EVALUATION OF STRESS-STRAIN STATE OF GAS PIPELINE SECTION WITH LOCAL STABILITY LOSS

A.A. RYBAKOV[1], **E.F. GARF**[1], **A.V. YAKIMKIN**[1], **I.V. LOKHMAN**[2] and **I.Z. BURAK**[2]
[1]E.O. Paton Electric Welding Institute, NASU
11 Bozhenko Str., 03680, Kiev, Ukraine. E-mail: office@paton.kiev.ua
[2]Company «Ukrtransgaz»
9/1 Klovsky Spusk Str., 01021, Kiev, Ukraine. E-mail: press@utg.ua

Causes for damaging of a gas pipeline pipe, which was accompanied by significant deformations and involves local loss of stability in a short pipe section, are considered. Certain characteristic indices of damage are established, namely damage is located in direct vicinity of the circumferential weld and develops on a lower strength pipe. A set of physico-mechanical studies did not reveal any lowering of metal performance that allows looking for the cause for pipe damage in the features of pipeline stress-strain state in service. It is shown that temperature deformations in the pipeline under the most unfavourable conditions induce insignificant stresses, which cannot lead to any local loss of pipe stability. Analysis of pipeline laying route showed that it passes through mining area and the pipeline stress-strain state is influenced by earth surface deformation. Magnitude of displacements and stress levels in the pipe, caused by earth surface deformation in the mining area, allow regarding them to be the cause for gas pipeline damage. 11 Ref., 2 Tables, 10 Figures.

Keywords: *damage, pipeline, pipe, mechanical properties, stress-strain stage, stability loss, stresses, displacements, calculation, welded butt joint, undermined territories*

In October 2013, damage of 325 mm diameter pipe with 6 mm wall thickness was detected in the branch of Shebelinka–Dnepropetrovsk–Odessa main gas pipeline, leading to the town of Ternovka. It was accompanied by gas outflow from the gas pipeline. Diagnostics of the gas pipeline section allowed establishing local loss of pipe stability at large longitudinal displacements (Figure 1).

Deformations were so significant that through-thickness cracks developed in the formed corrugations. Measurements showed that displacements at corrugation formation were equal from 260 up to 320 mm. A certain break (up to 7°) of pipeline axis was observed in the location of stability loss.

Stability loss occurred in the vicinity of circumferential weld on one of the abutted pipes, designated by letter A. No indications of local stability loss were observed on the other pipe (designation B).

Such pipe damage in gas pipeline system is a quite rare phenomenon, and it was not highlighted in special literature [1, 2]. Therefore, the cause for its formation is of scientific and practical interest and is the objective of this study.

In keeping with the project, pipes from steel 20 (GOST 1050–74)* with a longitudinal weld

Table 1. Composition of studied pipe base metal

Object of control	Weight fraction of elements, %					
	C	Mn	Si	S	P	Al
Pipe A	0.097	0.43	0.225	0.025	0.018	0.051
Pipe B	0.168	0.58	0.229	0.015	0.020	0.035
Certificate data	0.19–0.20	0.54–0.57	0.20–0.23	0.003–0.007	0.013–0.020	0.30–0.50
GOST 1050–74	0.17–0.24	0.35–0.65	0.17–0.37	≤0.035	≤0.030	–

*Pipe performance was studied by T.N. Filipchuk and L.G. Goncharenko.

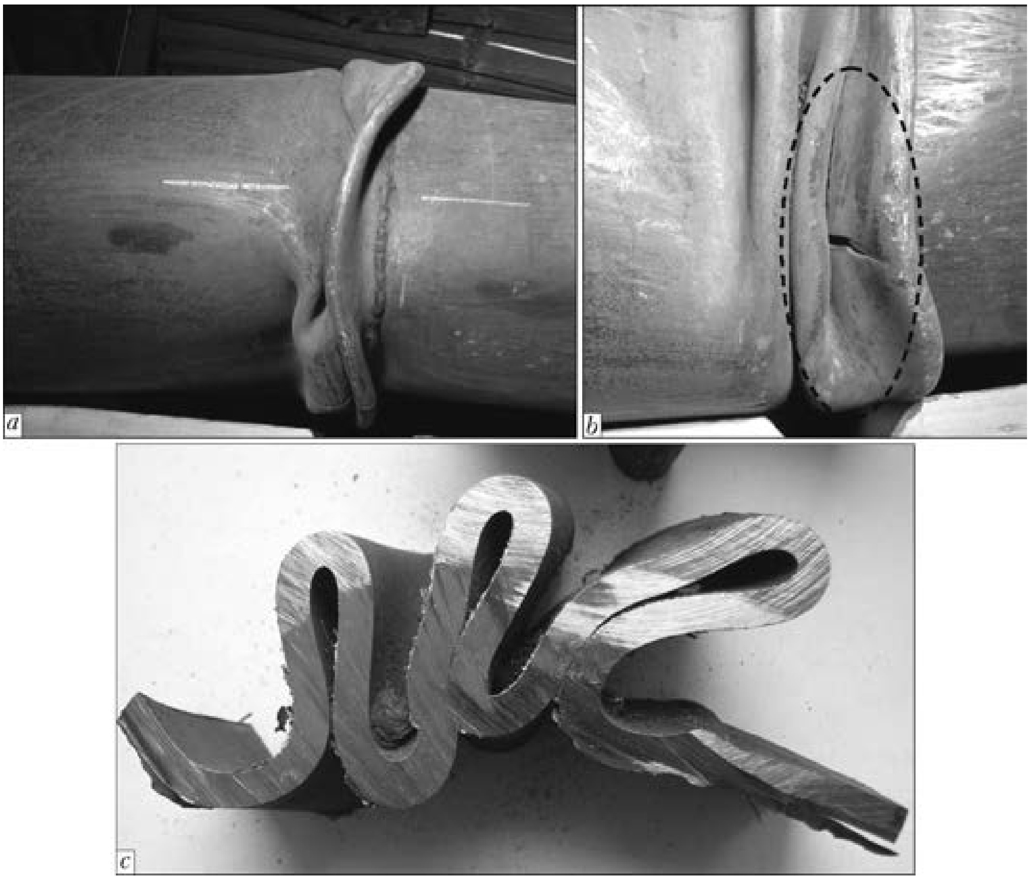

Figure 1. Damaged pipe section: *a* — general view of studied sample; *b* — damaged fragment with through-thickness crack; *c* — wall deformation

made by high-frequency welding were used in the considered pipeline section. Table 1 gives the data on pipe metal composition, in keeping with the certificates, normative requirements and results of spectral analysis performed at PWI in the Baird «Spectrovac-1000» instrument.

It follows from Table 1 that in keeping with control chemical analysis, main alloying element and impurity content, even though it is different from the certificate data, corresponds to the requirements of GOST 1050–74, except for carbon in base metal of pipe A, the weight fraction of which (0.097 %) is essentially lower than the required value (0.17 %). This gives reason to believe that pipe A is made from steel 10, and not steel 20, as indicated in the certificate. Base metal of pipe B, as to its composition, corresponds to normative requirements to steel 20, as well as to certificate data.

Mechanical properties of metal of pipes A and B were studied in the sections adjacent to stability loss zone, not subjected to deformation.

Longitudinal samples, to GOST 10006–80, drw. 2, were tested to determine the values of yield point (σ_y), ultimate strength (σ_t), relative elongation (δ_5) and reduction in area (ψ).

Impact toughness at temperature of 0 and −40 °C was determined on longitudinal samples of 5 × 10 mm section with a sharp-notch (GOST 9495–78, type 13). Bend testing of transverse samples, prepared to GOST 6996, type XXVII, was conducted to determine the deformability of longitudinal pipe welded joint. Table 2 gives the results of tensile and impact toughness testing of pipe metal.

Data of Table 2 are indicative of the fact that the values of pipe metal mechanical properties meet the requirements of GOST 20295–74 for steel 20. On the other hand, there is a significant difference in strength values (σ_y, σ_t) of base metal of the examined pipes. For pipe A yield point σ_y is lower than for pipe B by 22 %, and ultimate strength σ_t — by 11 %.

Impact toughness of pipe base metal at temperatures of 0 and −40 °C is quite high, and is considerably higher than the normative requirements. Results of welded sample bend testing also meet the normative requirements.

Structural state of pipe metal was studied in «Neophot-32» microscope. It is established that microstructure of base metal of both the pipes is typical for hot-rolled steel, and is a sufficiently fine-grained ferrite-pearlite mixture with ferritic grain, corresponding to number 8–9 to GOST 5639 (Figure 2). The fraction of pearlitic component in the structure of pipe A base metal is

Table 2. Mechanical properties of base metal of the studied pipes

Property monitoring	Tensile testing				Impact bend testing*	
	σ_y, MPa	σ_t, MPa	δ_5, %	ψ, %	KCV_0, J/cm^2	KCV_{-40}, J/cm^2
Pipe A	326.1 312.5	418 418.7	34.9 34	58.0 60.3	223.2–258.2 / 239.0	156.9–204.3 / 173.3
Pipe B	403.2 417.6	469.7 471	33.3 31	57.3 54.6	165.9–213.6 / 192.8	70.1–96.8 / 85.5
Certificate date	333–338	463–482	33.3–34.1	N/D	–	–
GOST 20295–74	≥245	≥410	≥25	≥55	29.4**	–

*The numerator gives the extreme values, and the denominator gives average values from three tests.
**Requirements to SNiP 2.05.06–85.

somewhat smaller that is due, as was noted above, to lower carbon content compared to pipe B.

The given results of examination of pipe metal performance reveal that the cause for gas pipeline damage is associated not with the quality of base metal or welded joints, but with the features of stress-strain state developing in its service.

There is no doubt that damage in the form of local stability loss with corrugation formation around the entire perimeter can be caused predominantly by compressive forces in the pipe. It should be noted that at loading by internal pressure the gas pipeline develops longitudinal tensile stresses, corresponding to half of the level of hoop stresses. Therefore, such conditions should develop in gas pipeline service, under which in the considered section the applied compressive forces would not only compensate the longitudinal tensile stresses in the pipe induced by internal working pressure, but would also induce compressive stresses, sufficient for local stability loss.

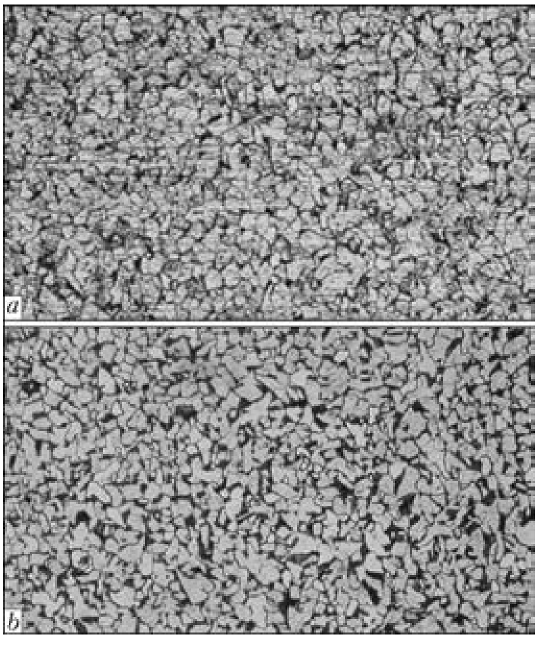

Figure 2. Base metal microstructure (×200): *a* — pipe A; *b* — pipe B

It is known [3] that critical stresses of local stability loss in a cylindrical shell (pipe) under the impact of uniform axial compression, are found from the following equation:

$$\sigma_{cr} = \frac{1}{\sqrt{3(1-\mu^2)}}\, E\, \frac{t}{R}, \qquad (1)$$

where μ is the Poison's ratio, which is within 0.25–0.35; E is the modulus of elasticity taken equal to $2\cdot10^5$ MPa; t is the pipe wall thickness; R is the pipe radius along the median section line.

Taking $\mu = 0.3$, we obtain critical stress of local stability loss

$$\sigma_{cr} = 0.6E\, \frac{t}{R}. \qquad (2)$$

Note that local stability loss in the pipe occurred in the immediate vicinity of the circumferential weld, while, on the other hand, the entire damage zone is located on one side of this weld, i.e. in one of the gas pipeline abutted pipes.

The fact of local loss of stability is observed near the circumferential welded joint of pipes and is attributable to the fact that when making the circumferential weld its shrinkage results in smaller pipe diameter [4, 5], and geometrical shape imperfection develops in the circumferential butt joint, which lowers critical stresses of local loss of stability, compared to an ideal pipe (Figure 3).

It was earlier shown that mechanical properties of the metal of pipes, abutted in the damage zone, differ markedly. A pipe, which has lost its stability, has the yield point approximately 100 MPa below that of the adjacent pipe. Measurements showed that the actual wall thickness of pipe A was in the range of 5.4–6.0 mm. In the other pipe the wall thickness was 6.2 to 6.4 mm.

Proceeding from expression (2), which is valid for circular shells (initial deflection amplitude should not exceed shell thickness [6]), critical stresses of local stability loss for pipe A are equal to ~4120 MPa, and for pipe B they are 4740 MPa.

Note that the derived values of critical stresses characterize local stability loss in the elastic work region. As these stresses many times exceed the yield point of steel, from which the pipes are made, then for specific pipes the values of pipe material yield point will be the critical stresses of local stability loss. It is natural that the local stability loss will occur in the pipe, requiring a smaller force, which, however, is capable of inducing yield point stresses in it. This is exactly what we see in this case. Local loss of stability is observed in a pipe with smaller wall thickness, and lower values of material yield point.

An open question still is what could have caused generation of forces in the gas pipeline, which induced compressive stresses, exceeding the steel yield point? The following factors were considered to provide an answer to this question:

- climatic temperature variations;
- wetting of soil foundation;
- earthquake;
- adjacent territory undermining by mining industry enterprises.

The latter assumption is based on the fact that operating Geroev Kosmosa and #4 mines of «Ternovskoe» Mine Management are located at a certain distance from the gas pipeline running zone. Figure 4 shows the locations of mine entrances and the route, including gas pipeline damaged section.

Considering that no earthquakes were registered in gas pipeline location areas during its service period this factor can be ignored.

Analysis of the results of engineering-geological surveys [7] allows eliminating from consideration the influence of wetting of soil foundation, as the foundation is composed of clay soils, namely loamy soils of solid and tight plastic consistency. Foundation soils do not have any subsidence properties.

Let us consider gas pipeline temperature deformations and the associated loads. Under certain conditions, temperature gradients during gas pipeline construction and service may induce compressive forces and stresses in it. Their level, however, will depend on the magnitude of temperature gradient. Compression may arise in the pipeline in the case when pipeline mounting and laying were conducted at maximum low temperatures, i.e. in winter, and in service pipe temperature reached its maximum.

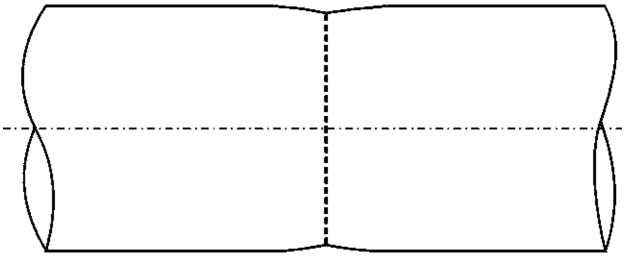

Figure 3. Geometrical imperfection in butt joint zone, caused by making the circumferential weld

Taking as the initial prerequisite the most unfavourable conditions of pipeline construction, i.e. in winter at ambient temperature of −20 °C, and considering that pipeline depth is equal to 0.8–1.0 m, and, therefore, its temperature will not be higher than 20 °C in the hottest months, the maximum possible temperature gradient will not be higher than 40 °C.

The coefficient of linear expansion for carbon steel, depending on chemical composition, varies in the range from $(11–15)\cdot10^{-6}$ deg^{-1}. At temperature gradient of 40 °C maximum relative elongation will be equal to $\varepsilon = 6\cdot10^{-4}$ mm.

Note that the connection between stresses and temperature elongation is given by the following expression:

$$\sigma = \varepsilon E. \qquad (3)$$

According to expression (3), temperature stresses in gas pipeline do not exceed 120 MPa.

Considering that thermal stresses are relatively uniformly distributed along the pipeline length, and their magnitude is much lower than pipe metal yield point, it is quite clear that they could not have caused local stability loss in the gas pipeline.

Deformations of soil foundations, arising during mining operations, have a significant influ-

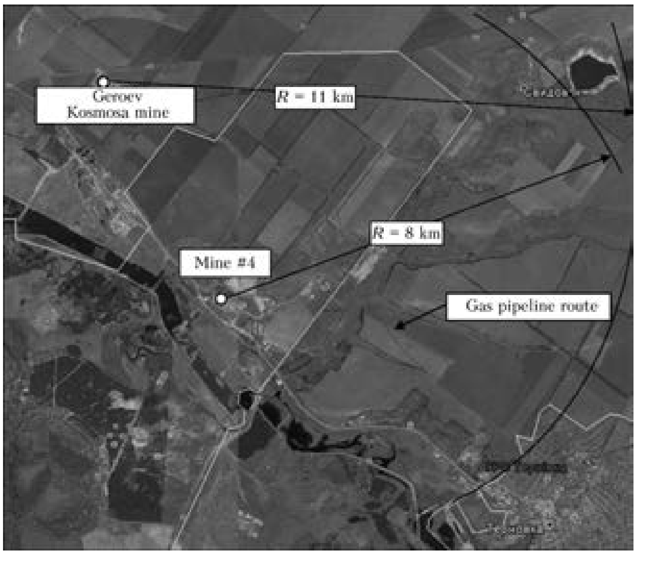

Figure 4. Gas pipeline location on the ground

ence on the strength and service characteristics of underground pipeline structures.

Relative location of gas pipeline calculated section and the mines (see Figure 4) leads to the assumption of mining operations influence on the gas pipeline, as in keeping with Table 1 of the Standard [8], the considered section pertains to group III of undermined territories.

At formation of the calculation procedure, pipeline section of length $L = 7.5$ m was taken, which consists of two pipes of $\varnothing 325 \times 6$ mm size, connected to each other by a circumferential weld. Calculated section length is due to the distance between the cantledges (cantledge spacing is 3.7 m).

Impact of internal service pressure $p = 5$ MPa and impact of friction forces, arising on the pipe outer surface as a result of soil shifting, was taken into account as the main loads.

Force of friction of pipeline outer surface against the soil depends on the perimeter of the pipe proper and on soil shear resistance in the form of tangential stresses τ. Nature of underground pipeline interaction with the soil can be conditionally divided into two sections, namely elastic and limit (Figure 5). In section I the bond between the soil and the pipe is elastic, characterized by the dependence proposed in [5]:

$$\tau(x) = k_u u(x), \tag{4}$$

where k_u is the soil resistance coefficient at pipeline longitudinal displacement; $u(x)$ are the displacements.

This region is characterized by relatively small displacement of soil (up to $u < 100$ mm). In point «k» tangential stresses reach their maximum value and in section II the soil goes into the limit stressed state (pipe slipping relative to the soil occurs).

Visual inspection of gas pipeline fragment in its fracture zone revealed that the magnitudes of pipe wall deformation in the direction of pipeline longitudinal axis Uz are much greater than

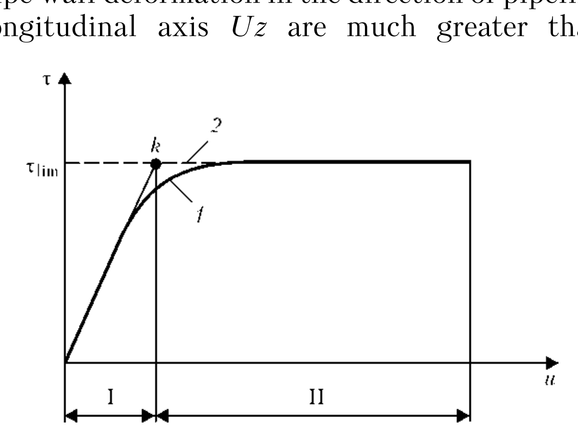

Figure 5. Nature of interaction of underground pipeline with the soil: *1* — actual curve; *2* — calculated

100 mm. Thus, it can be assumed that in the actual case considered the soil interaction with the pipe wall corresponds to the limit stressed state.

In keeping with [9], soil shear resistance for the limit stressed state is equal to

$$\begin{aligned}\tau_{lim} &= q_{pr}\,\mathrm{tg}\,\varphi_s + 2\gamma_s c_h \pi D_{out}^2\,\mathrm{tg}\,\varphi_s + 0.6\pi D_{out} c_s = \\ &= 537.2\cdot 0.344 + 2\cdot 1800\cdot 0.685\cdot 3.14159 \times \\ &\times 0.325^2\cdot 0.344 + \\ &+ 0.6\cdot 3.14159\cdot 0.325\cdot 2000 = 1691.51\ \mathrm{kg/m^2},\end{aligned} \tag{5}$$

where q_{pr} — weight of pipeline with the product is

$$q_{pr} = q_p + q_{gas} = 47.2 + 490 = 537.2\ \mathrm{kg/rm};$$

q_p — weight of 1 rm of pipe of 325×6 mm size is equal to 47.2 kg/rm; q_{gas} — weight of natural gas per 1 rm of pipeline, which is allowed to be taken equal to [10]

$$\begin{aligned}q_{gas} &= 10^{-2} p\cdot D_{in}^2 = 10^{-2}\cdot 5\cdot(0.313)^2 = \\ &= 0.0049\ \mathrm{MN} = 490\ \mathrm{kg/rm},\end{aligned}$$

where $p = 5$ MPa is the working pressure; $D_{in} = 0.313$ m is the pipeline inner diameter; $\varphi_s = 19°$ is the angle of soil internal friction; $\gamma_s = 1800$ kg/m^3 is the specific soil weight; c_h is the dimensionless coefficient equal for clay soils to

$$\begin{aligned}c_h &= 0.367(h/D_{out}) - 0.046(h^2/D_{out}^2) + 0.06 = \\ &= 0.367(0.8/0.325) - 0.046(0.8^2/0.325^2) + \\ &+ 0.06 = 0.685,\end{aligned}$$

where $h = 0.8$ m is the backfill height; $D_{out} = 0.325$ m is the gas pipeline outer diameter; $c_s = 2000$ kg/m^2 is the specific adhesion of soil around the pipe.

Proceeding from that, the limit value of tangential stresses on the surface of soil contact with pipeline wall, induced by soil shifting, does not exceed $\tau = 0.0169$ MPa.

In connection with the complexity of the process of the considered pipeline structure deformation, calculation was performed allowing for physical nonlinearity of pipe material properties. Change of physico-mechanical properties of pipe material was simulated in calculations by stress-strain diagram, derived by the results of testing the longitudinal samples cut out of the pipe (see Table 2). The accepted stress-strain diagram has the form given in Figure 6.

Finite element model of the pipeline is made in 3D formulation, using shell finite elements of general position. Numerical model includes two pipes (A and B) connected to each other by a circumferential weld. Initial geometrical imperfection was allowed for in the zone of pipe abut-

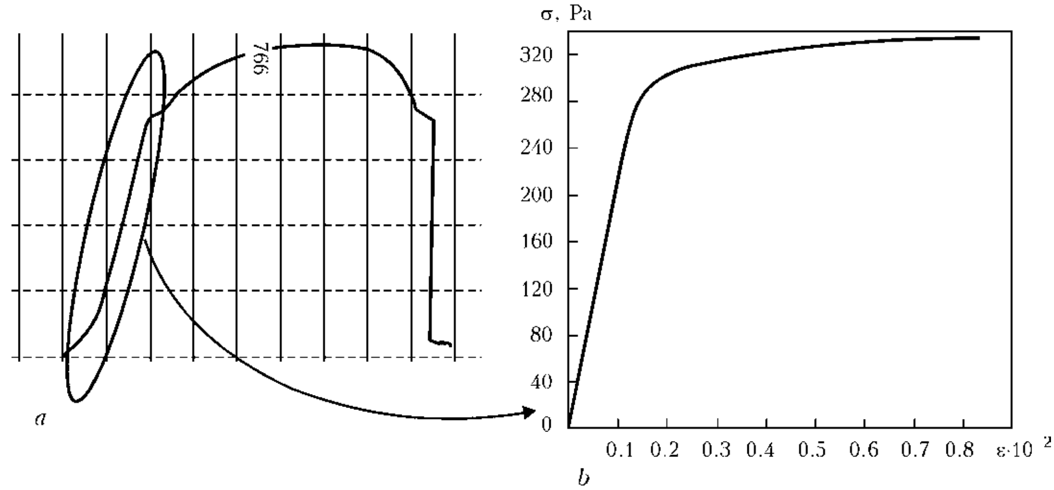

Figure 6. Stress-strain diagrams for tested sample of studied pipe base metal (*a*) and for numerical calculation model (*b*)

ment. General view of the geometrical and FE models of the gas pipeline is shown in Figure 7.

To ensure geometrical stability of the model, linear and angular displacements in the plane normal to longitudinal axis, are limited along the edges of calculation area. Linear displacements along gas pipeline axis are allowed.

At formation of calculation procedure, it was taken into account that from calculation point of view, the pipeline buried into the soil is a rod in an elastic medium [7, 11]. Here, the rigidity of this medium — the soil surrounding the pipe — is non-uniform. In particular, backfilling soil, located above the pipe body, has lower rigidity than soil located from the pipe sides or the underlayer.

Development of longitudinal compressive load in the pipeline under certain conditions can result in loss of stability, which is accompanied by pipeline section buckling in the direction of day surface (direction with the lowest rigidity of elastic medium). Here, one of the important parameters affecting the magnitude of critical force and form of stability loss is the value of free length of calculated pipeline fragment.

Mounting cantledges along the gas pipeline greatly lowers the possibility of pipe transverse displacement and changes the free length of calculated pipeline sections. Reduction of free length, in its turn, leads to increase of critical load, capable of leading to overall loss of pipeline stability. The required critical load force can exceed the axial load magnitude, which causes formation of plastic hinges in the pipe wall. This results in formation of the zone of local loss of pipe wall stability. Thus, cantledges can be a factor, influencing both the type and form of stability loss, and critical force values.

Influence of saddle-like concrete cantledges was simulated by limiting linear displacements of pipeline individual sections in the directions normal to gas pipeline longitudinal axis. It is assumed that cantledges are equidistant from the weld (for 1.85 m on each side).

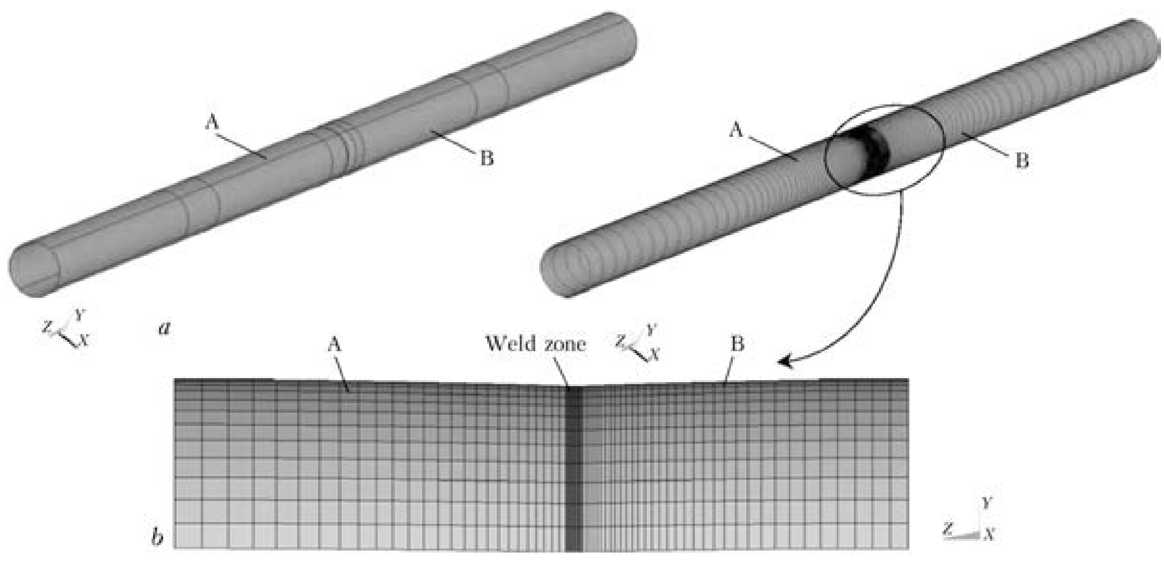

Figure 7. Geometrical (*a*) and finite-element (*b*) numerical models

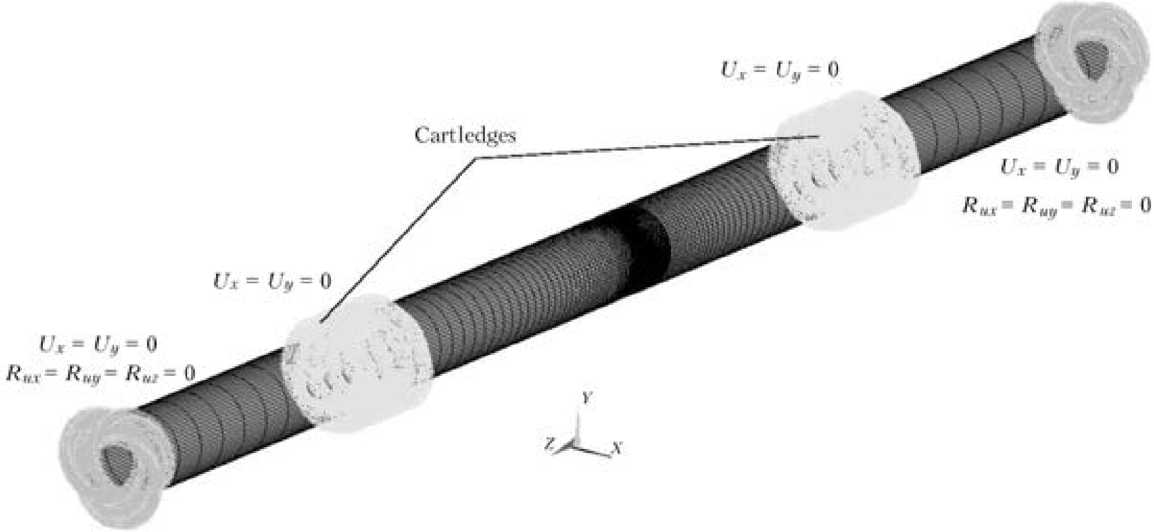

Figure 8. Boundary conditions: U_y, U_x — linear displacements; R_{ux}, R_{uy}, R_{uz} — angles of pipe axis rotation

Boundary conditions taken in calculation procedure are given in Figure 8.

The following assumptions and simplifications were taken, when plotting the FE model of gas pipeline calculated section:

• circumferential weld in the section of abutting two pipe edges was taken to be equivalent to pipeline base material;

• pipeline numerical model was formed for pipe wall median surface.

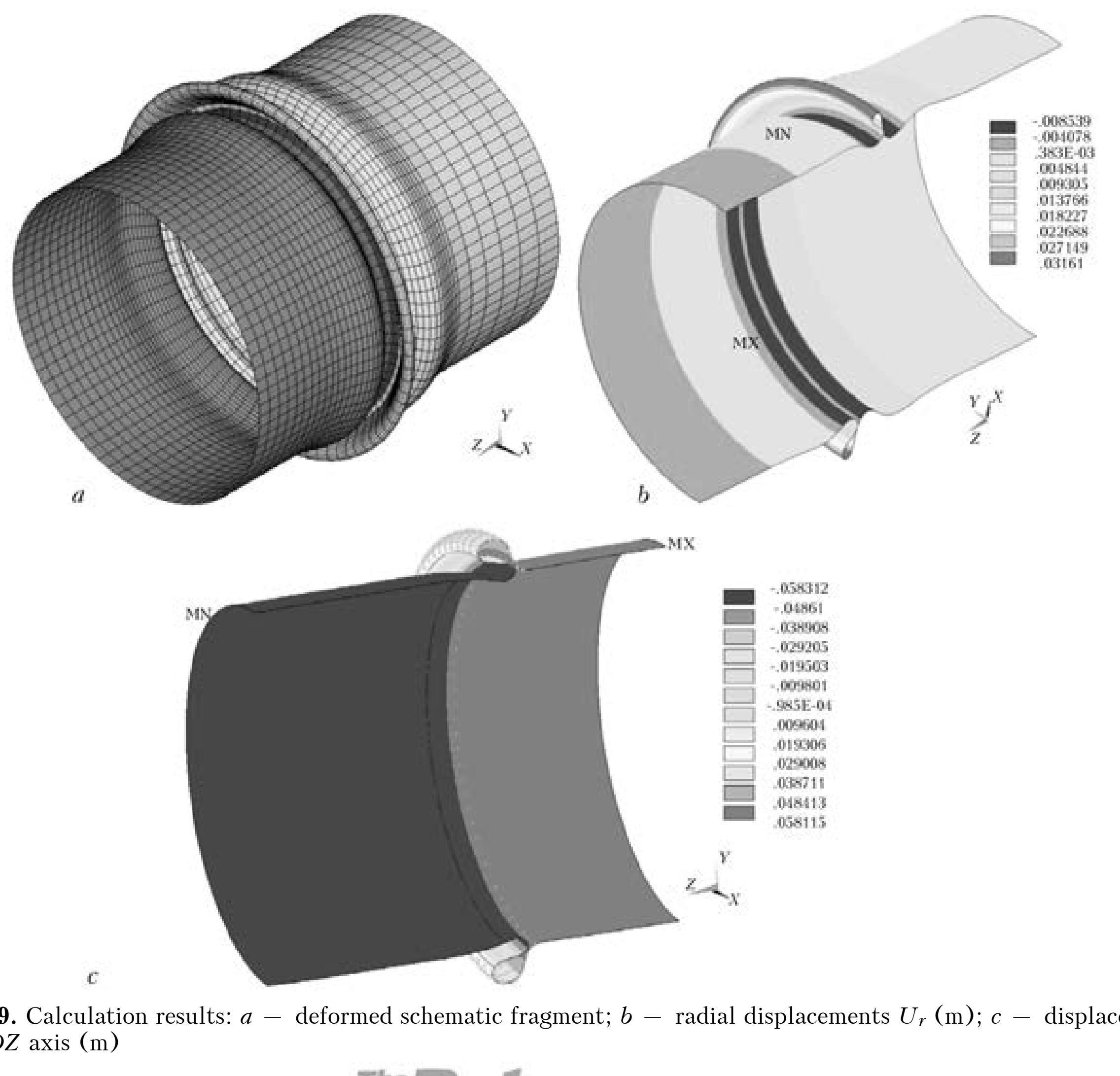

Figure 9. Calculation results: *a* — deformed schematic fragment; *b* — radial displacements U_r (m); *c* — displacements along *OZ* axis (m)

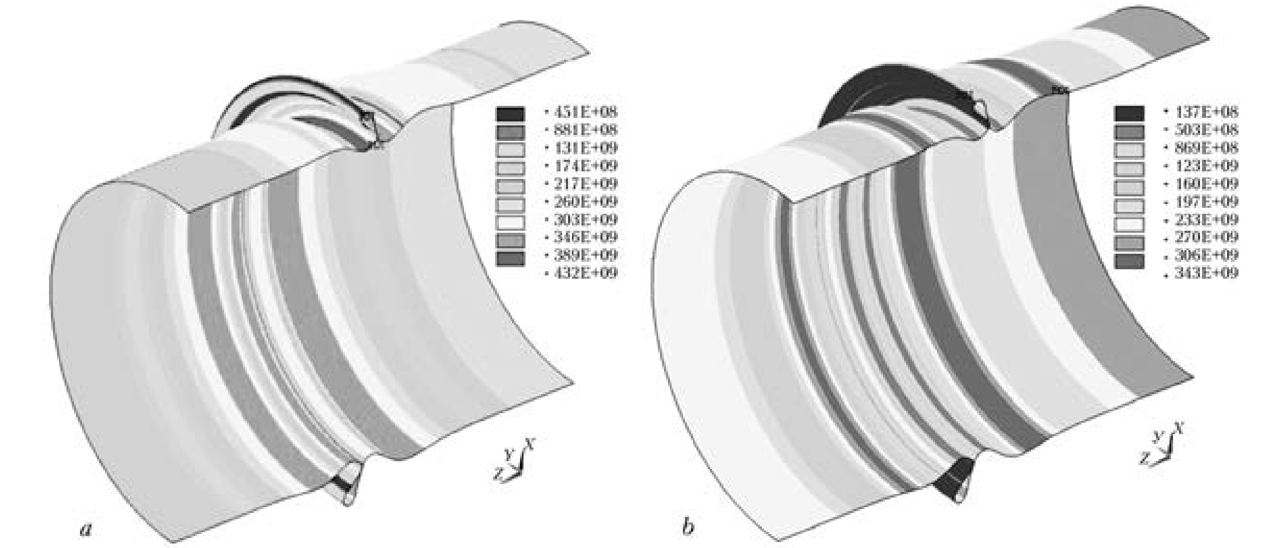

Figure 10. Equivalent stresses S_{mises} on face (*a*) and median (*b*) surfaces, MPa

Analysis of obtained results showed that under the impact of loads, the wall develops considerable deformations, and stress magnitudes exceed pipe material yield point.

Figure 9, *a* gives the deformed pipeline schematic. Deformed section of pipeline wall is characterized by buckling of pipe wall section in the radial direction (along axes U_y and U_x). At summary axial pipe displacements U_z = 116 mm in pipeline wall, closing of pipe walls and formation of the first wave of buckling is observed. Displacements in pipe wall reach $U_x = U_y$ = 30 mm in the radial direction. Isofields of linear displacements in the radial (along axes U_y and U_x) and axial (along axis U_z) directions are given in Figure 9.

Considerable deformations of gas pipeline wall are accompanied by formation of local zones with higher stress magnitudes. In the zones of pipe wall bending the magnitudes of equivalent stresses exceed the yield point value. On median surface stress values are equal to S_{mises} = = 342 MPa, and on face surfaces they reach values S_{mises} = 430 MPa. Isofields of equivalent stresses on median and face surfaces of gas pipeline wall are given in Figure 10.

Thus, it is established that soil shifting in territories undermined by mine working, results in pipe displacements in the axial direction, and is the cause for local loss of stability of the pipeline. Level of equivalent stresses arising in the wall exceeds the pipe material yield point. Cartledges have an additional influence on the form of stability loss and magnitude of critical load.

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