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Optical Fibre Sensing for Monitoring Shallow Buried Utilities Under Dynamic Loading

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ABSTRACT: The construction of urban light railway systems often requires costly diversion of buried utilities to mitigate potential damage from surface loads. However, understanding the behaviour of shallowly buried utility ducts due to dynamic loading is limited. This study investigated the structural behaviour of shallow buried utility pipes under cyclic loading (simulating tram loads). A 90 mm diameter high-density polyethylene (HDPE) pipe was buried at a depth of 300mm to the crown in a 10 m × 5.8 m x 5 m deep test pit at the National Buried Infrastructure Facility (NBIF), University of Birmingham, UK. To simulate a realistic surface track system, a reinforced concrete slab was constructed above the pipe to represent a tramway track bed. The pipe was offset by 600 mm from the edge of the track slab which was loaded using a 250kN dynamic actuator with dynamic loads ranging from 80–200 kN at frequencies of 1–8 Hz to simulate tram axle loads. Distributed optical fibre sensors (DOFS) were attached along the crown of the pipe and at three parallel circumferential positions. A Luna ODiSI 6100 interrogator was used to obtain dynamic, high-resolution strain measurements. Results showed that pipe strains remained within the elastic range under simulated tram axle loads, with a maximum measured strain of 36.7 $\mu\varepsilon$. However, they exceeded predictions from the Spangler method in BS 9295, which assumes homogeneous, elastic soil and underestimates soil pressures and bending moments at shallow depths, especially under dynamic loading. The findings reveal limitations in conventional design codes and highlight the capability of DOFS to capture detailed strain distributions with high spatial and temporal resolution. This study underscores the value of large-scale controlled testing and integrating optical fibre sensing into geotechnical monitoring frameworks, supporting future research on ageing infrastructure and pipe materials.

KEYWORDS: Optical Fibre Sensing, Dynamic Railway Loads, Shallow Buried Utilities, Urban Light Rail, Geotechnical Monitoring.

1 INTRODUCTION

The expansion of light rail transit (LRT) systems has emerged as a strategic response to the pressures of rapid urbanisation, offering reduced traffic congestion, lower greenhouse gas emissions, and improved air quality. Compared to buses and metro systems, LRT provides higher passenger throughput with lower operational emissions and capital costs, making it a cost-effective and sustainable urban transport solution (World Bank, 2014; UN General Assembly, 2015). However, their integration within existing highway corridors necessitates interaction with shallow buried utilities, including water, gas, electricity, and communications infrastructure.

The presence of shallow utilities, typically buried at depths of 400–1000 mm (NJUG, 2018), poses a persistent engineering challenge, as this range often intersects with or lies just below the track slab depth of approximately 600 mm (Real, 2011). To mitigate the risk of damage during construction and operation, utility diversion is commonly adopted, although this practice entails considerable cost and delay. Under the New Roads and Street Works Act (NRSWA, 1991), tram promoters bear 92.5% of diversion expenses, and reviews by the National Audit Office and the Edinburgh Tram Inquiry have identified such diversions as a primary contributor to project delays and budget overruns (NAO, 2004; Rumney, 2015).

Despite its widespread adoption, this conservative approach stems partly from insufficient understanding of the behaviour of shallow buried pipes under repeated dynamic loading. Conventional design methodologies, such as the Spangler method prescribed in BS 9295 (BSI, 2020), assume linear-elastic soil response and uniform loading conditions. These assumptions are poorly suited to shallow burial scenarios, where dynamic effects, non-uniform stress distribution, and complex soil - structure interactions can govern pipe performance (Mackey et al., 2014). Consequently, existing standards may lead to overdesign or unjustified diversions, highlighting a critical need for more representative data (Chapman et al., 2007). Advancements in sensing technologies now enable in situ performance monitoring of buried infrastructure with unprecedented precision. Distributed Optical Fibre Sensing (DOFS) offers high-resolution, continuous strain measurements with superior spatial and temporal fidelity compared to conventional instrumentation. When integrated with interrogation systems such as the Luna ODiSI 6100, DOFS provides full-field strain data under realistic loading conditions, supporting the validation of design assumptions and the early detection of structural degradation (Kechavarzi et al., 2016, Cassidy et al., 2024).

This study investigates the structural response of a shallowly buried high-density polyethylene (HDPE) pipe subjected to simulated tram-induced dynamic loading, employing DOFS within a controlled large-scale laboratory testing environment. The objectives are to evaluate the accuracy of conventional design predictions, assess the implications of dynamic loading at minimal cover depths, and explore the potential of DOFS to inform improved monitoring and design frameworks. The outcomes of this study will contribute to a more performance-based, risk-informed approach to utility protection in future urban rail developments.

2 EXPERIMENTAL SETUP

2.1 *Test Configuration*

A large-scale laboratory experiment was conducted at the National Buried Infrastructure Facility (NBIF), University of Birmingham, UK, using a modified setup adapted from a previous buried pipe study. The test was carried out in a 10 m × 5.8 m × 5 m deep pit, uniformly backfilled with compacted sand (bulk unit weight = 21 kN/m³), placed in 300 mm layers using a vibrating plate compactor. A shallow utility trench was hand-dug and offset laterally from a concrete track slab structure, designed to replicate light rail conditions (Figure 1). The pipe was embedded at a depth of 300 mm to the crown and offset by 600 mm from the slab edge to reflect typical urban utility configurations.

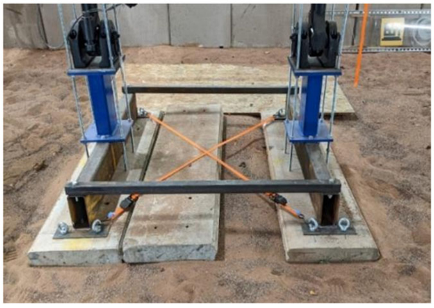

Figure 1. Image of the actuators and simulated railway slab.

2.2 *Pipe and Instrumentation*

The pipe was a PE100 HDPE pipe compliant with SHW Series 500 and BS EN 12201-2 standards (British Standards Institution, 2013; National Highways, 2020). Its key material and geometric properties are listed in Table 1, and the physical specimen is illustrated in Figure 2.

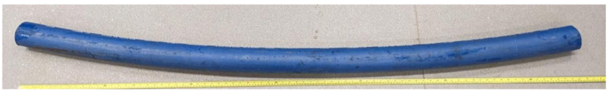

Figure 2. Image of test duct prior to instrumentation.

Table 1. HDPE Test Duct Characteristics.

Property	**Value**
Classification	PE100, PN 10
Outer Diameter (mm)	90
Wall Thickness (min–max, mm)	5.4 – 6.1
Standard Dimension Ratio (SDR)	17
Length (mm)	2000
Material	HDPE
Flexural Modulus (MPa)	1000
Tensile Strength at Yield (MPa)	23

Prior to installation, the pipe was instrumented with two types of optical fibre sensors to enable full-field strain monitoring. A dynamic sensing system (Luna ODiSI 6000 Series) was bonded along the full length of the pipe crown (Figure 3), providing high-resolution strain data with a 1.25 mm spatial resolution and a sampling frequency of up to 25 Hz. In parallel, static strain sensing was implemented using OBR4600 systems, installed circumferentially at selected locations (Figure 4), operating at a temporal resolution of one-minute.

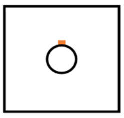

Figure 3. Position of ODiSI 6100 optical fibre on the crown of the pipe.

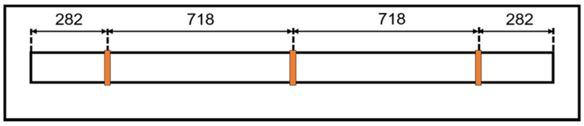

Figure 4. Position of circumferential OBR4600 optical fibres on test duct (dimensions in mm).

To ensure reliable strain transfer and minimise disturbance from soil-particle interaction, the optical fibres were bonded using epoxy resin. Splice zones, where fragile sensing fibres transitioned into ruggedised communications cables, were reinforced with protective wrapping to prevent stress concentrations and ensure long-term durability during soil placement and loading.

Due to constraints imposed by existing instrumentation and slab layout, the pipe was installed in an offset alignment relative to the concrete slab. A hand-dug trench was created adjacent to the slab, and the pipe was centred within the trench prior to backfilling (Figure 5). The pipe crown was embedded at a depth of 300 mm and laterally offset by 600 mm from the slab edge, remaining within the zone of influence for eccentrically loaded buried utilities, as reported by Yoo et al. (2000).

Figure 5. Image of the instrumented pipe in the trench.

The trench was backfilled with the original excavated (as-dug) material and compacted in layers using six passes of a vibrating plate compactor. While minor differential compaction may have occurred at the interface between native and disturbed soil, this condition is consistent with typical variability encountered in real-world utility installations beneath highways.

2.3 *Load Application*

Dynamic loading was applied to the track slab using hydraulic actuators to simulate repeated tram axle loads. Reference values were based on Shan et al. (2021), who reported a typical dynamic axle load of 81.6 kN. To capture upper-bound scenarios, a fully loaded axle value of 100 kN was adopted in line with estimates by Esveld (2001). Synchronous loading was applied to both rails to replicate realistic operational conditions.

Ten loading configurations were executed, varying in frequency and magnitude as summarised in Table 2. A preload of 10 kN was maintained throughout each test cycle to avoid impact effects and ensure smooth actuator transitions.

Table 2. Dynamic Test Configurations.

Test No.	Frequency (Hz)	Load (kN)	No. of Cycles	Test Time (min)
1	1	80	1800	30
2	2	80	1800	15
3	4	80	1800	7.5
4	4	100	1800	7.5
5	2	100	1800	15
6	1	100	1800	30
7	1	200	1800	30
8	1	150	1800	30
9	4	150	1800	7.5

Test No.	Frequency (Hz)	Load (kN)	No. of Cycles	Test Time (min)
10	8	150	1800	3.75

Tests 1–6 were representative of operational light rail conditions, with frequencies of 1-4 Hz corresponding to approximate tram speeds of 40, 80, and 160 km/h. The higher-speed of 160 km/h case was included for comparison with heavier rail systems. Tests 7-10 applied elevated loads beyond standard light rail design limits to explore potential overstress behaviour.

Each test consisted of 1800 loading cycles (equivalent to ~300 tram passes). Rest intervals were introduced between tests to allow strain dissipation and to minimise the risk of cumulative plastic deformation, following the recommendations of Grossoni et al. (2021). Dynamic strain measurements were re-zeroed between tests to ensure consistent baseline calibration.

2.4 *Data Processing and Analysis*

Dynamic strain data were processed in MATLAB using a Savitzky-Golay filter to remove high-frequency noise and clarify cyclic strain trends, while static strain readings were calibrated against baseline conditions to isolate deformation due to applied loading. Analytical strain predictions were computed using Spangler's method (BS 9295), incorporating the pipe's mechanical properties, burial geometry, and an interaction coefficient of 0.2492 selected based on the test conditions. This enabled direct comparison between measured and predicted strain responses under shallow, dynamically loaded conditions.

3 RESULTS AND DISCUSSION

3.1 *Strain Response Under Dynamic Loading*

High-resolution distributed optical fibre sensors were employed to monitor the strain along the pipe crown under both static and dynamic loading. Under static conditions (Figure 6), the pipe exhibited three distinct strain peaks - one tensile (+292 με) and two compressive (-1076 με and -764 με) - reflecting the combined effects of overburden pressure, slab dead load, and actuator weight. These values substantially exceed the static strain predicted by the Spangler's method (6.28 με), revealing significant discrepancies due to non-uniform soil-structure interaction and actual field conditions.

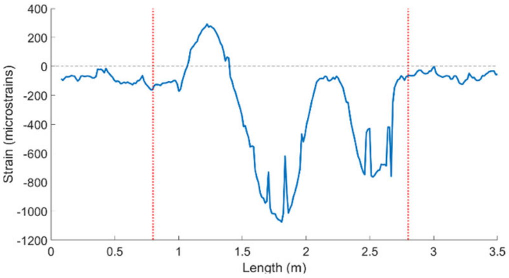

Figure 6. Diagram of reference strain measurement.

The mismatch between the measured and predicted static strains can be attributed mainly to two factors. Firstly, the actual vertical stress beneath the concrete slab and actuator was highly localised, unlike the uniform pressure distribution assumed in Spangler's method. Secondly, a trench effect was present: the pit backfill was well compacted, whereas the hand-dug trench backfill was softer, producing arching along the trench walls and reducing the vertical load transfer to the pipe. These installation-related effects generated non-uniform strain patterns that departed from the idealised static conditions assumed in BS 9295 (BSI, 2020). Spangler's equations also differentiate between embankment and trench installations; however, the code's default assumptions align more closely with an embankment case with uniform soil stiffness. The present test represents a shallow trench with variable stiffness, explaining part of the underprediction. Because these discrepancies already arise under static trench loading, the limitations of empirical methods become more pronounced under cyclic loading, where stress redistribution, bending effects and soil stiffness variability intensify.

Under dynamic loading (Figure 7), the peak circumferential strain reached 36.7 με (Test 7), with a consistent pattern across most tests: two small tensile peaks (0-10 με) aligned with the actuator points and compressive valleys (-5 to -15 με) in between. Notably, Tests 1 and 7 exhibited amplified strain at x = 1.17 m, suggesting localised bending effects or heterogeneous backfill stiffness. Minor fluctuations (±5 με) were observed and attributed to sensor-soil interaction and imperfect bonding, not structural deformation. Post-unloading the residual strains remained low (maximum 9 με), well within the pipe's elastic range based on yield strength (23 MPa) and flexural modulus (1000 MPa), confirming structural resilience.

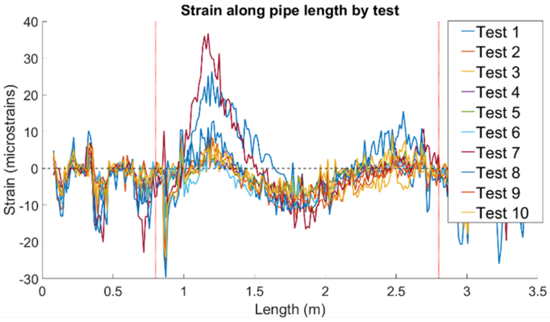

Figure 7. Diagram of maximum strain along pipe crown during loading.

3.2 *Limitations of Empirical Design Predictions*

BS 9295 (BSI, 2020) and the Spangler method (Spangler, 1964) estimate pipe strain using static, linear-elastic assumptions, including uniform soil pressure and idealised support. Dynamic loading is represented only by applying a Dynamic Amplification Factor (DAF), typically 1.2-1.6, but BS 9295 explicitly notes that DAF provides only an approximate correction and does not capture cyclic soil behaviour, backfill variability, or non-uniform load transfer, particularly critical for shallow cover (<1 m), where the method is not validated.

Consequently, even with DAF applied, the predicted strains remained much lower than the measurements (errors of -81% in Test 1 and -66% in Test 7), with only Test 9 showing partial agreement (-11%) under quasi-static conditions. Measured strain patterns, alternating tensile and compressive peaks and localised amplification (e.g., at x = 1.17 m), demonstrate highly non-uniform bending behaviour generated by shallow dynamic loading. Such behaviour is fundamentally incompatible with the uniform stress and soil-structure interaction assumptions of empirical methods. Thus, static empirical approaches, whether used directly or scaled with DAF, are inadequate for predicting the dynamic response of shallow-buried utilities.

4 IMPLICATIONS FOR DESIGN AND MONITORING

4.1 *Design Considerations for Shallow Utility Installations in Urban Rail Projects*

The results clearly show that shallow buried utilities experience higher and more variable strains than those predicted by simplified hand-calculation methods. This highlights the need to consider backfill stiffness, compaction quality, and trench geometry when designing for tram-induced loading. Strain variations linked to local differences in compaction (e.g., deviations from SHW 500 requirements) demonstrate that construction practices directly influence load transfer. These factors are particularly important for shallow installations subjected to frequent cyclic loading where soil non-uniformity governs structural response.

4.2 *Limitations of Existing Standards and the Need for Revised Approaches*

Measured strain responses consistently exceeded those predicted using BS 9295 and Spangler-based approaches. While prior studies (Young & O'Reilly, 1983; Yoo et al., 2000; Alzabeebee et al., 2017) have reported similar trends, the level of underprediction observed here - especially in Tests 1 and 7 - highlights an urgent need to revise or supplement existing standards. Design codes should incorporate dynamic load effects, installation errors, and varying soil support conditions. Static, elastic models are inadequate for low cover utilities in dynamic environments. Probabilistic or performance-based frameworks that reflect real construction and operational variability would provide a more robust foundation for urban infrastructure resilience.

4.3 *Understanding Ageing Infrastructure Under Operational Loads*

Although the HDPE tested remained within elastic limits, comparable strain levels could be critical for older or more brittle pipe materials (e.g., cast iron or uPVC). Much of the existing utility network predates modern design guidance, making their response under repeated tram loading uncertain. This underscores the need for ongoing condition assessment using technologies such as distributed optical fibre sensing, particularly during upgrades or rail expansion works. Integrating measured performance into long-term asset management will support safer and more resilient buried infrastructure networks.

5 CONCLUSIONS

This study investigated the deformation behaviour of a shallow-buried HDPE pipe subjected to dynamic loading conditions representative of tram operations. Results showed that measured circumferential strains remained within the elastic limit of the pipe material, confirming structural resilience under repeated axle loads. However, measured responses consistently exceeded predictions based on BS 9295 and the Spangler method, particularly at shallow cover depths.

These discrepancies reflect the limitations of applying static, linear-elastic models to dynamic, near-surface conditions. Non-uniform load transfer, localised bending, and soil-structure interaction effects contributed to strain patterns that diverged from standard assumptions, particularly during early loading cycles.

The findings underscore the need to revisit current utility design approaches for shallow-buried infrastructure in urban rail contexts. Consideration of construction-phase effects, bedding quality, and load variability is essential to ensure realistic assessments of strain demand and serviceability.

Future work should examine a wider range of burial depths, soil conditions, and pipe materials, along with long-term cyclic loading effects, to inform the development of more representative and performance-based design methodologies.

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