Integrated method of determining the size of clear opening area for through-thickness damages in underwater pipeline with encasement

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ABSTRACT
The article describes the problem solution option to determine the size of the clear opening area for through-thickness damage in the underwater pipeline with encasement. The integrated method is proposed to determine damages like ruptures, bursts, kinks/breaks, etc., formed in the pipeline wall or in pipeline encasement joints. According to the proposed method, the main indicators that enable calculating the size of such damage – the distance to the point of damage occurrence and the pressure at the point of damage occurrence are determined separately – using fundamentally different methods. According to the method proposed, the distance to the point of through-thickness damage is determined by piezoelectric cells placed with a certain spacing in the pipeline – encasement annulus, and the pressure in the point of damage is estimated using classical design methods. The formula is obtained to calculate the size of the clear opening area for through-thickness damage according to the proposed integrated method.

Key words: pipeline, through-thickness damage, piezoelectric cell, encasement, pressure, pipeline – encasement annulus.

INTRODUCTION
As noted in paper [1], pipeline crossings of water obstacles are traditionally considered to be the most vulnerable sections of the pipeline network. Bottom-laid underwater pipes are exposed to high dynamic impacts of bottom currents, moving sediments, artificial soils of ballast beds, increased aggressive attacks of the water environment.

According to authors [2], the parameters characterizing the technical condition of main oil pipeline underwater crossings include the presence of defects to be repaired. During the technical condition assessment, inspecting the pipeline crossings of water obstacles is carried out with updating the categories of pipeline sections, the depth of laying, the presence and geometric dimensions of encasement, as well as the analysis of the results of oil pipeline sections external inspection. At that, the external inspection can be carried out using acoustic emission testing, thickness measurement, hardness testing, x-ray inspection, ultrasonic tests, etc.

However, the inspection of the encased pipeline using the above methods requires additional measures to neutralize the interfering effect of the encasement, since the material of the encasement introduces some attenuation to the sensing waves in the active non-destructive testing methods, as well as to the signals received from ruptures when using passive inspection methods.

In particular, such integrated methods are relevant, where the main indicators, enabling to calculate the size of area for through-thickness damage and its equivalent diameter in the pipeline wall, are determined jointly using various methods. Such main indicators shall be the distance to the point of damage occurred and the pressure in this point.

This distance in underwater oil pipelines can be determined by methods of external or remote visual or spectral monitoring. As for the pressure in the point of damage, this parameter can be calculated after determining the specified distance, regarding the pipeline pressure readings in the nearby fixed control points, as well as the known pipeline leakage data.

Note that speaking about the damage to the pipeline, we will further mean various breaks, bursts and ruptures. Reference [3] gives the formulas linking the clear opening area of bursts, breaks and ruptures with a diameter of the hole having an equivalent leakage. Thus, for cracks in pipes, we have [3]:

\[
\omega = 0.03925 d^2
\]

where \(d\) – an equivalent hole diameter.

For breaks and bursts in pipes, we have [3]:

\[
\omega = 0.5625 d^2
\]

Formulas (1) and (2) enable us to develop the unified approach to the problem considered. The assessment of the clear opening area or the equivalent hole diameter is relevant regarding the preparation of urgent actions to restore the normal pipeline operation, or to prioritize such works in the event of many similar damages.

The purpose of this work is to develop an integrated method for determining the clear opening area and the equivalent diameter of the through-thickness damages like ruptures, bursts and kinks/breaks during inspection and planning works for the pipeline repair and rehabilitation.

A few more details on determining the distance to the point of through-thickness damage. For an underwater oil pipeline, remote spectral or visual detection of oil hydrocarbons on the pipe surface. Thus, the number of piezoelectric cell rows is equal to the number of such segments.

Proposed method
One of the main provisions of the proposed integrated method is the use of piezoelectric cells to determine the location of the pipeline wall through-thickness damage. As noted in [4], the passive leak detection methods are classified as follows:

- • pumping balance method
- • comparison of pressure values along the pipeline with pressures in the normal pipeline operation conditions
- • comparison of flow rates in the pipeline sections
- • analysis of the shock waves travel.

For underwater pipeline with encasement, this classification may include the following items:

- • comparison of pressure values along the pipeline in the annulus between encasement and outer wall of the pipe with pressure values in the normal pipeline operation conditions.

Such technical solution is used, inter alia, in the reference [5], where to solve the problem of determining the location of the through-thickness damages like bursts and ruptures, the authors proposed to install a certain number of bimorph cells in the in the annulus between outer wall of the pipe and encasement. As noted in [6], bimorph cells due to their compact design, ease of operation, high performance and low cost have earned a well-deserved interest among designers of equipment for various applications. Bimorph cells consist of two thin piezoceramic plates glued together with or without space between them. The piezoceramic plate is made of ZTS piezoelectric ceramics, which is a solid solution of lead titanate and lead zirconate with modifying agents.

A bimorph operating in generator mode is used as a flexible transducer. The generator-type transducer does not require external power supply for operation. The transducer is designed to convert dynamic deformations into electrical signals with their subsequent processing and recording by various instruments. The transducer can be used as an independent converter of mechanical deformation into the electrical signal or be a part of a more complex instrument. The transducer can be connected to the monitoring and control system using two circuits: piezoelectric cells’ voltages or charge detection. The corresponding technical solution is illustrated in Fig. 1.

Apparently, the entire technical implementation of the authors’ [5] idea requires installing several such transducer rows throughout the outer circumference of the encasement with equal segments on its surface. For example, if one selects 10 segments, equal central angles of 36 degrees are available.

The algorithm to locate the through-thickness damage using multi-row pattern of piezoelectric cells includes the following steps:

1. Determine the piezoelectric cell number in the row

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Key words: pipeline, through-thickness damage, piezoelectric cell, encasement, pressure, pipeline – encasement annulus.

INTRODUCTION

As noted in paper [1], pipeline crossings of water obstacles are traditionally considered to be the most vulnerable sections of the pipeline network. Bottom-laid underwater pipes are exposed to high dynamic impacts of bottom currents, moving sediments, artificial soils of ballast beds, increased aggressive attacks of the water environment.

According to authors [2], the parameters characterizing the technical condition of main oil pipeline underwater crossings include the presence of defects to be repaired. During the technical condition assessment, inspecting the pipeline crossings with the use of active techniques is performed by inspection, ultrasonic tests, etc., formed in the pipeline wall or in pipeline encasement joints. According to the proposed method, the main indicators that enable calculating the size of such damage – the distance to the point of damage occurrence and the pressure at the point of damage occurrence are determined separately – using fundamentally different methods. According to the method proposed, the distance to the point of through-thickness damage is determined by piezoelectric cells placed with a certain spacing in the pipeline – encasement annulus, and the pressure in the point of damage is estimated using classical design methods. The formula is obtained to calculate the size of the clear opening area for through-thickness damage according to the proposed integrated method.

However, the inspection of the encased pipeline using the above methods requires additional measures to neutralize the interfering effect of the encasement, since the material of the encasement introduces some attenuation to the sensing waves in the active non-destructive testing methods, as well as to the signals received from ruptures when using passive inspection methods.

In particular, such integrated methods are relevant, where the main indicators, enabling to calculate the size of area for through-thickness damage and its equivalent diameter in the pipeline wall, are determined jointly using various methods. Such main indicators shall be the distance to the point of damage occurred and the pressure in this point.

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For breaks and bursts in pipes, we have [3]:

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Formulas (1) and (2) enable us to develop the unified approach to the problem considered. The assessment of the clear opening area or the equivalent hole diameter is relevant regarding the preparation of urgent actions to restore the normal pipeline operation, or to prioritize such works in the event of many similar damages.

The purpose of this work is to develop an integrated method for determining the clear opening area and the equivalent diameter of the through-thickness damages like ruptures, bursts, and kinks/breaks during inspection and planning works for the pipeline repair and rehabilitation.

A few more details on determining the distance to the point of through-thickness damage. For an underwater oil pipeline, remote spectral or visual detection of oil hydrocarbons on the water body surface, which could be taken as an indication of damage at this point in leaking encasement, has the following disadvantages:

- Impossibility to detect instantly petroleum hydrocarbons leakage, as the oil floating-up to the surface of the sea in an amount sufficient to be detected takes some time.
- Non-uniformity of the petroleum hydrocarbons baseline concentration on the sea surface can significantly impair the reliability to the results of remote detection of petroleum hydrocarbons leaked from the damage.
- In leakproof encasement, the remote method of detection is not applicable at all.

In light of the above, this article proposes an integrated method for assessing the size of the clear opening area for through-thickness damage in the underwater pipeline with encasement that includes as follows: (a) determination of the distance to the point of damage using built-in piezoelectric cells; and (b) determination of the damage clear opening area taking into account the results of additional measurements of in-line pressure transmitters or the petroleum product's flow and take-off rates. At that, the accuracy of determining the damage location will be determined by the areal density of the piezoelectric cells both along the axis and the circumference of the pipe.

Such technical solution is used, inter alia, in the reference [5], where to solve the problem of determining the location of the through-thickness damages like bursts and ruptures, the authors proposed to install several such transducers at a certain number of bimorph cells in the in the annulus between outer wall of the pipe and encasement. As noted in [6], bimorph cells due to their compact design, ease of operation, high performance and low cost have earned a well-deserved interest among designers of equipment for various applications.

Bimorph cells consist of two thin piezoceramic plates glued together with or without space between them. The piezoceramic plate is made of ZTS piezoceramic ceramics, which is a solid solution of lead titanate and lead zirconate with modifying agents.

A bimorph operating in generator mode is used as a flexible transducer. The generator-type transducer does not require external power supply for operation. The transducer is designed to convert dynamic deformations into electrical signals with their subsequent processing and recording by various instruments. The transducer can be used as an independent converter of mechanical deformation into the electrical signal or be a part of a more complex instrument. The transducer can be connected to the monitoring and control system using two circuits: piezoelectric cells' voltage or charge detection. The corresponding technical solution is illustrated in Fig. 1.

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cell pattern is dictated by the need to account for the equal probability of a through-thickness defect in any segment of the pipe surface. Thus, the number of piezoelectric cell rows is equal to the number of such segments.

Proposed method

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- pumping balance method
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- comparison of pressure values along the pipeline in the annulus between encasement and outer wall of the pipe with pressure values in the normal pipeline operation conditions.
where the maximum signal is observed.

2. Determine the segment number with the maximum signal along the circumference of the pipe surface corresponding to the piezoelectric cell number determined in step 1.

3. For further signals processing, use the piezoelectric cells row corresponding to the pipe segment number determined in step 2.

As noted in [5], in the event of the underwater pipeline rupture the cells \( N_d \) and \( N_{d+1} \) will be subjected to mechanical impact of a shock wave, since the pressure in the underwater pipeline 2 is higher than in the annulus 1. In this case, the cell \( N_{d+1} \) located further from the rupture location 4 will bend after \( \Delta t \) time interval compared to the cell \( N_d \).

Taking into account the shock wave propagation velocity, the length of the interval between the transducers at a uniform placement of cells, as well as fixing the cell number \( N \), after which the damage occurred, and determining the value of the time difference \( \Delta t \) between the signal arrivals to neighboring cells \( N_d \) and \( N_{d+1} \), one can calculate the location of the through-thickness damage that led to a leakage using the formula:

\[
L_x = L_y \cdot N + \Delta L
\]

where: \( N \) – the number of the cell, after which the damage occurred; \( \Delta L \) – the distance from \( N \)th cell to the damage location, defined as follows:

\[
\Delta L = L_y \cdot \frac{\Delta t}{2}.
\]

Regarding (3) and (4):

\[
L_x = L_y \cdot \left( N + \frac{\Delta t}{2} \right).
\]

To determine the clear opening area for through-thickness damage formed in the pipeline wall, we use the formula given in the reference [3]:

\[
\omega = \frac{\Delta Q'}{9600 \cdot \sqrt{P_c}}.
\]

where: \( \Delta Q' \) – amount of leakage caused by the through-thickness damage;

\( \omega \) – clear opening area for through-thickness damage in the pipe wall;

\( P_c \) – pressure at the point of damage.

According to (3):\n
\[
\Delta Q' = Q' - \Delta Q,
\]

where: \( Q' \) – measured flow rate at the beginning of the pipeline;

\( \Delta Q \) – cumulative take-off from the pipeline users’ end.

Also, according to [5], the pressure at the point of damage can be defined as:

\[
P_c = \frac{S_{\omega}}{9600 \cdot \sqrt{L - L_2 \cdot \left( N + \frac{\Delta L}{2} \right)}} \cdot \beta^2.
\]

where:

\( \beta \) – unit drag of the pipeline;

\( L \) – length of rated section;

\( \omega \) – flow rate in the section without leaks.

Fig. 2 illustrates the positions of transducers and readings.

Regarding (7), (6) and (9):

\[
\omega = \frac{Q' - \Delta Q}{9600 \cdot \sqrt{L - L_2 \cdot \left( N + \frac{\Delta L}{2} \right)}} \cdot \beta^2.
\]

As can be seen from the obtained equation (10), the cross-sectional area of the through-thickness damage is inversely proportional to the flow rate in the pipeline with no leak and to the square root of the pipeline unit drag.

By substituting \( \beta = \frac{Q'}{\Delta Q} \) to (10), one can obtain:

\[
\omega = \frac{1 - \gamma}{9600 \cdot \sqrt{L - L_2 \cdot \left( N + \frac{\Delta L}{2} \right)}} \cdot \beta^2.
\]

where:

\[
\gamma = \frac{\Delta Q}{Q'}.
\]

\[
\beta = \frac{\omega}{\alpha}.
\]

Let’s call the ratio \( \gamma \) as the coefficient of the relative cumulative take-off, and the ratio \( \beta \) as the coefficient of the relative flow rate in the pipeline section. The formula (11) can be written as follows:

\[
\omega = \frac{1 - \gamma}{\alpha \cdot \beta}
\]

The curves for (14) at various \( \gamma \) values and \( \alpha = 10^4 \cdot 0.2; 0.4; 0.6 \) are shown in Fig. 3. The problem of ensuring the accuracy of determining the coordinates of through-thickness damages can be divided into two tasks:

- ensuring reliable recording of leaks using piezoelectric cells
- ensuring accuracy or spatial resolution of the system.

The first task is to calculate the pressure at the point of leakage and to select the appropriate sensitive material at a given...
To determine the clear opening area for through-thickness damage formed in the pipeline wall, we use the formula given in the reference [3]:

\[ \omega = \frac{\Delta q'}{9600 \sqrt{P_r}} \]  

(6)

where: \( \Delta q' \) – amount of leakage caused by the through-thickness damage;

\( \omega \) – clear opening area for through-thickness damage in the pipe wall;

\( P_r \) – pressure at the point of damage.

According to (3):

\[ \Delta q' = \frac{Q'^* - SQ_1}{\beta} \]  

(7)

where: \( Q'^* \) – measured flow rate at the beginning of the pipeline;

\( SQ_1 \) – cumulative take-off from the pipeline users’ end.

Also, according to [3], the pressure at the point of damage can be defined as:

\[ P_r = S_{\omega_r} \left( L - L_1 \right) \cdot \frac{v - \Delta L}{2} \]  

(8)

where:

\( S_{\omega_r} \) – unit drag of the pipeline;

\( \frac{v - \Delta L}{2} \) – flow rate in the section without leaks.

Fig. 2 illustrates the positions of transducers and readings.

Regard (3) and (6):

\[ L_2 = L_1 - \Delta L \]  

(5)

where: \( L_1 \) – length of the section without leaks.
minimum size of the through-thickness hole. The second task is solved by determining the interval of placing piezoelectric transducers along the length of the pipeline. We briefly show the ways to solve the first task.

Regarding (1) and (6):

\[ w = \frac{\Delta \alpha}{9600 \sqrt{\beta}} \]  (16)

From (16) using the minimum value \( \Delta \alpha_{\text{min}} \) one can obtain:

\[ \Delta \alpha_{f, \text{min}} = \left( \frac{\Delta \alpha_{\text{min}}}{9600 \sqrt{\beta}} \right) \]  (17)

Thus, using the minimum permissible value \( \Delta \alpha_{\text{min}} \) and the estimate value \( \alpha \), calculated by formula (11), one can define \( P_* \) – the pressure in the rupture point. Then, the first task of ensuring accuracy is selecting a piezoelectric cell’s material that would generate a reliable signal at any leakage with minimum value \( P_* \). Solving the second task – finding the interval of piezoelectric cells positioning is performed considering the given geometric accuracy of the system.

Discussion and conclusions

As one can see from formula (9), increase of \( N \) leads to the higher \( \sigma \) values, but this increment theoretically is compensated by possible increase of \( \gamma \) and \( \beta \) to the point of through-thickness damage occurrence. At that, the size of through-thickness damage is inversely proportional to the unit drag of the pipeline, \( \Delta \sigma \), and \( \gamma \) to the point of through-thickness damage point and pressure in this point – distance to the through-thickness damage point is determined using classic design methods.

3. The formula is derived to calculate the clear open area of the through-thickness damage in the pipeline wall according to the proposed integrated method.

Competing interests

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

References


