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MAINTENANCE OF STRENGTH OF MAIN PIPLINES, OPERATING IN NON-STANDARD CONDITIONS

Maintenance conditions of the pipelines, laid in swamped and flooded territories, or with sub-surfaced cavity of various origin (worked-up territories in places of mine's construction, territories with karst cavity), as well as in areas with ever-frozen and landslide grounds are defined as non-standard [3]. These pipelines may undergo considerable deformations in the course of the operation, accompanied with a tension-pressing of the long axial line and its bend. In this case, the pipeline may be destroyed not only due to axial pressing, when it loses its stability, which is accompanied with the formation of gofers on the pipe surface, but due to a bend, too, when almost a vertical cut of the pipe takes place. [7]. According to the enterprise "Permtransgas", a sagging of the gas pipeline over karst formations may reach values several times exceeding the pipe radius. In case, when a gas pipeline is laid in swamped and flooded territories, in areas of ever-frozen grounds, a maximum sagging of arches with a deformed pipe as per data of V.A. Dinkov and O.M. Ivantsov [2] reaches 5 m. Having a sagging, commensurable with the pipe radius, actual loads are re-distributed depending on its deformation, which itself is unknown. It makes the task insoluble in a linear statement. In order to design and erect pipelines of a new generation for gas and oil delivery to China with a length of 6000 km, or a gas line along the bottom of the Black Sea at a depth of 2,1 km with the operating pressure of 25 Mpa, it is necessary to elaborate reliable methods of pipelines' calculations, taking into consideration their extreme conditions of work.

The statement of a long-cross bend bar task is considered very often non-linear in case, when formulae are verified for the calculation of the curve of the bent central line, and the balance equations are made up for its non-deformed condition not taking into account a bar displacement in space. In this case projections of inner forces in rectangular decart's system of coordinates do not have physical sense, i.e. they are neither long, nor cutting-through forces. In ac. Yu.N. Rabotnov's [5] opinion, this approach is mistaken.

In this article, when the non-linear theory of a bar deformation was elaborated, and it was accepted as a mathematical model of the pipeline with big saggings, which are commensurable with the radius of the pipe, the bar's long central line is joined fixedly with a curve-lined mobile lagrange's coordinates system in space. Such approach allows to tie-in the deformation of the axial line with the movement of the attended lagrange's coordinates system of this line in space. In comparison with earlier elaborated models of the calculation [6], the corners of turns of the axes of the attended coordinates system are not set with the deformation of the axial line, but they are defined as components of the deformation of this line depending on the components of the vector of the displacements.

A calculated model of the stressed-deformed condition of the pipe is a bar of the tubular cross-section from a resilient material with a rectilinear or curve-linear forming line. It is proposed that a project location of the profile of the examined section of the pipeline is flat. The examined section of the pipeline is divided into bar and unit's elements. Their quantity depends on a profile of the trace, where the pipeline is laid, loading components, acting on the pipeline, and on the pipeline's branching and geometry of pipes as well. Supports and sections are units of the system, where limits are set for the components of vector of the displacements and a corner of the turn of normal of the axis of the pipe, or where external forces and moments are applied to the pipe, as well as points where the pipe does not have a contact with the surface of the ground per its axial coordinate.

Further, a global and local orthogonal decart's coordinates systems are introduced. The global fixed rectangular coordinates system for the total examined section determines a position of each bar's element. The local mobile curve-lined coordinates system is connected with the axial line of each bar's element, it displaces together with it in space and is deformed: it is tensioned, pressed and bent. In order to get more simple equations in the local mobile system, the axis OX is directed on the tangent to the deformed axial line of the bar's element, the axis OY- on the normal toward it to the side of concavity of the curve, and axis OZ – on the binormal.

A separate bar's element is taken into consideration. Its tensioned-deformed condition (TDC) is described by:

a) Geometrical non-linear co-relations, which set deformations pressing-expansion to the axis of the pipeline ε_{11}, an angle of turn of the normal of the long axis of the pipe ω_1 and bent deformations $\mathbf{k_{11}}$ depending on long displacements $\mathbf{u}$, sagging $\mathbf{w}$, as well as their derivatives, which are calculated per following formulae

$$\varepsilon_{11} = \frac{du}{dx} - k_1 w + 0{,}5 \cdot \omega_1^2, \qquad (1)$$

$$\omega_1 = -\frac{dw}{dx} - k_1 u, \qquad (2)$$

$$k_{11} = \frac{d\omega_1}{dx}, \qquad (3)$$

where $\mathbf{k_1}$ – the initial curve of the long axis of the pipeline;

$\mathbf{x}$ – the independent variable, which coincides with the long axial coordinate;

b) equations of the bar's element balance in a scalar form, referred to the deformed axial line of the bar and having the following appearance

$$\frac{dT_x}{dx} - k_1 Q_y - \frac{d\omega_1}{dx} Q_y = r_x + q_1 - q_n \omega_1 , \qquad (4)$$

$$\frac{dQ_y}{dx} + k_1 (T_x - p_o) + \frac{d\omega_1}{dx} (T_x - p_o) = r_y + q_n , \qquad (5)$$

$$\frac{dM_z}{dx} + Q_y = 0, \qquad (6)$$

where $\mathbf{T_x}$ - the long axial force, which is directed per the tangent towards the deformed axial line;

$\mathbf{Q_y}$ – the cutting-through force, directed per the normal to this line;

$\mathbf{M_z}$ **-** the axial bending moment;

$\mathbf{r_x}$, $\mathbf{r_y}$ – the components of the reaction from the part of the ground to the deformation of the pipeline, which are directed, accordingly, per the tangent and the normal to the deformed axial line of the bar. They are determined per models [1,3]. As well as per recommendations of these works, a pushing-out force is determined when the pipeline crosses karst formations or swamps filled with water;

$\mathbf{q_1, q_n}$ – the long and vertical components of the external distributed load, taking into account forces of the pipeline's weight with a liquid or gas, as well as the force of the ground weight, available on the pipe;

$\mathbf{p_o = \sigma_{кц} \cdot F_o}$ – the force effective of the inner pressure;

$\mathbf{\sigma_{кц}}$ – The ring stresses from the inner pressure;

$\mathbf{F_o}$ – the cross-section area of the pipe's wall;

c) physical correlations (7) – (8), which establish a connection between inner force factors and the deformations of the bar's axial line;

the long axial force $\mathbf{T_x}$ in the pipe's wall from the deformations of pressing-expansion ε_{11} of the axial line of the bar, caused by the inner pressure P_o and temperature difference ∇t, is calculated per the formula

$$\mathbf{T_x = E \cdot F_o \cdot \varepsilon_{11} + \mu \cdot \sigma_{кц} \cdot F_o - \alpha \cdot \Delta t \cdot E \cdot F_o} , \quad (7)$$

where α - coefficient of the linear expansion of the pipe's metal;

E,u –accordingly, module of elasticity and coefficient of Puasson of steel;

Axial bending moment $\mathbf{M_z}$, linearly depending on the pipe's stiffness **EJ** and bending deformations $\mathbf{k_{11}}$

$$\mathbf{M_z = E \cdot J \cdot k_{11}} . \quad (8)$$

The geometrical non-linear balance equations for the bar's element (4)-(6) were received in (7), where a detailed analysis was given. In comparison with the earlier received dependencies [1] the geometrical correlations, which describe the relation between the deformations and displacements of the axial line of the bar, take into account the primary curve $\mathbf{k_1}$ of this line in the calculations. They are true with saggings of the bar's axial line, a value of which may reach the pipeline radius value. The balance equations (4)-(6), referred to the unit vectors of the deformed axial line of the bar, are made taking into account the initial curve and its alteration when a displacement of the axial line occurred due to the influence of outer force factors. They describe a longitudinal-cross bent of the pipeline in the ground due to the influence of forces of the weight, inner pressure and a temperature difference.

It is accepted in a resilient field of the ground deformation, that the components of its reaction $\mathbf{r_x}$, $\mathbf{r_y}$ are proportional to longitudinal displacements and the pipe's axial sagging [1,3]. The coefficients of proportionality $\mathbf{c_{xo}}$, $\mathbf{c_{yo}}$, which are named, respectively, summarised coefficients of a touching and normal resistance of the ground, are determined as per elastic characteristics of the ground and the pipeline's diameter. In order to describe a ground's behaviour out of the borderline of its resilient work, the concepts of the ultimate ground resistance to the displacement $\mathbf{t_{alt}}$ and the conventional ground's ability $\mathbf{R_{gr.}}$ If $\mathbf{u>t_{alt}/(\pi D_H c_{xo})}$, then it is assumed, that an area of the ultimate balance is available, where it is necessary to accept $\mathbf{r_y = t_{alt.}}$ It is analogously, if $\mathbf{w>R_{gr}/c_{yo}}$, then it is assumed, that the ground lost its bearing ability and its component of the reaction $\mathbf{r_y}$ on the deformation of the pipe is constant and it is determined by the equation

$$\mathbf{r_y = R_{gr} w.}$$

In case, the ground is not available under the pipeline, it is assumed

$$\mathbf{r_y = r_y = 0.}$$

In case, a gas pipeline crosses karst formations filled with water (cavities or craters) or a swamp, where it is partially or completely submerged in water, then a pushing-out force, directed upwards acts on it depending on a water level. Its value, falling on the length unit of the pipeline, is determined by the formula [1]:

$$\mathbf{q_в = \gamma_в F_{обв}},$$

where $\mathbf{F_{обв} = \frac{D_н^2}{8}(\alpha - \sin\alpha)}$ -- the cross-section area of the pipe in water;

$\gamma_в$ – specific weight of water taking into account soluble and suspended substances in it;

α – an angle, which characterises a water level location in respect of the pipe's cross-section.

The value of angle α is calculated as per experimental formulae [1] depending on the distances from the filling top of the pipe to the water level, the upper and lower forming pipe.

The system from eight algebraic and differential equations (1)-(8) in respect of eight unknown values $\mathbf{u, w, \omega_1, \varepsilon_{11}, k_{11}, T_x, Q_y, M_z}$ may be reduced to six ordinary differential equations of the first order in respect of the unknown ones

$$\mathbf{y_1 = T_x, y_2 = Q_y, y_3 = M_z, y_4 = u, y_5 = w, y_6 = \omega_1.} \quad (9)$$

This system in a vector form has the appearance

$$\frac{\partial \overline{\mathbf{Y}}}{\partial \mathbf{x}} = \bar{\mathbf{f}}(\mathbf{x}, \overline{\mathbf{Y}}) + \bar{\mathbf{b}}(\mathbf{x}) , \quad (10)$$

where the components of vectors $\overline{\mathbf{Y}}, \bar{\mathbf{f}}, \bar{\mathbf{b}}$ are

$$\left.\begin{aligned} & f_1 = k_1 y_2 - \pi D_н c_{xo} y_4 - \frac{y_3}{EJ} y_2; \\ & f_2 = k_1 y_1 - D_н c_{yo} y_5 + \frac{y_3}{EJ}(y_1 - p_o); \\ & f_3 = -y_2; \quad f_4 = \varepsilon_{11} + k_1 y_5 - 0{,}5 y_6^2; \\ & f_5 = k y_5 - y_6; \quad f_6 = k_{11}; \end{aligned}\right\} \qquad (11)$$

$$b_1 = -y_6 q_n, \; b_2 = q_n, \; b_3 = b_4 = b_5 = b_6 = 0. \qquad (12)$$

the exchange of variables T_x for y_1 and M_z for y_3 is made in the algebraic equations(7,8) too

$$y_1 = E \cdot F_o \cdot \varepsilon_{11} + \mu \cdot \sigma_{кц} \cdot F_o - \alpha \cdot \Delta t \cdot E \cdot F_o \; ; \qquad (13)$$

$$y_3 = E \cdot J \cdot k_{11} \; . \qquad (14)$$

Right parts of the system of differential equations, which are represented in the appearance of (10), (11), contain non-linear members: $y_3 \cdot y_2$, $y_3(y_1 - p_o)$, y_6^2, $y_6 \cdot q_n$. Their linearity is completed by the iteration method of Newton – Kantorovich as per the algorithm, analogous to the scheme, elaborated by V. I. Miachenkov for the calculation of designs, consisting of the elements in shell [6].

Further, balance equations of the unit's elements are made up, which contain outer force factors and unknown reactions of the bar's elements. In joint solution of these balance equations and equations (1-8), the modification of the method of end elements, proposed by A.V. Aleksandrov is used. In this method, a definition of the elements of stiffening matrix, the component of a summarised vector of efforts at the butt ends of the bar's elements, as well as the characteristics of stressed-deformed condition of the bar and unit's elements is reduced to the solution of a normal system of the ordinary differential equations. This system of the differential equations is solved by means of the method of an orthogonal run-in with the intermediate ortho – rate setting as per Godunov.

The programmed mathematical provision of the above-mentioned methods consists of the following divisions:

1. A numeric integration system of the differential equations by the method of Runge-Kutt;
2. Ortho- rate setting and ortho-gonalization of vectors;
3. The decision of the system of algebraic equations by the methods of Gauss;
4. Finding out of matrixes of stiffness and the vector of summarised efforts at the butt ends of the bar's element;
5. The decision of a normal system of heterogeneous differential equations;
6. The algorithms of calculations of non-linearity in the successive approximations by the method of Kantorovich-Krylov;
7. Finding out of the intermediate values of the functions per interpolate formulae of Lagrange;
8. Multiplication and transposition of matrixes;
9. The program, which makes up an allowable system of the linear algebraic equations automatically for finding out the components of

vectors of displacements of the unit's elements taking into account the reaction of each bar's element, and limitations, which were put on the components of units' displacements and outer force factors, applied in these units.

The contents of the above-mentioned sections 1 – 8 due to a large size of the mathematical apparatus is not given here. It is realised in the program complex of the pipelines' strength calculation for the computer by means of separate modules, which allows to use them not only in the calculation of the underground pipelines, but the pipelines submerged in water.

The elaborated calculation method is used when a stressed-deformed condition (SDC) of the gas pipeline over karst formations is examined taking into account operation and weather-climatic loads.

Fig.1-4 show the calculated scheme of loadings on the pipeline as well as saggings **w(x)** and bending stresses $\boldsymbol{\sigma_{bend}(x)}$, where a length of the middle span, located over a karst cavity is designated by $\mathbf{L_2}$. Lengths of the sections, located to the left and right from the karst cavity, where the pipe is in the ground, are designated by $\mathbf{L_1}$ and $\mathbf{L_3}$. Two versions of loadings on the middle part are examined: fig. 1-2 shows a ground filling on the pipe, but nothing of the kind is under; fig. 3-4 shows the pipe completely submerged under water, and a distributed loading pushes the pipe out upwards over there. $\mathbf{P_o}$ and Δt under figures, designate an inner operating pressure in the pipeline and a positive temperature difference respectively (a difference between temperatures of maintenance and closing of pipes during the construction). In fig. 1 – 2 a distance from the top of filling of the pipe to its axis over all sections is constant and equal to 2,5 m, and in fig. 3 – 4 this distance is equal to 2,5 m in two marginal sections L_1 and L_3 and in the middle section, where the pipe is completely under water, the distance from the surface of water level to the pipe's axis is equal to 2 m.

While making up the initial calculation data we assume that adjacent to the karst cavity or crater from left and right pipeline's sections are in the grounds belonging to one-type. The ground of filling is also of one-type. Table 1 shows values of physical –mechanical characteristics of the foundation ground and filling ground, where the following designations are accepted: $E_{gr.}$ – deformation module; $V_{gr.}$ – Puasson' coefficient; γ_{gr} –volumetric weight; φ_{gr} - an angle of inner friction; c_{gr} – cohesion; c_{xo} – summarised coefficient of a tangent resistance; R_{gr} –bearing capability.

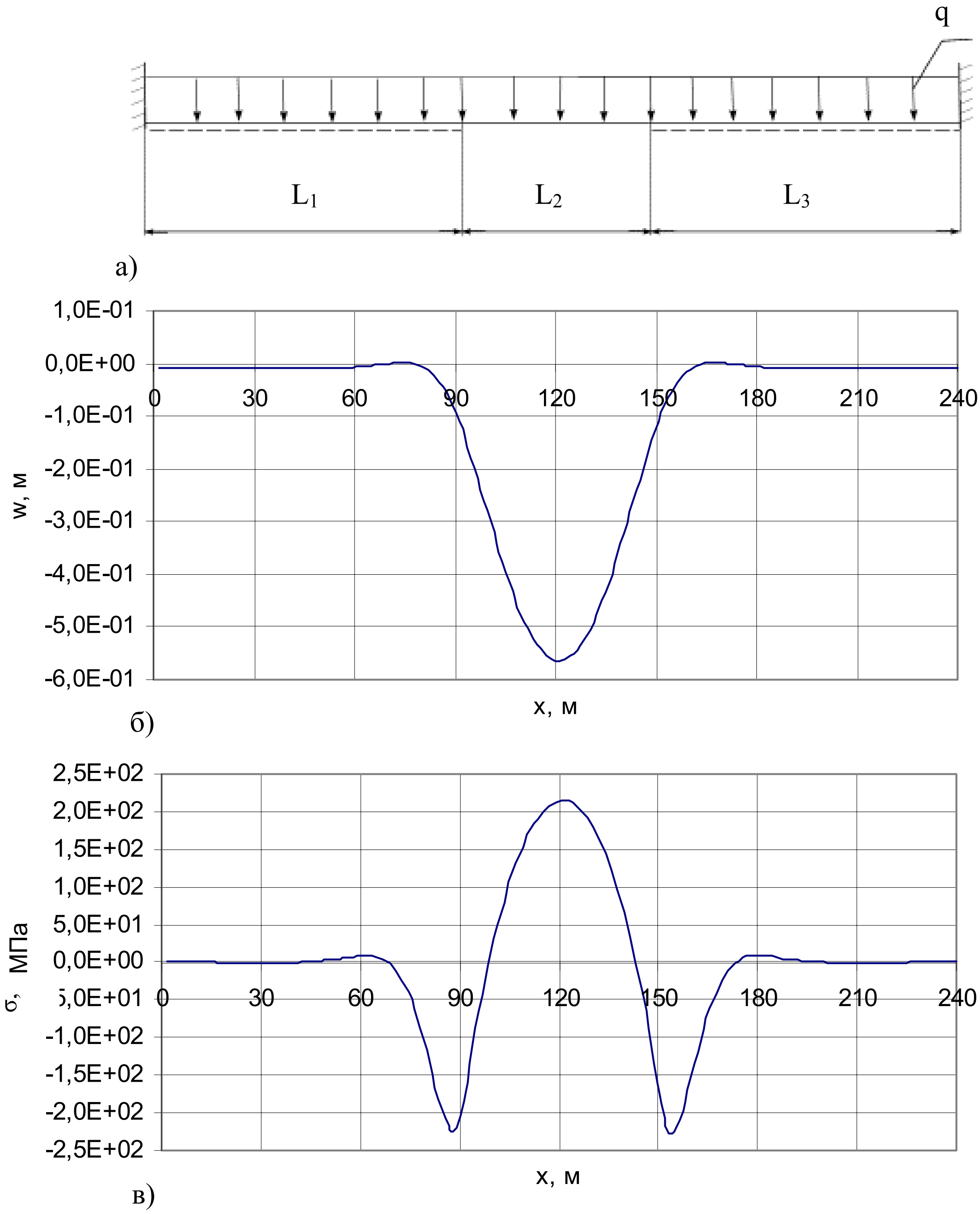


Fig.1 The calculation of main parameters of SDC of the submerged pipeline in the carst zone: a) a designed pipeline diagram (L1=L3=90m, L2=60m; p_o=7,5Mpa; Δt=20 deg.C); b)diagram of saggings; c) bending stresses

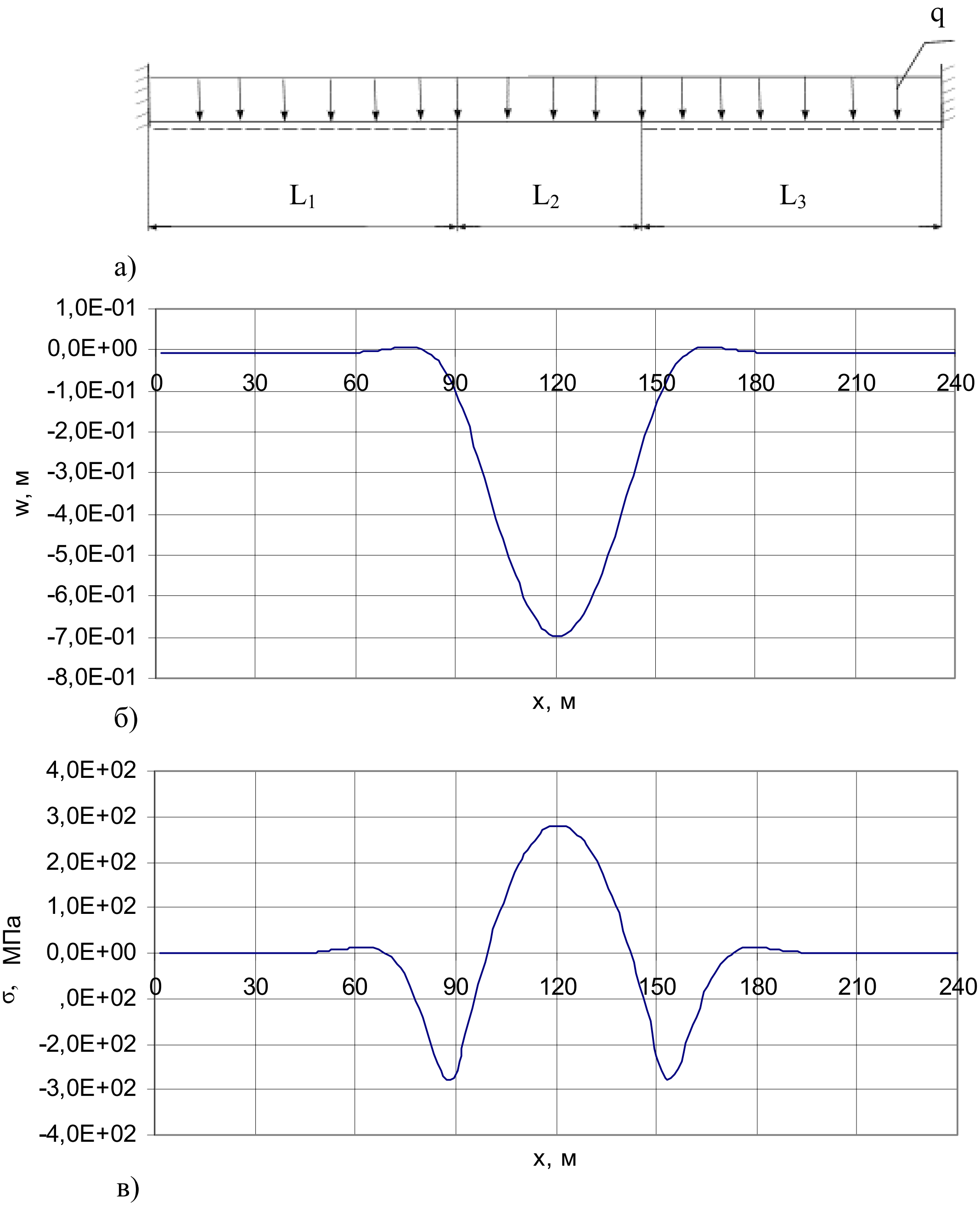


Fig.2 The calculation of main parameters of SDC of the submerged pipeline in the carst zone: a) a designed pipeline diagram ($L1=L3=90m$, $L2=60m$; $p_o=0$; $\Delta t=50$ deg.C); b)diagram of saggings; c) bending stresses

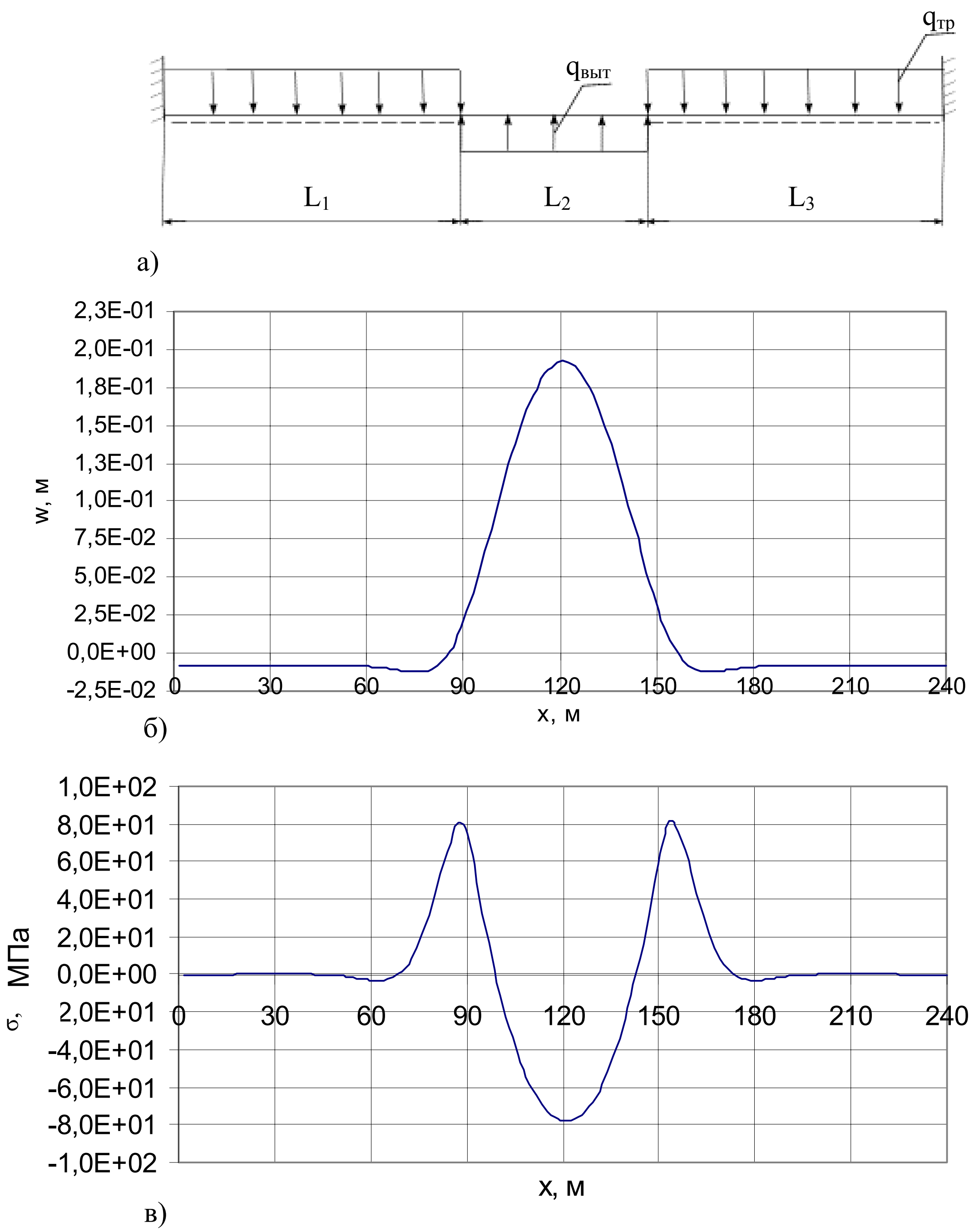
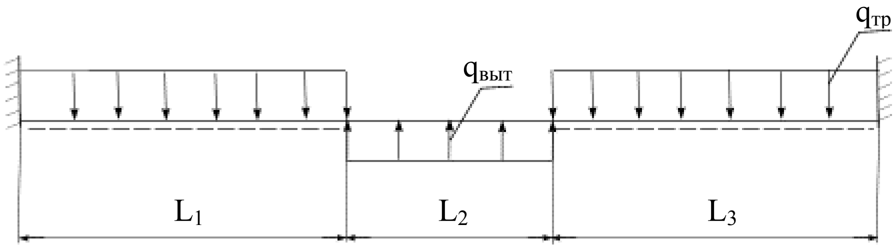


Fig.3 The calculation of main parameters of SDC of the submerged pipeline in the carst zone: a) designed pipeline diagram ($L3=90m$, $L2=60m$; $p_o=7{,}5Mpa$; $\Delta t=20$ deg.C); b)diagram of saggings; c) bending stresses



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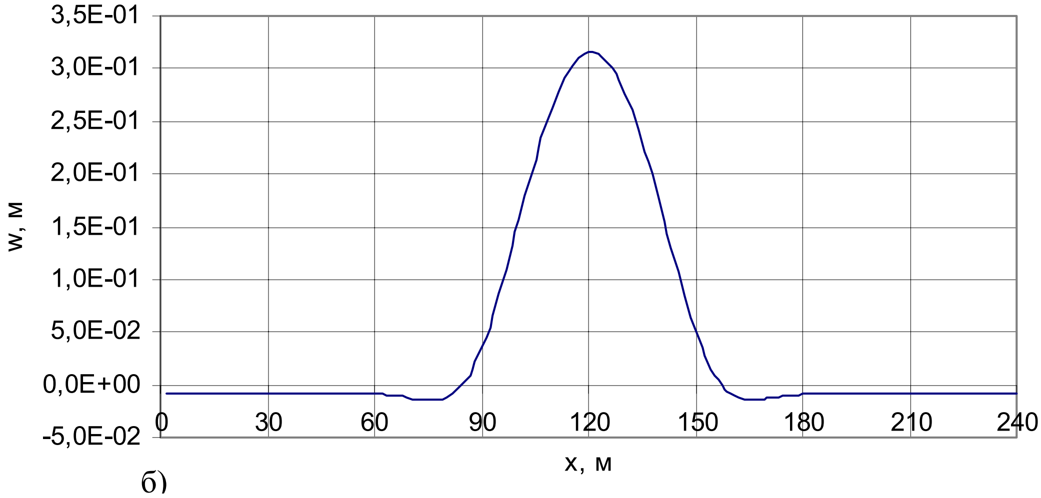

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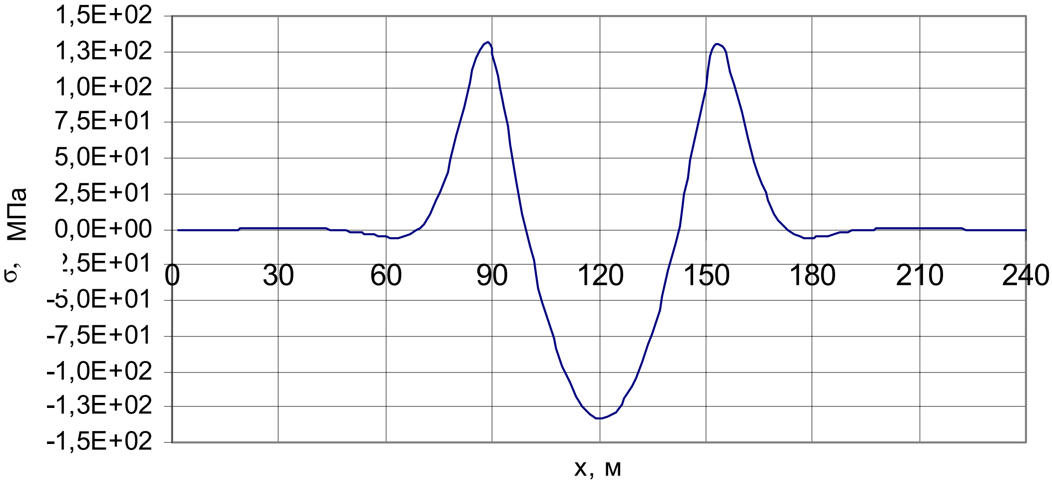

в)

Fig.4 The calculation of main parameters of SDC of the submerged pipeline in the carst zone: a) designed pipeline diagram (L1=L3=90m, L2=60m; po=0; Δt=50 deg.C); b)diagram of saggings; c) bending stresses

Table 1

Values of physical –mechanical characteristics of the foundation and filling grounds

Ground type	Physical-mechanical characteristics of the ground						
	$E_{gr.}$, Mpa	$V_{gr.}$	$\gamma_{gr.}$, N/m^3	$\varphi_{gr.}$, deg	$c_{gr.}$, Mpa	$c_{xo.}$, Mpa/m	$R_{gr.}$, Mpa
Foundation	20	0,3	19	32	0,003	3	0,02
Filling	16	0,4	19	2	0,001	1	0,01

The pipeline is made of pipes of dimensions 1,420 x 0,0195 m. The pipe steel has a temporary resistance of R_1 = 600 Mpa and yield point R_1=470 Mpa.

CONCLUSIONS

Based on the carried out calculations and analyses of diagrams (fig. 1-4) the following conclusions may be made:

1. A sagged part of the pipeline over the carst cavity is streched in the axial direction under the influence of an inner pressure due to the pinch of the adjacent to the karst cavity sections of the pipeline. It causes a decrease in the level of bending tensions over all pipelines' length. A degree of the reduction depends on the pipeline's span length, which is located over the kars cavity. In case, when the length of this span is such, that a maximum level of bending tensions is determined by span moments, the influence of the inner pressure on this maximum level is not significant. In case, when the length of this span is such, that a maximum level of bending tensions is determined by support moments, then due to a stretch of pipeline's axis from the inner pressure, its saggings and bending stresses are reduced significantly in comparison with the case, when the inner pressure is equal to zero. Thus, when the inner pressure is present, a radius of bending of the sagged part over the karst cavity is reduced in comparison with the case, when this pressure is not present;
2. The middle section of the gas pipeline, which is under water, when in a normal mode of the operation, moves upwards a little under the influence of a pushing force of water. A more dangerous, in sense of a pipeline's strength, is a mode of the operation when an abrupt drop of the inner operating pressure occurs and, meanwhile, the pipe still remains heated-up for a some period of time. At the expense of pressing of the long axis due to an influence of temperature stresses, a derrick and bending stresses increase abruptly. In particular, as per data of diagrams in fig.3-4, this increase for saggings amounts to over 1,5 times, and 2 times – for bending stresses. Thus, when fulfilling scheduled works, connected with a drop of the excessive pressure, this decrease in pressure is required to carry out gradually in order to provide with a smooth decrease of temperature stresses.

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