NUMERICAL MODELING OF GEOLOGICAL ENVIRONMENT IMPACT ON THE PIPELINES

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In assessing the impact of geological environment on the pipeline it is important to note that its destructive effect could be substantially neutralized at a stage of pipeline's design and construction. However, at these stages it is impossible to conduct the qualitative and quantitative assessment of the overall effect of the adverse natural factors. The extent and direction of the effect of these factors can be determined only after the comprehensive prospecting and special engineering work.

In the stationary pipeline regimes, the impact of geological environment is minimized and has little effect on the safety and longevity of pipeline operation. However, there is always the risk that the geological conditions behave in an un-controlled manner, with real threats of damage and destruction. The factors that influence negatively on the safe functioning of the pipelines are as follows:

- the water-erosive processes within the premises of the pipelines related to the temporary and permanent streams;
- existence of the perpetually frozen and seasonally frozen grounds and various cryogenic processes;
- gravitational processes related to the ruggedness of the relief;
- tectonic and seismic processes in the different rheological mediums.

We propose the general method and computer modeling to define the stress-strain state of the system "geological environment-pipeline" and an assessment technique for the impact of the cryogenic processes, flows, landslides and temperature fluctuations on the pipelines. Two related problems were studied: the stress-strain state of the environment with the pipeline, and the stress-strain state of the environment under the gravity and humidity influence. In both cases the Modified Boundary Element Method was used. In addition, for the first problem the modification of the iterative method of elastic solutions was applied.

Methods of the research:

○ **landscape-climatic analysis;**

○ **geomorphological analysis;**

○ **structural-geological analysis;**

○ **GIS analysis;**

○ **mathematical modeling.**

Methods of the research of the system "GEOLOGICAL ENVIRONMENT-PIPELINE"
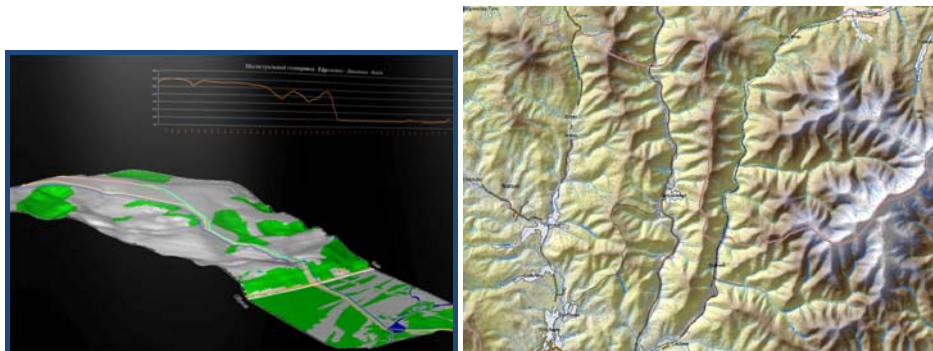
Mathematical model and algorithm

The forecast of the qualitative and quantitative characteristics of the geological environment and assessment of their impact on the pipeline are underpinned by using mathematical models of the stress-strain state.

1. Pipeline-environment stress-strain state problem. Mathematical modeling and stress-strain state evaluation were carried out using authors approach for solving this kind of problems (Lavrenyuk et al., 1996) .We studied the problem of the stress-strain state of the pipeline located in the heavy medium.
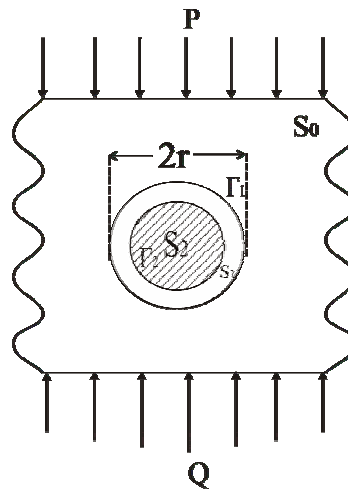
Given fragment of a pipeline (sectional view).

Estimation has been undertaken of the mechanical forces affecting the pipeline due to the freeze-thaw effects of the ground regime, especially the volumetric effects caused by these processes.

The main factors that result in the pressure on the pipeline are as follows:

(i) the impact of gravitation on the pipeline (the weight of the medium);

(ii) the impact of the forces arising due to the volumetric expansion of the water-saturated environment during freezing;

(iii) the impact of loads from the pipeline warping;

(iv) the differences in the temperature of the heated pipeline and of the surraunding area;

(v) the internal pressure of the gas in a pipeline (Shevchuk et al., 2006).

Stresses and strains obey the Duhamel-Neumann law: $\sigma_{ij} = s_{ij} - 3K\alpha T\delta_{ij}$, $i, j = 1, 2$ (1)

where $K = \dfrac{E}{3(1-2\nu)}$, $s_{ij} = \lambda\theta\delta_{ij} + 2\mu\varepsilon_{ij}$, $\psi_i = \dfrac{\partial p}{\partial x_i}$, (2)

Elastic equilibrium equations for considered system, subjected to gravitation, warping, frost injury, and temperature field can be written down as follows:

$$\sigma_{ij,j} - \frac{\partial p}{\partial x_i} - 3\langle K_0\rangle\langle\delta V_0\rangle_{,i} - 3\langle K_0\rangle\langle\alpha_0\rangle T_{,i} = 0 \quad (3)$$

$$\sigma_{ij,j} - \frac{\partial p}{\partial x_i} - 3\langle K_p\rangle\langle\delta V_p\rangle_{,i} - 3\langle K_p\rangle\langle\alpha_p\rangle T_{,i} = 0, \quad p = 1,...,N \quad (4)$$

Boundary conditions in stresses:

$$s_{ij}^0 n_j^0\big|_{\Gamma_0} = 3\langle K_0\rangle\big(\delta V(\Gamma_0) + \langle\alpha_0\rangle T(\Gamma_0)\big)n_i^0, \quad i, j = 1, 2 \quad (5)$$

Contact conditions in stresses on the boundary pipe-medium:

$$s_{ij}^p n_j^p - \chi(p)3\langle K_p\rangle \delta V\left(\Gamma_p\right)n_i^p - 3\langle K_p\rangle\langle\alpha_p\rangle T\left(\Gamma_p\right)n_i^p\,|_{\Gamma_p} =$$
$$= s_{ij}^{p+1}n_j^{p+1} - \chi(p)3\langle K_{p+1}\rangle\delta V\left(\Gamma_p\right)n_i^p - 3\langle K_{p+1}\rangle\langle\alpha_{p+1}\rangle T_p\left(\Gamma_p\right)n_i^0\,|_{\Gamma_p}. \quad (6)$$

The system of boundary integral equations for matrix

$$\chi(S)u_k^{(0)}(\xi) = \int_{\Gamma_0} s_{ij}^{(0)}n_j^{(0)}U_i^{k(0)}d\Gamma + \int_{\Gamma_1} s_{ij}^{(0)}n_j^{(1)}U_i^{k(0)}d\Gamma_1 - \int_{\Gamma_0} g_i^{k(0)}u_i d\Gamma_0 - \int_{\Gamma_1} g_i^{k(0)}u_i d\Gamma_1 -$$
$$- \int_{S_0\backslash S_1} U_i^{k(0)}\psi_i^{(0)}dS_0 - 3\int_{\Gamma_0}\langle K_0\rangle\langle\alpha_0\rangle Tn_i^0 U_i^{k(0)}d\Gamma_0 - 3\int_{\Gamma_1}\langle K_0\rangle\langle\alpha_0\rangle Tn_i^1 U_i^{k(0)}d\Gamma_1 + 3\int_{S_0\backslash S_1}\langle K_0\rangle\langle\alpha_0\rangle TU_{i,i}^{k(0)}dS_0,$$

for each layer

$$\chi(S)u_k^{(p)}(\xi) = \int_{\Gamma_p} s_{ij}^{(p)}n_j^{(p)}U_i^{k(p)}d\Gamma + \int_{\Gamma_{p+1}} s_{ij}^{(p)}n_j^{(p+1)}U_i^{k(p)}d\Gamma_{p+1} - \int_{\Gamma_p} g_i^{k(p)}u_i d\Gamma_p - \int_{\Gamma_{p+1}} g_i^{k(p)}u_i d\Gamma_{p+1} -$$
$$- \int_{S_p\backslash S_{p+1}} U_i^{k(p)}\psi_i^{(p)}dS_p - 3\int_{\Gamma p}\langle K_p\rangle\langle\alpha_p\rangle Tn_i^p U_i^{k(p)}d\Gamma_p - 3\int_{\Gamma_{P+1}}\langle K_p\rangle\langle\alpha_p\rangle Tn_i^{p+1}U_i^{k(p)}d\Gamma_{p+1} + 3\int_{S_p\backslash S_{p+1}}\langle K_p\rangle\langle\alpha_p\rangle TU_{i,i}^{k(p)}dS_p$$

and for the inclusion

$$\chi(S)u_k^{(N)}(\xi) = \int_{\Gamma_N} s_{ij}n_j U_i^{k(N)}d\Gamma_N - \int_{\Gamma_N} g_i^{k(N)}u_i d\Gamma_N - \int_{S_N} U_i^{k(N)}\psi_N^{(N)}dS_N -$$
$$-3\int_{\Gamma_N}\langle K_N\rangle\langle\alpha_N\rangle Tn_i U_i^{k(N)}d\Gamma_N + 3\int_{S_N}\langle K_N\rangle\langle\alpha_N\rangle TU_{i,i}^{k(N)}dS_N, \quad (7)$$

is solved using modified Boundary Element Method (Lavrenyuk et al., 1996) which allows to define all stresses and displacements at once.

The problem of the stress-strain state of pipeline fragment subjected to bending due to the influence of waterflows, mudflows, underground flows, etc. is adjacent to the above considered problem and can be solved separately using stress analysis of the pipeline bending when treating pipeline as a beam.

2. Stress-strain state of fragment of geological environment under influence of humidity and gravity. We assume humidity distribution in the given fragment is known and problem can be considered as two-dimensional, i.e. we look at the section of our fragment. Hence if we know dependence of the elastic characteristics of the given region upon the humidity we can build iterative process of solving the sequence of problems for 2D elastic homogeneous region, where all inhomogeneity is treated as pseudo-mass forces. We also assume that rheologic law holds:

$$\sigma_{ij}(h) = \lambda(h)\theta\delta_{ij} + 2\mu(h)\varepsilon_{ij} - 3K(h)ah\delta_{ij} = s_{ij} - 3K(h)ah\delta_{ij} \quad (8)$$

where $K(h) = \dfrac{E(h)}{3(1-2\nu)}$, a is humidity change coefficient and h is consistency of deposits.

Differentiating this relation, we obtain equilibrium equation in displacements:

$$\left(\lambda(h)u_{l,l}\delta_{ij} + \mu(h)\left(u_{i,j} + u_{j,i}\right)\right)_{,j} - 3\left(K(h)ah\right)_{,i} = 0 \quad (9)$$

Finally we have:

$$(\lambda_0 + \mu_0)u_{l,li}\delta_{ij} + \mu_0\Delta u_i + \frac{1}{E(h)}\frac{\partial E}{\partial h}\frac{\partial h}{\partial x_j}s_{ij}^0 - 3\frac{E_0}{E(h)}\left(K(h)\alpha h\right)_{,i} = 0, \quad (10)$$

where $s_{ij}^0 = \lambda_0 u_{l,l}\delta_{ij} + \mu_0\left(u_{i,j} + u_{j,i}\right)$.

Thus we have iterative scheme, k-th step of it looks like this:

$$(\lambda_0 + \mu_0)u_{l,li}^{(k)}\delta_{ij} + \mu_0\Delta u_i^{(k)} + \frac{\partial E}{\partial h}\frac{\partial h}{\partial x_j}s_{ij}^{k-1} - 3E_0\left(\frac{K(h)ah}{E(h)}\right)_{,i} = 0,$$

$$\left(\lambda_0 u_{l,li}^{(k)}\delta_{ij} + \mu_0\left(u_{i,j}^{(k)} + u_{j,i}^{(k)}\right)\right)n_j = \frac{ahn_i}{(1-2\nu)}, \quad (11)$$

This system can be transformed into a system of boundary integral equations with the help of Somigliana formula. Hence on each step of iterative process we have homogeneous problem, where all the unhomogeneity is accounted in the surface integral and in the boundary conditions.

We solve this system with the help of modified Boundary Element Method (Lavrenyuk et al., 1996, Krishnasamy et al., 1994, Zhang et al., 2001, Dong et al., 2002). As the result, we obtain the system of linear algebraic equations; its solution gives us the distribution of stresses and displacements on the boundary of considered region. To calculate the stresses in internal points for the k -th iterative step we use Somigliana formula.

The iterative process runs until condition $\max_{x \in V} \left\| \sigma_{ij}^{(k)} - \sigma_{ij}^{(k-1)} \right\| > \varepsilon$ holds.

Example of cryogenic effect assessment

One of the developed modules based on the above described algorithm assumes an assessment of the impact of cryogenic processes on the pipeline complex.

Estimation has been considered of the mechanical forces acting on the pipeline due to the freeze-thaw effects of the regime of grounds, especially the volumetric effects caused by these processes. From the research and the development of the program algorithm the main factors that result in loading on the pipeline are follows: a) the influence of gravitation forces on the pipeline (the weight of environment); b) the influence of the forces arising owing to volumetric expansion of the water-saturated environment during freezing; c) the influence of loads from pipeline warping; d) the influence of temperatures differences of the heated pipe and its environment; e) the influence of internal pressure of gas in a pipe.

To demonstrate this impact we propose here, as an example, the computation of the stress intensity of the ground stress on the pipe edge (Figure 2). We study the system "pipe – geological environment" with the following parameters. The type of the rock is frozen sand (modulus of general deformation 22500 MP, Poisson ratio 0.41, density 1750 kg/m^3). The force parameters of warping are changing from 20 to 90 sm, frost injury 3 %, depth of pipe deposition 2 m, distance from source of warping 2 m, pipe thickness 0, 0186 m, pipe radius 0,71 m. The stress intensity on the external pipe edge ranging from 514,03 MP to 970, 48 MP. The intensity of the ground stress on the pipe edge ranging from 492,8 MP to 995 MP.
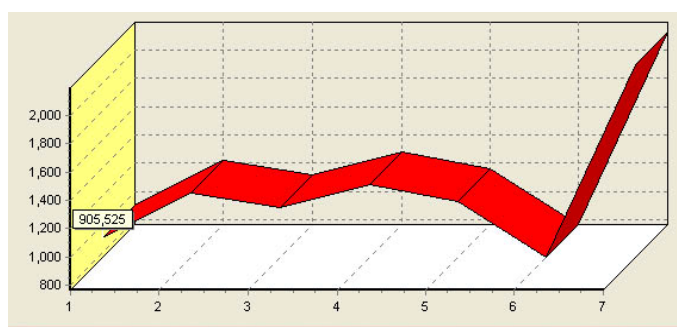
The changes of the ground stress intensity on the pipe edge.

Example of the numerical evaluation of stresses for the area with saturated layers

One of the developed modules bases on above described algorithm assumes an assessment of the impact of water saturation processes on the area with the slope. To demonstrate the impact of saturation effects the main stresses s_2 values distribution in the given area are shown (Figure 3). We

look at the slope with the following parameters. The type of the rock is the loam (modulus of general deformation in unsaturated state 11 MP and in saturated state 7.2 MP respectively, Poisson ratio 0.3, density 1700 kg/m^3). The dimensions of slope are as follows: width of saturated area (d) – 5 m, height (h) – 20 m, slope angle (α)- 75^0, distance from the slope edge (b) – 10 m.
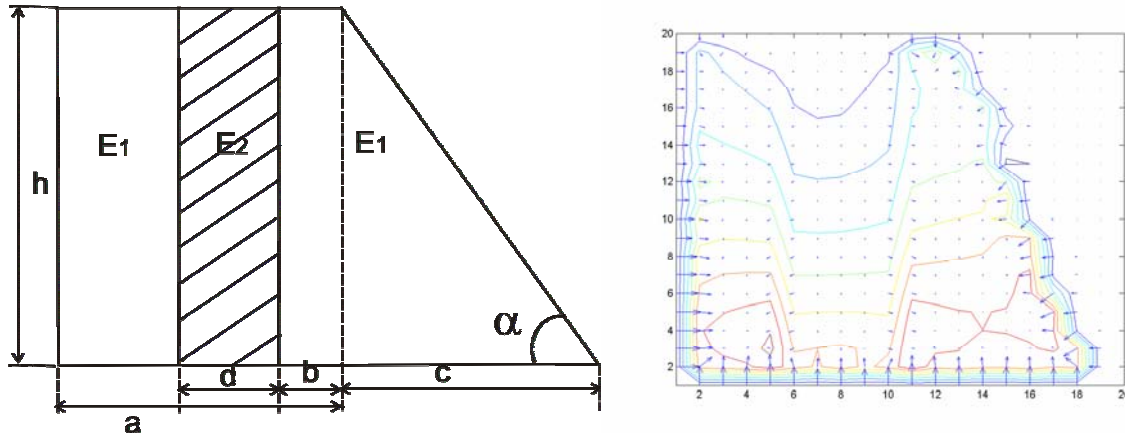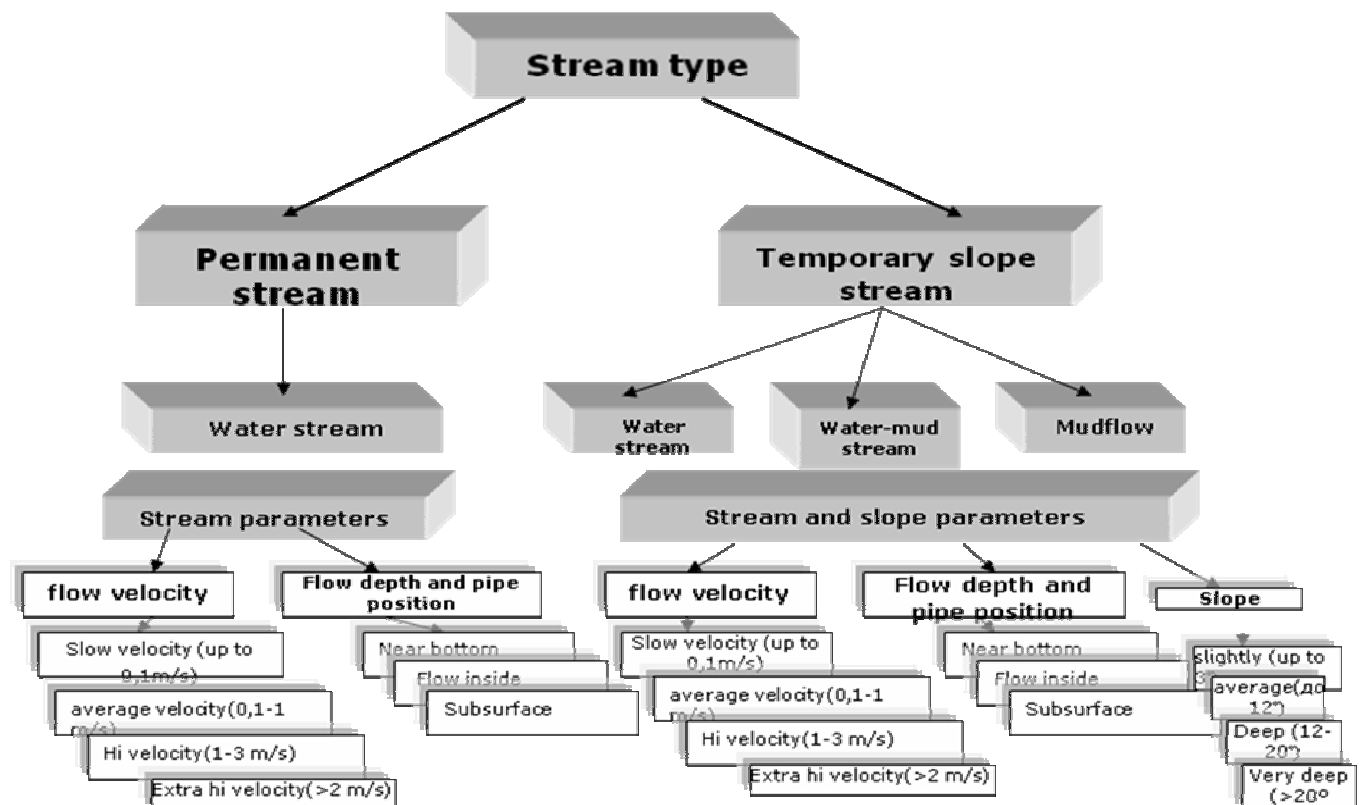

Given fragment of saturated area. From left to right: sectional view, the changes of main stresses s_2 over given area.

Assessment of the streams impact on the pipeline

Numerical models were created to take into account the influence of streams, their effect on viscous and viscous-plastic mediums within geological environments, and subsequently on the pipeline. Estimation of the influence of various types of streams on pipelines, the program module calculates hydrodynamic load on its cross section, set within a stream of viscous and viscous-plastic mediums. Experimental and theoretical research have allowed solution of the levels hydrodynamic forces acting on a pipe, and determine the limiting critical loads.

Examples of the streams impact on the pipeline

Stream type

Permanent stream

Temporary slope stream

Water stream

Water stream

Water-mud stream

Mudflow

Stream parameters

Stream and slope parameters

flow velocity

Flow depth and pipe position

flow velocity

Flow depth and pipe position

Slope

Slow velocity (up to 0,1m/s)

average velocity(0,1-1 m/s)

Hi velocity(1-3 m/s)

Extra hi velocity(>2 m/s)

Near bottom

Flow inside

Subsurface

Slow velocity (up to 0,1m/s)

average velocity(0,1-1 m/s)

Hi velocity(1-3 m/s)

Extra hi velocity(>2 m/s)

Near bottom

Flow inside

Subsurface

slightly (up to 3

average(до 12°)

Deep (12-20°)

Very deep (>20°)

Classification of various types of flows for the assessment of there impact on pipelines

Algorithm *(condensed version)*

Reynolds number is the typical parameter for the estimating the hydrodynamic load on pipeline's cross section:

$$\text{Re} = \frac{Vd}{\nu},$$

V – stream speed, d – pipe diameter, ν – cinematic viscosity.

$$F_D = \frac{4\pi\mu V}{\ln\dfrac{h}{r} - 0.9157 + 1.7244\left(\dfrac{r}{h}\right)^2 - 1.7302\left(\dfrac{r}{h}\right)^4}, \quad r = d/2,$$

h – distance from cylinder axis to wall.

$$F_D = \frac{4\pi\mu V}{\ln\dfrac{2h}{r}} \quad , \quad r = d/2 ,$$

$$V = \frac{\rho g \sin\beta}{2\mu}(H^2 - y^2) \quad ,$$

If $\quad \mathrm{Re} \geq 0.1$

$$F_D = C_n \frac{d\rho V^2}{2} .$$

F_D – running resistance force on 1 meter of the pipe in the flow, C_n – coefficient of hydrodynamic
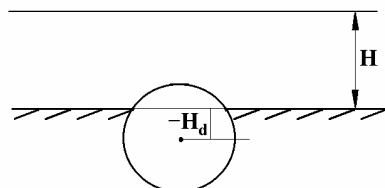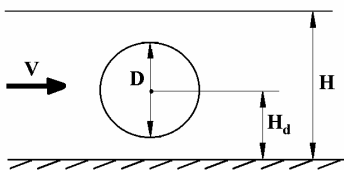
Nonstationary flow, $\mathrm{Re} \leq 50$, hydrodynamic force:

$$F_L = C_L \frac{\rho d V^2}{2}\sin\pi\omega t , \quad \omega = V \cdot Sh/d ,$$

$$Sh = \begin{cases} 0,2 ; & \mathrm{Re} < 2\cdot 10^5 \\ 0,4; & 2\cdot 10^5 \leq \mathrm{Re} \leq 2\cdot 10^6 ; \\ 0,3 ; & \mathrm{Re} > 2\cdot 10^6 . \end{cases}$$

$$F_w = 4\pi^2 g\rho \frac{r^4}{H^2}\frac{\xi^2 \, ch^2 b\xi}{ch^2\xi - 2\xi} \quad Fr = \frac{V}{\sqrt{gH}}, \quad b = \frac{H - h_p}{H}, \quad r = \frac{d}{2},$$

$$Fr^2 = \frac{th\xi}{\xi} .$$

a
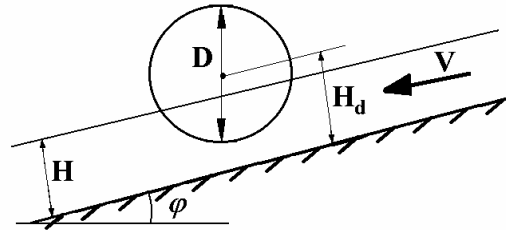
b

Types of pipeline position in the flow: permanent stream (a) and temporary slope (b) stream.

Module "Flows"

Input parameters:
- Fluid kinematic viscosity, μ (N sec/m^2);
- Fluid density, ρ (kg/m^3);
- Pipe diameter, D (m);
- Flow depth, H (m);
- Slope between the flow direction and pipe long axis, α (degree);
- Distance between the pipe long axis and bottom, Hd (m);
- Flow velocity, V (m/sec);
- Slope φ (degree).

Output parameters:
linear load F [N/m]

MODULE "MUDFLOWS"

The algorithm calculating the mudflow impact on engineering objects in Carpathians has been developed. It based on the empiric data and fundamental hydrodynamic lows. Calculating module for the external medium loading estimations has been proposed. Module allows the simulating mudflow effects on techniques objects in Carpathians. Parameters of mudflows and geological-geomorphological and hydrometeorological data have been considered.

Mudflows and their impact on engineering objects in Carpathians
Algorithm *(condensed version)*

$$P_{total} = 0.1\,\gamma_c\left(5H_0 + v_c^2\right)$$

P_{total} $[t/m^2]$ – total pressure; γ_c $[t/m^3]$ – mudflow density; H_0 $[m]$ – mudflow depth;

v_c $[m/\sec]$ – mudflow velosity.

$$Q_c = \frac{0.28\alpha\, H_t\, F_v}{t} f_h$$,

Q_c $[m^3/\sec]$ – flow discharge; H_t $[mm]$ – rainfalls (mm); α – runoff coefficient; t [hours] – time of flood raising; F_v $[\kappa u^2]$ – drainage area [km^2] ; f_h – form hydrograph coefficient

$$T = \mu\tau_n$$

T – rainfall ; τ_n – lag time ; μ – coefficient of flood deceleration

$$Q_{max} = k_p a\alpha F$$

k_p - dimension coefficient ; a – average rainfall intensity; α – runoff coefficient; F – drainage area [km^2.]

$$V_{max} = 17,0J^{0,40} h_{cp}^{0,50}$$,

V_{max} – maximum speed in the section line; J – channel slope; h_{cp} – average depth
Hydrodynamic force

$$F = P_{total} \cdot S$$

Initial parameters:
- Rainfalls (mm);
- Duration of rainfall (h);
- Drainage area km^2;
- Channel length (m);
- Runoff coefficient;
- Mudflow width (m);
- Left slope (degree);
- Right slope (degree);
- Mudflow density (t/m^3).

Results:
Total mudflow pressure (*T/* m$^{2)}$);
**Hydrodynamic force(T).**

Rain-falls (mm)	Duration of rain-fall (h);	Drainage area km^2.	Channel lenght (m);	Run-off coeffi-cient;	Mud-flow density (t/m^3)	Mud-flow width (m)	Left slope (degree)	Right slope (degree)	Mud-flow velocity, m\s ec	Flow dis-charge, Qc, m^3/s	Hydrody-namic force (T)
50	0,7	8.9	2	**0,05**	1,5	2	30	35	0,6	0,2	0,02
50	0,7	8.9	2	**0,1**	1,5	2	30	35	0,6	0,3	0,07
50	0,7	8.9	2	**0,2**	1,5	2	30	35	0,6	0,6	0,28

50	0,7	8.9	2	**0,3**	1,5	2	30	35	0,6	1	0,62
50	0,7	8.9	2	**0,4**	1,5	2	30	35	0,6	1,3	1,09
50	0,7	8.9	2	**0,5**	1,5	2	30	35	0,6	1,6	1,68
50	0,7	8.9	2	**0,6**	1,5	2	30	35	0,6	1,9	2,4
50	0,7	8.9	2	**0,7**	1,5	2	30	35	0,6	2,2	3,2
50	0,7	8.9	2	**0,8**	1,5	2	30	35	0,6	2,6	4,21

Drainage area km^2.	Channel lenght (m);	Runoff coeffi-cient;	Mudflow density (t/m^3)	Mud-flow width (m)	Left slope (degree)	Right slope (degree)	Mudlow velocity, m\ s ec	Flow dis-charge, Qc, m^3/s	Hydro-dy-namic force (T)
8.9	2	0,5	**1**	2	30	35	0,6	1,6	1,12
8.9	2	0,5	**1,1**	1,8	30	35	0,6	1,6	1,23
8.9	2	0,5	**1,2**	0,6	30	35	0,6	1,6	1,35
8.9	2	0,5	**1,3**	0,5	30	35	0,6	1,6	1,46
8.9	2	0,5	**1,4**	2	30	35	0,6	1,6	1,6
8.9	2	0,5	**1,5**	2,2	30	35	0,6	1,6	1,68
8.9	2	0,5	**1,6**	1,65	30	35	0,6	1,6	1,89
8.9	2	0,5	**1,7**	1,7	30	35	0,6	1,6	1,90
8.9	2	0,5	**1,8**	1,7	30	35	0,6	1,6	1,02
8.9	2	0,5	**1,9**	1,7	30	35	0,6	1,6	2,13
8.9	2	0,5	**2,0**	1,7	30	35	0,6	1,6	2,24
8.9	2	0,5	**2,1**	1,7	30	35	0,6	1,6	2,35
8.9	2	0,5	**2,2**	1,7	30	35	0,6	1,6	2,5
8.9	2	0,5	**2,3**	1,7	30	35	0,6	1,6	2,6
8.9	2	0,5	**2,4**	1,7	30	35	0,6	1,6	2,7

| 8.9	2	0,5		1,7	30	35			
			2,5				0,6	1,6	2,8

The problem of the stress-strain state of pipeline fragment subjected to bending due to the influence of waterflows, mudflows, underground flows, etc. is adjacent to the above considered problem and can be solved separately using stress analysis of the pipeline bending when treating pipeline as a beam.
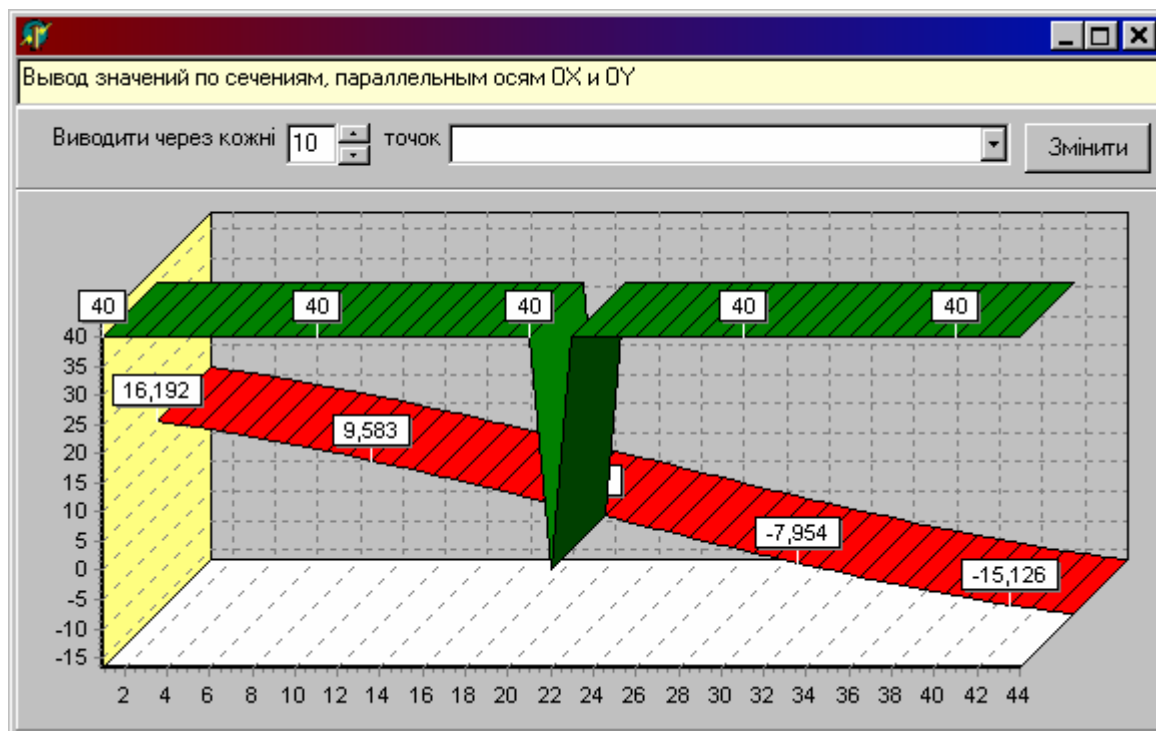
Stress analysis of the pipe bending

Conclusions

The general technique of assessment of the stress-strain state of the system "geological environment-pipeline" that is subject to hazardous geological processes has been proposed. It is based on the numerical-analytical algorithms of stresses and displacements calculations in inhomogeneous objects. These algorithms are applying the modified boundary elements method. They allow to assess the impact on the pipeline of the different factors of geological environment. Application of the developed modules integrated in the pipeline GIS will allow to carry out timely calculations of the stress-strain state of the trans-pipeline system in order to minimize risks of the non-controlled behavior of such systems.
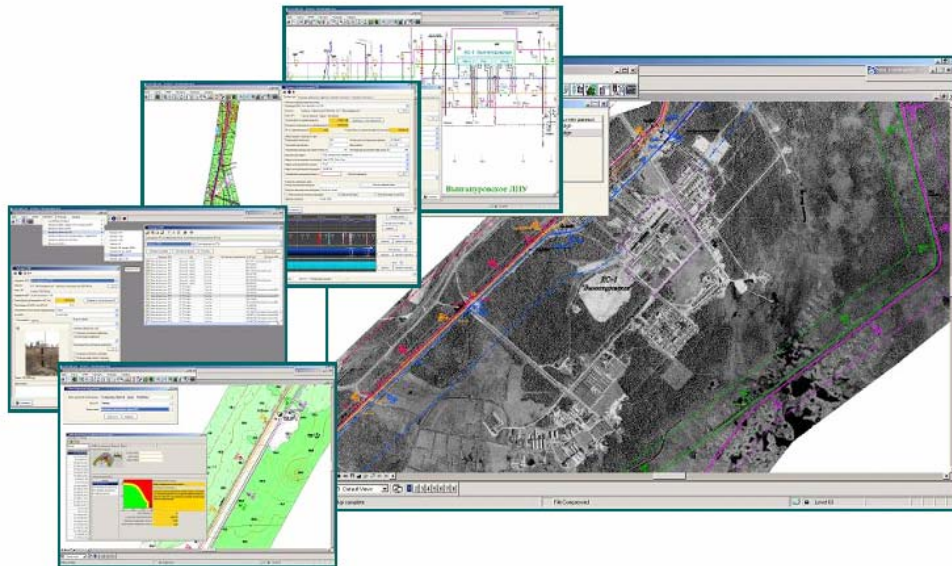
Integration in the pipeline GIS

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