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INTERACTION BEHAVIORS OF LONGITUDINAL AND TRANSVERSE SEISMIC WAVES WITH UNDERGROUND GEOENGINEERING OBJECTS

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Main pipelines as long linear objects are vulnerable to dangerous natural and man-made influences. One of the technogenic sources is large-scale explosions, which cause a sharp fluctuations of soil and cause serious damage to underground pipelines. When calculating the strength of pipeline systems, it is assumed that the damage occurs mainly due to additional axial stretching. However, the destruction and damage of pipelines can occur during seismic impacts directed perpendicular to the longitudinal axis of the pipeline.

To assess the impact of longitudinal and transverse waves on the underground pipeline during seismic action a software-calculation module is developed. It implements a model of dynamic strength analysis, which allows estimating the magnitude of longitudinal and transverse seismic loads on the underground pipeline to establish safe parameters of seismic loads and geometric dimensions of the protected object. The final system of equations of motion of N nodes of a discrete system for a single length of the pipeline is presented as a system of $4N$ equations of the first order.

The efforts on the internal nodes are determined by the strain stresses at the displacement of the nodes of the adjacent rods. The efforts on the nodes of the pipe contour are the diffraction interaction of seismic waves in the soil with the pipe. The system of equations is supplemented by the corresponding initial and boundary conditions.

The dependences of the inflow of longitudinal and transverse pressure of explosive seismic pressure on the pipeline are established. The dependences of stresses in the pipeline of the diameter, thickness and type of soil are researched.

Keywords: *Combined effect of seismic load and transported product, longitudinal and transverse seismic waves, mathematical simulation, underground geoengineering objects.*

1. INTRODUCTION

Intensive development and active modernization of the system of main pipelines of the oil and gas industry are associated not only with the development of fields of new production areas and construction of pipelines, but also with the need for reliable and safe transport in difficult areas and under difficult climatic and engineering-geological conditions, and also in military territories.

Main pipelines as long linear objects are vulnerable to dangerous natural and man-made influences. One of the sources of man-made threats to pipelines is large-scale explosions, which cause sharp fluctuations in the soil and cause serious damage to underground pipelines.

When calculating the strength of pipeline systems, it is assumed that damage to the linear part of the pipeline occurs mainly due to additional axial stretching that occurs in the pipe during a seismic wave and increases when the axis of the pipeline coincides with the direction of wave propagation [1], [2]. This approach has a number of disadvantages. In particular, the effects directed normally to the longitudinal axis of the pipeline are not taken into account, as well as the design features of the linear part of the pipeline (pipe diameter, wall thickness, etc.) and, finally, the effect of pipe slippage on the ground. Interactions of seismic explosive waves with underground and surface structures are considered in [3]–[8]. It is assumed that the waves are volumetric. However, as shown in [9] and [10], the destruction and damage of pipelines can occur during seismic impacts directed perpendicular to the longitudinal axis of the pipeline.

In this regard, **the aim of the research** is to assess the impact of transverse waves on the underground pipeline during seismic action from an explosive source.

2. MATERIALS AND METHODS

Numerical modelling of the impact of longitudinal and transverse waves on the underground pipeline is carried out to predict the seismic action on the geoengineering objects.

To achieve this aim, a software-calculation module is developed, which implements the model of dynamic strength analysis [9], [11].

When studying the strength of the pipeline, taking into account the seismic impact, the following characteristics are changed: the diameter of the pipeline – 820, 1020, 1220 mm; pipe wall thickness – 12, 16, 20, 24, 28 mm; soil – sand, sandy loam (Table 1 [7]); seismic intensity of the earthquake – 7, 8, 9, 10 points. The following steel indicators are adopted: density – 7850 *kg/m*^{3}; Poisson's ratio – 0.3.

Table 1. Soil Characteristics

Type	Density, *kg/m*^{3}	The modulus of elasticity of rock, *MPa*	Specific adhesion of rock, *kPa*	Angle of internal friction, *deg*	Velocity of seismic waves in the rock, *m/s*
Granite	2300	40	2	35	150
Sandstone	1970	21	8	20	350

3. THE IMPACT OF TRANSVERSE WAVES ON THE UNDERGROUND PIPELINE

Figure 1 shows the calculation scheme of seismic action of the explosion with a non-uniform step in the spatial coordinate before and after 1 second after it. The circle indicates the position of the pipeline, the seismic wave falls to the right of the pipeline.

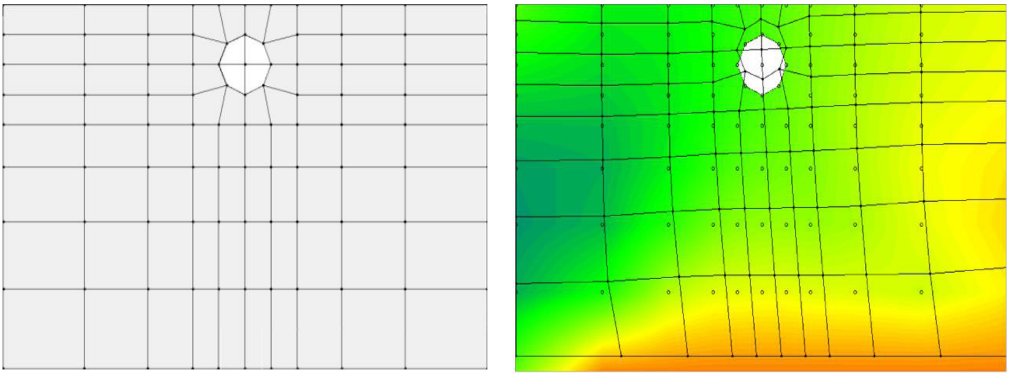


Fig. 1. Calculation scheme with a non-uniform step to the beginning (left) and during (right) seismic impact.

The final system of equations of motion of *N* nodes of a discrete system for a single length of pipeline has the form

$$\ddot{X} = P_x / m, \;\; \ddot{Y} = P_y / m, \tag{1}$$

and it reduces to a system of first-order *4N* equations

$$\begin{aligned} \dot{V}_x &= P_x / m, \;\; \dot{X} = V_x, \\ \dot{V}_y &= P_y / m, \;\; \dot{Y} = V_y, \end{aligned} \tag{2}$$

where P_x,P_y – components of the force on the node of mass *m* in the projections on the axis of the inertial coordinate system XOY; V_x, V_y, $\dot{V}_x$, $\dot{V}_y$ – speed and acceleration of nodes.

The forces P_x, P_y on the nodes are determined by the strain stresses during shear of the nodes of the adjacent rods. The forces on the nodes of the pipe contour represent the diffraction interaction of seismic waves in the soil with the pipe.

Load from seismic impact is determined by the ratio

$$N_{xy} = \sqrt{N_x^2 + N_y^2} = P_m R, \tag{3}$$

where N_x and N_y – components of the load vector N_{xy} in the respective axes with maximum pressures: $P_x = N_x/R$ and$P_y = N_y/R$; $P_m = N_{xy}/R$ – pressures; *R* – radius of the pipe.

These seismic effects cause annular bending and compression of the wall of the shell of the pipeline. The stresses arising in the pipe have an uneven distribution and depend on the angle φ in the range of 0 ... 2π. The highest voltage values are at the points of intersection A (φ = *0;* π*) i C (*φ = ±π */ 2)* [11, 12]:

- normal fibre flexural stresses

$$\sigma_{MA} = \pm 0{,}305 P_m R^2 / W_k, \tag{4}$$

$$\sigma_{MC} = \pm 0{,}16847 P_m R^2 / W_k, \tag{5}$$

- normal compression stresses

$$\sigma_{NA} = -0{,}02653 P_m R / F, \tag{6}$$

$$\sigma_{NC} = -0{,}5 P_m R / F, \tag{7}$$

where $W_k = d\delta^2 / 6$ and $F = \delta d$ – moment of resistance, m^3, and the cross-sectional area of the shell wall, m^2, per unit length *d*. When simulating the seismic impact along the normal to the longitudinal axis of the pipeline, the maximum normal fibre bends σ_M^S and compress σ_N^S stresses are calculated. The total transverse seismic stress (the first component of the effective stress) is determined from the ratio

$$\sigma_I = \sigma_M^S \pm \sigma_N^S. \tag{8}$$

Longitudinal forces $F_k(t)$and bending moments $M_k(t)$ from seismic impact are also determined taking into account the registered three-component accelerograms. The formulas for their definition in this approach take a dynamic form:

$$F_K(t) = \frac{EAv(t)}{\alpha_k V_k} \leq F_\tau(T),\ H, \tag{9}$$

$$M_K(t) = \frac{EJa(t)}{(\beta_k V_k)^2},\ H{*}m, \tag{10}$$

where *E* – modulus of elasticity of the pipe material, Pa; *A* – cross-sectional area of the pipe, m^2; *v (t)* – velocities of soil particles, which are determined by the velosogram, *m/s*; V_k – velocity of seismic waves; α_k, β_k – characteristic coefficients depending on the type of wave; *k* – type of seismic wave (1 – longitudinal wave, 2 – transverse wave) [10], [11]; *J* – moment of inertia of the cross-section of the pipe, *a(t)* – seismic acceleration, which is determined by the accelerogram, m/s^2; $F_\tau(t) = \lambda_k f_\tau / 4$ – ultimate force of interaction between the soil and the surface of the pipeline, *H*; $\lambda_k \approx T_0 V_k / 2$ – wavelength, *m*; T_0 – dominant period of the seismic spectrum, which is determined by the method of Fourier rapid transform to the stationary part of the calculated accelerogram; $f_\tau(t)$ – running friction force, *H/m*.

The maximum running force of friction between a construction and soil is defined taking into account force of wave influence and coupling of soil with a pipe [11]:

$$f_\tau(t) = \pi D(K_T \rho_0 v(t) V_k + C_0), \tag{11}$$

where *D* – external diameter of a pipe, *m*; $K_T = tg\varphi_z$ – coefficient of friction; φ_z – angle of internal friction of the backfill soil, *deg*; ρ_0 – soil density, kg/m^3; C_0 – adhesion of soil/backfill, *Pa*.

When modelling the seismic impact along the axis of the pipeline there are calculated:

- longitudinal axial stresses

$$\sigma_l^S = \frac{\min(F_k(t), F_\tau(t))}{A}, \tag{12}$$

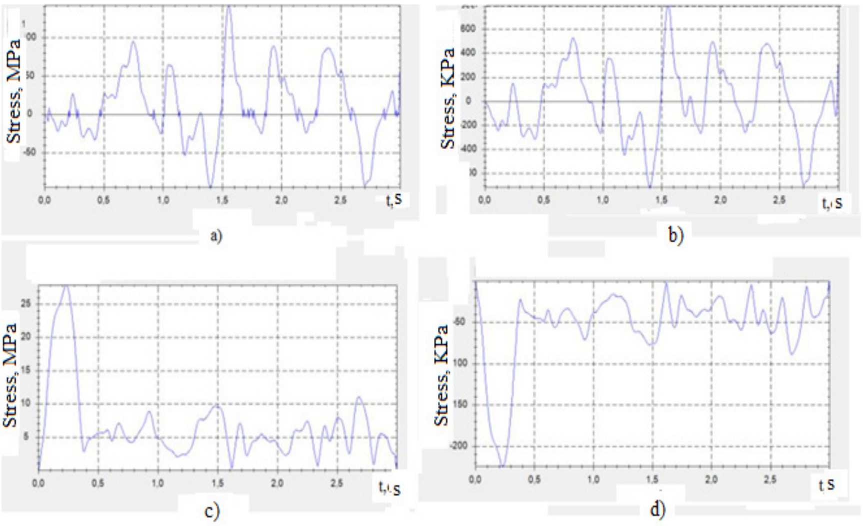
- fibre transverse stresses from the bending of the pipeline under the dynamic influence of seismic waves

$$\sigma_t^S = \frac{M_k(t)}{W_{np}}, \tag{13}$$

where *Wnp* – moment of resistance of profile of a pipe, m^3. Thus, the second component of the effective stresses has the form:

$$\sigma_2 = \sigma_l^S + \sigma_t^S,\ Pa. \tag{14}$$

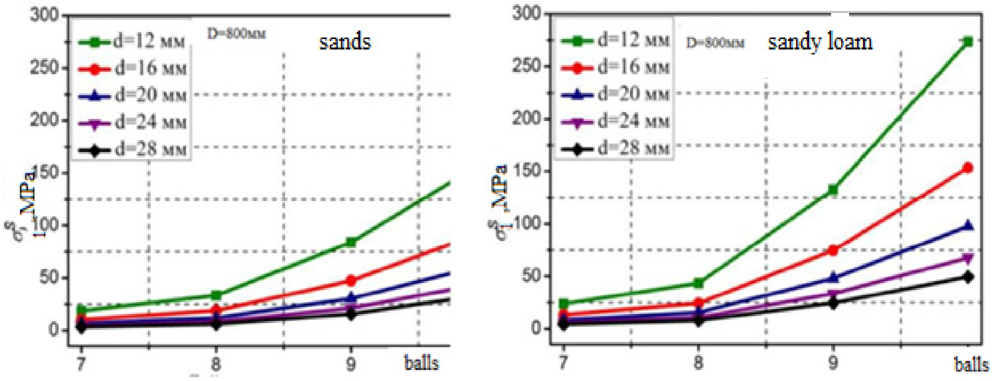
Figure 2 shows the dependences of seismic stresses on the time obtained in the simulation of seismic action with a capacity of 8 points for a pipe deepened into the sandstone with a diameter of 1.22 m and a thickness of 18 mm.



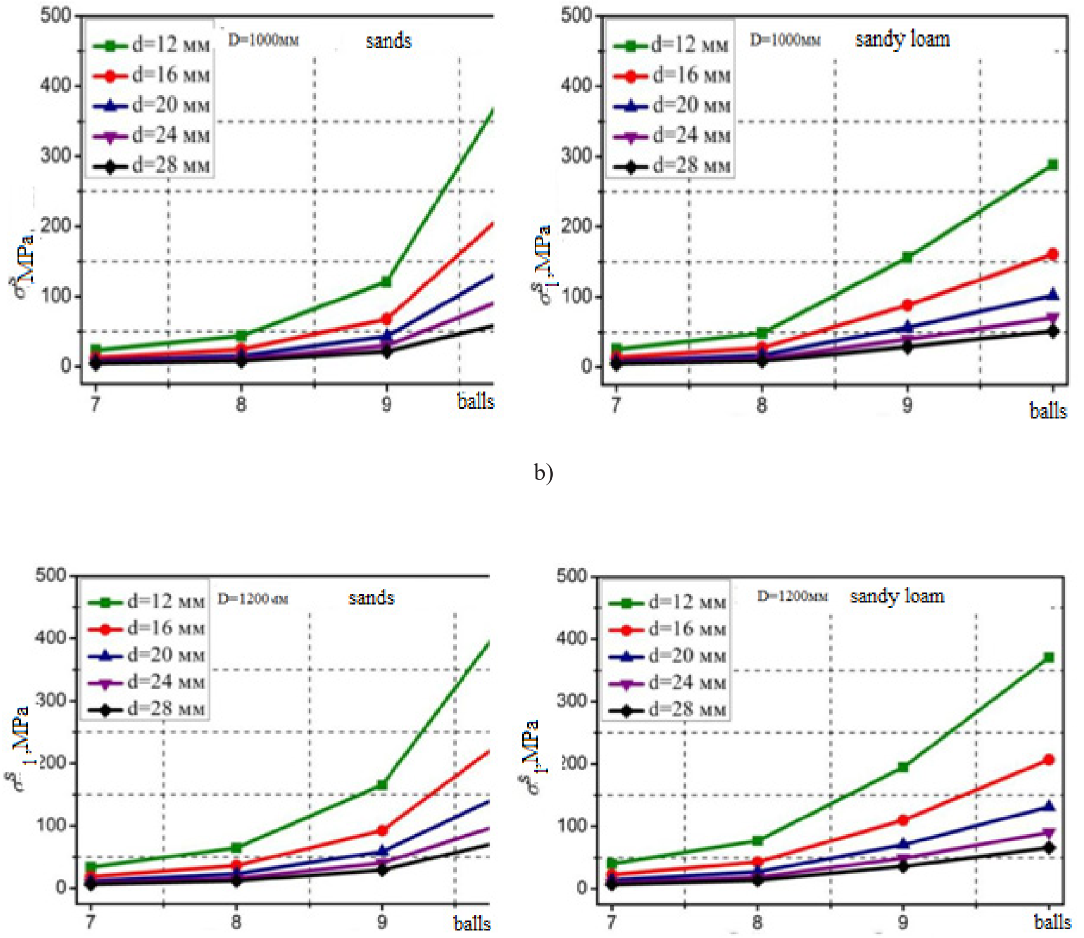
a) axial stresses along the *Z* axis; b) bending stresses along the *Z* axis; b) stresses of the annular bend in the *XY* plane; c) stresses of the annular compression in the *XY* plane

Fig. 2. Dependences of seismic stresses on time.

The impact of seismic influences on the *X, Y* and *Z* axes is determined on the basis of studies of the contribution of transverse impact on the normal to the pipeline axis (on the *X* and *Y* axes) and longitudinal impact (on the *Z* axis) along the pipeline in the overall stress state of the pipeline. The results of study are shown in Fig. 3.



a)



b)

c)

Fig. 3. Dependence of transverse seismic stress on the intensity of seismic impact for deepened in the sand (left) and sandstone (right) pipelines of different thicknesses and diameters – 800 (a), 1000 (b) and 1200 (c) *mm*.

Thus, the value of transverse seismic stresses increases rapidly with increasing intensity of seismic loads. Since the value of spacing resistance for pipes of standard steel grades does not exceed several hundred MPa, taking into account the pressure from the transported product (oil) at an earthquake load of more than 8 points, pipe material goes into an inelastic stage, which can lead to cracks and possible pipeline rupture.

To quantify the contribution of these stresses to the resulting seismic loads, the coefficient K⊥ is introduced, which is determined by the ratio of equivalent seismic stresses to transverse seismic stresses (Table 2).

Table 2. Coefficient K⊥ Taking into Account the Transverse Effect of the Seismic Wave

Wall thickness, *mm*	Pipe diameter, *mm*					
	800		1000		1200	
	Load intensity, point					
	7–8	9–10	7–8	9–10	7–8	9–10
16	1.2	1.25	1.25	1.35	1.40	1.50
20	1,15	1.2	1.2	1.25	1.3	1.40
24	1,10	1.15	1.15	1.2	1.25	1.3
28	1.05	1.10	1.10	1.15	1.2	1.25

As follows from Table 2, depending on the intensity of the earthquake, the diameter of the pipeline, the wall thickness of the pipe and the type of soil, the total stress of the steel material from seismic impact increases by 1.1 ... 1.5 times.

Next, the explosion of a charge of 10 kg of TNT at a depth of 10 m from the earth's surface is considered. It is assumed that the pipeline has a diameter of 1.5 m and is made of steel with the following physical and mechanical characteristics: yield strength 235 H/m^2, Poisson's ratio 0.3, elastic modulus 210 H/m^2, density = 7855 kg/m^3. The depth of laying the pipe is 5 m. Clay is considered as soil.

Figure 4 shows the distribution of stresses in the pipeline from the action of the longitudinal wave, while in the figure their values are indicated by different colours.

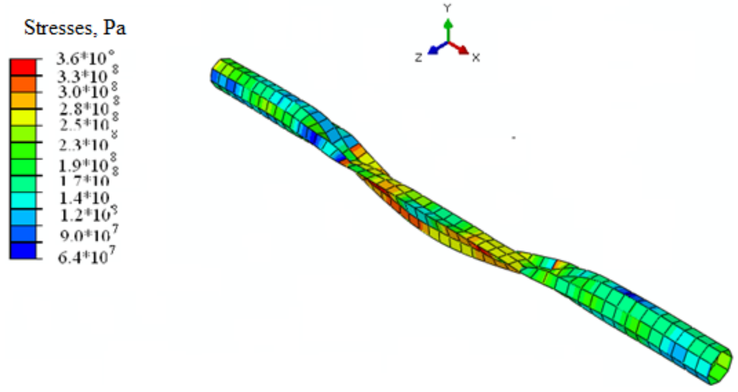


Fig. 4. Stress distribution in a steel pipe with a diameter of 1.5 m under the action of a longitudinal wave during an explosion of a TNT charge weighing 10 kg.

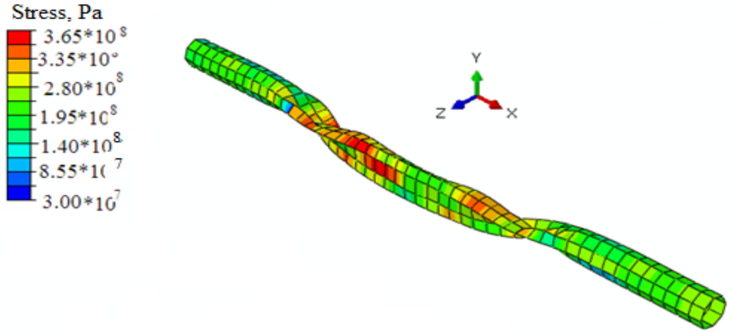


Fig. 5. Stress distribution in a steel pipe with a diameter of 1.5 m under the action of a transverse wave during an explosion of a TNT charge weighing 10 kg.

It is shown that the maximum stress in the pipe reaches a value of 360 MPa, which is significantly more than the steel yield strength.

Figure 5 shows the distribution of stresses in the pipeline from the action of transverse waves.

From the comparison of Figs. 4 and 5, it can be concluded that the transverse wave causes much more damage in the pipe than the longitudinal – the area of damage increases by 1.5 times.

4. CONCLUSIONS

1. The software-calculation module, which implements the model of dynamic strength analysis and allows estimating the magnitude of longitudinal and transverse seismic loads, has been developed within the study.
2. The regularities of the influence of longitudinal and transverse loads from the influence of explosive and seismic waves directed normally to the longitudinal axis of the pipeline on the strength of the pipeline have been revealed.
3. With increasing load intensity and increasing pipe diameter, the voltage changes (increases) as follows: for pipes with a diameter of 800 mm – by 1.05...1.25 times, for pipes with a diameter of 1000 mm – by 1.10...1.35 times, for pipes with a diameter of 1200 mm – by 1.20...1.50 times.
4. The transverse wave causes much more damage in the pipe than the longitudinal one – the area of damage increases by 1.5 times.

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