

The Effect of Dynamic Processes in the System “Pipe-Soil” on the Pipeline Deviation from Design Position

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Abstract. This article explains the changes of the main gas pipeline geometrical shape, i.e. the deviation of its position from the project one, as one of the important factors affecting the operating safety of underground main pipelines. In the study of the processes occurring at interaction between main gas pipeline and foundation soil, a rod model, fixed on one side, with the load applied to, it was examined. Action of elastic foundation across the pipeline is modeled with spring substrate that resists cross motion. As a result, the effect of soil impact on the vibration frequency of the pipe wall, appearing at the stage, preceding its deviation from the design position, was determined. Detection the frequency of these vibrations can make it possible to forecast pipe bending not at the stage of growth but at the stage preceding its appearance.

1. Introduction

An important factor, affecting the operating safety of underground pipelines, is changing the geometric shape of the pipeline, that is, the deviation of its position from the project one. Pipelines upfloating and bending is one of the factors that affect their stress-strain state, which is known to affect significantly the mechanical properties of the pipe.

According to many authors [1, 3, 6, 7], the most important element of this problem is the interaction between underground pipeline and the surrounding soil. This interaction takes place not only on the part of ground due to thermal processes, the humidity, the cohesive forces, but also on the part of the pipeline on the ground due to the current loads caused by temperature and pressure.

2. Methods

During the construction of the pipeline, its stable position is achieved through the use of weighting agents, as a means of ballasting, or direct anchoring. However, in many areas, especially in northern ones, despite the effect of weighting agents, pipelines turn out to be located higher than the project level, up to the formation of vertical and horizontal bends.

From the analysis of the above models, the following general patterns can be identified. The models consider longitudinal motion of the linear section of pipeline with low soil resistance in the perpendicular direction. This area can be defined as dangerous from the standpoint of the arch formation. If the pipe wall is compressed, with increasing longitudinal force (on its origin models vary) on the studied area, there is a loss of stability of rectilinear form above the critical value. The value of the critical force depends on the coefficient of soil bedding and bending stiffness of pipe [5]. Bedding ratio sharply decreases with increase in soil water cut, which corresponds to the seasonal thawing. The interaction with the soil can significantly weaken due to vibration.



Along with soil water cut, buoyancy increases, which changes the high-rise pipe position in the ground. It is considered that the emergence of dangerous areas (with low resistance and high water cut) is caused by a complex combination of climatic and hydrogeological conditions, which complicates the forecasting of arcing. In models studied, arcing forecast is based on calculations of the dangerous area parameters depending on the time and soil characteristics.

Therefore, it can be concluded that despite the difference of models in their forecasting part, based on the calculation of implementing "bending deflection", they are good enough in forecasting the increase of deflection, if it already exists.

The mechanisms that cause increase in length of the linear part of the pipeline, are still not completely understood. Thus, the interaction between weighting agents and a pipeline turns out to be beyond the scope of models. Because before the coming of realization the condition of instability of the pipeline horizontal position, weighting agents should be dropped.

Let us consider a stage, prior to pipeline bending. As a model, we choose rod with length L fixed at one side and with the applied load F . Motion of the rod will be determined by the function $\varphi(x)$. The curvature of the rod is determined by changing the angle:

$$\frac{d\theta}{dx} = \frac{d}{dx} \arcsin \varphi'(x) = \varphi' \sqrt{1 - \varphi'^2} = \frac{d^2\varphi}{dx^2} \sqrt{1 - \left(\frac{d\varphi}{dx}\right)^2} \quad (1)$$

where θ is the angle of the rod curvature; $\varphi(x)$ is the motion of the rod.

Deformation energy of a rod will be determined by the equation:

$$\delta V = \frac{1}{2} EI \left(\frac{d\theta}{dx} \right)^2 \delta x \quad (2)$$

where E is elastic modulus; I is a moment of inertia of the pipe section.

As the unit of length, choose mass value m , then the expression for the kinetic energy will be:

$$\delta \varepsilon = \frac{1}{2} m (\varphi'(x))^2 \delta x \quad (3)$$

Potential energy of a bent rod is given by:

$$V = U - \frac{1}{2} F \int_0^L \varphi'^2 dx \quad (4)$$

where U - potential energy of deformation; F - compressive force.

Flexural mode $\varphi(x)$ with arbitrary amplitude can be selected as a half of sinusoid:

$$\varphi(x) = w(t) \sin \frac{\pi x}{L} \quad (5)$$

According to a paper [2], at a stage preceding the time of pipeline bending, vibrations should be developed in it, as a result of instability:

$$\omega_0^2 \approx \frac{\pi^4 EI}{2L^3} \left[1 - \frac{Sl}{\pi^2 I} \left(\frac{16}{\pi^2 \rho h} P \sum_{m=1}^{\infty} \frac{\cos \alpha_m \xi \sin \varphi}{m \omega_{mn}^2} \sin \omega t \right)^2 \right] \quad (6)$$

where L - length of the pipe; P - pressure; p - the mass of the shell per unit area; h - thickness of the wall; ; $\xi = \frac{x}{r}$; x - changing shell radius; φ - angle; , $\alpha_m = \frac{m\pi r}{l}$, l - length of the shell, m - number of half-waves in the direction of a generator of a shell, n - the number of waves around the circumference; ω_{mn} - natural frequency of vibration.

Extraction of frequency of these vibrations can serve as a basis for the development of the pipeline condition monitoring method at a stage preceding its bending. In this case, a geometry deformation is a consequence of the nonlinearity of pressure surges at an unstable gas flow. Reducing the angular vibration frequency (1) defines an approximation of the system to the bifurcation point. The task outlines two balance state paths. In subcritical area, vibrations (ω_0) correspond to the steady state with amplitude (Q_1).

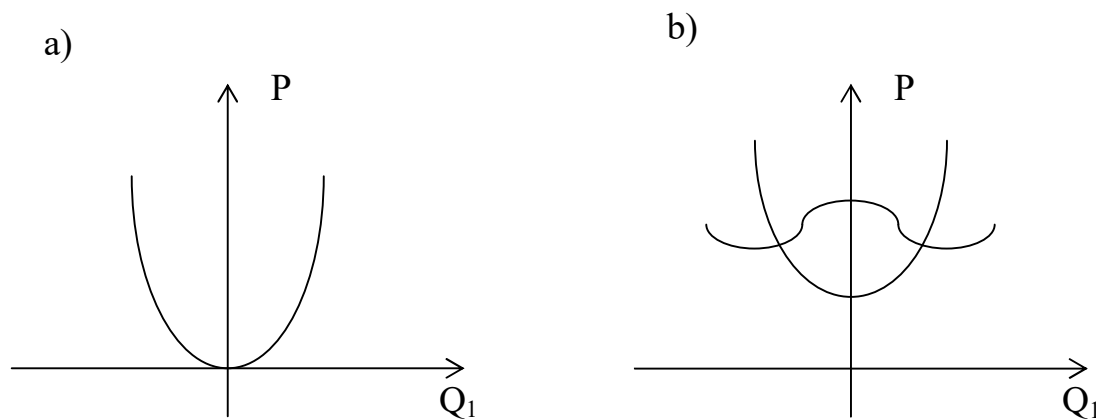


Figure 1. The dynamic behavior of the pipe.

a) far from the bifurcation point, $P < P_c$

b) near the bifurcation point, $P \approx P_c$

Control parameter in this task is $\lambda = P_c - P$. As we approach to the bifurcation point, the control parameter decreases to zero, along with it natural vibrations frequency (ω_0) approaches to zero. At the bifurcation point, the potential energy is modified, going from single-well (steady) state (Fig. 1a) to a two-well (Fig. 1b).

The emergence of the critical load P_c corresponds to the disappearance of the potential energy minimum. As a result, the vibration frequency tends to zero. Thus, the transformation of vibration frequency into zero defines the moment of the pipeline bending formation, as a transition to a new stable state.

The main component of the load (P) is a longitudinal motion caused by a dynamic load. Researches [1, 7, 9] calculate the value of the longitudinal displacement at interaction with the ground not at the stage of bending formation, but at its growth when bending has already occurred. It seems that at the stage of bending formation, the interaction with ground will also be an important condition.

Let us consider emergence of a bending mode at longitudinal loading of pipeline with variable dynamic load in terms of interaction with the ground. Since the ground has the binding ability, from all types of interaction we choose its elastic shear resistance. Consider the stationary case, then the movement of $u(x)$ must satisfy the equation of longitudinal-transverse bending:

$$\frac{d^2u}{dx^2} - \frac{\pi D_1 k_n}{ES} = \frac{dP}{dx} \quad (7)$$

where D_1, k_n – coefficients characterizing the elastic properties of the ground [9]; x - distance from the beginning of pipeline section.

The pressure distribution along the length of pipeline we choose as a model function:

$$P(x) = P_0 - a_1 e^{-\alpha_1 x} \quad (8)$$

Define the boundary conditions:

$$\begin{aligned} u(0) &= 0 \\ \frac{du(L)}{dx} &= \frac{1}{ES} F \end{aligned} \quad (9)$$

where L - length of pipeline section on which the bending occurred.

Equation (4) must be supplemented by the expression of the internal strain forces, compressing the pipe [1].

$$F = \frac{ES}{2} \int_0^L \left[\left(\frac{dz}{dx} \right)^2 + \left(\frac{dy}{dx} \right)^2 \right] dx \approx ES \left(\frac{w}{l} \right)^2 l \quad (10)$$

where w - the value of pipeline deflection.

Given equations form a system, the solution of which is determined by expression, obtained with the terms of approximation.

$$\begin{aligned} u(x) &\approx \frac{Fsh(\theta x)}{\theta ch(mL)} - \frac{\alpha_1 a_1}{\theta^2 - \alpha^2} (e^{\theta x} - e^{-\alpha x}) = \\ &= \frac{1}{\theta L} \left(\frac{16}{\pi^2 \rho h} P \sum_{m=1}^{\infty} \sum_{n=1}^{\infty} \frac{\cos \alpha_m \xi \sin \varphi \sin \omega t}{mn(\omega_{mn}^2 - \omega^2)} \right) \frac{sh(\theta x)}{ch(\theta L)} - \frac{\alpha_1 a_1}{\theta^2 - \alpha^2} (e^{\theta x} - e^{-\alpha x}) \end{aligned} \quad (11)$$

Interaction with the ground as an elastic base changes the frequency of a mode, by which instability of the horizontal pipeline position develops. The action of elastic ground across the pipeline can be modeled with spring substrate that resists cross motions (w). Consider the linearized expressions for the energy in the analysis of the stability of an elastic rod. To bending strain energy

$$\varepsilon_D = \frac{1}{2} EI \int_0^L \left(\frac{d^2 w}{dx^2} \right)^2 dx \quad (12)$$

and potential compressive load energy

$$U_D = -\frac{1}{2} P \int_0^L \left(\frac{dw}{dx} \right)^2 dx \quad (13)$$

the elastic base deformation energy is being added:

$$\varepsilon_k = \frac{1}{2} K \int_0^L w^2 dx \quad (14)$$

where K - stiffness of the base.

Looking at the initial stage of supercritical position, w can be determined by the expression:

$$w = Q \sin\left(\frac{\pi x}{L}\right) \quad (15)$$

where Q - mode amplitude.

As a result of transformations, it is possible to obtain an expression for ω_i^2 (i -th mode, by which instability develops):

$$\omega_i^2 = \frac{EI \left(\frac{i\pi}{L} \right)^4 + K - P \left(\frac{i\pi}{L} \right)^2}{m} \quad (16)$$

From this expression, it follows that the frequency of the mode, at which instability is realized, is larger due to the elastic interaction with the ground.

Interaction of pipeline with the ground affects the process of changing its geometric shape, i.e., a deviation from the design position. Researches [3, 8] show that at frequencies from 10 Hz to 100 Hz, maximum amplitudes of the vibrations, and the maximum reduction of tangential resistances to both the longitudinal and cross motions are observed. It was found that no matter how small the amplitude of the vibration is, anyway there is a noticeable decrease in the elastic soil impact.

3. Conclusion

Thus, the dynamic processes in the "soil-pipe" system have an impact on the process of extension of the linear part of the pipeline due to the growth of longitudinal compressive stresses. As approaching the system to the time of stability loss of the design position, there should appear certain changes. Thus, at the stage prior to the pipeline bending, low frequency vibrations (ω_i) develop in it, which damp if pressure increases. Based on the above, it is possible to develop a method of forecasting the beginning of bending formation; more precisely one can define the range of frequencies at which instability can appear.

References

- [1] Vagner V V 2008 *Changing the height position of the pipeline at a variable water cut of soil in the trench* The thesis for the degree of Candidate of engineering sciences (Tyumen) 119
- [2] Voronin K S 2013 *Forecasting the development of damages on gas pipelines under the influence of dynamic load* Thesis for scientific degree of candidate of engineering sciences (Tyumen, TSOGU) 111
- [3] Gorkovenko A I 2006 *Fundamentals of the theory of calculating the spatial position of an underground pipeline under the influence of seasonal processes* The thesis for the degree of Doctor of Sciences (Tyumen, TSOGU) 305
- [4] Gumerov A G and Azmetov H A 2007 Strain calculation in the pipe system while eliminating deviations of their cross-sectional shape and diameter of the nominal values *Oil Industry* **1** 78-79
- [5] Ibragimov A A, Podorozhnikov S Yu, Shabarov A B, Medvedev M V and Zemenkova M Yu 2014 Calculation model and algorithm for determining the residual life of the pipeline under periodic changes of strains and corrosion *Mining informational and analytical bulletin (scientific and technical journal)* (Moscow, Gornaya Book) **S4** 199-206
- [6] Mikhailenko E S 2007 *Development of the method of calculating and forecasting critical parameters of main gas pipeline arcing* The thesis for the degree of Candidate of engineering sciences (Tyumen) 200
- [7] Pulnikov S A 2007 *Interaction of vibro-loaded main gas pipelines with surrounding grounds* The thesis for the degree of Candidate of engineering sciences (Tyumen) 172
- [8] Toropov S Yu, Dorofeev V S and Zemenkov Yu D 2013 On determining the longitudinal force in the pipeline at formation of the arch *Mining informational and analytical bulletin (scientific and technical journal)* (M , Gornaya book) **S3** 223-229
- [9] Harinovskiy V V 2000 *The reliability and resource of pipeline construction* (M, Nedra) 467
- [10] N.N. Malushin, A.P. Kovalev, D.V. Valuev, E.A. Shats, I.F. Borovikov, Developing and studying the methods of hard-facing with heat-resisting high-hardness steels, J. IOP Conference Series: Materials Science and Engineering. 142 (2016) p. 1-6
- [11] R.A. Gizatuln, D.V. Valuev, R.S. Dariev, V.A. Trifonov, I.F. Borovikov, Distribution of liquid flow rates in the process of bubbling with gas through gas-permeable inserts, J. IOP Conference Series: Materials Science and Engineering. 142 (2016) p. 1-6
- [12] Zemenkova, M.Y., Shipovalov, A.N., Zemenkov, Y.D. 2016 Mathematic Modeling of Complex Hydraulic Machinery Systems When Evaluating Reliability Using Graph Theory IOP Conference Series: Materials Science and Engineering 127 (1) DOI: 10.1088/1757-899X/127/1/012056
- [13] Zemenkova, M.Yu., Zemenkov, Y.D., Pimnev, A.L., Kurushina, E.V. System of Controlling the Reliability of Hydraulic Machinery in Oil and Gas Facilities IOP Conference Series: Materials Science and Engineering 127 (1) DOI: 10.1088/1757-899X/127/1/012055