The Behavior of Variable-Diameter Pipeline Segments on Landslides in Numerical Simulations

Iwona KOWALSKA-KUBSIK[1)]

[1)] Faculty of Drilling, Oil and Gas, AGH University of Krakow, Poland; ORCID: https://orcid.org/0000-0003-0708-2937; email: ikk@agh.edu.pl

http://doi.org/10.29227/IM-2025-01-31

Submission date: 15-06-2025 | Review date: 28-06-2025

Abstract

The construction of pipelines in mountainous areas presents significant engineering challenges, primarily due to landslide risks and complex geological conditions. Pipelines laid on slopes are exposed to forces resulting from soil mass movements, which can lead to serious deformations or even structural failures. While minor ground displacements can often be managed without the need for costly geotechnical solutions, landslide-prone areas require precise routing, continuous monitoring, and strict adherence to safety regulations. The strategic importance of gas pipelines, combined with their vulnerability to landslide-induced damage, underscores the need for detailed geotechnical assessments and an interdisciplinary approach involving engineers, designers, and environmental specialists. Despite ongoing research into pipeline behavior under landslide conditions, there is still a lack of practical tools for predicting and preventing such damage.

This article discusses the key natural and anthropogenic factors that trigger landslides and highlights the growing role of numerical modeling in analyzing pipeline performance under various landslide scenarios. Particular attention is given to the behavior of a steel pipeline in a zone of diameter transition located within a landslide area. Improving monitoring systems and developing predictive indicators are essential for reducing risk and enhancing emergency response capabilities in slope-affected regions.

Keywords: *umerical simulation, landslide, gas pipe, materials*

INTRODUCTION

Constructing pipelines in mountainous regions affected by landslides poses a significant engineering challenge due to inherently complex geological conditions. Installing pipelines on slopes—often unavoidable in such terrain—requires meticulous planning to mitigate the risk of adverse geohazards such as landslides. When a landslide occurs, the displacement of soil masses generates substantial forces that can act on the pipeline. These forces may cause severe deformation, including local constriction, misalignment, or even rupture.

In cases of minor ground movement, standard pipeline materials typically exhibit sufficient strength to withstand resulting stresses, eliminating the need for expensive geotechnical solutions such as retaining walls or deep anchoring systems. In such scenarios, optimal pipeline alignment—ensuring that local stress concentrations remain below critical thresholds—can often be the most efficient strategy.

Construction in these areas must also comply with relevant regulations and industry standards. Regulatory authorities generally mandate comprehensive geotechnical investigations, formal risk assessments, and strict adherence to safety guidelines to protect infrastructure, the environment, and public safety.

Mitigating these risks demands a multidisciplinary approach that integrates the expertise of geotechnical engineers, pipeline designers, and environmental specialists. Effective risk management in such areas requires thorough investment planning, detailed site investigations, and the implementation of engineering solutions tailored to local geotechnical conditions.

Gas pipelines are considered critical infrastructure, and protecting them from natural hazards and anthropogenic threats is of paramount importance. Owing to their long, linear geometry, gas pipelines are particularly vulnerable to damage from landslides [1–3]. Such events can cause major deformation or rupture, potentially leading to gas leakage, operational shutdowns, and serious threats to human safety.

The risk of landslide occurrence and the mitigation of related losses is the subject of extensive research [4–11]. Most existing studies focus on understanding the behavior of pipelines on landslides to identify critical sections of the gas transmission system. Despite the growing body of work in this field, there is still a lack of practical and well-developed indicators that would allow for reliable prediction and effective prevention of damage to pipelines located in landslide-prone areas.

In the field, early indicators of slope instability—such as surface cracks, fissures, and localized ground displacement—are often observable before a full-scale landslide occurs. These features may offer preliminary insight into the possible timing and extent of slope failure. However, systematic monitoring and accurate risk assessment remain essential. For instance, knowing the anticipated width of a landslide can improve the accuracy of pipeline risk evaluations. Developing predictive tools and early-warning indicators would support effective emergency response planning and enable rapid intervention to reduce potential damage.

Landslides are inherently complex to predict and control due to their variability in scale, speed, and behavior. Common contributing factors include:

- Stratified soil layers parallel to the slope: This condition promotes sliding and destabilization.
- Buoyant forces increase the likelihood of landslide initiation.
- Pore pressure and seepage: Accumulated water reduces soil shear strength.

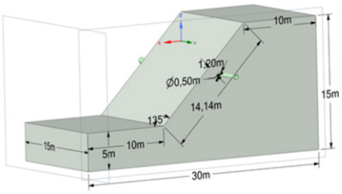

Fig. 1. Geometrical slope model with pipeline
Rys. 1. Model nachylenia geometrycznego z rurociągiem

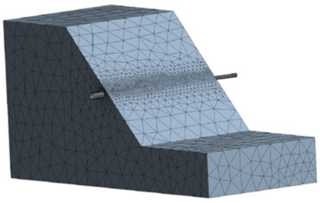

Fig. 2. Tetrahedral mesh of the landslide model with the pipeline
Rys. 2. Siatka tetraedryczna modelu osuwiska z rurociągiem

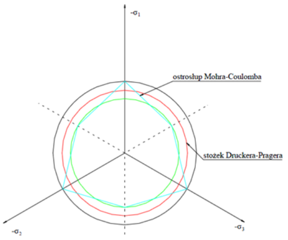

Fig. 3. The Drucker–Prager model are represented by cone, and the blue hexagon illustrates the Coulomb–Mohr model
Rys. 3. Model Druckera-Pragera jest przedstawiony w postaci stożka, a niebieski sześciokąt ilustruje model Coulomba-Mohra

- Rain-induced soil saturation: Waterlogged soils expand and lose strength.
- Pre-existing slip surfaces: Common in clayey soils, these act as failure planes.
- Erosion or undercutting of slope bases: Often caused by surface runoff or groundwater flow, this compromises slope stability.

Landslides are typically the result of a complex interplay of multiple contributing factors, often exacerbated by human activity. In urbanized or altered landscapes, anthropogenic influences frequently become the dominant trigger. Such actions include slope undercutting, terrain modification, the addition or removal of loads on slopes, dynamic impacts such as vibrations, changes in land use (e.g., deforestation or agricultural development), and the redirection of water flow toward geologically unstable areas.

Given the logistical challenges and high costs associated with conducting full-scale experimental studies in sloped terrain, numerical modeling has become an increasingly valuable tool for analyzing pipeline behavior under landslide conditions. These computational methods enable engineers to simulate a wide range of movement scenarios and material responses without the need for expensive field testing. As a result, numerical simulations play a critical role in improving engineering decision-making and enhancing the accuracy of risk assessments in landslide-prone regions.

SIMULATION

Numerical analyses were conducted using the ANSYS software environment [12], based on the Finite Element Method (FEM). FEM is a numerical technique that enables the approximation of solutions to partial differential equations, which describe the mathematical models of complex engineering problems. It is one of the most fundamental and widely used tools for discretizing continuous geometric systems by dividing a structure into a finite number of subdomains, known as finite elements.

In this method, the continuous model is discretized into finite elements connected at nodal points, resulting in a system with a finite number of degrees of freedom. This transformation allows problems that are analytically unsolvable—due to their infinite number of variables—to be converted into a computationally solvable form.

One of FEM's key advantages is its ability to transform differential equations describing physical behavior into a system of algebraic equations. Within each finite element, displacement and stress fields are approximated, making it possible to simulate realistic structural responses. FEM is applicable to both static and dynamic analyses and is particularly effective in modeling actual slope geometries, landslide zones, or subsidence areas. It also supports the use of advanced soil constitutive models, including elastic–plastic formulations, commonly used for granular materials.

Depending on the nature of the problem under investigation, other numerical methods may also be used alongside FEM. The Finite Volume Method (FVM), based on the control volume approach, is frequently applied in flow-related analyses. The Discrete Element Method (DEM) is suitable for modeling the mechanical behavior of granular materials. Meshless methods, such as the Material Point Method (MPM), offer

Tab. 1. Steel parameters

Tab. 1. Parametry stali

	Parameters
Density [kg/m³]	7 850
Young's modulus [GPa]	200
Poisson's ratio [–]	0,3
Shear modulus [GPa]	76,9
Bulk modulus [GPa]	167
Specific Heat [J/kg ·°C]	434
Yield strength [MPa]	390
Tensile strength [MPa]	550

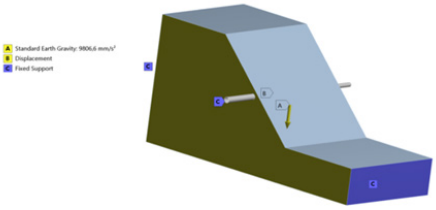

Fig. 4. Boundary conditions of mathematical model

Rys. 4. Warunki brzegowe modelu matematycznego

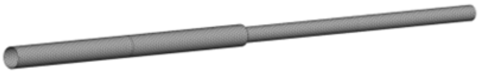

Fig. 5. Mach of steel pipe in case I

Rys. 5. Mach rury stalowej w przypadku I

Fig.6. Deformation pattern of the gas pipeline with a sharp diameter transition from 700 mm to 500 mm within the landslide zone, with the pipeline ends fixed at the edges of the slope

Rys. 6. Schemat deformacji gazociągu z ostrym przejściem średnicy z 700 mm do 500 mm w strefie osuwiska, z końcami gazociągu zamocowanymi na krawędziach skarpy

advantages in cases involving large deformations or discontinuities, as commonly encountered in soil modeling.

Numerical modeling enables time-dependent simulations, allowing the evolution of deformation, displacement, and stress within the model to be tracked over successive time steps under varying loads and boundary conditions. This makes it possible to observe and analyze the full development process of pipeline damage over time, providing valuable insight into the long-term behavior of pipelines in landslide-prone conditions.

Numerical Analysis Overview

Geometry

The landslide slope adopted for modeling has a width of 15 meters and a height of 15 meters. In the upper part of the slope, a horizontal ground section 10 meters in length was assumed. The slope itself has an inclination angle of 45° and a length of 14.14 meters. At the base of the landslide slope, a second horizontal area was also assumed, with a length of 10 meters. The height of the horizontal base was set at 5 meters.

The dimensions of the landslide slope model used in the simulation were determined based on discussions and consultations with gas industry companies, as well as an on-site inspection of natural landslides in areas traversed by pipelines (gas pipelines).

Discretization

The geometric model of the slope with the gas pipeline was discretized using 3D tetrahedral and hexahedral elements, with mesh density tailored to the specific requirements of each model. The soil domain, due to its relatively large scale, was meshed more coarsely to optimize computational efficiency. The pipeline geometry was discretized using a finer hexahedral mesh to achieve greater accuracy in capturing stress and deformation responses. Figure 2 presents the meshing strategy adopted for the numerical simulations.

Materials, soil and steel

Model of Soil

The adopted soil model was based on data characterizing soils from existing landslides. A homogeneous, non-cohesive soil material was assumed for the analysis, with the following parameters:

- density $\rho = 1750$ kg/m^3,
- Young's modulus $E = 50$ MPa,
- Poisson's ratio $\nu = 0.29$,
- bulk modulus = 3.96×10^7 Pa,
- shear modulus = 1.938×10^7 Pa.

The landslide behavior was analyzed using the Coulomb–Mohr soil constitutive model.

Fig. 7. Stress in the pipeline with a sharp diameter transition from 700 mm to 500 mm, with fixed-end constraints at the edges of the slope
Rys. 7. Naprężenia w rurociągu o ostrym przejściu średnicy z 700 mm do 500 mm, z ograniczeniami na końcach nachylenia

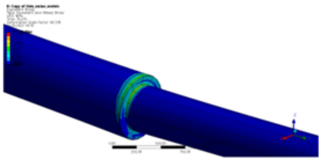

Fig. 8. Stress in the pipe at the location of the diameter transition
Rys. 8. Naprężenie w rurze w miejscu przejścia średnicy

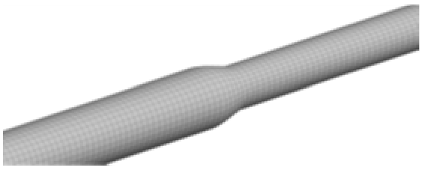

Fig. 9. Mesh of pipe model
Rys. 9. Siatka modelu rury

The yield condition for both the Drucker–Prager and Coulomb–Mohr models can be presented as follows [13]:

$$f(\sigma_{ij}) = q - mp - k \tag{1}$$

where the parameters m and k are defined as:

$$m = \frac{18 \sin \phi}{9 - \sin 2 \phi} \tag{2}$$

$$k = \frac{18c \cos \phi}{9 - \sin 2 \phi} \tag{3}$$

with: ϕ – internal friction angle, c – cohesion and p and q – stress tensors invariants, given by:

$$p = -\frac{1}{3}\sigma_{ii}, \quad q = \sqrt{\tfrac{3}{2}}(s_{ij}s_{ij}). \tag{4}$$

The deviatoric stress tensor s_{ij}. is defined as:

$$s_{ij} = \sigma_{ij} + \delta_{ij} \tag{5}$$

where σ_{ij} is the total stress tensor, and δ_{ijj} represents the Kronecker delta.

In most works related to plasticity theory, the coefficients m and k in equation (1) are defined as shown in the equations below (6) and (7):

$$m = \frac{6 \sin \phi}{3 - \sin \phi} \qquad 6)$$

$$k = \frac{6\,c \cos \phi}{3 - \sin \phi} \tag{7}$$

Figure 3 presents a geometric interpretation of the principal stress space, where the red circle represents the Drucker–Prager cone, and the blue hexagon illustrates the Coulomb–Mohr model.

Steel pipe

For the analysis of pipeline behavior, it was assumed that the gas pipeline is made of steel with material properties in accordance with the PN-EN ISO 3183:2013-05 standard.

The parameters of steel pipe are presented in Table 1.

Landslide

Based on the distribution of forces acting on pipelines during landslide events [14] and established research on pipeline–soil interaction [15–19], the following modeling assumptions were applied:

- forces considered: only gravitational forces responsible for landslide movement were included in the analysis.
- pipeline–soil interaction: simulated as frictional contact, with a coefficient of friction set at 0.6, in accordance with standard design guidelines for buried pipelines.

This modeling approach enabled a realistic simulation of stress conditions induced by landslides and provided meaningful insights into the mechanical interaction between the pipeline and the surrounding soil.

Simulation configuration, boundary conditions and loads

The selection of the computational model was based on findings from previous studies [20–22]. A slope model with an embedded pipeline was adopted to realistically represent the interaction between the pipeline and the deforming soil under landslide conditions. Various boundary conditions were applied to both the slope and the pipeline supports to assess their impact on pipeline response. To simulate natural landslide movement, the boundaries of the slope were allowed to move freely along the direction of inclination. At the same time, the pipeline ends were fixed to reflect realistic anchoring conditions.

Fig. 10. Deformation pattern of the gas pipeline with a gradual diameter transition from 700 mm to 500 mm (connected using a diffuser/cone reducer) within the landslide zone, with free lateral boundaries of the slope model

Rys. 10. Przebieg deformacji gazociągu o stopniowej zmianie średnicy z 700 mm do 500 mm (połączonego dyfuzorem/reduktorem stożkowym) w strefie osuwiska, z wolnymi granicami bocznymi modelu zbocza

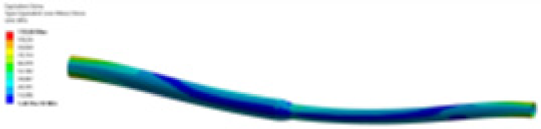

Fig. 11. Stress distribution in the gas pipeline with a gradual diameter transition from 700 mm to 500 mm (connected using a diffuser/cone reducer) within the landslide zone, with free lateral boundaries of the landslide slope

Rys. 11. Rozkład naprężeń w gazociągu o stopniowej zmianie średnicy z 700 mm do 500 mm (połączonym dyfuzorem/reduktorem stożkowym) w strefie osuwiska, z wolnymi granicami bocznymi zbocza osuwiska

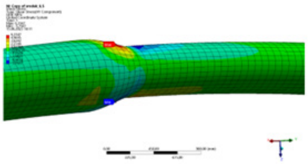

Fig. 12. Stress in the gas pipeline with a gradual diameter transition from 700 mm to 500 mm

Rys. 12. Naprężenia w gazociągu przy stopniowej zmianie średnicy z 700 mm do 500 mm

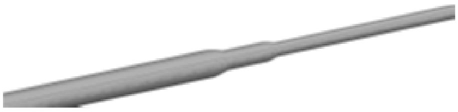

Fig. 13. Mesh of steel pipe

Rys. 13. Siatka z rury stalowej

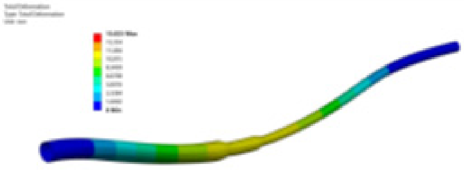

Fig. 14. Deformation pattern of the gas pipeline with a two-stage diameter transition from 700 mm through 500 mm to 350 mm (connected using two diffusers/cone reducers) within the landslide zone, with free lateral boundaries of the slope model

Rys. 14. Przebieg deformacji gazociągu o dwustopniowej zmianie średnicy od 700 mm przez 500 mm do 350 mm (połączony dwoma dyfuzorami/reduktorami stożkowymi) w strefie osuwiska, z wolnymi granicami bocznymi modelu zbocza

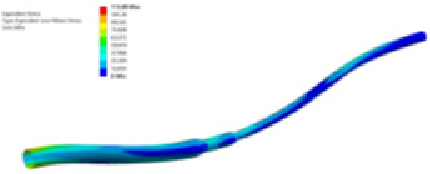

Fig. 15. Stress in the gas pipeline with a two-stage diameter transition from 700 mm through 500 mm to 350 mm (connected using two diffusers/cone reducers) within the landslide zone, with free lateral boundaries of the landslide slope

Rys. 15. Naprężenia w gazociągu o dwustopniowym przejściu średnicy od 700 mm przez 500 mm do 350 mm (połączonym dwoma dyfuzorami/reduktorami stożkowymi) w strefie osuwiska, z wolnymi granicami bocznymi zbocza osuwiska

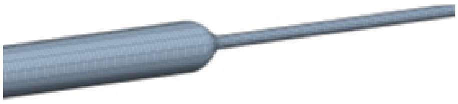

Fig. 16. Mesh of steel pipe

Rys. 16. Siatka z rury stalowej

It is important that the boundary conditions used in this study—such as contact surface dimensions, loading magnitudes and directions, and the pipeline–soil interface configuration—represent just one scenario among countless possible real-world cases. These parameters were selected to strike a balance between realistic field representation and computational clarity, ensuring the results remained interpretable and analytically consistent.

This configuration formed the basis for the numerical simulations and enabled a detailed investigation into the structural performance of pipelines under landslide-induced loading. Figure 4 illustrates the boundary conditions adopted for the analysis.

Analysis

Case I

In presented case I, model, which includes a gas pipeline with a sharp diameter transition from 700 mm to 500 mm, deformation analysis was conducted under the assumption of free lateral boundaries of the slope. Mesh of steel pipe are presented on Figure 5

As shown in Figure 6, the maximum deformations (on the order of 20 mm) occur at the location of the sharp diameter transition, which is situated in the central part of the landslide. In contrast, in the lateral regions of the slope, pipeline deformations are minimal. This observation is logical, as the pipeline in those boundary zones is embedded in stable ground outside the landslide-affected area.

The stress distribution pattern in the pipeline featuring a sharp diameter change from 700 mm to 500 mm—within the landslide zone and under fixed lateral boundaries of the slope model—is illustrated in Figure 7.

Figure 8 shows the stress distribution at the location of the diameter transition.

The analysis revealed that the highest stress values—reaching approximately 200 MPa—occur in the gas pipeline near the lateral edges of the landslide zone. The pipeline is subjected to both bending and torsion, induced by frictional forces between the soil and the pipeline surface.

The stress and deformation patterns observed in the pipeline with a sharp diameter transition from 700 mm to 500 mm, as presented in Figure 6 and 7, are consistent with real-world behaviors previously observed in pipelines that experienced failure while located on landslide-affected slopes. These findings also align with expert assessments provided by specialists from gas industry companies.

The torsional effects acting on the pipeline result from differences in the displacement velocities of the soil masses above and below the pipeline, combined with frictional interaction between the soil and the pipeline surface.

Case II

In case II is presented landslide model with an embedded gas pipeline featuring a gradual diameter transition from 700 mm to 500 mm (using a diffuser/cone reducer connection), (mesh in Figure 9) deformation analysis was carried out under the condition of free lateral boundaries of the slope.

The resulting deformation pattern of the pipeline is shown in Figure .10.

As shown in Figure 10, the maximum deformations reach approximately 14 mm. These occur at the gradual diameter transition located in the central area of the landslide zone. In contrast, minimal deformations are observed in the lateral sections of the slope, where the pipeline remains largely unaffected.

The stress distribution in the gas pipeline with a gradual diameter transition from 700 mm to 500 mm (connected using a diffuser/cone reducer), within the landslide zone and under free lateral boundary conditions of the slope model, is presented in Figure 11.

The analysis showed that the highest stress values occur in the gas pipeline at the points of fixation. The pipeline is subjected to both bending and torsion, primarily caused by friction between the soil and the pipeline surface.

The deformation and stress characteristics of the pipeline with a gradual diameter transition from 700 mm to 500 mm (connected using a diffuser/cone reducer), as illustrated in Figures 10, 11 and 12, exhibit a similar pattern to that observed in the case of a sharp diameter transition. This indicates that deformation tends to concentrate around the pipe connection zone, while stress concentrations appear near the lateral edges of the landslide.

Such results are consistent with real-world observations of pipeline behavior in landslide-affected areas.

Case III

In Case III, a landslide model with an embedded gas pipeline featuring a two-stage diameter transition—from 700 mm through 500 mm to 350 mm—was analyzed. The transition was implemented using two diffuser/cone reducer connections. Mesh of pipe in case III is presented on Figure 13.

Deformation simulations were carried out under the condition of free lateral boundaries of the slope. The resulting deformation pattern of the pipeline is shown in Figure 14.

As shown in Figure 12, the maximum deformations—approximately 10 mm—occur in the region of the two-stage diameter transition, which is located in the middle of the landslide zone. In contrast, minimal pipeline deformations are observed in the lateral sections of the slope.

The stress distribution in the gas pipeline with a two-stage diameter transition from 700 mm through 500 mm to 350 mm (connected using two diffusers/cone reducers), within the landslide zone and under free lateral boundary conditions of the slope model, is presented in Figure 15.

The analysis demonstrated that the highest stress values in the gas pipeline occur near the lateral edges of the landslide. The pipeline is subjected to both bending and torsional stresses, primarily caused by frictional interaction between the soil and the pipeline surface.

The deformation and stress behavior of the gas pipeline with a two-stage diameter transition from 700 mm through 500 mm to 350 mm (connected using two diffusers/cone reducers), as shown in Figures 14 and 15, exhibits a similar pattern to that observed in the cases of both sharp and gradual diameter transitions. This indicates that deformation tends to concentrate in the pipe connection zones, while stress concentrations are observed near the lateral boundaries of the landslide.

Case IV

In Case IV, a landslide model with an embedded gas pipeline featuring a diameter transition from 200 mm to 50

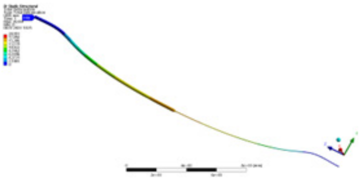

Fig. 17. Deformation pattern of the gas pipeline with a diameter transition from 200 mm to 50 mm (connected using a diffuser/cone reducer) within the landslide zone, with free lateral boundaries of the slope model

Rys. 17. Przebieg deformacji gazociągu o średnicy przejścia od 200 mm do 50 mm (połączonego dyfuzorem/reduktorem stożkowym) w strefie osuwiska, z wolnymi granicami bocznymi modelu zbocza

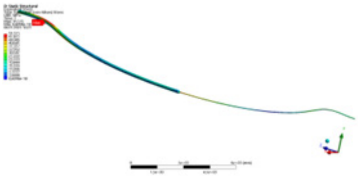

Fig. 18. Stress in the gas pipeline with a diameter transition from 200 mm to 50 mm (connected using a diffuser/cone reducer) within the landslide zone, with free lateral boundaries of the landslide slope

Rys. 18. Naprężenia w gazociągu o średnicy przejścia od 200 mm do 50 mm (połączonym za pomocą dyfuzora/reduktora stożkowego) w strefie osuwiska, przy swobodnych granicach bocznych zbocza osuwiska.

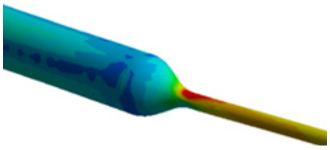

Fig. 19. Stress in the gas pipeline

Rys. 19. Naprężenia w gazociągu

mm (connected using a diffuser/cone reducer) was analyzed. Mesh of stell pipe is presented on Figure 16. Deformation simulations were conducted under the condition of free lateral boundaries of the slope. The resulting deformation pattern of the pipeline is shown in Figure 17.

As shown in Figure 17, the maximum pipeline deformations—approximately 20 mm—occur at the diameter transition zone, located in the middle of the landslide. In contrast, minimal deformations are observed in the lateral regions of the slope.

The stress distribution in the pipeline with a diameter transition from 200 mm to 50 mm, within the landslide zone and under free lateral boundary conditions of the slope model, is presented on the Figures 18 and 19.

The analysis revealed that the highest stress values in the pipeline occur near the lateral cut edges of the landslide. During the displacement of soil masses, the pipeline is subjected to both bending and torsion, primarily due to friction between the soil and the pipeline surface.

The deformation and stress characteristics in the pipeline with a diameter transition from 200 mm to 50 mm (connected using a diffuser/cone reducer), as shown in Figures 17, 18, and 19, are similar to those observed in the cases of both sharp and gradual diameter transitions. This indicates that deformation tends to concentrate in the pipe connection zone, while stress concentrations are located near the lateral boundaries of the landslide.

CONCLUSION

Analyzing the results obtained from simulations of deformations and stresses in the pipeline located in a landslide area—within the framework of the research objective, which was to investigate the behavior of gas pipelines in diameter transition zones—it can be concluded that understanding the potential behavior of pipelines with such specific geometric changes enables more accurate pipeline design and more effective monitoring.

The presented analysis can support the identification of hazardous zones along the pipeline route and help determine their extent. Technological advancements now allow for the installation of intelligent stress monitoring systems in gas pipelines, contributing to safer operation.

Comparing the results of analyses involving different pipeline geometry variants in unstable soil conditions (landslides) allows for a more accurate assessment of critical points in gas pipelines operating under challenging geotechnical conditions, such as landslide-prone areas.

ACKNOWLEDGEMENTS

The article was supported by the AGH University of Krakow under subsidy no. 16.16.190.779.

Literatura – References

1. Zhou X.Y., Guo Y.H., Lv X.H., Yang Y.: Study on Effects of Different Factors on Pipelines Risk under Landslide.Industrial Safety and Environmental Protection, 38, 2012, pp. 42–44.
2. Xue H., Yang X.Q.: Design and Construction of Sino-Burma Oil-Gas Pipeline in Typical Geological Hazard Areas.Oil & Gas Storage and Transportation, 32, 2013, pp. 1320–1324.
3. Ho D., Wilbourn N., Vega A., Tache J.: Safeguarding a Buried Pipeline in a Landslide Region. Pipelines 2014, Port-land Oregon, 3–6 August 2014, pp. 1162–1174. https://doi.org/10.1061/9780784413692.105.
4. Lin D., Lei Y., Xu K.F. et al.: An Experiment on the Effect of a Transverse Landslide on Pipelines. Acta Petrolei Sini-ca, 32, 2011, pp. 728–732.
5. Lin D., Xu K.F., Huang R.Q. et al.: Landslides Classification of Pipeline for Transporting Oil and Gas. Welded Pipe and Tube, 32, 2009, pp. 66–68.
6. Wang L., Deng Q.L.: Mechanical Analysis on the Safety of Gas-Transporting Pipeline Caused by Landslide for Deformation. Journal of Engineering Geology, 18, 2010, pp. 340–345.
7. Kinash O., Najafi M.: Large-Diameter Pipe Subjected to Landslide Loads. Journal of Pipeline Systems Engineering and Practice, 3, 2012: 1–7. https://doi.org/10.1061/(ASCE)PS.1949-1204.0000091.
8. Magura M., Brodniansky J.: Experimental Research of Buried Pipelines. Procedia Engineering, 40, 2012, pp. 50–55. https://doi.org/10.1016/j.proeng.2012.07.054.
9. Zhao X.Y., Zhao Y.: Strain Response Analysis of Oil and Gas Pipelines Subject to Lateral Landslide. Journal of Nat-ural Disasters, 23, 2014, pp. 250–256.
10. Huang K., Lu H.F., Wu S.J. et al.: The Stress Analysis of Buried Gas Pipeline Crossing the Landslide. Chinese Journal of Applied Mechanics, 32, 2015, pp. 689–693.
11. Liu W.Q., Zheng J., Wu H.G. et al.: Experimental Study on Effect of Orthogonal Landslide on Pipe by Model Simu-lation. Railway Engineering, 6, 2015, pp. 117–120.
12. ANSYS Inc.: ANSYS Documentation. 2024.
13. Więckowski Z.: The Material Point Method in Large Strain Engineering Problems. Computer Methods in Applied Mechanics and Engineering, 193(39–41), 2004, pp. 4417–4438. https://doi.org/10.1016/j.cma.2004.01.035.
14. Hao J.B., Liu J.P., Jing H.Y., Zhang H., Shen F., Tong H., Liu L.: A Calculation of Landslide Thrust Force to Trans-verse Pipeline. Acta Petrolei Sinica, 33(6), 2012, pp. 1093–1097. https://doi.org/10.7623/syxb201206025.
15. Calvetti F., di Prisco C., Nova R.: Experimental and Numerical Analysis of Soil-Pipe Interaction. Journal of Geo-technical and Geoenvironmental Engineering, 130, 2004, pp. 1292–1299. https://doi.org/10.1061/(ASCE)1090-0241(2004)130:12(1292).
16. Li H., Xu Z., Yang Y.H., et al.: Strength Failure Analysis of Buried Piping Loaded with Landslide. Process Equip-ment & Piping, 49, 2012, pp. 54–57.
17. Alam S., Allouche E., Bartlett C. et al.: Experimental Evaluation of Soil-Pipe Friction Coefficients for Coated Steel Pipes. Pipelines 2013 Conference, Fort Worth, 22–26 June 2013, pp. 360–371. https://doi.org/10.1061/9780784413012.034.
18. Dezfooli M., Abolmaali A., Razavi M.: Coupled Nonlinear Finite-Element Analysis of Soil-Steel Pipe Structure Interaction. International Journal of Geomechanics, 15, 2015, art. 04014032. https://doi.org/10.1061/(ASCE)GM.1943-5622.0000387.
19. Vazouras P., Dakoulas P., Karamanos S.A.: Pipe-Soil Interaction and Pipeline Performance under Strike-Slip Fault Movements. Soil Dynamics and Earthquake Engineering, 72, 2015, pp. 48–65. https://doi.org/10.1016/j.soil-dyn.2015.01.014.
20. Baek J., Schlinkman R. T., Beckwith F. N., and J.-S. Chen, "A deformation-dependent coupled Lagrangian/semi-Lagrangian meshfree hydromechanical formulation for landslide modeling," Advanced Modeling and Simulation in Engineering Sciences, Vol. 9, No. 1, p. 20, Sep. 2022, https://doi.org/10.1186/s40323-022-00233-9
21. Yan Y., Zhou J., Xie C., Yin S., Hu S., and Wang R., "Quantitative estimation of pipeline slope disaster risk in China," International Journal of Disaster Risk Science, Vol. 14, No. 2, pp. 298–312, Feb. 2023, https://doi.org/10.1007/s13753-023-00462-5
22. Zhang, J., Huang, S., Wang, H., He, J., Zhao, H., Zhou, B., & Liu, J. (2024). Interaction of pipelines with landslides: Analysis of mechanical properties at different strengths. Vibroengineering Procedia, 57, 59–65. https://doi.org/10.21595/vp.2024.24307

Zachowanie segmentów rurociągów o zmiennej średnicy na osuwiskach w symulacjach numerycznych

Budowa rurociągów w terenach górskich stanowi istotne wyzwanie inżynieryjne, głównie z powodu ryzyka osuwisk oraz złożonych warunków geologicznych. Rurociągi układane na stokach są narażone na oddziaływanie sił wynikających z przemieszczeń mas ziemnych, co może prowadzić do poważnych odkształceń, a nawet uszkodzeń strukturalnych. Podczas gdy niewielkie przemieszczenia gruntu można często kontrolować bez konieczności stosowania kosztownych rozwiązań geotechnicznych, obszary szczególnie narażone na osuwiska wymagają precyzyjnego trasowania, ciągłego monitoringu oraz ścisłego przestrzegania przepisów bezpieczeństwa.

Strategiczne znaczenie gazociągów, w połączeniu z ich podatnością na uszkodzenia wywołane przez osuwiska, podkreśla konieczność przeprowadzania szczegółowych ocen geotechnicznych oraz zastosowania interdyscyplinarnego podejścia, obejmującego inżynierów, projektantów i specjalistów ds. środowiska. Pomimo trwających badań nad zachowaniem rurociągów w warunkach osuwiskowych, wciąż brakuje praktycznych narzędzi umożliwiających skuteczne przewidywanie i zapobieganie takim uszkodzeniom.

W artykule omówiono kluczowe czynniki naturalne i antropogeniczne wywołujące osuwiska oraz podkreślono rosnącą rolę modelowania numerycznego w analizie pracy rurociągów w różnych scenariuszach osuwiskowych. Szczególną uwagę poświęcono zachowaniu stalowego rurociągu w strefie zmiany średnicy zlokalizowanej w obrębie obszaru osuwiskowego. Udoskonalanie systemów monitoringu oraz rozwój wskaźników prognostycznych są kluczowe dla ograniczania ryzyka i zwiększenia skuteczności działań awaryjnych w rejonach zagrożonych ruchami masowymi.

Słowa kluczowe: *symulacja numeryczna, osuwisko, rurociąg gazowy, materiały*