Centrifuge Apparatus for Simulating Axial Restraint in Pressurised Buried Pipe subjected to Traffic Loading

T. Elmrom, E.T. Bowman and M.A. Alfergani
School of Mechanical, Aerospace and Civil Engineering
University of Sheffield, Sheffield, The UK
telmrom@gmail.com, e.bowman@sheffield.ac.uk, maalfergani@gmail.com

ABSTRACT: This study presents an experimental apparatus for simulating axial restraint in buried High-Density Polyethylene (HDPE) pipe systems subjected to surface traffic loading within a centrifuge environment. In UK water networks, internal pressures typically range from 2–7 bar; instead of replicating full internal pressurisation, the apparatus applies controlled axial restraint representing the mechanical effects of such pressures under fixed boundaries. This enables investigation of pipe behaviour governed by Poisson effects and structural constraints, supported by analytical estimations of axial and hoop stresses. The apparatus was used to examine cyclic loading on HDPE pipes under restraint levels corresponding to service pressures of 1.5, 2.5, and 5 bar. Results show that increasing axial restraint substantially reduces bending moments and pipe deflection, especially in early cycles. These findings highlight the importance of axial boundary conditions and the usefulness of this approach for centrifuge studies on buried pipeline performance under repeated surface loading.

1 INTRODUCTION

Detecting leaks in buried pipelines is a growing challenge in the UK and globally due to declining water availability, ageing networks, and increasing demand. Leaks also pose public health risks by allowing contaminants to enter drinking water supplies (Muggleton et al.,2006). Much of the UK's infrastructure consists of 18th- and 19th-century cast iron mains that are highly susceptible to corrosion and fatigue (John et al., 2024), contributing to losses of about 2,700 ML/day in 2023–24 (Ofwat, 2024). This highlights the need for targeted asset renewal, improved materials, and advanced monitoring.

HDPE pipes provide enhanced corrosion resistance compared with metallic pipes but remain vulnerable to oxidative ageing, UV exposure, chemical attack, slow crack growth, and mechanical stresses from pressure fluctuations or ground movement, all of which progressively reduce structural capacity (Rathnayaka, 2016). Understanding how these stresses develop is essential.

When a PE pipe is pressurised and axially restrained, it experiences hoop stress that causes circumferential expansion, expressed as:

$$\sigma_\theta = \frac{P.D_i}{2t} \tag{1}$$

where P is the internal pressure, D_i is the internal diameter, and t is the wall thickness. Due to Poisson's effect, this lateral expansion generates a tendency for longitudinal contraction, expressed by:

$$\varepsilon_L = -\,\upsilon.\varepsilon_\theta \tag{2}$$

with v representing Poisson's ratio. Because the pipe is axially restrained, this contraction is not allowed, leading to the development of internal compressive axial stress. This longitudinal stress is given by:

$$\sigma_L = \frac{P.D_i}{4t} \tag{3}$$

These combined stresses influence the long-term mechanical behaviour and failure processes of buried PE pipes (Figure 1). To investigate how traffic loading and internal water pressure interact to shape this behaviour, this study develops an apparatus capable of replicating these conditions within the 50gT geotechnical centrifuge at the University of Sheffield (Bayton et al., 2018).

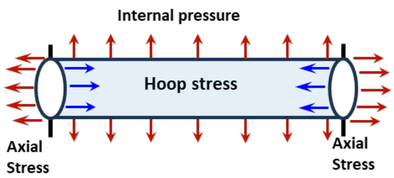


Figure 1 Hoop and axial stresses in a pressurised pipe.

2 EXPERIMENTAL METHODOLOGY

Centrifuge tests were performed in a 50 g-ton facility using CH30 sand as the burial medium. The HDPE pipe was mounted in the strongbox and connected to a custom actuation system for applying controlled axial restraint. Surface loads representing heavy-vehicle axle loads were imposed, while axial forces of 18 N, 30 N, and 60 N at centrifuge accelerations of 19.2 g were applied to simulate internal-pressure effects (Figure 2). This enabled simultaneous measurement of bending moment, pipe deflection, and cyclic response under combined axial and vertical loading.

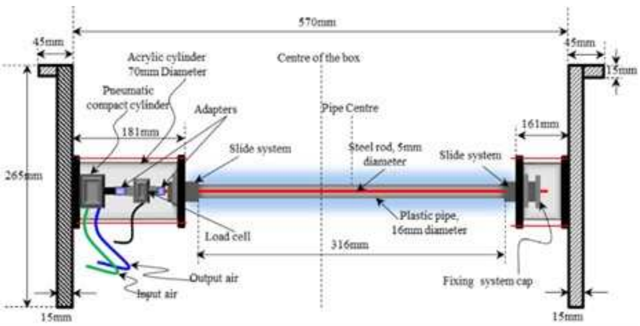
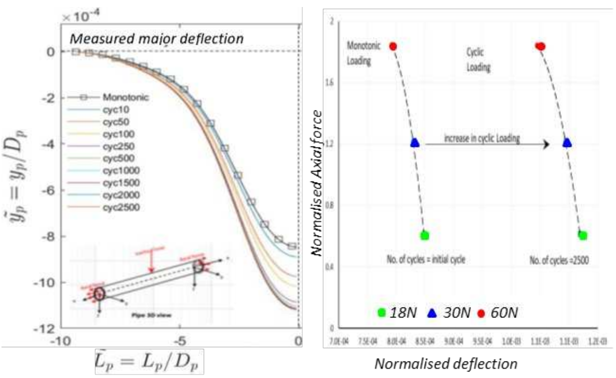


Figure 2 Schematic of the actuation system apparatus (Elmrom, 2021)

3 RESULTS

The results show that pipe deflection decreased consistently with increasing axial force, which was applied in three different magnitudes: 18 N, 30 N, and 60 N, with the highest load producing the greatest reduction in deflection and a notable increase in structural stiffness (Figure 3). Measured deflections demonstrated that axial tension mitigated flexural deformation, functioning similarly to a pre-stressing mechanism.



(a) (b)

Figure 3 (a) Pipe deflection normalised by pipe diameter along pipe under under monotonic and cyclic loading and (b) reduction of peak deflection with applied axial force.

Under cyclic loading, the system's response stabilises after approximately 250 cycles, and higher axial forces effectively limit the accumulation of deformation.

4 CONCLUSION

Internal water pressure plays a structurally beneficial role in buried plastic pipelines by generating axial pre-tension that limits flexural deformation during surface loading events. The experiments confirm that axial restraint significantly enhances pipeline resistance to both instantaneous and cyclic loads. For the tested HDPE pipe, an internal-pressure equivalent of 5 bar increased bending stiffness by approximately 40% and reduced maximum bending response by nearly 30%. These findings highlight the importance of incorporating axial boundary conditions and internal pressure effects into design guidance for buried flexible pipelines, particularly in traffic-loaded environments.

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