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Theoretical And Computational Assessment Of The Stress–Strain Behavior Of Underground Plastic Pipes Under Internal Hydraulic Pressure And External Soil Loads

Radjabov Mansur Rustamovich

Associate Professor, Department of General Technical Sciences Karshi State Technical University, Uzbekistan

Abstract: Orthopedic dental treatment is now widespread. This article presents a theoretical and computational analysis of the stress–strain behavior of underground plastic pipes (HDPE, PVC-U, GRP) subjected to internal hydraulic pressure and external soil loads. Classical models of internal pressure (Lamé, Barlow) and soil load theories (Marston–Spangler, Iowa, Terzaghi, Winkler–Pasternak) are reviewed. Special emphasis is placed on the pipe–soil interaction, including contact mechanics, lateral soil reactions, the soil-arching effect, and time-dependent deformation mechanisms su ch as creep and stress relaxation. Modern numerical approaches—linear and nonlinear analysis, viscoelastic modeling (Prony series, Burgers model), and 3D FEM simulations with contact—are discussed. The results contribute to improved assessment and design of underground pressure and non-pressure plastic pipeline systems.

Keywords: HDPE, PVC-U, GRP, internal pressure, soil load, pipe–soil interaction, stress–strain behavior, viscoelasticity, FEM.

Introduction: Underground plastic pipes—pressure and non-pressure pipeline systems made of HDPE, PVC-U and GRP materials—are among the most common structural elements used in water supply, irrigation, sewerage, gas distribution, chemical industry, and oil-gas infrastructure. Their wide application is primarily associated with corrosion resistance, ease of installation, low density, flexibility under large deformations, and a service life of up to 50–100 years during operation [1, p.12].

At the same time, placing plastic pipes underground exposes them to two main groups of loads: **internal hydraulic pressure,** i.e., pressure generated by the flow of water, gas, or oil; and **external soil loads,** which include overburden weight, lateral compression, burial depth, and time-dependent deformations of the surrounding soil [4, p.56].

Although scientific literature separately and extensively studies the Lamé hoop stresses generated by internal pressure, as well as external loads through the Iowa and Marston–Spangler theories, in real operating conditions these loads act simultaneously. As a result, the pipe–soil system exhibits complex and nonlinear mechanical behavior [7, p.41].

The viscoelastic nature of HDPE pipes—i.e., the gradual increase in deformation over time (creep) and the reduction of stress (stress relaxation)—reduces the effective elastic modulus of the pipe wall under internal pressure and increases lateral deformations under external soil loading [5, p.22]. Therefore, the traditional linear elastic model often fails to provide sufficient accuracy. Recent studies in **Polymer Testing** and **Engineering Structures** journals emphasize the importance of using the Prony-series viscoelastic model, the Burgers model, and nonlinear FEM approaches specifically for HDPE pipes [9, pp.88–90].

egarding external soil load theories, the Spangler–Iowa model demonstrates that pipe flexibility depends on soil stiffness; however, it does not fully account for factors such as contact conditions, soil-arching effect, bedding angle, and the partial load-bearing capacity of the soil [12, p.103]. Modern evaluations of the Marston–Spangler theory indicate that the lateral soil-arching effect becomes more pronounced with increasing burial depth, playing a particularly important role for flexible polyethylene pipes [14, p.57].

Furthermore, in the soil–pipe interaction, the contact mechanism—including normal pressure, tangential friction, bedding reaction, and Pasternak shear stiffness—is one of the primary sources of pipe deformation. Studies by Fattah et al. in the Soils and Foundations journal report that the surrounding soil layers transfer a portion of the load laterally during deformation (arching), which can reduce the maximum hoop stresses in the pipe by 10–25% [15, p.64].

On the other hand, when internal pressure is combined with external soil load, cross-sectional ovalization, geometric distortions, and stability loss may occur. Although GRP materials possess high compressive stiffness, PVC-U pipes are more sensitive to external loading because of their lower rigidity [11, p.51]. In high-pressure HDPE pipes, nonlinear shape deformation intensifies due to internal-pressure-induced wall stretching, which requires the application of Riks or Arc-length algorithms in FEM simulations [19, p.92].

Consequently, determining the stress–strain state of a pipe under the combined action of internal hydraulic pressure and external soil loading requires consideration of multiple interacting factors such as viscoelastic behavior, contact mechanics, burial depth, soil modulus, loading history, pressure pulsation, and nonlinear geometric deformation. This necessitates the use of modern computational techniques—particularly 3D nonlinear FEM, contact analysis, creep–relaxation models, and fully coupled soil–pipe interaction approaches [20, p.37].

Therefore, this study focuses specifically on analyzing the stress–strain behavior of HDPE, PVC-U, and GRP pipes under combined internal pressure and external soil load using theoretical and computational models. This approach provides a more accurate foundation for determining safety factors, evaluating deformation limits, and improving the operational reliability of underground pipeline systems.

METHODOLOGY

In underground pressure pipelines, internal hydraulic pressure generates three main stress components in the pipe wall: radial stress σ_r, circumferential (hoop) stress σθ, and longitudinal stress σz. These stresses depend on the pipe material, wall thickness, internal pressure amplitude, and temperature variations; in polymer pipes, they change significantly over time due to viscoelastic behavior [1, p.14].

To analyze the internal pressure effect in thick-walled pipes, Lamé equations are used. This approach is widely applied as an initial estimation method for HDPE, PVC-U, and GRP pipes [4, p.57].

The Lamé formula is expressed as follows:

$$\sigma_r = \frac{p_i r_i^2 - p_o r_o^2}{r_o^2 - r_i^2} - \frac{(p_i - p_o) r_i^2 r_o^2}{(r_o^2 - r_i^2) r^2}$$

$$\sigma_\theta = \frac{p_i r_i^2 - p_o r_o^2}{r_o^2 - r_i^2} + \frac{(p_i - p_o) r_i^2 r_o^2}{(r_o^2 - r_i^2) r^2}$$

Here, p_i is the internal pressure; r_i and r_o are the inner and outer radii of the pipe; σθ is the circumferential (hoop) stress, which is the most critical component responsible for pipe bursting; and σ_r is the radial stress.

The dominance of hoop stress over radial stress explains why burst failure in HDPE pipes is primarily governed by σ_θ [5, p.41]. In GRP pipes, however, anisotropy caused by fiber orientation makes the $\sigma\theta$–σ_r distribution highly sensitive to the material lay-up and fiber direction.

FEM simulations also yield results very close to the Lamé stress distribution; however, in polymer pipes, a significant reduction of $\sigma\theta$ over time (stress relaxation) is observed, demonstrating the limitations of Lamé equations for viscoelastic materials [9, p.94].

If the pipe wall is relatively thin ($t \le D/20$), the effect of internal pressure can be estimated using the simplified Barlow formula [7, p.51]:

$$\sigma_\theta = \frac{p_i D}{2t}$$

This formula is also widely used in determining the design pressure of PVC-U and GRP pipes. The Barlow equation is one of the primary design approaches in standards that require high safety factors—such as ISO 4427 and ASTM F714 [11, p.12].

Limitations: it does not account for viscoelasticity; it neglects geometric distortions (ovalization); and it does not include the interaction with external loads. Therefore, modern studies consider the Barlow formula applicable only for short-term evaluations [18, p.63].

In polymer pipes such as HDPE, the following time-dependent effects occur under internal pressure: creep → gradual increase in deformation; stress relaxation → reduction of stresses by up to 30–65%; time-dependent decrease of the elastic modulus.

These behaviors occur due to the time-dependent stretching of polymer molecular chains [9, p.88].

Prony-series model:

$$E(t) = E_\infty + \sum_{i=1}^{n} E_i e^{-t/\tau_i}$$

This model makes it possible to accurately determine the stiffness gradient across the pipe wall thickness under internal pressure.

Burgers model:

$$\epsilon(t) = \frac{\sigma}{E_1} + \frac{\sigma}{E_2}(1 - e^{-t/\eta_2}) + \frac{\sigma t}{\eta_1}$$

This model is the most suitable for representing the stress-relaxation phenomenon. Studies show that in HDPE pipes, the stress may decrease by 35–60% within 1000–5000 seconds [12, p.77]. Therefore, directly applying Lamé or Barlow formulas for evaluating internal pressure leads to inaccurate results.

Viscoelastic models are especially necessary for long-term pressure evaluations (up to 50 years) [19, p.92].

In oil–gas transportation and irrigation systems, pipelines often operate under cyclically varying pressure. This activates the fatigue mechanism, leading to: formation of micro-cracks; local reduction of wall thickness; increase in circumferential (hoop) stress; SCG — slow crack growth [14, p.59].

In HDPE materials, this process is directly related to pressure cycle frequency, and the risk of failure significantly increases in the range of 10^5–10^7 cycles [15, p.64].

Therefore, to assess pulsating pressure effects, the Miner–Palmgren rule, the Paris crack-growth equation, or FEM-based fatigue modules are used.

The influence of temperature on internal pressure is also significant: as temperature increases, the elastic modulus of HDPE decreases by 20–40% [13, p.48], PVC-U may become brittle, and GRP responses depend on the resin component of the laminate. Thus, temperature–pressure coupling must be considered when evaluating thermally loaded pipes.

Underground plastic pipes are subjected to external loads such as soil mass pressure, lateral compression, burial depth, traffic loads, and time-dependent soil deformations (settlement, soil creep). The distribution of external loads is closely related to pipe stiffness, trench geometry, bedding material, soil type, and degree of compaction [4, p.58].

Since polymer pipes (especially HDPE) are more flexible compared to metal pipes, external pressure may change their cross-sectional shape, increase ovalization, and create complex mechanical processes in the soil–pipe interaction zone [7, p.41].

Therefore, several theoretical approaches have been developed to evaluate external soil loads. The most widely used ones are described below.

The works of Marston (1930) and Spangler (1947) are among the earliest fundamental theories for calculating soil loads on buried pipes, and they are still widely used in evaluating PVC-U and HDPE pipelines [11, p.51]. The main principles of the model are: trench walls carry a portion of the soil load; vertical pressure varies with soil density and burial depth; the bedding angle directly affects load distribution.

The Marston–Spangler load is expressed as follows:

$$W = C_d \gamma H B$$

Here, C_d is the load coefficient, γ is the unit weight of the soil, H is the burial depth, and B is the trench width. This model shows that due to the arching effect, the effective load on flexible plastic pipes may be significantly reduced [15, p.64].

The Iowa model is the most widely used method for determining the deformation of flexible pipes. This model is based on the equilibrium between the lateral deformation of the pipe, the external soil pressure, and the stiffness of the pipe wall [12, p.103].

General formula:

$$\Delta x = \frac{KW}{0.149E' + 0.061E_t}$$

Here, Δx is the pipe deformation (ovalization), K is a coefficient dependent on trench geometry, W is the applied load, **E'** is the soil modulus (modulus of soil reaction), and E⍰ is the elastic modulus of the pipe wall.

The Iowa model is highly effective for HDPE pipes because the time-dependent reduction of elastic modulus (creep) increases deformation [9, p.95].

The Terzaghi model describes the bedding reaction of the soil, which provides resistance against the upward displacement of the pipe. According to this model, the soil beneath the pipe behaves like a "single-layer spring" [14, p.57]:

$$q = k_s \cdot y$$

Here, k⍰ is the vertical subgrade reaction (Winkler constant), and **y** is the settlement (downward displacement of the pipe). This model clearly represents the support mechanism beneath the pipe. As the compaction of the bedding material increases, k⍰ rises, and the pipe deformation decreases [17, p.44].

The Winkler model considers soil as a vertical system of independent springs only. However, real soil exhibits lateral interaction during pipe installation. Therefore, the Pasternak model introduces an additional shear layer (a horizontal connecting layer) [18, p.63]:

$$q = k_w y - k_g \frac{d^2 y}{dx^2}$$

Here, k_w is the Winkler vertical stiffness, and k_g is the Pasternak shear-coupling stiffness.

The Pasternak model provides especially accurate results for PVC-U and GRP pipes because these materials have higher wall stiffness and stronger interaction with the surrounding soil [11, p.53].

Soil arching is the process in which the trench walls carry part of the soil pressure, thereby reducing the load transferred to the pipe [15, p.64]. This effect becomes more pronounced in dense soils, narrow trenches, and stiff bedding conditions. FEM analyses also show that soil arching can reduce the maximum hoop stresses in the pipe wall by **10–25%** [19, p.92].

External soil pressure causes the pipe cross-section to become oval. This phenomenon is more prominent in flexible HDPE pipes [7, p.41]. If the external pressure exceeds the internal pressure, the pipe may experience geometric distortions, loss of stability (buckling), and cross-sectional collapse. Because GRP pipes have a higher compressive modulus, their buckling risk is lower, whereas PVC-U pipes exhibit a comparatively higher risk [11, p.51].

The physical–mechanical properties of soil vary over time due to factors such as moisture changes, density variations, settlement, and freeze–thaw cycles. Therefore, uncertainty in soil behavior is one of the greatest sources of error when evaluating external loads [20, p.37].

Soil–Pipe Interaction

Accurate evaluation of external loads on underground plastic pipes requires treating the pipe not as an isolated structural element but as part of an **integrated soil–pipe system,** which incorporates the mechanical response of the surrounding soil. The soil and pipe do not behave independently—they deform together in a coupled manner. Therefore, **soil–pipe interaction** is one of the most important scientific and engineering aspects of underground pipeline systems [12, p.104].

The following factors play a determining role in soil–pipe interaction: normal and tangential forces in the contact zone; the stiffness ratio between pipe and soil; trench geometry, bedding material, and degree of compaction; time-dependent soil deformations (consolidation, settlement); viscoelastic behavior of the pipe wall [4, p.59].

Below are the main components of soil–pipe interaction.

1. **Normal pressure (p⍰).** This is the pressure acting perpendicular to the pipe wall. As the soil mass increases, **p⍰** also increases. Normal pressure directly controls the degree of ovalization of the pipe cross-section [7, p.42].

2. Tangential friction (τ). This is the resistance to relative sliding between the soil and the pipe. The friction coefficient **μ** strongly affects the stability of the soil–pipe interface.

3. **Contact stiffness (k⍰ and k⍰).** These values characterize the soil's ability to provide reactive resistance (soil reaction). In the Winkler model, only the vertical stiffness **k⍰** is considered, whereas in the Pasternak model an additional lateral stiffness **k⍰** is included [18, p.63]. Higher contact stiffness reduces

pipe deformation, while lower stiffness increases ovalization.

Soil arching is the ability of soil to transfer its self-weight laterally to the trench walls instead of transmitting it vertically onto the pipe. This effect becomes stronger under the following conditions: narrow trenches; dense soils; and high bedding stiffness [15, p.64].

FEM studies show that soil arching can reduce the maximum hoop stress in the pipe wall by 10–25% [19, p.92]. This effect is particularly important for HDPE pipes because flexible pipes deform together with the surrounding soil.

Under external soil loading, the pipe cross-section shifts from a perfect circle to an oval shape: the crown (top) → moves downward, the sidewalls → expand outward, the invert (bottom) → moves upward [11, p.51].

Ovalization is sensitive to the following factors: elastic modulus of the pipe (HDPE < PVC-U < GRP); stiffness of the bedding material; soil compaction level; burial depth; time-dependent soil deformation (soil creep). Although HDPE pipes exhibit relatively large short-term deformation, long-term viscoelastic effects lead to steady-state ovalization over time [9, p.95].

Lateral soil pressure around the pipe also generates longitudinal stresses. These arise due to: compression of trench walls, temperature gradients (thermal expansion of the pipe), differential soil settlement [14, p.58]. When the pipe stiffness is lower than the stiffness of the soil (as in HDPE pipes), axial deformations become more significant. In PVC-U pipes, such deformations are smaller due to the higher modulus.

The bedding material beneath the pipe (sand, gravel, crushed stone) plays a decisive role in soil–pipe interaction [17, p.45]. The bedding angle is the angle of the supporting soil layer that is in contact with the bottom of the pipe.

Typical ranges are: 90° — minimal support, 120–150° — standard bedding, 180° — full support (optimal), < 90° — critical zone (buckling probability increases).

As the bedding angle increases, the pipe's resistance to external pressure improves significantly.

Time-dependent soil deformation (settlement, soil creep). Soil settlement and time-dependent deformation can substantially modify the soil–pipe system over the long term: the bedding settles, the pipe shifts downward, ovalization increases, contact pressure redistributes [20, p.38].

These processes are typically evaluated using long-term FEM analyses.

In highly viscoelastic pipes such as HDPE, the dynamic nature of soil–pipe interaction is characterized by the pipe gradually "adapting" to the surrounding soil over time. That is: initial deformation increases; stress relaxation reduces internal stresses; and, together with the soil reaction, the system reaches a new equilibrium. Therefore, HDPE pipes are classified as **flexible pipes**, whereas PVC-U and GRP pipes belong to the category of **stiff pipes** [5, p.43]. As a result, the interaction mechanism is strongly dependent on the pipe material.

In modern computational studies, soil–pipe interaction is modeled using the following **contact formulations:** Penalty contact, Augmented Lagrangian, Coulomb friction law, Hard contact.

Nonlinear FEM models enable the evaluation of complex mechanical processes in the soil–pipe system, such as geometric distortions, sliding/friction in the contact zone, viscoelastic effects, differential settlement, and loss of stability [19, p.92].

Internal Pressure + External Soil Pressure: Combined Loading Regime

In underground pipelines, internal hydraulic pressure and external soil load act simultaneously. Their combined effect creates a complex stress–strain state in the pipe wall. The key phenomenon is that **internal pressure tends to stretch and expand the pipe**, while **external soil pressure tends to compress it**. As a result, the mechanical response is not the sum of two independent stress states but an **integrated and coupled stress field** [7, p.41].

The following stresses develop in the pipe wall simultaneously:

1. Hoop stress (σ_θ). Generated by internal pressure. This is the dominant stress component governing pipe burst failure.

2. Radial stress (σ_r). Internal pressure → outward radial expansion;
external soil pressure → inward radial compression.

3. Longitudinal stress (σ_z). Associated with temperature variations, differential soil settlement, and the tensile effect of internal pressure [11, p.53].

Because of the interaction among these stress components, stresses do **not** combine linearly—this nonlinearity is especially significant in polymer pipes [12, p.104].

Geometric Effects in Combined Loading

External soil pressure compresses the pipe, while internal pressure expands it. Under combined loading: Internal pressure → restores circularity of the pipe (re-rounding effect), External soil pressure → increases ovalization.

This behavior is described in both the Iowa model and FEM analyses [15, p.64].

As a result, the following mechanical processes occur in the pipe: the cross-section shifts from a perfect circle to a dynamic shape; the crown moves downward; he sidewalls expand outward; the invert rises; the contact pressure redistributes around the pipe.

In metallic pipes, which behave approximately elastically, the internal and external stresses can be combined by simple superposition. However, in plastic pipes (HDPE, PVC-U, GRP): geometric nonlinearity, viscoelastic behavior, contact and friction effects, soil uncertainty make simple stress superposition invalid [18, p.63]. Therefore, combined loading requires a **dedicated nonlinear FEM analysis.**

When the external soil pressure exceeds the internal pressure, the pipe may experience large deformation and ovalization, eventually leading to **buckling (loss of stability).** This is especially common in: deeply buried pipes, poorly compacted bedding conditions, PVC-U and stiff GRP pipes, and in cases where external loads are high [14, p.58].

The stabilizing role of internal pressure is a very important scientific principle: **Internal pressure tensions the pipe → reducing the risk of external buckling.** This phenomenon is called **internal pressure stiffening.** Studies have shown that an internal pressure of **0.3–0.5 MPa** can increase the external buckling load by **20–40%** [19, p.92]. Therefore, internal pressure can act as a "protector" for the pipe in certain conditions.

The degree of ovalization (ΔD/D) under combined loading behaves as follows: Low internal pressure → ovalization increases; Moderate internal pressure → ovalization stabilizes; High internal pressure → ovalization decreases (re-rounding); Very high internal pressure → burst failure risk increases. The re-rounding effect is strongest in HDPE pipes [5, p.43].

Modern Approaches for Combined Load Simulation

1. Nonlinear geometric analysis (NLGEOM) — accounts for cross-sectional shape changes.

2. Material nonlinearity (viscoelastic HDPE model) — using Prony-series or Burgers model.

3. **Contact analysis** — using Penalty or Augmented Lagrangian methods.

4. Step-by-step loading:

a) soil loading →

b) internal pressure →

c) temperature gradient →

d) long-term creep analysis [20, p.38].

In this approach, the soil–pipe system is treated as a full **3D FEM model.**

Scientific Conclusions from Combined Loading

Combined loading demonstrates that: internal pressure inflates the pipe, external soil pressure compresses it, stresses do not superpose linearly, ovalization changes in a complex manner, buckling risk may increase or decrease depending on conditions, only FEM provides an accurate and complete analysis.

EXPERIMENTAL RESEARCH ANALYSIS

Accurate assessment of the stress–strain behavior of underground HDPE, PVC-U, and GRP pipes requires not only theoretical models but also laboratory and field tests close to real operating conditions. Over the past 20–30 years, research has shown that **viscoelasticity, creep, stress relaxation, and ovalization** have a strong long-term influence on HDPE pipe performance [12, p.105]. Below are the main experimental methods and the scientific results obtained from them.

Ring Test (ASTM D2412) – Determining Pipe Flexibility

The ring stiffness test is the most widely used method for evaluating pipe deformation under external loading. It helps determine: ring stiffness (SN), lateral elasticity of the pipe wall, degree of ovalization (ΔD/D), critical deformation limit. In the test, a pipe section is compressed between two plates and the force–deformation curve is recorded. In HDPE pipes, linear elasticity is maintained up to **3–5% deformation,** after which a transition to the viscoelastic zone begins [15, p.67]. GRP pipes maintain linearity for a longer range (up to **7–10%**) due to their high stiffness [11, p.54]. PVC-U pipes exhibit medium stiffness, with deformation increasing more rapidly [7, p.43].

Creep Test — Measuring Deformation Growth Over Time

Creep tests are among the most important experiments for studying the long-term deformation behavior of HDPE.

Research shows that with **1–2% initial deformation**, an additional **0.1–0.3% deformation growth** is observed over **10–30 minutes** [9, p.95]. This means that even under constant load, the ovalization of HDPE pipe cross-sections continues to increase over time due to soil pressure. Creep cannot be directly accounted for by Barlow or Lamé formulas, which demonstrates the necessity of extending theoretical models with viscoelastic corrections [18, p.63].

In **stress-relaxation tests,** the deformation applied to the pipe material is held constant, and the decrease in stress over time is recorded. In HDPE materials, scientific studies report that over **1000–5000 seconds,** the stress may decrease by **30–65%** [19, p.92]. This phenomenon leads to a reduction in pipe-wall stiffness under internal pressure and causes long-term stress redistribution. In PVC-U and GRP materials, stress relaxation is significantly smaller because these materials are either anisotropic (GRP) or brittle-elastic (PVC-U) [14, p.58].

Hydrostatic Pressure Test (HPT) – Long-Term Internal Pressure Stability Test

The HPT test, defined in ISO 4427 and ASTM F714 standards, is used to evaluate pipe performance under long-term internal pressure. For HDPE pipes, the standard test conditions are: at **20°C**: 12.4 MPa stress **→ 100 hours**, at **40°C**: 8.0 MPa stress → **165 hours,** at **80°C**: 5.0 MPa stress → **1000 hours** [11, p.53].

HPT results help identify creep in the pipe wall, reduction of hoop stress ($\sigma\theta$), local stretching, and **slow crack growth (SCG)** under internal pressure.

Soil-Box Test – Simulating Underground Conditions in the Laboratory

In this test, the pipe is placed inside a special box filled with a uniform type of soil, and the system is tested under: different soil compaction levels, various burial depths, different bedding angles, additional surface loads [20, p.39].

Results show: **HDPE pipe:** – 0.5–1.0% ovalization → normal range, – 3–5% → borderline, – >5% → critical zone. **GRP pipe:** – 0.1–0.2% ovalization → extremely small (very stiff), – ovalization rate very low. **PVC-U pipe**: – 0.3–0.6% ovalization, – relatively stable, but with higher crack risk due to brittleness.

These tests help verify the accuracy of the **Iowa model** in real conditions.

Comparison with Steel Pipes

Early-generation research compared HDPE pipes with steel pipes. Results showed: HDPE pipes can withstand **±5% deformation** (plastic behavior), steel pipes experience high stress even at **±1% deformation** (elastic behavior).

This became the fundamental basis for classifying HDPE pipes as **flexible pipes** in soil–pipe systems [11, p.54].

Validation of FEM Models

Many scientific papers validate **3D contact FEM,** viscoelastic models, and nonlinear geometric analyses with experiments. When FEM results are compared with ring-test and soil-box test data: average deviation: **5–12%,** maximum deviation: **20%,** local wall stretching under internal pressure is captured much more accurately by FEM [18, p.63].

This proves that FEM is the most reliable approach for predicting combined loading behavior.

Overall Experimental Conclusions

Experiments show the following key facts for HDPE, PVC-U, and GRP pipes:

1. HDPE pipes: strong viscoelasticity, creep → deformation increases over time, stress relaxation → stress decreases, clear re-rounding effect, highly sensitive to external soil pressure.

2. PVC-U pipes: brittle-elastic behavior, small deformation but higher crack risk, very sensitive to internal pressure.

3. GRP pipes: highest stiffness, minimal ovalization, high stability under external loads.

Experimental results confirm theoretical models (Lamé, Iowa, Marston–Spangler) and FEM predictions, although viscoelastic behavior, contact zones, bedding materials, and soil uncertainties remain the primary sources of deviation for real pipelines [19, p.92].

CONCLUSION

The performance of underground HDPE, PVC-U, and GRP plastic pipes under internal hydraulic pressure and external soil loading is, from a mechanical standpoint, a complex, multi-factor, and highly uncertain system. The study demonstrates that the stress–strain state of a buried pipe is determined not by internal or external pressure alone, but by their **combined and continuously varying interaction.** As a result of this combined loading, wall stresses, ovalization levels, contact pressures, and long-term deformations change significantly.

This article presented a comparative analysis of classical theoretical models such as Lamé, Barlow, Marston–Spangler, Iowa, Terzaghi, and Winkler–Pasternak. Although these models are useful for initial assessments, they do not fully account for the **time-dependent mechanical behavior** of polymer pipes—namely creep and stress relaxation. For HDPE pipes in particular, strong viscoelasticity can cause initial theoretical estimates to differ significantly from long-term performance.

Experimental investigations (ring test, creep test, stress-relaxation test, hydrostatic pressure test, soil-box test) revealed the actual distribution of deformation and stresses in pipe walls. Results show that while HDPE pipes exhibit relatively small initial deformation, viscoelastic effects cause progressive deformation over time. GRP pipes, due to their high stiffness, exhibit minimal ovalization and remain more stable under external soil pressure.

Conversely, under combined loading (internal pressure + external soil pressure), stresses do **not** superpose linearly. Geometric changes, redistribution of contact pressures, and reductions in viscoelastic moduli create an **integrated and interdependent mechanical response**. This process becomes especially dynamic when the ratio of internal to external pressure changes. Internal pressure may "tighten" the pipe and reduce buckling risk, but excessive internal pressure increases the risk of burst failure.

Analysis of modern computational models shows that **3D nonlinear FEM** (including geometric nonlinearity, viscoelastic material modeling, and contact analysis) is the most reliable method for evaluating soil–pipe systems. The agreement of FEM predictions with experimental measurements in the range of **5–15%** confirms the practical accuracy of this approach. However, uncertainties in soil modulus, friction coefficient, viscoelastic parameters, and bedding angle can still cause significant variations in the results.

The main challenges identified in this research include: variability of soil parameters, complexity of the soil–pipe contact zone, insufficient study of cyclic internal pressure behavior, difficulty in determining precise viscoelastic parameters for HDPE, nonlinearity of the buckling process, and discrepancies among design standards. These challenges highlight the need for additional fundamental research and a broader experimental database to ensure accurate and reliable evaluation of plastic pipelines.

Overall, this article provides a **comprehensive analysis**—theoretical, experimental, and computational—of the mechanical behavior of plastic pipes under internal pressure and external soil loading. The findings offer an important scientific and practical foundation for improving the reliability of pipeline systems used in irrigation, water supply, oil–gas infrastructure, and underground utilities design and operation. The results also form a basis for developing new design methodologies, improved material models, and optimized installation technologies.

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