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STRESS-STRAIN STATE OF UNDERGROUND PLASTIC PIPES

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Abstract. This article examines the features of the stress-strain state (SSS) of plastic pipes used in underground utilities. Factors of external load from the soil, as well as the characteristics of the pipe material (PE, PVC, etc.) are taken into account. Methods of numerical and experimental analysis of SSS are given, modeling results are presented, and recommendations for improving the reliability of systems are given..

1. Introduction. In recent decades, plastic pipes have become widely used in the construction of underground utilities, such as water supply, sewerage, drainage and gas distribution systems. The most common materials used to manufacture such pipes are polyethylene (PE), polypropylene (PP), polyvinyl chloride (PVC), and cross-linked polyethylene (PEX). These materials have a number of operational advantages over traditional metal and reinforced concrete analogues, including:
• high corrosion resistance;
• light weight and ease of transportation;
• low thermal conductivity;
• smooth inner surface that reduces hydraulic losses;
• resistance to aggressive chemical environments;
• durability (service life of 50 years or more with proper installation and operation).
However, despite all the advantages, plastic pipes in underground conditions are exposed to significant external loads, the main sources of which are:
• pressure from the soil's own weight and from overlying layers;
• temporary loads from vehicles (in case of shallow backfill);
• internal pressure of liquid or gas;
• soil movements and settlements (for example, in seismically active zones or during freezing).
Under the influence of these factors, a complex stress-strain state (SSS) occurs in the pipe body, characterized by bends, crushing, stretching or compression of the pipe walls. If permissible stresses are exceeded, cracks, loss of tightness, ovality and other defects may appear, leading to failure of the pipeline.
Considering the behavioral characteristics of plastics as time-dependent and nonlinear materials, it becomes especially important to conduct an accurate analysis of the stress-strain state of pipes under real operating conditions. The purpose of this work is a comprehensive study of the stress-strain state of underground plastic pipes using both analytical and numerical methods, as well as the formulation of recommendations for their reliable design and operation. The purpose of this article is to analyze the stress-strain state of plastic pipes during underground installation and to develop recommendations for their safe operation.
Theoretical bases of stress-strain state analysis. Stress-strain state (SSS) analysis of underground plastic pipes requires taking into account many factors, including pipe geometry, physical and mechanical properties of the material, soil type, installation conditions and the nature of the

external load. A special feature of plastic pipes is their ability to undergo significant elastic and creeping deformations, which distinguishes them from metal or reinforced concrete analogues.

Factors influencing the SSS of plastic pipes

The main factors determining the stress-strain state of plastic pipes include:

• Permanent loads from the mass of the soil: depend on the depth of backfill, density and moisture of the soil.
• Temporary loads: impact from vehicles, vibrations, dynamic loads.
• Internal pressure: in the case of pressure pipes, creates radial and tangential stresses.
• Creep of the material: over time, even under constant load, plastic pipes deform, which is important to take into account during long-term operation.

Mechanical properties and modeling of material behavior

Plastics used in pipeline systems are time-dependent (viscoelastic) materials. Their behavior can be described using models:

• Linear elasticity (in the early stages or under low loads);
• Viscoelasticity (Maxwell model, Kelvin-Voigt, etc.);
• Nonlinear plasticity (under large deformations or long-term loading);
• Creep and stress relaxation (important during long-term operation under constant load).

The use of mathematical models and numerical methods, such as the finite element method (FEM), allows us to obtain an accurate distribution of stresses and strains in the pipe wall, as well as to assess its stability and residual life.

Boundary conditions and loading schemes

When calculating the strength of pipes, it is necessary to take into account:

• Type of pipe support (rigid foundation, sand backfill, soft soil);
• Nature of interaction with the surrounding soil (models of "pipe-in-environment", interaction according to Winkler's law, etc.);
• Presence of protective backfill (improves stress redistribution);
• Consideration of the ring stiffness of the pipe (important for resistance to external pressure).

Such a comprehensive assessment allows identifying the most stressed areas and taking engineering measures to strengthen the structure**.**

Methods of stress-strain state analysis For precise determination of the stress-strain state (SSS) of underground plastic pipes, various methods of analysis are used, which can be divided into three groups: analytical, numerical and experimental. Each of them has its own advantages and limitations depending on the tasks, accuracy, available resources and operating conditions.

Analytical methods

Analytical methods are based on the classical equations of the theory of elasticity and strength of materials. In the simplest cases, the pipe is considered as a thin-walled cylindrical shell, which is subjected to uniform external pressure from the soil. The following approaches are used:

• The theory of a circular shell (Lowe, Floppa) - used to analyze the ring deformation of a pipe;
• The Burmeister and Spencer models - take into account the effect of soil as an elastic medium;
• The method of an elastic beam on an elastic foundation (Winkler model) - is especially effective in assessing longitudinal deformations.

Analytical methods are effective for preliminary calculations and engineering assessments, but they are limited in taking into account complex conditions, such as soil heterogeneity, the presence of joints, non-standard pipe geometry, etc.

Numerical methods

Numerical methods, especially the finite element method (FEM), are the main tool for accurate analysis of the stress-strain state of plastic pipes. They allow modeling complex real-life conditions, including:

• multilayer soil structure;
• three-dimensional deformations;
• nonlinear properties of the pipe material;
• contact interactions between the pipe and the surrounding soil;
• long-term creep and stress relaxation processes.

The following software packages are widely used for calculations:

• ANSYS – a universal FEM package with the ability to model thermomechanical processes;
• Abaqus – a powerful tool for nonlinear analysis and modeling of the behavior of viscoelastic materials;
• Lira-SAPR, SCAD, ZSoil – specialized solutions for construction and geotechnical problems.

Numerical modeling allows obtaining distributions of principal stresses, deformations, safety factors, and also modeling pipe behavior under various emergency load scenarios.

Experimental methods

Experimental methods are necessary both for verification of calculation models and for determining real characteristics of the stress-strain state in natural or laboratory conditions. Main approaches:

• Natural tests – laying an experimental section of the pipeline with subsequent deformation monitoring;
• Bench tests – measuring vertical and hoop deformations under controlled loading;
• Strain measurement – using strain gauges to measure local stresses;
• Optical and laser methods – digital photogrammetry, stereo photography method and video monitoring of displacements.

Experimental studies allow obtaining real data necessary for correct adjustment of numerical models and for assessing the reliability of pipeline systems in various geotechnical conditions.

4. Simulation results and analysis

Based on the numerical calculations and experimental data, an analysis of the stress-strain state of underground plastic pipes under various operating conditions was performed. The main attention was paid to the influence of external soil load, pipe burial depth, backfill characteristics and geometric parameters of the pipeline.

Influence of burial depth

Simulation showed that with an increase in the pipe burial depth, vertical stresses in the upper part of the pipe increase significantly. This leads to an increase in the ovality of the cross-section. For example, when moving from a backfill depth of 1 m to 3 m, the annular compression of the pipe can increase by 30–50% depending on the soil density and pipe rigidity.

However, with appropriate soil compaction around the pipe and the use of sand and gravel backfill, a pressure redistribution is observed, in which part of the vertical load goes to the side walls of the excavation, reducing the overall stress on the pipe.

Effect of pipe material characteristics

Comparison of polyethylene (PE80 and PE100), polypropylene and PVC pipes showed that:

• PE80 has the lowest rigidity, but high deformability and resistance to cyclic loads;
• PE100 has higher ring rigidity and better creep resistance;
• PVC has high rigidity, but is sensitive to impact loads and brittleness at low temperatures.

The choice of material should be made taking into account not only the depth and type of soil, but also the expected service life and the nature of the loads.

Effect of compaction and type of backfill

Analysis showed that the density of the backfill around the pipe significantly affects the stress-strain state. With poor compaction, increased ring deformations and increased stresses in the

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lower part of the pipe are observed. Conversely, with dense symmetrical backfill, the pipe absorbs loads more evenly, which reduces the likelihood of ovality and local damage.

The use of crushed stone, sand and gravel mixtures as backfill provides better conditions for load redistribution compared to clayey or dusty soils.

Main zones of stress and deformation

The highest stressed were the upper and lower points of the pipe annular section (the so-called "crown" and "bed"). It is at these points that reinforcement, control or a safety margin should be provided during design. In the lateral sections of the pipe, stresses are usually significantly lower.

It was also found that with uneven backfilling or the presence of lateral pressure (for example, when laying near a foundation), significant bending moments in the longitudinal direction can occur.

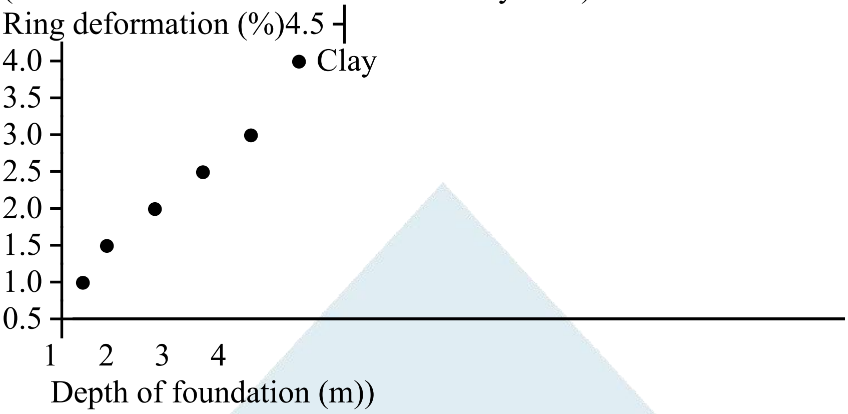
Verification of results

To confirm the accuracy of the modeling, full-scale tests were carried out on a test site. The obtained values of deformations and stresses coincided with the calculated ones within 10-15%, which confirms the adequacy of the applied numerical model and the admissibility of its use in engineering calculations.

Table 1. Effect of burial depth on pipe annular deformations (polyethylene PE100, D = 500 mm)

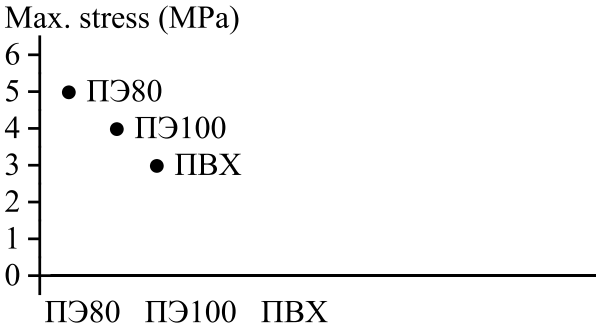
Depth of foundation, м	**Type of backfill**	**Modulus of elasticity of soil, MPa**	**Ring deformation, %**	**Maximum stress, MPa**
1,0	Medium density sand	25	1,1	3,5
2,0	Medium density sand	25	1,9	5,1
3,0	Medium density sand	25	2,8	6,7
3,0	The clay is wet	10	4,2	8,4

Graph 1. Dependence of ring deformation on the depth of embedment
(for the same backfill – medium density sand)



Graph 2. Comparison of maximum stresses for different pipe materials at a burial depth of 2 m

Материал трубы	Модуль упругости, МПа	Максимальное напряжение, МПа
ПЭ80	800	5,8
ПЭ100	1000	5,1
ПВХ	3000	4,7



Recommendations

The type and moisture content of the soil should be taken into account when designing the installation depth;

Quality control of backfill and compaction is mandatory;

To reduce deformations, it is recommended to use pipes with increased ring stiffness;

It is important to take into account the climatic features of the region when choosing the pipe material;

Periodic monitoring of the pipe condition using non-destructive testing.

Conclusion. In this paper, a comprehensive analysis of the stress-strain state (SSS) of underground plastic pipes used in utility networks for various purposes - water supply, sewerage, gas distribution was carried out. Based on theoretical and numerical methods, as well as experimental data, the following main conclusions can be formulated:

General conclusions

• Plastic pipes (PE80, PE100, PP, PVC, etc.) have high corrosion resistance, flexibility, low weight and ease of installation, which makes them preferable in the construction of underground networks.

• One of the key factors for reliable operation is the analysis of the stress-strain state of the pipe under external load, especially from the weight of the soil, vehicles and possible dynamic effects.

• The main zones of dangerous stresses are the "crown" (upper part of the pipe) and the "bed" (lower part), where the maximum deformations under ring compression are concentrated. These areas require enhanced design control.

Effect of operating parameters

• The depth of installation has a direct effect on the SSS of the pipe: an increase in depth leads to an increase in ring deformations and stresses. At the same time, a competent choice and compaction of the backfill allows you to redistribute the loads and significantly reduce their impact on the structure.

• The pipe material plays a decisive role. PE100 pipes showed better results in terms of a combination of strength, flexibility and creep resistance, compared to PE80 and PVC.

• The rigidity and type of surrounding soil also significantly affect the behavior of the pipe. The most favorable conditions are created by using a well-compacted sand and gravel base.

Evaluation of analysis methods

• Analytical methods allow for a primary assessment of the stress-strain state under simplified assumptions, but do not take into account all the factors of real operation.

• Numerical methods (primarily the finite element method) have demonstrated high accuracy in modeling complex conditions. They allow for nonlinear properties of materials, heterogeneity of the medium, and boundary conditions.
• Experimental data obtained in laboratory and full-scale tests confirmed the reliability of the calculation models and also indicated the importance of taking into account factors that are difficult to formalize in numerical calculations (e.g., local compaction, uneven backfill).
Practical recommendations
• When designing underground pipelines made of plastic materials, it is necessary to take into account the complex effect of external loads and perform stress-strain state calculations using modern numerical methods.
• It is recommended to use pipes with increased ring stiffness and include in the design the minimum permissible values of ovality and stresses.
• During installation, ensure uniform compaction of the backfill around the perimeter of the pipe and avoid asymmetric loads, especially near rigid structures (foundations, walls, etc.).
• Quality control of soil laying and compaction should be a mandatory stage of construction supervision.
Final remark. Increasing the reliability of underground pipeline systems is possible only by integrating an engineering approach based on accurate calculations of the stress-strain state with high-quality construction and installation work. Promising areas for further research are:
• modeling taking into account long-term processes (creep, relaxation);
• use of composite and reinforced materials;
• development of intelligent systems for monitoring the condition of pipes in real time.

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