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NON-CONTACT METHOD OF ESTIMATION OF STRESS-STRAIN STATE OF UNDERGROUND PIPELINES DURING TRANSPORTATION OF OIL AND GAS

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Summary. Development and implementation of contactless methods for determining the stress-strain state of pipelines in the process of transportation of energy hydrocarbons is important for ensuring its safe operation. The authors developed a method for determining the change in the stress-strain state of the underground part of the main oil and gas pipelines according to the data about the displacement of a certain set of points of the axis of the pipeline. This study was conducted on a linear section of the main gas pipeline, where a landslide in 2010 created a force pressure on the pipeline, resulting in a pipeline rupture.

Keywords: underground pipelines, stress-strain state, methodology, risk assessment, mathematic model, axis coordinates

1. INTRODUCTION

It is known that some main pipelines have been operating for more than 20 years and about a quarter for more than 30 years. The high level of technical requirements for the reliability and efficiency of their operation requires the improvement of the accuracy of the evaluation of their properties during operation [7,14]. The accumulation of any damage changes the reliability, material characteristics and stability of pipeline materials to static and dynamic loads. It is important to establish changes in the stress-strain state and the physical and mechanical properties of the pipe material. Particular attention should be paid to the determination of the stress-strain state since its changes in the degradation of pipeline material contribute to the propagation of damage, in particular, the origin and growth of microcracks. It is known that during the operation of pipeline transport, the properties of the pipe material deteriorate. It is proved that cyclic loading increases the intensity of damage, which causes a higher defect of the metal of the main pipeline [11,12,15,16]. In addition, there are some known works wherein a large effect of structural defects on the properties of materials is revealed [6,8,11,13]. Interest in such phenomena is caused by the specific nature of changes in the mechanical and physical properties of the material after prolonged operation, when the anisotropy of the material is very clearly manifested [11,12]. For this reason, the stress-strain state under cyclic loading of pipeline transport and the structure and properties of the material to be exploited differ significantly from those in the initial state. The problem of safe and reliable transportation of energy hydrocarbons to the end consumer is one of the priority areas of any state to be solved. Most pipeline failures are due to mechanical and corrosion factors. Depressurisation and release of transported product into the environment pose significant environmental risks [1,2,25,28]. Therefore, it is necessary to regularly monitor the state of the pipeline [20,25,26] and the condition of its insulating coating. In recent years, the problem of ensuring reliable and long-term mechanical stability of long-length engineering structures is increasingly being considered in view of assessing and prognosis the processes that take place in the earth's crust. According to the statistics of pipeline accidents [3,5], 14.9% of the accidents are because of geodynamic processes (damage to pipelines as a result of the earth's surface activity: landslides, mudflows, etc.).

When erosion forms are crossed with oil and gas pipelines, bends (crimps) are formed in those areas, in particular, in the vertical plane at short distances. With increased geodynamic stresses and external influences in such areas, loads can locally grow, stimulating violations of the tightness and integrity of the pipeline. Moving the axis of the pipeline results in the stress-strain state change, the critical values of which cause the destruction of the metal.

Control of the stressed-deformed state of the pipeline is important for ensuring its working capacity. It is especially important for long-term operated pipelines [6,8,12,22,24], as well as in difficult sections of the route (saline soils, landslides, marshy areas). There, stress corrosion cracking [6,8,10,19,22,27], pitting corrosion [6,7] and the like may occur due to the strengthening of the corrosion factor by mechanical stresses. Worthy of note is the influence of the induced current on the areas near the transmission line [4,6,8,9,22].

An analysis of existing methods for determining the stress-strain state of oil and gas pipelines under conditions of geological risk [25] made it possible to evaluate their advantages and disadvantages. The main obstacle is in the difficulties of underground oil and gas pipelines availability for contact diagnostic methods. Based on this, the urgent task is to create a system to prevent accidents of pipelines laid in severe engineering and geological conditions. To solve this problem, for the process of further research, it is necessary to outline the changes influence in operating conditions and operating parameters concerning the strength and stability of the pipeline, as well as to find potentially dangerous sections.

2. METHOD OF INVESTIGATION

As a result of theoretical studies, a method was developed to determine the change in the stress-strain state of an underground section of an oil and gas pipeline using the data on the movement of a certain set of points [25], based on a developed mathematical model of the deformation process at the underground section of a pipeline under the influence of soil weight and its movement.

As input data for determining stresses, the displacement values of a pipeline axis certain set of points are used. For this purpose, the specific and design spatial position of the oil and gas pipeline is compared. The spatial coordinates of the oil and gas pipeline axis are determined by the non-contact method, using modern locating detectors and global positioning tools.

The modelling of deformation process at the underground sections of the main pipelines according to the data on the change of the spatial configuration of their axis is based on the approach proposed in [18] for the aboveground sections of the pipelines. In this case, the geometric configuration of the pipeline axis is determined with some accuracy at the control point in time using the experimental methods [17].

For this research, a linear section of the "Pasichna-Dolyna" gas pipeline D 500 per km 5.1 was selected. This is where the landslide, which occurred in 2010, caused a force pressure on the pipeline, resulting in a pipeline rupture.

The initial position of the pipeline was taken as a geodetic survey conducted by PJSC "Prykarpattransgaz" (Fig. 1) in the form of a topographic plan with the pipeline route and the coordinates of the pipeline axis. Surveying was carried out after repair works as a result of the landslide in 2010.

By imposing on the primary profile of the coordinate route, the measured true position of the pipeline axis, the data necessary to determine the magnitude of the stress-strain state of the pipeline by the developed method were obtained.

The initial data for the calculation are the values of displacements of a certain set of points of the pipeline axis, which are expressed as functions that describe the change of the studied area geometry in the radial, transverse and longitudinal directions, respectively: $\rho(s, \phi, r, t)$; $\omega(s, \phi, r, t)$; $\Psi(s, \phi, r, t)$. They are either given or expressed during problem solving.
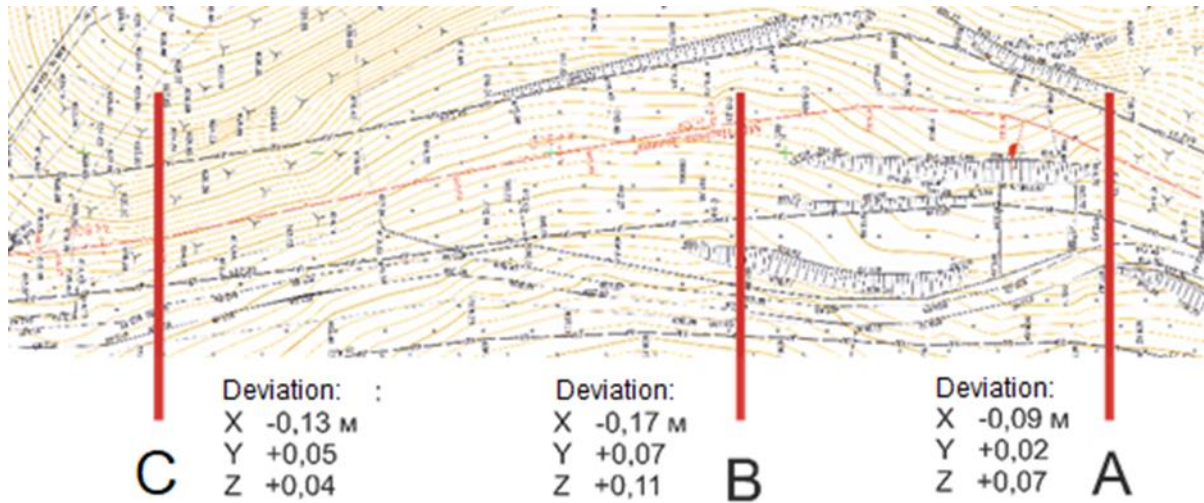
Fig. 1. Fragment of a topographic map of pipeline position geodetic survey

3. MATHEMATICAL MODELLING OF THE UNDERGROUND SECTION DEFORMATION PROCESS

While modelling the process of main pipelines underground sections deformation, based on data of change in the spatial configuration of their axis, the approach suggested for the on-surface pipeline part is applied. In such a case, using the experimental methods [21,29], the geometrical configuration of the pipeline axis is determined, including the specific accuracy at the control moment of time. It is assumed that the initial position of the pipeline axis is known (for example, according to the design documentation). Thus, for the radius vector of the pipeline point, the following relationship is written.

$$
\begin{aligned}
\vec{r}(s,\phi,r,t) = {}& \vec{r}_l(s,\phi,r,t) + \rho(s,\phi,r,t) \times \\
& \times (\cos\omega(s,\phi,r,t)\vec{b}_l + \sin\omega(s,\phi,r,t)\vec{n}_l) + \\
& + \Psi(s,\phi,r,t)\vec{\tau}_l - \frac{D}{2}\vec{n}_l
\end{aligned}
\tag{1}
$$

where:
s, ϕ, r - related to the investigated area of underground pipeline, which is simulated as the curved cylindrical body with coordinates respectively:
s - along the pipeline axis;
ϕ - by vectorial angle;
$\vec{r}_l$ - radius vector of the point on the upper generatrix of the pipeline;
D - exernal diameter of the pipeline;
$\rho(s, \phi, r, t)$; $\omega(s, \phi, r, t)$; $\Psi(s, \phi, r, t)$ - functions that describe the geometry change of the investigates site, respectively, in radial, transverse and longitudinal directions and are either given or those that are expressed in the process of solving the problem;

$\vec{\mathrm{T}}_l$; $\vec{b}_l$; $\vec{n}_l$ - vectors of the tangent binormal and normal to the upper generator. At the initial time, when the pipeline is considered an object with a rectilinear axis, the dependence (1) in coordinate form can be written as follows:

$$\vec{r}_l = \begin{cases} x = s & P \le \phi \le \\ y = r\sin\phi & R_1 \le r \le R_2 \\ z = r\cos\phi & D \le s \le L \end{cases} \qquad (2)$$

where:
R_1, R_2 - respectively inner and outer radii of the pipeline;
L - length of the investigated area.

In controlled time moment the dependence (1) is written as:

$$\vec{r}_t = \begin{cases} x = s - \dfrac{D}{2}\alpha_n(s) + (\alpha_n(s)\sin\phi\_\alpha_b(s)\cos\phi)r \\[2mm] y = y(s) - \dfrac{D}{2}\beta_n(s) + (\beta_n(s)\sin\phi + \beta_b(s)\cos\phi)r \\[2mm] z = z(s) - \dfrac{D}{2}\gamma_n(s) + (\gamma_n(s)\sin\phi + \gamma_n(s)\cos\phi)r \end{cases} \qquad (3)$$

where positions of s, ϕ, r gain the same meaning as in (2), s ; $y(s)$; $z(s)$ - points position of the upper simulated area, D - pipeline diameter; $\alpha_n(s)$; $\beta_n(s)$; $\gamma_n(s)$ - positions of normal vector to the upper generatix; $\alpha_b(s)$; $\beta_b(s)$; $\gamma_b(s)$ - position of binormal vector.

When constructing the (3), the following suppositions were used.
Thus, the only output information concerning the geometry change of the underground sections are the coordinates of its' deformed axle, then in (1), it is assumed that:

$$\begin{cases} \vec{r}_l(s,\phi,r,t) = \{s; y(s); z(s)\} \\ \rho(s,\phi,r,t) = r \\ \omega(s,\phi,r,t) = \phi \\ \psi(s,\phi,r,t) = 0 \end{cases} \qquad (4)$$

That is due to the fact, that, coordinates of the upper generatrix are experimentally defined and are set in the form of points position $s_i; y(s_i); z(s_i)$, and for origination of ($s; y(s); z(s)$) interpolation or approximation procedures [10,19,21] are used, while there is no information about the behaviour of $\rho(s;\phi;r;\tau)$; $\omega(s,\phi,r,\tau)$ та $\psi(s,\phi,r,\tau)$, which makes their record in such a form in which it was written for undeformed areas. If the representation of (3) leads to physically unrealistic results, these functions are simulated by the techniques, where the cross-section configuration change is counted towards the various types of its presentation; ellipticity, pear-shape, ellipticity parameter spacing of axle degree of deformability, thus, the mentioned methods are justified for surface areas when the information concerning the cross-section damages is available at least visually. In the case of the underground sections, the representation of (3), is justified with the lack of information concerning the cross-section deformation. This explains the choice of $\psi(s,\phi,r,\tau)=0$, as taking into account the underground areas, it is also not impossible to perform the visual inspection of the hypothesis justification concerning the flat sections. If the same methods are used as for the investigation of both underground and surface

areas, it is thus, at different ways of setting $\rho(s;\phi;r;\tau)$; $\omega(s,\phi,r,\tau)$; $\psi(s,\phi,r,\tau)$, there is one more problem; it is difficult to make the balance equation for underground areas, as it is impossible to take into account in these equations, the action of mass forces (weight of the pipe, weight of the product, weight of the soil acting on each section of the pipeline).

Thus, given (2) and (3), the following sequence of calculations is performed:

1. In the controlled and initial moment of time, the vectors of local basis are defined in each point of the simulated area [17,22]:

$$\vec{\Im}_i = \frac{\partial \vec{r}_0}{\partial \xi}$$
$$\vec{\Im}_i^k = \frac{\partial \vec{r}_t}{\partial \xi} \tag{5}$$
$$\xi_1 = s; \ \xi_2 = \phi; \ \xi_3 = r;$$
$$i = 1,2,3 \ ,$$

where $\vec{r}_0$ is calculated according to (2), a - according to (3).

Calculating the derivatives are carried out by direct differentiation of (2) and (3) corresponding to the coordinates.

2. Based on (4), the components of metric tensor are defined:

$$g_{ij}^0 = \vec{\Im}_i^0 \cdot \vec{\Im}_j^0, \ \ j,i = 1,2,3 \tag{6}$$
$$g_{ij}^k = \vec{\Im}_i^k \cdot \vec{\Im}_j^k, \ \ i,j = 1,2,3$$

3. Components q_{ij}^0 and q_{ij}^k form matrix, and for the correctness of the calculations the hypothesis should be carried out:

$$G^0 = \det\left\{g_{ij}^{\,0}\right\} \neq 0;$$
$$G^k = \det\left\{g_{ij}^{\,k}\right\} \neq 0. \tag{7}$$

Performing of (6) based on (5) allow to provide calculations of matrix contravariant components $\{G^0\}$ and $\{G^k\}$ as matrix components, inverse to these:

$$g_0^{ij} = \left\{g_{ij}^{\,0}\right\}^{-1};$$
$$g_k^{ij} = \left\{g_{ij}^{\,0}\right\}. \tag{8}$$

It is obvious, that according to (2)

$$G^0 = r^2;$$
$$G^k = r^2(g_{II} - (\alpha_\beta \frac{d\alpha_n}{ds} + \beta_b \frac{d\beta_n}{ds} +$$
$$+\gamma \frac{d\gamma_n}{ds})(R^2 - 2Rr\sin\phi + r^2)). \tag{9}$$

Thus, in case of small strains, the statements of (6) are performed, as in this case:

$$\left|\frac{d\alpha_n}{ds}\right| \ll 1, \quad \left|\frac{d\beta_n}{ds}\right| \ll 1, \quad \left|\frac{d\gamma_n}{ds}\right| \ll 1$$

4. Components of tensor strain are calculated by the [20]:

$$\varepsilon_{ij} = \frac{1}{2}(g_{ij}^0 - g_{ij}^k)_1 \, i, j = 1, 2, 3 \tag{10}$$

5. Based on (4) - (9), the tensor strain components are defined according to Hook's Law by applying the linear elastic theory device [21]:

$$\sigma_{ij} = \lambda I_I(\varepsilon) g_{ij} + 2\mu \cdot \varepsilon_{ij} \tag{11}$$

The listed calculations can be performed within the model of an anisotropic body:

$$\sigma_{ij} = \sum_{k,l=1}^{3} Cijkl \cdot \varepsilon_{ij} \tag{12}$$

where $Cijkl$ - tensor components of material elastic modulus, although (11), is used only if the pipeline material is substantially anisotropic, and coefficients $Cijkl$ are known. For engineering calculations, (10) is typically used, where μ and λ - material Lame parameters, related to Young's modulus and Poisson coefficient of the material in the following way:

$$\begin{cases} \mu = \dfrac{E}{2(1+\sigma)} \\ \lambda = \dfrac{\sigma E}{(1-2\sigma)(1+\sigma)} \end{cases} \tag{13}$$

As for pipeline steels, it is generally taken E=210000 MPa= 0,3.
In represented (10) function is the first strain invariant and is calculated by the formula:

$$I_,(\varepsilon) = \sum_{j=1}^{3} \sum_{i=1}^{3} \varepsilon_{ij} g_0^{ij} \tag{14}$$

Where ε_i is calculated by (9), and g^{ij} - according to (7).

Determination of σ_{ij} components allows to identify the most dangerous investigating areas, concerning the sector stress state changes, and if at the initial time the pipeline stress is equal zero, then (10) allows to assess the true strain values. Stress acceptance criterion may be elastic strength value $(\sigma_{np} \approx 350 M\Pi a)$, or yield strength $(\sigma_m \approx 440 M\Pi a)$, in case when the given values are different for various types of piping steels and are determined from the reference literature. It should be mentioned that the described approach to the assessment of the underground stress state is integral, and it does not require the detailed information on loading

and stress, the impact of which on the areas is due to displacement measurements. In case, when some tensions (for instance, due to pressure impact, temperature changes, etc.) are acquainted, it is possible to use the superposition principle of elastic theory:

$$\sigma_{ij} = \sigma_{ij}^H + \sigma_{ij}^B \tag{15}$$

where σ_{ij} - tensions, determined by (10), σ_{ij}^B - acquainted tensions, σ_{ij}^H - tensions of unknown nature.

4. ACCURACY EVALUATION FOR SPATIAL ATTITUDE INTERPOLATION OF ABOVE-GROUND PIPELINE DEFORMED AXLE

For realisation of the method of stress-strain state assessment, expressed by the dependencies (1)-(13), it is necessary, by means of experimentally measured upper generatrix points positions (s_c, ycs_i), $z(s_i)$) to get the expression for radius vector for every generatrix position as $\vec{r} = (S; ycs); z(s))$, where $y(s)$ and $z(c)$ are continuous functions. For this purpose, the widely known interpolation device is used, applying interpolative cubic spline [19,21] or interpolative cubic spline with test data smoothing. For interpolative cubic spline, the interpolation grid settings are set [12,22], characterised by the relationships between the minimum and maximum distances between interpolation nodes:

$$\left(\frac{h_{max}}{h_{min}}\right)^{1/2} = \frac{8|\varepsilon_1 - z\varepsilon|\sqrt{3}}{3\|f''\|_2 \, h_{max}^{3/2}} - \frac{2}{3} \tag{16}$$

where ε_1 - accuracy necessary for interpolating of the function $f(x)$ by spline $S_{f(x)}$, value of ε sets the accuracy level of function value assignment at interpolation nodes; $\|f''\|_2$ - norm of function $f''(x)$ at given metric space [10]. Dependence (14) can be written in a more compact form, bearing in mind that for the main pipelines, the radius of axis curvature should meet the hypothesis:

$$R(x) \geq C \cdot D_{TP} \tag{17}$$

where D_{TP} - pipeline diameter, C - the constant given by the value $C \in [900;1000]$, $R(x)$ - radius of pipeline curvature, which for engineering calculations can be written in the form:

$$R(x) = \frac{1}{|f''(x)|} \tag{18}$$

Taking into account (16) and (17), the dependence (15) for equally spaced grid for nodes coordinates measuring in increments h can be written in the form:

$$h^{3/2} = \frac{8|\varepsilon_1 - z\varepsilon| \cdot CD_{TP}\sqrt{3}}{L^{1/2}}$$

(19)

$$h = \left[\frac{8|\varepsilon_1 - z\varepsilon| CD_{TP}\sqrt{3}}{L^{1/2}} \right]^{2/3}$$

(20)

For pipeline section with the length $L = 100 м$, pipe diameter $D_{TP} = 1,21 м$ with measurement accuracy level 1 cm, step value h, with which it is necessary to measure the coordinates of the points of the upper generatrix, with step $h = 6$ metres, which is quite acceptable in critical. The interpolation cubic spline peculiarity is the following: at its' development, the accuracy of the interpolation setting affects significantly the axis interpolation accuracy. As a rule, the significant deviation from real data yields results that do not correspond to the actual physical picture of the process. The way out is possible by means of implementation of two approaches:

1. Applying the other implementation methods (Lagrange, Chebyshev and Hermite polynomial) or approximation by the LS method, with the resulting curves can differ significantly from real in some cases (insufficient number of interpolation nodes, their inappropriate placement, etc.);

2. Use of approaches, related to embedding the smoothing spline device, allowing to reduce the error of points position measuring by means of some correction coefficients that depend on the accuracy of measuring these points position by testing methods. While embedding the smoothing splice device, the desired smoothing function minimises on class $W_2^2[a;b]$ integrated on $[ab]$ function interval with their square of functional in the form of [23]:

$$\Phi(u) = \int_a^{10} U''(x)^2 dx + \sum_{k=0}^n P_k (U(x_k) - \tilde{f}_k)^2$$

(21)

Formula (18) requires detailed explanation: $\tilde{f}_k$ - positions of actually measured points; $U(x_k)$ - points positions on the curvature, describing the spline; P_k - weighting coefficients. Minimisation problem (18) is solved for different values P_k. In extreme cases, if $P_k \to \infty$ for any K, then the constructed spline will not actually be a smoothing, it will pass through all nodes with point positions $(x_k; \tilde{f}_k)$. If $P_k \to 0$, then the actually obtained line will be straightforward since it delivers the extremum of a functional in the form of.

$$\Phi(u) = \int_a^D U''^2(x) dx$$

(22)

which, obviously, will have a minimum for $U''(x) = 0 \Rightarrow U(x) = Ax + B$ - that is, $U(x)$ - straightforward line. With the knowing of performed measurements accuracy f_k, it is possible to get the values P_k, where in the function configuration $U(x)$ will, on the one hand, smooth the effect of measurements error, and on the other hand, will not allow to lose the features of the real section configuration. This can be depicted as a simulation in the following way (Fig. 2).
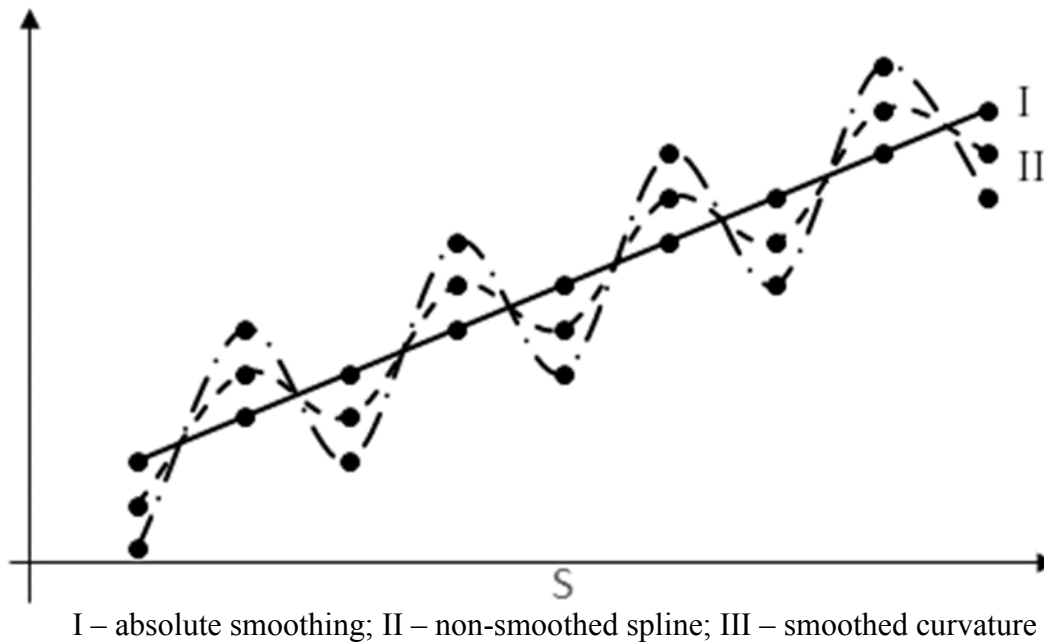
I – absolute smoothing; II – non-smoothed spline; III – smoothed curvature

Fig. 2. Test data smoothing

Optimising methods (21) with parameters P_k, which characterise the level of data smoothing depending on the measurement accuracy, are well-known, and they are used for above-ground sections [21], for this reason, their application for underground sections is well-reasoned. In particular, the procedure of functional minimising (20) is used, by implementation of iteration procedure, at each step of which the coefficients are based on the formula:

$$P_k^{(j+1)} = P_k^{(j)} \cdot \frac{\left| U^{(j)}(x_k) - \tilde{y}_k \right|}{\varepsilon} \tag{23}$$

which is realised until the fulfilment of the condition is achieved

$$\frac{U^{(j)}(x_k) - \tilde{y}_k}{\varepsilon} \to 1 \tag{24}$$

In formulae (22), (23) j - iteration process step number; ε - accuracy of node points position measurement, $P_k^{(j)}$ - smoothing coefficient value at iteration process step j, $U^j(x_k)$ - smoothed positions of node point x_k after minimising procedure (20) at iteration process step under number j; y_k - initial non-smoothed positions of this node point. Test calculations within implementation of these method show, that by the embedding this smoothing iteration procedure, the error of stress evaluation is $\pm 5\,$MPa for the operating pipeline section, displacement measurement of which is carried out with the accuracy of 1 mm for the pipeline section with the L=100м.

The following assumptions were used in building the mathematical model:

- since the only initial information about the change in the geometry of the underground section is the coordinates of its deformed axis, it is assumed in (1) that the coordinates of the upper generatrix are determined experimentally and are given as coordinates of points $s_i; y(s_i); z(s_i)$, and for obtaining ($s; y(s); z(s)$) interpolation or approximation procedures are used [25], whereas no information on the nature of the behaviour $\rho(s;\varphi;r;\tau)$; $\omega(s,\varphi,r,\tau)$ and $\psi(s,\varphi,r,\tau)$ is available, which causes them to be recorded in the form in which it was done for an undistorted area. If the presentation results in physically unrealistic data, these functions are modelled according to the methods described in [21], which takes into account, the change in the sections configuration with different types of its representation; ellipticity, pear-shape, proportionality of the ellipticity parameters to the axis deformation degree, however, the indicated approaches are for open areas where the information on section deformation is available, at least visually.

- in the case of underground sections, the representation of equations is reasonable because of information limitation on the sections deformation. This explains the choice of $\psi(s,\varphi,r,\tau) = 0$, since it is also impossible for the underground section to check at least visually that the flat section hypothesis is not possible. If while studying of the underground section, the same approaches as for terrestrial are applied, then different ways of setting $\rho(s;\varphi;r;\tau)$; $\omega(s,\varphi,r,\tau)$; $\psi(s,\varphi,r,\tau)$ cause one more problem; it is difficult to build an equilibrium equation for an underground section since it is almost impossible to account for the action of mass forces (pipe weight, product weight, soil weight, acting on each section of the pipeline) in these equations.

5. FIELD RESEARCH

The developed technique requires precise determination of the pipeline axis coordinates. The soil layer above the pipeline is a significant obstacle. Data on the position of the pipeline axis with maximum accuracy can be obtained by pit sampling using geodetic positioning methods, though it takes considerable time and resources. Currently, technologies are available that allow determining the spatial position of the pipeline from the ground with the sub-centimetre precision.

1 - ROUTE SEARCHING   2 - COORDINATES SETTING   3 - DATA PROCESSING

Fig. 3. Procedure for obtaining pipeline SSS data

The procedure for data obtaining the pipeline SSS changes is shown in Fig. 3, which is carried out in the following sequence:

1. Contactless determination of the planned position and depth of the pipeline using the already described tracer.
2. According to the points obtained on the earth surface, their spatial coordinates are determined using high-precision GPS receivers.
3. The data obtained are recorded electronically and transmitted for processing.

A linear section of the "Pasichna-Dolyna" gas pipeline of D 500 for 5.1 km, where a landslide occurred in 2010 causing a force pressure on the pipeline and as a result, a pipeline rupture occurred was selected for conducting industrial research.

A graph of the calculated values of changes in the pipework metal stresses in evenly spaced generating points at intervals of 20 m is shown in Fig. 3. These points define the cross-sections of the pipe section under study, where the values of the change in stresses at 16 points uniformly distributed along the circle of the cross-section were calculated. The graph (Fig. 4) shows that anomalous changes in stresses are recorded at the section "400 - 600 m" of the pipeline, which is further confirmed by the measurements results of strain test stations STS1, STS2, and STS3.
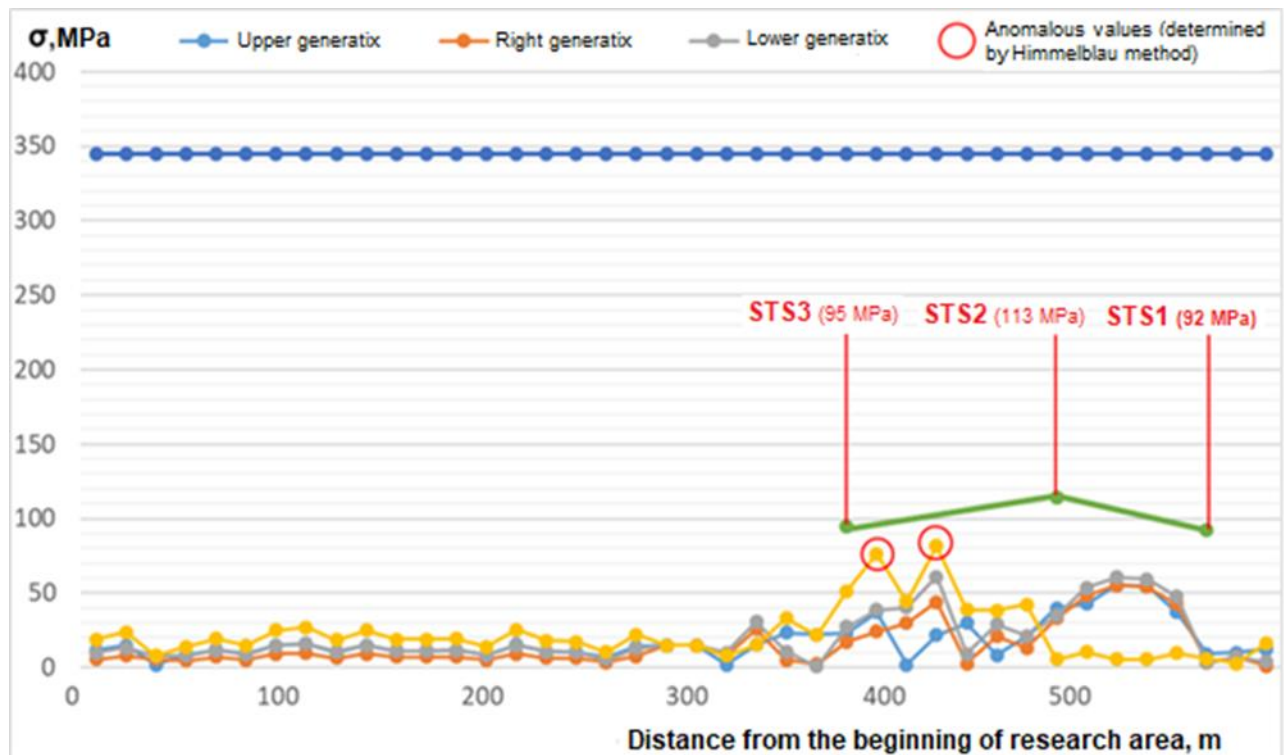

Fig. 4. Graph of changes in the pipe stresses at the investigated section of the "Pasichna-Dolyna" gas pipeline D 500 with a length of 800 m

The basic load on the main pipelines is the internal pressure (the pressure of the product being pumped). The underground pipeline is in a difficult stress state, being influenced not only by internal pressure but also by other loads that occur in special situations (mountainous areas, swamps and deserts). Under the influence of transverse and longitudinal forces, main pipelines, laid in mountainous areas, significantly change their initial position which is determined by diagnostics using the developed methodology.

The spurious operating conditions of underground pipelines in areas of abnormal behaviour (wetlands, karst cavities or technological developments, places of subsidence and slipping of soil, zones of tectonic faults, neotectonics or formation of terraces, seismic and mudflow hazardous areas) require additional analysis. It should be noted that for pipeline systems laid in mountainous areas, it is rather difficult for prognosis of the mechanical load on the pipeline. This makes it partly impossible to use existing models for estimating the SSS of pipelines in such anomalous areas. Therefore, the solution to this problem can be the use of the developed model for calculating the stress state and the corresponding value of the pipelines deformation

As a result of the calculations, the pipework stresses values in cross-sections with an interval of 15 m were obtained. In each section of the pipe, the values of the stresses in uniformly distributed 16 points of the cross-section were obtained. The stress distribution according to the calculations results of the stress-strain state of one of the pipe cross-sections is shown in Fig. 5.
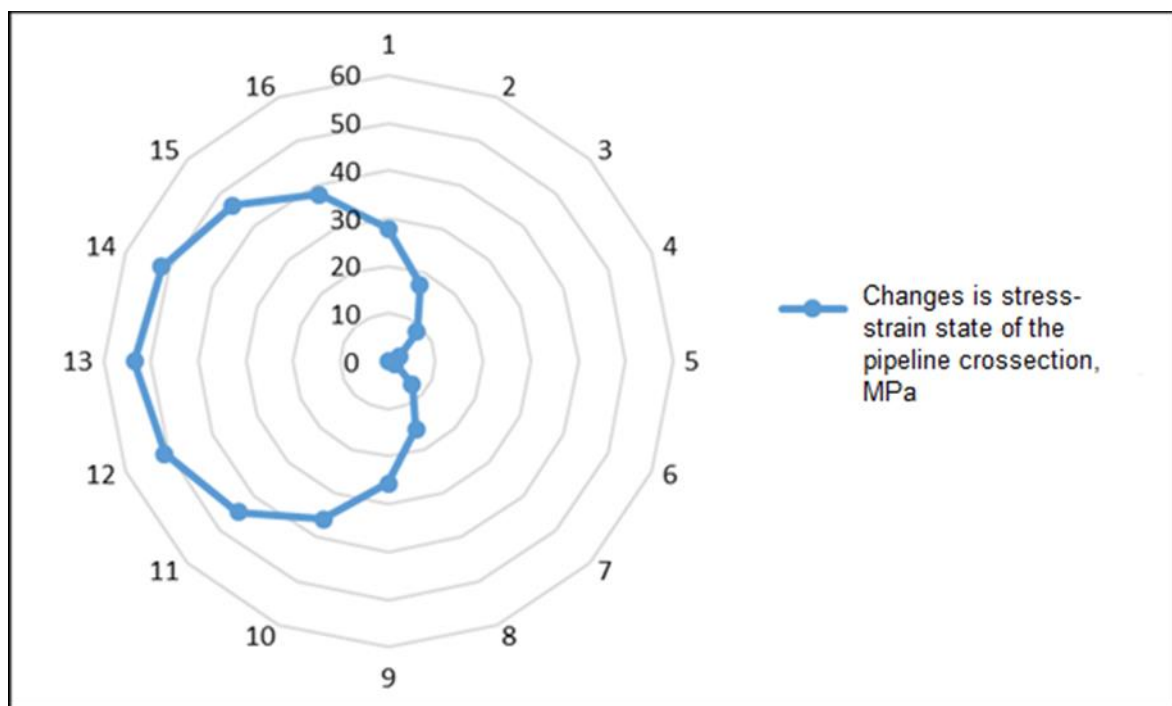

Fig. 5. Distribution diagram of stress-strain state changes in pipeline cross-section at 300 m of the investigated section

The change in the stress-strain state of the transverse displacement pipeline is shown in Fig. 5. This indicates the presence of lateral loads in this section of the investigated area. These loadings are the basic reason for the movement of the "Pasichna - Dolyna" underground gas pipeline, which is confirmed by the measurements of the routing.

The spurious operating conditions of underground pipelines in areas of abnormal behaviour (wetlands, karst cavities or technological developments, places of subsidence and slipping of soil, zones of tectonic faults, neotectonics or formation of terraces, seismic and mudflow hazardous areas) require additional analysis. It should be noted that for pipeline systems laid in mountainous areas, it is rather difficult for prognosis of the mechanical load on the pipeline. This makes it partly impossible to use existing models for estimating the SSS of pipelines in such anomalous areas.

6.   CONCLUSION

The proposed method allows to identify the most dangerous sectors of the investigated area in terms of changes in the stress state, and if it is assumed that at the initial moment of time the pipeline stresses were equal to zero, then the technique allows to estimate the real values of stresses. The criterion of stress tolerance can be the value of the elastic limit or the yield strength when the values are different for different types of pipeline steels and are determined from the reference literature. It should also be noted that the described approach to the assessment of the stress state of underground pipelines is integral, it does not require detailed information on forces and loads, the effect of which on this pipeline section is due to displacement measurements. The reliability of the results of the applied methodology is confirmed by the results of stress-testing measurements of stresses in the pipe body.

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