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ARTICLE

SIMULATIONS OF THE BEHAVIOR OF A PIPELINE MADE FROM THREE DIFFERENT TYPES OF MATERIALS ON A LANDSLIDE

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Abstract: The study presents numerical analyses of the behavior of pipelines made from various materials (steel, polypropylene, composite) under landslide conditions. Landslides are phenomena most commonly occurring in foothill and mountainous areas, and pipelines located on slopes can sustain damage during the landslide process. To determine the nature and extent of potential damage, numerical simulations were conducted based on advanced computational methods. The analysis employed the Drucker-Prager constitutive soil model.

Numerical analyses make it possible to determine the deformation and stress states in pipelines without the need for costly experimental studies. By comparing simulation results for different materials, it is possible to assess the suitability of various pipes for placement on slopes.

Keywords: numerical simulation, landslide, gas pipe, materials

1. Introduction

The problem of constructing pipelines in mountainous areas in relation to landslides is challenging to solve due to the typically complex geology. When laying pipelines on slopes, which is unavoidable in mountainous regions, one must consider the potential adverse phenomena that may occur, such as landslides. During the landslide process – characterized by the movement of soil masses – a pipeline situated in this zone is subjected to forces caused by the movement of these soil masses. This leads to deformations that can result in significant distortions (e.g., pipeline constrictions) or even ruptures. Pipes used in pipeline construction are, in most cases of minor mass movements, strong enough that there is no need for costly geotechnical solutions like retaining walls or pipeline anchoring. Often, it is sufficient to identify the most suitable position on the slope where the forces acting on the pipeline do not exceed its strength.

Pipelines in landslide areas require regular maintenance and monitoring to ensure their continuous safety and functionality. This may include regular inspections, geotechnical slope monitoring, and early warning systems to detect any signs of instability or potential landslide activity.

Constructing pipelines in landslide areas involves adherence to specific regulations and standards. Regulatory organizations may require comprehensive geotechnical studies, risk assessments, and compliance with safety guidelines to protect people, property, and the environment.

Addressing these issues requires a multidisciplinary approach involving geotechnical engineers, pipeline designers, and environmental experts. Careful investment planning, thorough field studies, and the implementation of appropriate engineering solutions are crucial to reducing the risks associated with pipeline construction in landslide-prone areas

Gas pipelines are critical strategic infrastructure and avoiding damage to them caused by natural phenomena or human activities is of great practical importance. However, as long, linear engineering structures, such pipelines are often vulnerable to landslide-induced damage [1–3]. Such damage can lead to significant deformation or pipeline rupture, resulting in natural gas leaks, interruptions in pipeline transport, and even potential threats to human lives.

Preventing losses caused by adverse phenomena in landslide-prone areas and controlling these hazards is an issue requiring further research. The number of studies on landslides impacting gas and oil pipelines is steadily increasing [4–11]. Most of these studies focus on examining mechanical behavior, analyzing weak points in these structures, and identifying factors affecting pipeline behavior during landslide activity. These works primarily provide theoretical results, while practical indicators for predicting and preventing pipeline damage due to landslide activity are lacking.

Practice shows that before the ground collapses, characteristic features such as cracks, fissures, or soil sliding can be observed on the surface. These signals allow for an approximate estimation of when the advanced landslide process will begin and what its range might be. However, it is still necessary to monitor and even assess the potential pipeline damage caused by landslides. For example, if the landslide's range, such as its width, were known, it would be possible to more accurately estimate whether the pipeline would be damaged. Furthermore, a developed indicator would provide a reliable basis for emergency response actions, allowing rescue services to take appropriate measures to minimize damage.

Landslides are difficult-to-control and unpredictable phenomena in terms of their range and nature. The most common factors contributing to landslides include main points:

- Layered soil structure parallel to the slope incline: This alignment promotes slippage and slope destabilization.
- Water buoyancy and seepage pressure in the slope: Water accumulation in the slope can increase pressure and reduce shear resistance, leading to landslides.
- Upward water pressure on the upper soil layers: Water accumulating at the base of a slope often contributes to the initiation of landslides.
- Soil saturation from rainfall: Rainfall causes soil to become saturated with water, resulting in swelling and a reduction in shear strength.
- Presence of natural potential slip surfaces: Such surfaces, especially in clay soils, facilitate the formation of landslides.
- Erosion or undercutting of the slope: Erosive actions, such as surface water flow or undercutting by groundwater, can destabilize the slope.

Landslides are usually triggered by a combination of several factors, often exacerbated by human activities. In urbanized areas, human influence is frequently decisive, with adverse actions including slope undercutting, changes in landform, loading or unloading of slopes, dynamic actions on the ground (e.g., vibrations), changes in land use (deforestation, plowing), and the manipulation of water flow direction towards slopes.

Given the complexity of situating pipelines on slopes, conducting experimental studies is challenging and highly costly. Therefore, the use of numerical tools to analyze pipeline behavior on landslides, particularly in the context of using different pipeline materials, enables the creation of multiple landslide movement scenarios using only computational resources.

The conclusions drawn from these numerical analyses can provide essential engineering insights for pipeline designers, operators, and regulatory institutions. This approach facilitates more informed decision-making in design, construction, and management, ensuring safe and reliable pipeline operation in landslide-prone areas.

The study conducted simulations of the behavior of pipelines made from various materials under the conditions of progressive landslides. The analysis aimed to compare the performance of three materials: standard steel typically used in the construction of high-pressure gas pipelines, polyethylene used in the construction of low-, medium-, and elevated-medium-pressure gas pipelines, and a composite material based on an epoxy resin matrix reinforced with fiberglass, suitable for high-pressure gas pipelines.

To simulate the phenomena causing pipeline damage, initial-boundary conditions closely resembling real-life scenarios were applied in the models, utilizing records and failure reports from gas distribution networks. In the selected cases, the key factors influencing failures were the strength parameters and quality of the materials used for pipeline construction, as well as the pipeline's foundation – specifically, its placement on potential landslides or subsidence areas, which significantly affect the extent of the resulting damage.

2. Fundamentals of simulation

Numerical analyses were conducted using the Finite Element Method in the ANSYS system [12]. The FEM method is a numerical approximation technique used to solve partial differential equations, which serve as the mathematical model for solving the given engineering problem. FEM is one of the discretization methods for continuous geometric systems, dividing the body into a finite number of subdomains. The main idea of FEM is to model even highly complex structures by representing them with geometrically simple components, including accounting for discontinuities.

The method involves dividing the continuous geometric model into finite elements interconnected at nodes, resulting in a discrete geometric model. This discretization transforms a system with an infinite number of degrees of freedom into one with a finite number of degrees of freedom. FEM's most significant advantage is its ability to replace an analytical problem, expressed through differential equations, with an algebraic one. The method approximates displacement fields, stress fields, or both within each finite element.

FEM can be used for both static and dynamic analyses. It allows for the evaluation of actual geometries of slopes or subsidence areas and supports advanced constitutive models for granular materials. One of the most commonly used soil constitutive models is the elastic-plastic model.

In addition to FEM, other numerical approaches are used for phenomena such as flows or large deformations, including methods such as Finite Volume Method – based on volume elements, Discrete Element Method and Meshless Methods e.g. Material Point Methods.

The numerical methods allow for tracking the phenomenon over time, monitoring the elements (their deformations, displacements and stresses) in successive time steps under changing boundary conditions or loads. As a result, it is possible to trace the entire process of pipeline damage development.

3. Numerical analysis overview

Simulations were performed for pipelines made of three different materials: polyethylene, composite, and steel. Each pipeline was modeled operating on a landslide. For simulation purposes, geometric models of the landslide were created, with the pipeline positioned at a depth of 0.8 m in soil in the middle part of slope. For each material, three separate pipeline models were created to account for differences in pipe geometry, including variations in diameter and wall thickness. Consequently, numerical simulations were conducted for three cases.

Landslide geometric model

The slope model had a height of 15 m and an angle of inclination of 31°, as shown in Figure 1.

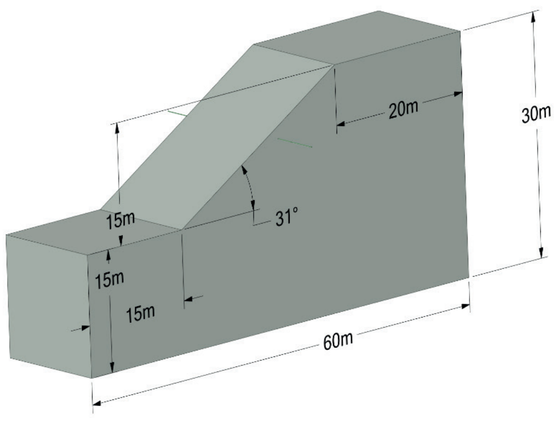

Fig. 1. Geometric model of the slope with a pipeline placed on it

The geometric models were discretized using hexahedral and tetrahedral meshes of varying sizes, depending on the analyzed model. The soil models required a coarser mesh due to their larger scale, while the pipeline was discretized with a dense hexahedral mesh for accuracy. Figure 2 presents the mesh of elements used for the analysis.

The material properties and dimensions of the pipes were based on actual operating pipeline segments. The dimensions and material properties of the composite pipe were obtained from a manufacturer's specifications, which promoted the pipe as safe for transporting 100% hydrogen. The material properties are presented in Table 1.

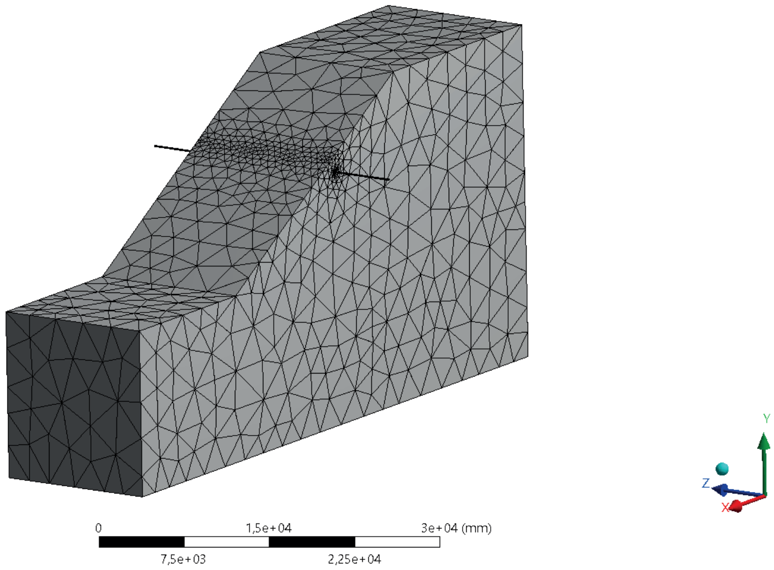

Fig. 2. Mesh of elements of landslide

Table 1. Summary of material parameters used in simulations

Property	Material		
	Composite	Polyethylene	Steel
Density [kg/m^3]	1 450	950	7 850
Thermal expansion coefficient [1/°C 0 · 10^6]	X: 2.2	230	–
	Y: 2.2		
	Z: 10		
Young's modulus [GPa]	X: 61.3	1.1	200
	Y: 61.3		
	Z: 6.9		
Poisson's ratio [–]	XY: 0.04	0.42	0.3
	YZ: 0.3		
	XZ: 0.3		
Shear modulus [GPa]	X: 3.3	0.39	76.9
	Y: 2.7		
	Z: 2.7		
Bulk modulus [GPa]	–	2.29	167
Specific heat [J/kg · °C]	–	2 300	434
Yield strength [MPa]	–	25	390
Tensile strength [MPa]	900	33	550
Isotropic thermal conductivity [W/m · °C]	–	0.28	–

Pipe parameters of materials and dimensions:

1. Polyethylene Pipe (PE100HD):
   – internal gas pressure: 3 bar,
   – external dimension of pipe: 110 mm,
   – internal dimension of pipe: 90 mm,
   – wall thickness: 10 mm;
2. Steel Pipe (L360):
   – internal gas pressure: 30 bar,
   – external dimension of pipe: 108 mm,
   – internal dimension of pipe: 100.4 mm,
   – wall thickness: 3.8 mm;
3. Composite Pipe (Fiberglass-Epoxy Matrix):
   – internal gas pressure: 30 bar,
   – external dimension of pipe: 115 mm,
   – internal dimension of pipe: 100 mm,
   – wall thickness: 7.5 mm.

The presented internal pressures of pipelines result from the operating pressures for these types of pipes. For polyethylene, internal pressures up to 3 bar are applied, while for other materials, significantly higher pressures, up to 30 bar, are used.

Numerical analysis of soil using constitutive models

Two primary soil constitutive models are commonly used for numerical analyses: the Coulomb-Mohr model and the Drucker–Prager model. For example, the yield condition for the Drucker–Prager model can be expressed as follows [13]:

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

The parameter m is defined as:

$$m = \frac{18\sin\phi}{9-\sin 2\phi} \quad (2)$$

The parameter $\boldsymbol{k}$ is expressed as:

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

where:
ϕ – internal friction angle,
c – cohesion,
p and q – stress tensors invariants, defined as:

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

where:

$$s_{ij} = \sigma_{ij} + \delta_{ij} \quad (5)$$

represents the deviatoric part of the stress tensor σ_{ij}.

In most works related to plasticity theory in equation (1), coefficients m and k are defined as follows in (6) and (7) when the Drucker–Prager cone is inscribed around the external edges of the Coulomb–Mohr pyramid:

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

$$k = \frac{6c\cos\phi}{3-\sin\phi} \quad (7)$$

Figure 3 provides a geometric interpretation of the principal stress space σ_1, σ_2, σ_3 on the plasticity surfaces in showing the Coulomb–Mohr pyramid and the Drucker–Prager cone.

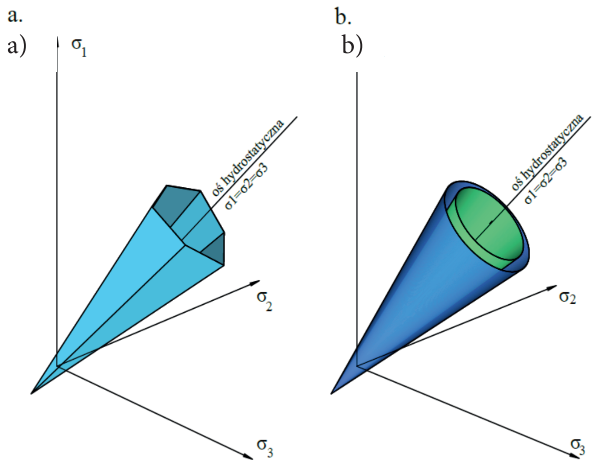

Fig. 3. Drucker–Prager Cone vs. Coulomb-Mohr Pyramid: a) Coulomb–Mohr pyramid; b) Drucker–Prager cones: blue (inscribed around external edges of the pyramid), green (circumscribed around internal edges of the pyramid)

The Drucker–Prager model was applied to the soil of the slope in this analysis, with the parameters outlined in Table 2.

Table 2. Soil parameters for simulation

Parameter	Value
Density ρ [kg/m³]	1 750
Young's modulus E [MPa]	50
Poisson's ratio ν [–]	0.29
Uniaxial compressive strength σ_c [MPa]	15
Uniaxial tensile strength σ_t [MPa]	5 × 10 – 5
Biaxial compressive strength σ_b [MPa]	20

Landslide-induced forces and pipeline-soil interaction

Based on the distribution of forces acting on the pipeline caused by landslide activity [14] and studies on pipe-soil interaction [15–19], the following assumptions were made:

- Forces modeled: Only gravitational forces causing landslide movement.
- Pipeline-soil interaction: Modeled as frictional contact, with a coefficient of friction of 0.6, consistent with design guidelines for pipelines embedded in soil.

This setup enabled a realistic simulation of landslide-induced stress and the resulting interaction between the soil and pipeline.

Boundary conditions and simulation setup

The analysis of prior research [20–21] significantly influenced the selection of the computational model. A slope model with an embedded pipeline was adopted, allowing for a realistic representation of pipeline-soil interaction. Additionally, various boundary conditions for the slope and pipeline end fixations were examined to assess their impact on pipeline behavior.

For simulation of free soil movement along a slope incline, the slope's boundaries were permitted to move freely in the direction of the incline, simulating natural landslide conditions, while the ends of the pipeline were fixed.

It is essential to note that the boundary conditions applied in the analysis, including contact surface size, load magnitudes, and directions, and contact configuration between the pipeline and soil, represent one example out of an infinite number of possible scenarios. These were modeled to approximate real-world conditions while allowing for predictable and interpretable results.

This detailed dataset formed the basis for simulating and analyzing the performance of the pipelines under landslide conditions.

4. Results

Figure 4 illustrates the deformation of the landslide along with the pipeline situated on it, highlighting the direction of soil mass movement during the landslide process. As the soil masses shift during the landslide, forces act on the pipeline located on the slope. These forces, determined by the nature of the soil movement, directly influence the deformation characteristics of the pipeline.

Due to the material properties (such as anisotropy), the figures below reveal varying deformation and stress patterns across the different types of materials used for the pipelines.

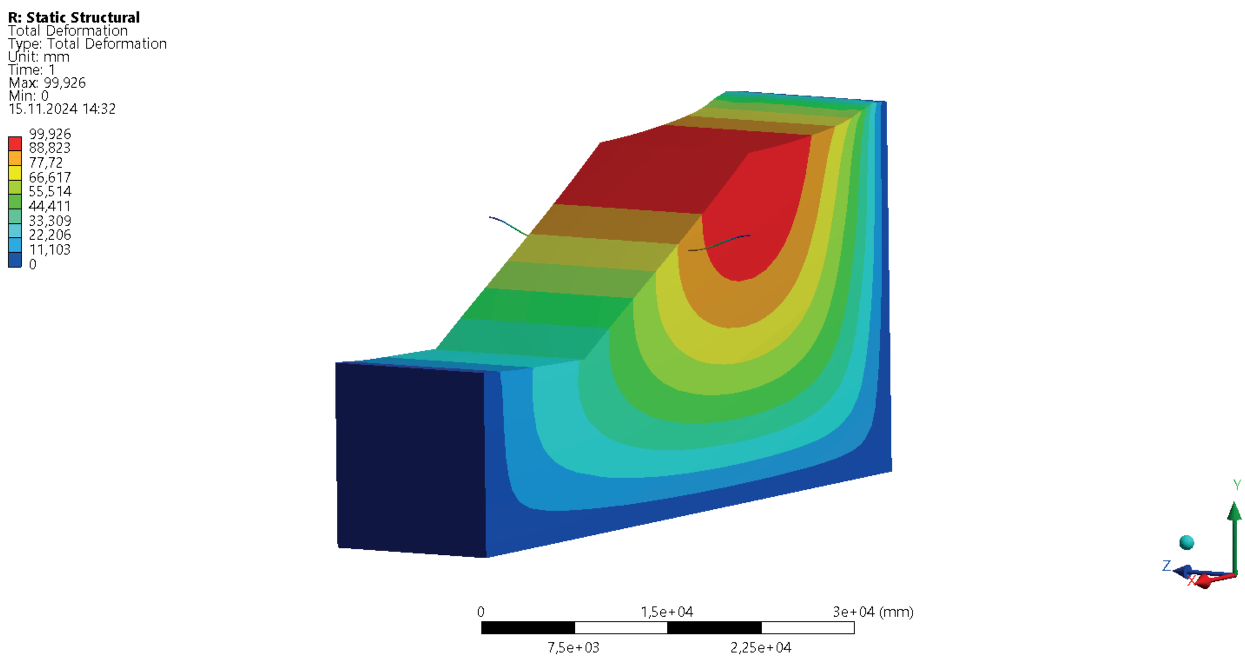

Fig. 4. The deformation profile of the landslide along with the embedded pipeline

Steel pipeline

Figure 5 presents the deformation profile of the steel gas pipeline at the maximum deformation recorded (at a specific time step), with a displacement of 111 mm. Figure 6 presents the stress distribution in the steel gas pipeline at the same moment in the simulation. The deformation visuals have been exaggerated to emphasize their characteristics.

Composite pipeline

Figure 7 presents the deformation profile of the composite gas pipeline at the maximum deformation recorded (at a specific time step), with a displacement of 99 mm. Figure 8 presents the stress distribution in the composite gas pipeline at the same moment in the simulation.

A uniform stress distribution is visible along the entire length of the pipe, with no distinct areas of higher intensity.

Polyethylene pipeline

Figure 9 presents the deformation profile of the polyethylene gas pipeline at the maximum deformation recorded (at a specific time step), with a displacement of 84 mm. Figure 10 presents the stress distribution in a polyethylene pipeline at the same moment in the simulation.

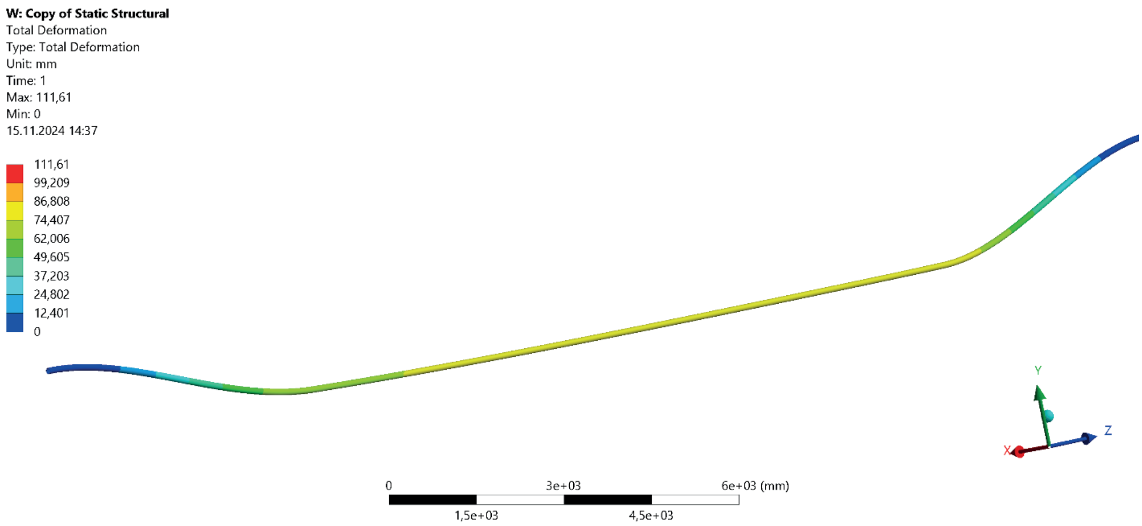

Fig. 5. The deformation profile of the steel pipeline

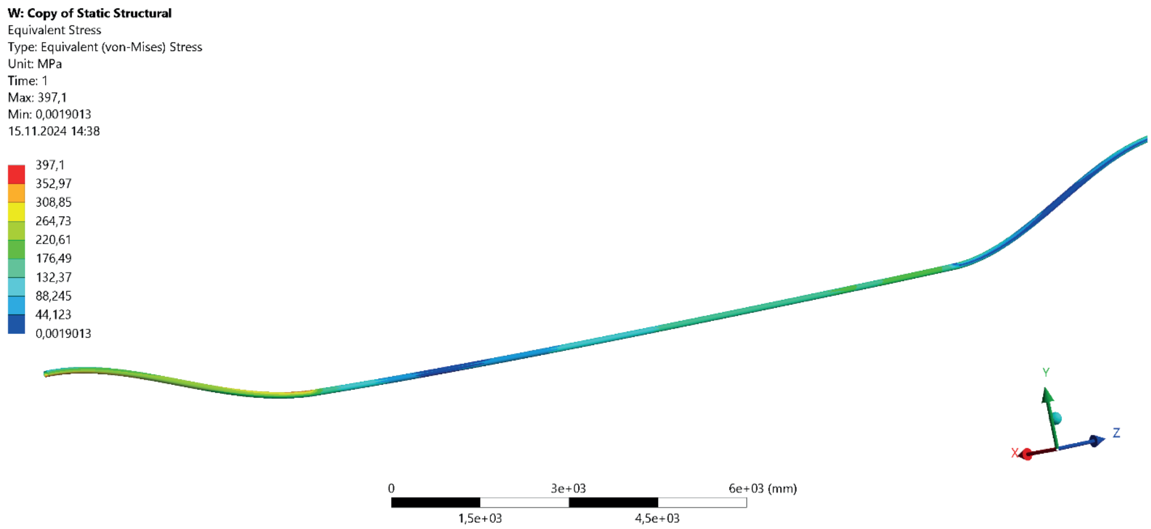

Fig. 6. Stress map of the steel pipeline

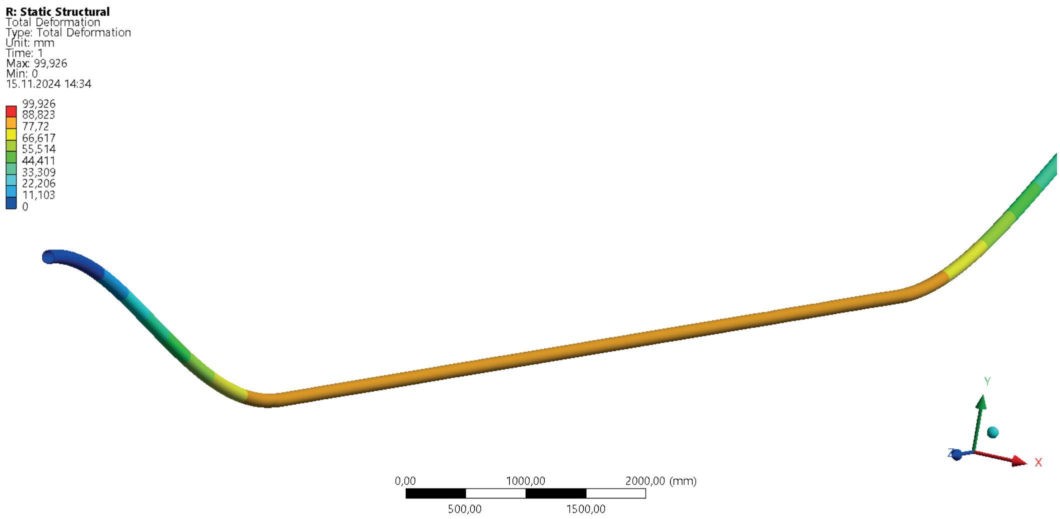

Fig. 7. The deformation profile of composite pipeline

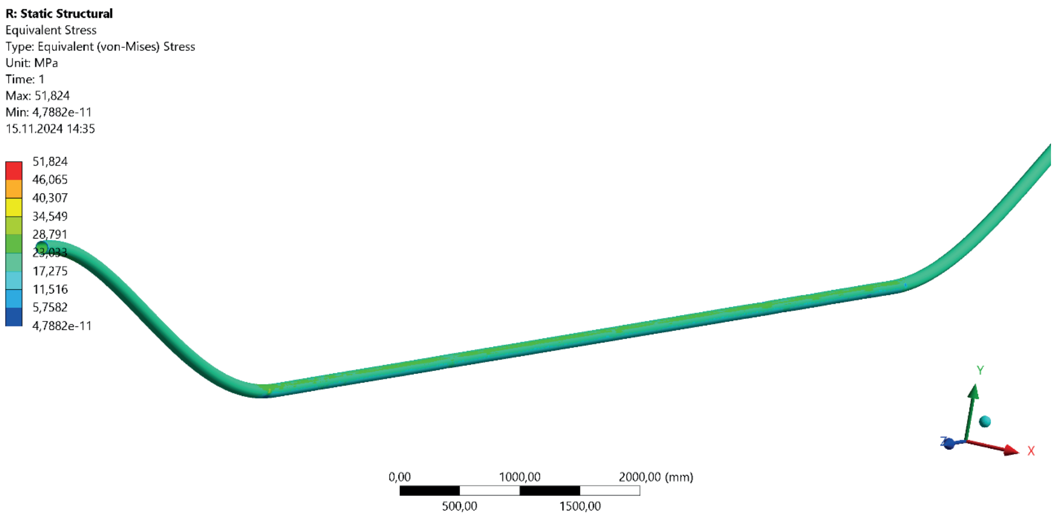

Fig. 8. Stress map of composite pipeline

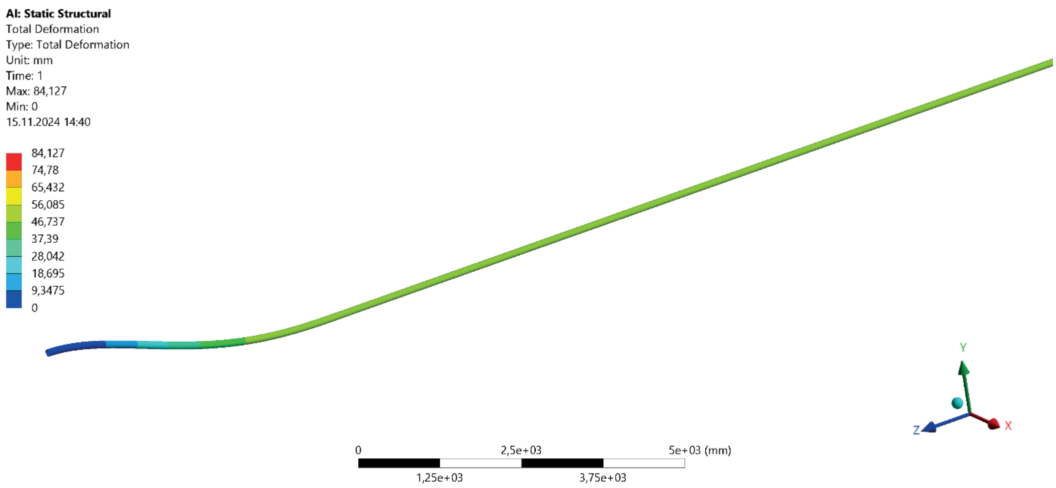

Fig. 9. The deformation profile of polyethylene pipeline

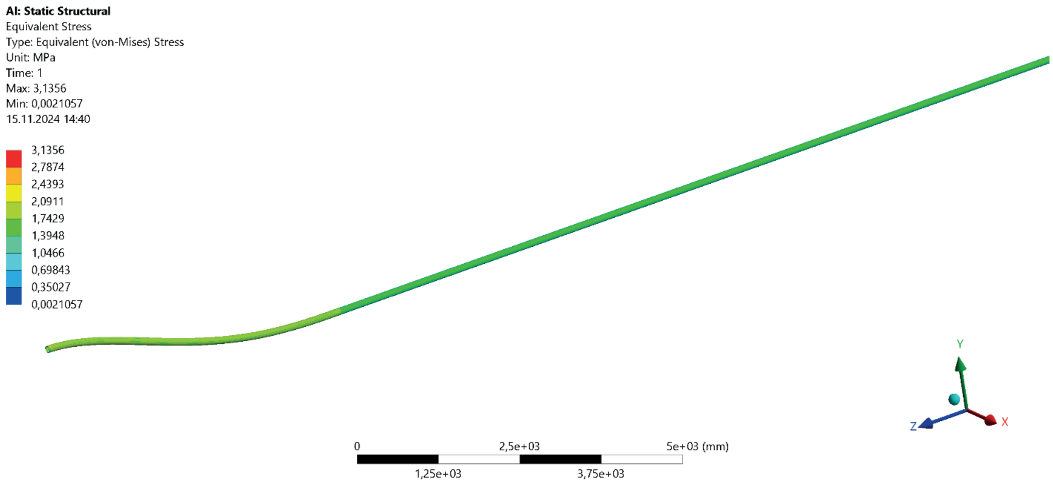

Fig. 10. Stress map of polyethylene pipeline

5. Conclusions

Analyzing the results obtained from the simulations of both deformations and stresses in the pipeline within the context of the research assumptions – namely, determining the behavior of different pipeline materials on landslides – it can be concluded that the most versatile material is the composite. This is evidenced by its relatively low stress values on the pipe at the edge of the landslide compared to steel pipes, although higher than polyethylene pipes. Polyethylene also exhibits greater susceptibility to deformation compared to steel, with maximum stress values of approximately 6 MPa, reflecting its flexibility. In steel pipes, the stress reaches around 300 MPa, while in composites, it is about 50 MPa. Comparing analyses of various pipeline materials under similar landslide conditions allows for a more accurate selection of pipeline materials in the design processes of gas transmission systems.

The comparative analysis of different pipeline materials under similar landslide conditions enables a more informed selection of materials during the design process of gas pipelines.

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Conflicts of Interest: The author of this paper declares no conflicts of interest.

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