, the statistical study of the ‘Druzhba’ oil pipeline operational loading was performed at 4 linear sections in Belorussia with total length 882 km [12]. About 400,000 pressure data samples were acquired in 8 years using the control panel internal pressure readings at intake and discharge ends of line booster stations in Mozyr, Turov, Pinsk and Kobrin. Their analysis has shown that the pressure during the normal pipeline operation hours, in general, shall not be considered as stationary; it may increase or decrease several times even within 24 hours. The amplitude of fluctuations at that (from minimum to maximum) may be 0.4–3.7 MPa at daily average value 3.76 MPa. As an example, a typical diagram of the annual pressure variations is shown in Fig. 4. One can see that its amplitude is from 0.4 to 3.7 MPa, i.e. the pressure is repeatedly alternated from 0.4 to 3.7 MPa, i.e. the pressure is repeatedly alternated at any operation conditions. The maximum deviation of the average daily pressure $(p_{av})$ from the average annual value $(p_{av\_year})$ exceeds 2 MPa, which is more than the half of the maximum figure. Besides that, it occurs that the loading process parameters are different in various seasons (summer, autumn, winter, spring). For example, the average daily pressure variations in seasons are as follows: summer $-2.82$ MPa, winter $-2.89$ MPa, autumn $-2.75$ MPa, spring $-2.76$ MPa. Stresses in the pipe wall vary in compliance with pressure changes. Fig. 5 shows the density and distribution of average annual and monthly (January and July) hoop stresses. Processing of statistics data was performed using the assumption that the pressure distribution is described by the normal law. One can see that the more stable is the pressure (January), the lower is its root-mean-square deviation, and the scatter of the hoop stresses is not high, accordingly (just 12 MPa, curve 3 in Fig. 5). Such loading conditions are the most favorable for linear sections (LS) of the pipeline, but the hoop stress scatter is most often ~130 MPa (curves 1, 2 in Fig. 5).

Based on the above, the general conclusion was made that the pipeline operating pressure is the stochastic variable subjected to the unpredictable scatter. The pipe metal at that is subject to the cyclic direct tensile stress with asymmetry coefficient $R_S$ changing from 0 to 1. The further LS loading analysis using methods of the stochastic processes theory established that the stochastic process of pressure changes is non-steady, and the characteristics of its quality were obtained (Fig. 6). One can see that depending on the operating conditions in various pipeline sections, the root-mean-square pressure deviation is two-fold different. One can assume that in a section, where it is the maximum, $(6.90\cdot10^3$ MPa), the operation reliability of the oil pipeline will be minimum. It happened that such assumption has a real confirmation. So, one can define, regarding the results of similar studies, which particular section is the most critical and requires actions to decrease the loading process cyclicity. As long as LS pipes loading is cyclic, their serviceability and operating time may be determined by the pipe steel fatigue strength. The analysis showed that $-2.5\cdot10^6$ loading cycles occur during the depreciation period of operation. It means that the basic duration of tests shall be about 10 cycles. Hence, LS operate in the high-cycle fatigue conditions.

**Pipe steel tests and operational properties**

Let’s note that in the known multiple experimental studies of oil pipeline fractures no typical fatigue damage of the pipe wall was found (rubbed smooth crack initiation source, slow crack front growth, etc.). Because of that, it is considered that the multi-cycle fatigue is not the case in the pipeline operations. But this conclusion does not seem to be justified. In fact, thin inner pipe layers with primary fatigue cracks are removed (worn-down) due to erosion-corrosion processes and cannot be found because of that. The convincing evidence of that, as the measurements showed, is ~10% reduction in the wall thickness after 30 years of pipeline operation. Such is the role of the wall friction in the oil flow. And the key conclusion is that the operational reliability of OLP is determined by an integrated wear-fatigue damage of its inner surface, which is initiated by joint action of the cyclic internal pressure and the wall friction. In other words, the oil pipeline shall be considered as a tribo-fatigue system [2, 3, 13–16], and the usually observed OLP fracture during operation in fact is simply the rupture, i.e. the final phase of the wear-fatigue damage process.

As long as it is forecasted that the OLP damage tolerance is determined, in particular, by the multi-cycle fatigue, the fast-track fatigue test of the pipe elements was developed and implemented (Fig. 7) on the base of $N_{cycles}=10^6$ cycles [12, 13]. It is worth noting that the test pieces for fatigue tests were

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**Figure 3. Oil line pipe as the tribo-fatigue system.**

**Figure 4. The diagram of average daily pressure variations within a year at the discharge end of the booster pumping station ‘Turov’.**

**Figure 5. Distribution of the average hoop stress $\sigma_{hoop}$ in the pipe: annual (1), monthly in July (2) and January (3).**

**Figure 6. To the analysis of operation quality of various 820 mm pipeline sections.**

**Figure 7. Multi-test piece resonance method of accelerated fatigue tests: 1 – pipe elements; 2 – vibrator table; 3 – special fixture for elements; 4 – weights with varied mass.**
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As long as LS pipes loading is cyclic, their serviceability and operating time may be determined by the pipe steel fatigue strength. The analysis showed that ~$\left(2+6\right)$·$10^6$ loading cycles occur during the depreciation period of operation. It means that the basic duration of tests shall be about 10$^6$ cycles. Hence, LS operate in the high-cycle fatigue conditions.

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machined from the pipe with preservation of the both surfaces where the operational damages are accumulated (Fig. 7). At that, there is the opportunity to accumulate the damages to the working zone of the tested pipe elements in the area of the smallest cross-section of test pieces. The size of rounding-out in the test pieces are specially selected in order not to cause the stress concentration.

The geometry of cantilever loading with transverse bending in one plane is accepted for mechanical fatigue tests of the pipe elements. The problem of the stress cycle asymmetry coefficient selection for the fatigue tests of the pipe steel elements has no single-valued solution, because this coefficient is, similar to the internal pressure, the stochastic parameter. Due to that, the symmetrical cycle is accepted ($R_c = \pm 1$). This choice is justified by two concepts. First, the symmetrical cycle provides the option to test the fatigue strength of the outer and inner pipe surfaces simultaneously using one and the same test piece, which is principal. Second, the symmetrical cycle is the most dangerous and the most sensitive to operational damages. Also, this cycle can be converted to any another cycle using the well-known formulas, if necessary.

Let’s consider the testing results of the pipe elements in the initial condition and after long-term operation (Fig. 8). The key finding is that the fatigue strength of the OLP elements after long-term operation of the pipeline is systematically and substantially lower than prior to operation; this conclusion is correct for all pipe elements (of parent metal and containing weld joint).

After long-term operation, the average pipe elements endurance limit in the parent metal zone decreased by 14.9%, its root-mean-square deviation decreased by 18%, in the weld zone these characteristics decreased by 9.5 and 24%, accordingly. Thus, the decrease in the fatigue strength is substantial; at that, the pipe elements’ damage in the parent metal zone is much higher than in the weld zone (approximately by 50%). On the other hand, the fatigue strength level, estimated by the average value of the endurance limit, is systematically and substantially lower in the weld zone than in the parent metal: 200 and 265 MPa (decrease by 24%) – prior to operation, and 181 and 226 MPa (decrease by 20%) – after operation.

Let’s notice also that the scatter of the endurance limits for the elements with the weld joints is, as rule, higher than that for the elements of parent metal (variation coefficient 0.077–0.092 and 0.051–0.051, accordingly). The fatigue strength of the elements of parent metal (variation coefficient is, similar to the internal pressure, the stochastic parameter. This can be explained by the influence of corrosion-erosion processes and, consequently, by the pipe inner surface strength degradation due to prolonged interaction with the liquid fluid – oil. Indeed, the thickness of the pipe wall after long-term operation in some areas decreased, as already noted, by ~ 10% due to the development of corrosion-erosion processes. It was found for welded joints (see Fig. 9) that if the outer and inner surfaces of the new pipe are almost equally strong (55 and 45%, respectively), then after prolonged operation, the fatigue cracks in these test conditions were not formed on the outer surface at all – entire 100% of the cracks were generated on the inner surface. Consequently, the decrease of the pipe elements’ fatigue strength in the zone of welded joints is manifested by the properties degradation at the inner surface of the pipe – so high is the impact of corrosion-erosion damage on the degradation of the properties in the welded joint.

An original method of integrated wear-fatigue testing of pipe steel with simulation of simultaneous action of pressure and wall friction has also been developed (Fig. 10) [2].

The specific of the contact interaction between the test piece 1 and the counterface 2 is that the diameter of the contact surface of the counterface is twice the diameter of the test piece. Therefore, the contact is carried out along a narrow strip, and a structural wedge is formed between the test piece and the counterface, where the liquid is sucked in when the test piece rotates. If the contact between the test piece and the counterface is purely liquid, the counterface only acts as a device for creating a working pressure at the solid-liquid contact patch in the tensile zone of the test piece. The continuous movement of the liquid through the structural wedge and the contact patch causes either hydroerosion (if the fluid is weakly corrosive) or corrosion-erosion (if the fluid is corrosive towards the test piece’s metal). Thus, the proposed test method simulates, for example, all the basic operating conditions of the inner surfaces of the oil line pipes.

The corrosion-erosion fatigue tests in oil environment of two series of low-alloy pipe steel test pieces were carried out under simulated operation conditions. As a counterface, a polymer was used, by means of which the necessary contact was established. The continuous movement of the liquid through the test piece and the counterface, where the liquid is sucked in when the test piece rotates. If the contact between the test piece and the counterface is purely liquid, the counterface only acts as a device for creating a working pressure at the solid-liquid contact patch in the tensile zone of the test piece. The continuous movement of the liquid through the structural wedge and the contact patch causes either hydroerosion (if the fluid is weakly corrosive) or corrosion-erosion (if the fluid is corrosive towards the test piece’s metal). Thus, the proposed test method simulates, for example, all the basic operating conditions of the inner surfaces of the oil line pipes.

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The corrosion-erosion fatigue tests in oil environment of two series of low-alloy pipe steel test pieces were carried out under simulated operation conditions. As a counterface, a polymer was used, by means of which the necessary contact was established. The continuous movement of the liquid through the test piece and the counterface, where the liquid is sucked in when the test piece rotates. If the contact between the test piece and the counterface is purely liquid, the counterface only acts as a device for creating a working pressure at the solid-liquid contact patch in the tensile zone of the test piece. The continuous movement of the liquid through the structural wedge and the contact patch causes either hydroerosion (if the fluid is weakly corrosive) or corrosion-erosion (if the fluid is corrosive towards the test piece’s metal). Thus, the proposed test method simulates, for example, all the basic operating conditions of the inner surfaces of the oil line pipes.
The most sensitive to operational damages. Also, this cycle strength of the outer and inner pipe surfaces simultaneously using one and the same test piece, which is principal. Second, the symmetrical cycle is the most dangerous and the most sensitive to operational damages. Also, this cycle can be converted to any another cycle using the well-known formulas, if necessary.

Let’s consider the testing results of the pipe elements in the initial condition and after long-term operation (Fig. 8). The key finding is that the fatigue strength of the OLP elements after long-term operation of the pipeline is systematically and substantially lower than prior to operation; this conclusion is correct for all pipe elements (of parent metal and containing weld joint).

After long-term operation, the average pipe elements endurance limit in the parent metal zone decreased by 14.9%, its root-mean-square deviation decreased by 18%, in the weld zone these characteristics decreased by 9.5 and 24%, accordingly. Thus, the decrease in the fatigue strength is substantial; at that, the pipe elements’ damage in the parent metal zone is much higher than to the weld zone (approximately by 50%). On the other hand, the fatigue strength of the weld joint was found for the parent metal elements in the initial state and after long-term operation (Fig. 8). The results of the first series of tests are shown in Fig. 11.

Let’s notice also that the scatter of the endurance limits for the elements with the weld joints is, as rule, higher than for that for the elements of parent metal (variation coefficient - 0.077 - 0.092 and 0.051 - 0.051, accordingly).

In the process of statistical tests of pipe elements, it was found that the number of primary fatigue cracks in the working cross-section is significantly different on the outer and inner surface of the pipe, although the loading conditions were strictly the same. The relevant data are shown in Fig. 9, from which the following conclusions can be drawn. It was found for the parent metal elements in the initial state that the number of damages formed during the tests on the inner surface of the pipe (~17%) is significantly less than on the outer surface (~83%). Therefore, if before operation the inner surface of the pipe was stronger than the outer (due to the conditions of the pipe rolling and bending), then after operation, on the contrary, the outer surface was stronger. This can be explained by the influence of corrosion-erosion processes and, consequently, by the pipe inner surface strength degradation due to prolonged interaction with the liquid fluid - oil. Indeed, the thickness of the pipe wall after long-term operation in some areas decreased, as already noted, by ~10% due to the development of corrosion-erosion processes.

It was found for welded joints (see Fig. 9) that if the outer and inner surfaces of the new pipe are almost equally strong (55 and 45%, respectively), then after prolonged operation, the fatigue cracks in these test conditions were not formed on the outer surface at all - entire 100% of the cracks were generated on the inner surface. Consequently, the decrease of the pipe elements’ fatigue strength in the zone of welded joints is manifested by the properties degradation at the inner surface of the pipe - so high is the impact of corrosion-erosion damage on the degradation of the properties in the welded joint.

An original method of integrated wear-fatigue testing of pipe steel with simulation of simultaneous action of pressure and wall friction has also been developed (Fig. 10) [2].

The specifics of the contact interaction between the test piece 1 and the counterface 2 is that the diameter of the contact surface of the counterface is twice the diameter of the test piece. Therefore, the contact is carried out along a narrow strip, and a structural wedge is formed between the test piece and the counterface, where the load is sucked in when the test piece rotates. If the contact between the test piece and the counterface is purely liquid, the counterface only acts as a device for creating a working pressure at the solid-liquid contact patch in the tensile zone of the test piece. The continuous movement of the liquid through the structural wedge and the contact patch causes either hydroerosion (if the fluid is weakly corrosive) or corrosion-erosion (if the fluid is corrosive towards the test piece’s metal). Thus, the proposed test method simulates, for example, all the basic operating conditions of the inner surfaces of the oil line pipes.

The corrosion-erosion fatigue tests in oil environment of two series of low-alloy pipe steel test pieces were carried out under different operating conditions. As a counterface, a polymer was used, by means of which the necessary and controlled level of contact load (F_c) is arranged. By this, it was possible to avoid the difficulties associated with creation and control of the internal pressure in the liquid medium.

The results of the first series of tests are shown in Fig. 11. It is seen that the limit of corrosion-erosion fatigue of pipe steel varies approximately by 8% depending on its condition. According to available information, systematic experimental studies of wear-fatigue damage of pipe steel based on the tribofatigue concept have not yet been performed. Meanwhile, the high practical significance of the results of such tests is considered undoubted, because, as already noted, they to a certain extent adequately simulate the basic conditions of the oil operation.

The brief summary is that considering an oil pipe as a tribofatigue system, it is necessary to conduct a complex of systematic studies for adequate assessment of its loading and damage tolerance in a variety of operating conditions. The results of such work will continue to be the implementation of the OLP problem (see Fig. 2) in its respective constituent parts, including the lifetime assessment and forecasting.

Oil line pipes testing by internal pressure to fracture

Hydraulic testing of pipes by internal pressure to fracture

Figure 8. Empirical functions of distribution of the pipe elements endurance limits prior to operation and after 34-year operation.

Figure 9. Fatigue cracks distribution on the outer (light areas) and inner (dark areas) surfaces of the pipe elements prior to (I) and after (II) operation.

Figure 10. The corrosion-erosion fatigue test set-up.

Figure 11. Comparison of corrosion-erosion fatigue curves of pipe steel in two structural states.

Figure 12. The test site layout and two-step loading program.
is of high practical importance. As a result of these tests, it is possible to study the effect of complex wear-fatigue damages during the pipe operation on its deformation and fracture. As an example, let’s present the results of hydraulic tests of pipe strings with 630 mm diameter and 7 m length [17]. They are cut from rigged-down underwater crossings with a service life of more than 40 years. The strings selected and prepared for the tests were placed on a specially equipped test site (Fig. 12).

To determine strains in the metal, including in the zone of operational defects, the strain-gage method was used. The test technique and procedure have the following features:

- tests are performed using 10-fold strings, where the pipe length-to-diameter ratio LD > 10 and guarantees the fracture in the working area, sufficiently remote from the welded end plates;
- the test pressure is increased in a stepwise manner, which allows stabilization of the measured deformation during the exposure at each step and enables ‘catching’ the material yield;
- two-step loading of tested pipes by internal pressure is provided (Fig. 12); step 1 – control loading up to the pressure 15-20% below the operating and full unloading of the pipe; a pneumatic pump station is used for better accuracy of low-pressure measurements, which enables the reliable assessment of the operating stability and error of the strain gages readings; step 2 – work loading to failure using the hydraulic pump station to ensure the required test speed at high pressures.

It was shown that during the operation of underwater crossings, two types of local corrosion damage (LCD) are found in the pipes – oval (Fig. 13a) and strip type (Fig. 13b).

Experimental data show that sometimes the hoop strains in the pipe at its axisymmetric loading by internal pressure after long-term operation are non-uniform along the perimeter of the cross-section (see Fig. 14, left), i.e. local ‘bulging’ of the pipe is detected. This may be due, for example, to the pipe or its wall bending.

At 10 MPa test pressure, the average relative (hoop) strain in pipes with and without LCD is approximately the same (1.8...3.3x10^-3)), however, the fracture centers of the first pipes were zones with LCD, but not welds. This is because the SSS is localized in a limited LCD area, so that the weakest point in that is points of a local increase (concentration) of strains that attain values (6.7...10.5)x10^-3). This is 3...5 times more than the average strain, i.e. the strain concentration factor K = 3...5.

For comparative tests, a pipe without LCD was also prepared, for which only uniform wear was detected after 40 years of operation.

The general picture of all pipes fracture (Fig. 15) – along the weld axis that is typical for oil pipelines (more than 90% of failures). However, the fracture of pipes with LCD is non-typical: not along the weld, which was observed in the fracture of the string without LCD (Fig. 15a), but along internal corrosion damages (see Figs. 13, 15 and Table 1).

According to the experimental data, the reduction in the fracture stress of the pipe with LCD (compared to the pipe without LCD) is 10-18%, and the size of the fracture zone, on the contrary, is significantly larger for the pipe without LCD. The main finding from the results of these tests is that after a long-term (more than 40 years) operation, the near-weld zones of longitudinal welded joints are not so near-weld zones. Therefore, the prediction of pipe performance should be carried out not only using the traditional criterion of the welded joint strength but using also the second criterion – the corrosion-mechanical strength of pipe steel, including corrosion-mechanical fatigue, since the operation conditions of oil pipelines, as stated above, cause a repeatedly-alternated process of their loading. Another important finding is that the pipe testing by internal pressure to fracture is sensitive for the assessment and analysis of integrated wear-fatigue operational damage of pipeline LS.

In this regard, it is necessary to point out the particular importance of testing pipes by internal cyclic pressure. The described test rig has the disadvantage that due to the relatively low loading frequency, the tests are conducted in the low-cycle fatigue mode. To attain the multi-cycle fatigue (10^3...10^7 loading cycles), a significant increase in the duration and, consequently, the cost of testing is required. Because of that, specialists of ‘Gosnetransnft Druzhba’ JSC and ‘NPO TRIBOFATIKA’ LLC have drafted a proposal to design a test rig for hydraulic pipe tests with a frequency of about several thousand cycles per minute which would enable us to conduct effective studies in the area of multi-cycle fatigue. The feasibility of this project should be discussed with the stakeholders.

The brief conclusion here is that on one hand, experimental test methods provide the key to understanding the processes of OLP operational damage tolerance. On the other hand, they make it possible to obtain a number of quantitative characteristics of the OLP metal properties and state in diverse and various operating conditions. And all this is necessary for the practical implementation of the OLP algorithm (see Fig. 2).

Stress-strain state of the pipe
A large number of works [18-24, etc.] devoted to the pipe two-dimensional design are well known. However, with regard to oil line pipes, there is a need to assess the wall friction responsible for operational wear-fatigue damage, as well as the SSS of the pipe surface layers, considering the structure and size of operational defects. According to data available, such problems have not been solved (insufficiently studied).

As is known [3], a separate class of problems in the tribofatigue is the evaluation of the mechanical states of systems consisting of fluids that are simultaneously in different aggregate states: liquid – solid, for example. Such problems require simultaneous coupled solution of hyperbolic and elliptic equations for liquid and solid, respectively [25, 26]. This is due to the fact that the state of each fluid, except for the displacements, is described by different characteristic types of their derivatives. To describe the state of a liquid, the derivative of displacement with time (velocity) is used, and to describe the state of a solid, the derivatives with spatial coordinates are used [27, 28].

Since a liquid, unlike a solid, is practically unable to retain its shape, the condition of contact interaction of these...
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![Figure 13. Typical local corrosion damages (LCD) of the pipe inner surface: oval (a) and strip type (b) (MC – main crack trajectory).](image)

![Figure 14. Distribution of the hoop relative strains ε in the pipeline cross-section. Digit mean: measured hoop strain ε / pipe wall thickness h. Letter Т means the zones of strain gages location.](image)

Experimental data show that sometimes the hoop strains in the pipe at its asymmetric loading by internal pressure after long-term operation are non-uniform along the perimeter of the cross-section (see Fig. 14, left), i.e. local ‘bulging’ of the pipe is detected. This may be due, for example, to the pipe or its wall bending.

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### Stress-strain state of the pipe

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However, with regard to oil line pipes, there is a need to assess the wall friction responsible for operational wear-fatigue damage, as well as the SSS of the pipe surface layers, considering the structure and size of operational defects. According to data available, such problems have not been solved (insufficiently studied).

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Since a liquid, unlike a solid, is practically unable to retain its shape, the condition of contact interaction of these...
media is formulated only in stresses. It should be noted that the SSS of a solid does not affect the pressure and flow velocity, which are affected only by the shape of the body. Consequently, the boundary conditions for both cases will be as follows:

\[v^2 \mid_{\alpha} = 0,\]

\[\sigma^{ax} \mid_{\alpha} = \rho \nabla \cdot u,\]

\[\sigma^{ax} \mid_{\text{r}_2} = -\tau,\]

\[\tau^{ax} \mid_{\text{r}_2} = p^{(ax)},\]

where the subscripts mean the direction of the normal and tangent at the point of the body surface; \(T\) means the temperature.

As an example of the fluid-solid interaction in accordance with (2–4), let’s consider some results of analyzing the conditions:

The stress state of the pipe model \(\sigma^{m(2)}\) can be described using the general relationship:

\[\sigma^{(2)} = \sigma^{(1)} + \sigma^{(3)} + \sigma^{(4)},\]

where \(\sigma^{(1)}, \sigma^{(2)}, \sigma^{(3)}\) mean stress states, caused by the internal pressure, friction force and temperature, accordingly. The calculations were performed for the following boundary conditions:

\[\sigma \mid_{\text{r}_2} = \rho \nabla \cdot u, \quad \sigma \mid_{\text{r}_1} = -\tau, \quad \tau \mid_{\text{r}_2} = p^{(ax)}, \quad \tau \mid_{\text{r}_1} = 0,\]

where \(\tau\) mean the tangential forces simulating the friction loads; \(\text{r}_1\) and \(\text{r}_2\) mean inner and outer radii, radially. Soil impact was simulated by the contact interaction between the external pipe surface and the internal surface of the soil ring:

\[\sigma^{(2)} \mid_{\text{r}_2} = -\sigma^{(3)} \mid_{\text{r}_2} - \sigma^{(4)} \mid_{\text{r}_2} = \sigma^{(1)} \mid_{\text{r}_2} = \frac{f \sigma^{(1)} \mid_{\text{r}_2}}{u^{(1)} \mid_{\text{r}_2} - u^{(2)} \mid_{\text{r}_2}} = 0,\]

where subscripts 1 corresponds to the pipe and 2 to the soil; \(\text{r}_2\) means the tangential component of the stress vector; \(f\) means the friction coefficient; \(\text{r}_1\) means the outer radius of the soil.

Pipe diameter 0.612 m and pipe length 6.12 m were taken for the hydrodynamic analysis. The corrosion patch was located in the middle of the lower part of the pipe. Its corrosion has the elliptical profile elongated in the axial pipe direction.

The critical Reynolds number for a fluid moving in a pipe with round cross-section is assumed to be equal to \(Re_c = 2300\), which indicates the turbulent nature of the flow. The stick model of turbulence was used in the calculations carried out with using the Fluent software package.

The calculations showed that the highest turbulence intensity is observed in the near-wall zone of the pipe [3, 29, 31]. At high values of the initial velocity \(v_0\), the intensity of vortex formation is higher, while it is the lowest on the symmetry axis. The presence of a corrosion defect has an impact on the kinematics of the moving liquid. In this zone of geometry, transverse displacements appear, which form a recirculation zone (Fig. 16a).

Let’s note that the turbulent stress \(t = \rho \nabla \cdot u, \psi\) mainly determines the value of stress \(\sigma = \tau + \Delta \tau\), making roughly 80% and 93% of \(\tau\) for velocities 1 m/s and 10 m/s, accordingly. The analysis shows that the calculation of the viscous liquid flow in the pipe as laminar can lead to a very distorted picture of the tangential force’s distribution on the inner surface of the pipe. It can be concluded that the analysis of viscous friction in the interaction of the liquid flow with the pipe wall should be carried out on the basis of the calculation of the flow motion as essentially turbulent.

The corrosion patch strongly affects the change of tangential wall stresses in the pipe defect zone. Fig. 16b shows that a sudden change in the value of the tangential (wall) stress (friction force) occurs in the corrosion defect zone. The magnitude of this change increases with the flow velocity.

To analyze the interaction between a moving viscous liquid and a solid body, the following initial data are taken: internal pressure \(p_1 = \rho = 4\) MPa, the friction force between the turbulent fluid flow and the pipe in the form of a tangential load uniformly distributed over the inner surface of the pipe \(t \mid_{\text{r}_1} = -t_{\text{r}_1} = 260\) Pa in the axial direction. Pipe anchorage condition looks like \(u_{\text{r}_1} = u_{\text{r}_2} = 0, \text{Differential temperature } \Delta T = 20°C.\)

The results of finite element calculations (Fig. 17) showed a significant impact of the wall friction on the formation of the pipe stress state \(...\) at the circumferentially and radially anchored outer surface of the pipe. The stress distribution in the pipe have changed by about 10% due to the action of the friction force. Analysis of the hoop stress \(\sigma^{(h)}\) distribution shows that it is almost twice higher in the area of corrosion defect compared to the defect-free surface of the pipe. Fig. 17 shows the large impact of the differential temperature on the formation of stress state \(\sigma^{(h)}\). Temperature stresses are dominant; they are no less than 3–4 times higher than the stresses caused by the action of \(p_1, \tau_1\). In the calculation for the pipe in the soil (see Fig. 17b), \(\sigma^{(h)}\) distribution is similar to the distribution in the absence of external anchors of the level, being on average three times smaller than the latter.

Thus, the analysis of interaction between moving viscous liquid and a solid body enables us to conclude that the estimation of the viscous friction value in the interaction of the flow with the pipe wall should be carried out on the basis of the calculation to the flow motion as essentially turbulent, considering the geometry irregularities of the inner pipe surface. In addition, wall friction and temperature difference across the thickness of the pipe significantly changes its SSS, which must be considered when further assessing the damage to the durability of the pipe.

The brief conclusion here is that even the first works on the pipe SSS multi-factor analysis were both interesting and practically useful. Their systematic development and subsequent use in the OLP algorithm (see Fig. 2) will undoubtedly contribute to a significant increase in the accuracy of the calculation.

**Pipe operational damages: ILI and the analysis of its results**

Operational damages in an oil line pipe (OLP) can be detected using many and various methods. In the last decade, in-line inspection (ILI), developed by Diascan company, has been widely used. 100% inspection of both the pipe and its inner surface is attained. For many years, the key task is to identify and assess the danger of identified defects, considering their large number (dozens of thousands) and a range of sizes (from microns to tens of mm).

In this regard, the Belarusian State University scientists have developed a technique for generating multiple pipe defects using its ILI data. One of the results is shown in Fig. 18: the projection of 43 defects on the unfolded flat pattern of the quarter section of the pipe. The analysis showed that both plenty of small defects and a limited number of large defects are existing. Statistical data processing enables us to build the distribution of the number of defects in the pipe wall thickness (Fig. 19a) and along its inner surface circumference (Fig. 19b). The generalized data are presented in the defect depth – defect area coordinates (Fig. 19c), consistent with...
media is formulated only in stresses. It should be noted that the SSS of a solid does not affect the pressure and flow velocity, which are affected only by the shape of the body. Consequently, the boundary conditions for both cases will be as follows:

\[ \gamma^\text{in} \big|_{r_1} = 0, \quad \sigma_\text{m}^\text{in} \big|_{r_1} = -p, \quad \sigma_\text{m}^\text{in} \big|_{r_2} = -p, \quad \tau^\text{in} \big|_{r_1} = \tau_1, \quad \tau^\text{in} \big|_{r_2} = \tau_2, \]

where \( \gamma \) means the tangential force simulating the friction of the near-wall tangential stress in the liquid; \( \sigma_\text{m} \) and \( \tau \) in the subscripts mean the direction of the normal and tangent at the point of the body surface; \( \rho \) means the temperature.

As an example of the fluid-solid interaction in accordance with (2–4), let’s consider some results of analyzing the system: pipe with a corrosion defect – viscous liquid flow.

Finite element computer simulation of the SSS of the pipe model with an elliptical corrosion defect was carried out considering the simultaneous integrated impact of several load factors: internal pressure, friction of the oil flow against the inner surface of the pipe, action of the soil [3, 29–35].

The stress state of the pipe model \( \sigma^\text{opm} \) can be described using the general relationship:

\[ \sigma^\text{opm} = \sigma_\text{opm} + \sigma_\text{af} + \sigma_\text{ds}, \]

where \( \sigma_\text{opm}, \sigma_\text{af}, \sigma_\text{ds} \) mean stress states, caused by the internal pressure, friction force and temperature, accordingly. The calculations were performed for the following boundary conditions:

\[ \sigma_\text{m} \big|_{r_\infty} = -p, \quad \sigma^\text{tau} \big|_{r_1} = -\tau_1, \quad \sigma^\text{tau} \big|_{r_2} = -\tau_2, \quad \sigma^\text{tau} \big|_{r_1} = \frac{f}{\rho} \sigma^\text{tau}, \quad \sigma^\text{tau} \big|_{r_2} = \frac{f}{\rho} \sigma^\text{tau}, \quad \sigma^\text{tau} \big|_{r_1} = \frac{f}{\rho} \sigma^\text{tau}, \]

where \( \sigma^\text{tau} \) means the tangential forces simulating the friction loads; \( \tau \) and \( \gamma \) mean inner and outer radii, accordingly. Soil impact was simulated by the contact interaction between the external pipe surface and the internal surface of the soil ring:

\[ \sigma^\text{tau} \big|_{r_1} = -\sigma^\text{tau}, \quad \sigma^\text{tau} \big|_{r_2} = -\sigma^\text{tau}, \quad \sigma^\text{tau} \big|_{r_1} = -\sigma^\text{tau}, \quad \sigma^\text{tau} \big|_{r_2} = -\sigma^\text{tau}, \]

where \( \gamma \) means the tangential component of the stress vector; \( f \) means the friction coefficient; \( \gamma \) means the outer radius of the soil.

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The brief conclusion here is that even the first works on the pipe SSS multi-factor analysis were both interesting and practically useful. Their systematic development and subsequent use in the OLP algorithm (see Fig. 2) will undoubtedly contribute to a significant increase in the accuracy of the calculation.
the number of defects. All this enables us to formulate the problem of calculating local SSS in the vicinity of defects. Further as an example, the impact of defects on the SSS change at 4.76 MPa internal pressure was studied applicable to a section of 720 mm pipe with 8.8 mm wall thickness from 17GS (17MnSi) steel and static friction coefficient between the pipe and the ground equal to 0.8 [36, 37]. It follows from Fig. 20–22 that in the case of a generalized statistical model with multiple defects, plastic strains can occur both in the pipe section with a free outer surface and in the pipe section with a surface in the soil. Stresses of maximum intensity are concentrated within the defect areas in all models.

Fig. 20a and 20b show that in a model with multiple damages, the maximum stress intensity $\sigma_{\text{int}}$ is approximately 46.3% higher than in a model with one large damage. This means that the traditional risk analysis of large defects identified by ILI methods, while important, is not always productive. And in the model with pipe in soil and multiple damages, the maximum stress intensity $\sigma_{\text{int}}$ is approximately 36.6% higher than in the model with one large damage. Similar conclusions can be drawn from the analysis of the hoop stress $\sigma_{\phi}$ (Fig. 21).

Fig. 21a and 21b show that in a model with multiple damages, the maximum hoop stress $\sigma_{\phi}$ is approximately 96.5% higher than in a model with one large damage. In the model with soil and multiple damages, the maximum hoop stress $\sigma_{\phi}$ is approximately 68.7% higher than in a model with one large damage.

In general, the soil has a significant quantitative and qualitative impact on the SSS of the pipe section loaded with internal pressure. Thus, the pipeline trenching by 0.8 m increases the stress and deformation tensor components compared with the pipe section in the air. The impact of physical and mechanical properties of soil and conditions of pipe laying on its SSS by the above methods has not yet been studied.

It is particularly important to emphasize that multiple internal defects significantly increase (approximately by 17.7 times) the maximum radial tensile stress $\sigma_r$ and decrease (approximately by 2 times) the minimum compressive stress $\sigma_r$. The maximum stress intensity $\sigma_{\text{int}}$ and concentration of stresses occur both in the pipe section with a free outer surface and in the pipe section with a surface in the soil.

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Figure 18. Distribution of multiple internal defects generated on the basis of statistical ILI data.

Figure 19. Statistical ILI data: characteristics of pipeline defects.

Figure 20. Distribution of stress intensity $\sigma_{\text{int}}$ (MPa) in the pipe section: with large internal defect a) in air; b) in soil; with multiple small internal defects c) in air; d) in soil.

Figure 21. Distribution of hoop stress $\sigma_{\phi}$ (MPa) in the pipe section: with large internal defect a) in air; b) in soil; with multiple small internal defects c) in air; d) in soil.

Figure 22. Distribution of radial stress $\sigma_r$ (MPa) in the pipe section: with large internal defect a) in air; b) in soil; with multiple small internal defects c) in air; d) in soil.

Figure 23. Dangerous volumes calculated for the stress intensity in the pipe section: with large internal defect a) in air; b) in soil; with multiple small internal defects c) in air; d) in soil.

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It is particularly important to emphasize that multiple internal defects significantly increase (approximately by 17.7 times) the maximum radial tensile stress $\sigma_r$ and decrease (approximately by 2 times) the minimum compressive stress $\sigma_c$ (Fig. 22).
In the model with soil, the maximum tensile stress σ increases approximately by 392 times, and the minimum compressive stress decreases approximately by 18.5 times. This means that small defects of some shape change the SSS of the pipe section in such a way that radial stress begins to contribute to the total SSS, and their input is comparable to hoop and axial stresses, and the metal can transit into an elastic-plastic state. In conditions of multi-cycle fatigue, the dangerous volumes of the model with a large internal defect are larger than those of the model with multiple small defects, amounting to 62,283.4 mm³ against 24,235.4 mm³. The soil weight load on the pipe leads to an increase in the value of the dangerous volume by 8.3% for a single extended damage, and to a decrease by 68.2% for multiple damages.

**Competing interests**

The authors declare that there is no competing interest regarding the publication of this paper.

**References**


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Thus, the pipe SSS should be considered as essentially three-dimensional, while elastic-plastic deformations can occur in the zone of dangerous volumes by 8.3% for a single extended damage, and to a decrease by 68.2% for multiple damages.

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By Annie Ferguson, Chief Executive Officer, Great Southern Press

John Tiratsoo, the former Editor-in-Chief of Pipelines International and the co-founder of the Pipeline Pigging and Integrity Management Conference and Exhibition (PPIM) in Houston, sadly passed away on 10 November 2019 aged 71. John was also the founder of the Journal of Pipeline Engineering (JPE) and spearheaded the initiative to establish the Pipeline Science and Technology Journal.

John spent his 30+ years in the pipeline industry focused on building international networks of pipeline professionals, connecting like-minded individuals, encouraging knowledge sharing, and helping to build and grow a number of associations and events that will continue to benefit the sector for years to come.

He played important role in the development of events and associations including the International Pipeline Conference in Calgary, RIO Pipeline in Brazil, the Pigging Products and Services Association (PPSA), and the Professional Institute of Pipeline Engineers (PIPE). Through all of these projects, John brought his infectious enthusiasm and passion for the sector, made many friends, and built lasting memories.

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A service was held to celebrate John’s life in November in Winchester, UK. Great Southern Press is currently collecting photos and messages to be passed on to his family. Please send any photos or messages to: aferguson@gs-press.com.au

Forthcoming industry events

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OGWA 2020
3–9 March 2020
Muscat, Oman
www.ogwaexpo.com

Oil and Gas West Asia (OGWA) is an international event that brings together local and international upstream companies, technology and service providers, equipment suppliers, and other companies directly serving the industry’s requirements. It is a platform for discussing the latest developments and directions of the industry, as well as for trade and business opportunities among the local and international upstream companies.

North Africa Petroleum Exhibition & Conference
15–18 March 2020
Oran, Algeria
www.napec-dz.com

North Africa Petroleum Exhibition & Conference (NAPEC) is one of the largest and most influential international exhibition and conferences dedicated to the North African market. With its unique mix of more than 650 operators, technology and service companies from more than 45 countries, NAPEC is an important event to explore investment opportunities, business and development relationships with national and international oil companies.

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NEFTEGAZ 2020
13–16 April 2020
Moscow, Russia
www.neftegaz-expo.ru/en/
The 20th International Exhibition Equipment and Technologies for the Oil and Gas Industries, NEFTEGAZ has a solid reputation as an effective professional platform for contracting, business contacts, exchange of experience and information on new technologies and state-of-the-art equipment for the oil and gas industry. It is the largest trade fair for the oil and gas industry in Russia and one of the top ten oil and gas fairs in the world.

Mexican Petroleum Congress
24–27 June 2020
Monterrey, Mexico
www.congresomexicandelpetroleo.com
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Caspian Oil & Gas 2020
2–4 June 2020
Baku, Azerbaijan
www.caspianoilgas.az
Caspian Oil & Gas traditionally demonstrates the latest oil and gas equipment, showcased innovative technologies in oil and gas production and presented new opportunities for the transportation of energy resources. The list of exhibitors and conference participants includes the leading oil and energy companies of the world.

The International Fair INNOPROM
6–9 July 2020
Ekaterinburg, Russian Federation
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INNOPROM is an international industrial fair held annually since 2010. It is the main industrial, trade and export platform in Russia. One of the key sites of the Ministry of Industry and Trade for the Russian Federation, INNOPROM serves as a platform where the foundations of industrial policy are laid. About 80 per cent of the exhibition visitors are professional buyers from around the world and specialists from industrial enterprises that make decisions about the introduction of new products and technologies in the production.

International Conference on Flow-Induced Vibration
6–9 July 2020
Paris, France
www.fiv2020.sciencesconf.org
Despite many decades of intensive research, flow-induced vibration is still present in many industries ranging from aerospace, automotive and civil engineering to marine structures, electricity generation and chemical processing. The European Flow-Induced Vibration Conference provides a unique opportunity to assemble a community of academics and engineers involved in understanding and mitigating the phenomena, in the interests of human safety.

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Almaty, Kazakhstan
www.kioge.kz/en
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KOGS 2020
6–7 October 2020
Kuwait City, Kuwait
www.ewckuwait.com
Kuwait Oil & Gas Show and Conference is a conference and exhibition dedicated to oil and gas hardware and services and various topics in all areas of the oil and gas industry, including exploration & production, petroleum geosciences, petrochemical products and services and refining with relation to Kuwait, the Southern oil fields in Iraq and the Divided Neutral Zone (shared with Saudi Arabia).

Energy Efficiency and Energy Development International Forum
‘Russian Energy Week’
2–5 October 2020
Moscow, Russia
www.rusenergyweek.com/en
The Russian Energy Week International Forum was established by the Russian Government in 2016. The 2020 event will highlight the prospects of the Russian fuel and energy industry and the potential for international cooperation in energy. It will serve as a platform for a discussion of the main challenges faced by the energy sector and topical problems involving the development of the gas industry, oil industry, coal industry, petrochemistry, electricity, and energy conservation and increased energy efficiency.

Australian Pipeline and Gas Association Convention and Exhibition
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Brisbane, Australia
www.apga.org.au
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PIPELINE SCIENCE AND TECHNOLOGY

Pipeline Pigging and Integrity Management Conference and Exhibition Middle East
3–4 November 2020
Muscat, Oman
gpexpress.eventair.com/ppim-middle-east-2020
PPIM Middle East will bring asset integrity leaders together in Muscat, Oman, offering opportunities for learning more about the integrity issues specific to the Middle East region, developing business relationships, and sharing knowledge. A number of networking opportunities will be held throughout the event to allow delegates and sponsors time to develop strong business connections.

Abu Dhabi International Petroleum Exhibition and Conference
9–12 November 2020
Abu Dhabi, United Arab Emirates
www.adipec.com
The Abu Dhabi International Petroleum Exhibition and Conference (ADIPEC) represents a global opportunity to connect with more than 2,200 exhibiting companies. Attendees will engage with national and international oil companies, do business with engineering, procurement and construction contractors and service companies to expand their business portfolio. This year’s ADIPEC will host series of exciting highlights where buyers meet suppliers, visitors meet global trade professionals, delegates meet great industry leaders and exhibitors meet prospective clients.

OSEA 2020
24–26 November 2020
Marina Bay Sands, Singapore
www.osea-asia.com
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COTECH Conference
November, 2021
Moscow, Russian Federation
www.rusinsais/CO Tech
This conference is organised as joint event of the 2nd Computational Methods in Offshore Technology (COTech) and Oil and Gas Technology (OGTech). In the offshore-related engineering area in particular, numerical computation approach is not only serving as a means to cultivate and realise innovative ideas, but it is also becoming the primary choice to solve complex engineering problems for the harsh and unfriendly environment. Through this area for research, the conference ambition is to become a center of excellence in offshore technology. OGTech focuses on building a bridge of research and educational activities between the two countries, Norway and Russia, that share the Arctic region.
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Submission guidelines

The editors of the scientific journal *Pipeline Science and Technology* recommend the following instructions when preparing manuscripts for publication. The layout rules for papers by authors of the *Pipeline Science and Technology* are based on the following:

- the recommendations of Web of Science and Scopus for preparing papers for publication in top-rated international journals (Vancouver Protocols).
- short methodological recommendations for preparing and formatting scientific papers in journals indexed in international research databases: Ministry of Education and Science of the Russian Federation; Association of Science Editors and Publishers, 2017, p. 11.

Materials accepted for publication must be relevant to the subject matter of the journal. All articles undergo obligatory double-blind reviewing by invited independent experts in the relevant field. Authors should submit their articles to the editors through the online system of manuscript submission at the site: www.pipeline-science.com or to the email address MalininaVN@ititm.nmru transfed.ru.

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