Proceedings of the 11th ICPMG 2026
11th International Conference on Physical Modelling in Geotechnics
8-12 June 2026, Zurich, Switzerland

Distributed Fibre Optic Sensing for capturing long-term soil deformations in railway trackbeds in a model test

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ABSTRACT: This paper describes a test setup developed to investigate the behaviour of railway trackbeds under cyclic loading using novel Distributed Fibre Optic Sensing (DFOS). The model was constructed at full scale (1:1) to ensure realistic stress level and to replicate in-service track conditions. Vertical cyclic loading was applied to a bi-block sleeper placed on a compacted subballast gravel layer underlain by a soft subgrade. In addition to extensive conventional instrumentation, DFOS-based sensors were embedded at two depths within the subgrade layer. The experimental data will support the validation of numerical models and contribute to optimising railway trackbed design.

1 INTRODUCTION

Infrastructure managers aim to reduce railway maintenance costs and optimise the design of trackbeds to ensure their long-term performance under cyclic loading from railway traffic. Experimental data obtained under controlled, realistic track conditions remain scarce, though such data are essential for validating numerical models and developing reliable design approaches. Within the framework of the EU-funded GEOLAB project, a novel full-scale (1:1) test setup was developed at the Technical University of Darmstadt to study the long-term deformation behaviour of railway trackbeds under cyclic loading, combining DFOS with extensive conventional instrumentation.

2 TEST SETUP

The test setup is schematically depicted in Figure 1. The Geotechnical Test Pit has internal dimensions of 5.0 m x 5.44 m x 3.0 m, allowing the reproduction of realistic stress conditions. A soft trackbed subgrade with $E_{V_2}\approx 10$ MPa was modelled via a sandwich-like scheme consisting of two layers of medium-coarse sand with a layer of crumb rubber in between. Grids of DFOS sensors were placed at two depths within the upper sand layer, along with 14 vertical earth pressure sensors. Above the subgrade, a subballast layer composed of well-graded crushed limestone gravel 0/20 (≈30 cm) was compacted layerwise using a vibratory plate. The sand and gravel layers were separated by a non-woven geotextile layer without any mechanical function. Static and dynamic plate load tests were conducted at different depths to characterise the mechanical properties of the assembly.

On the top of the subballast layer a bi-block sleeper (Type B 244 NP) was installed. The vertical load was applied on a steel crosshead to distribute it evenly between the sleeper blocks. Four load cells were installed in between the crosshead and the sleeper blocks.

The model was subjected to 250,000 loading cycles, corresponding to 50,000 four-car passenger train passes. The first cycles were applied at low frequency to allow the adjustment of the parameters of hydraulic loading system, but the equivalent train speed was rapidly increased to 100–120 km/h. Figure 2, top row, shows the loading pattern, with the vertical force varying between 3.54 and 31.15 kN, representing a contact pressure range of 15 to 85 kPa under the sleeper blocks. The corresponding evolution of the sleeper settlement with time is shown in Figure 2 (bottom row).

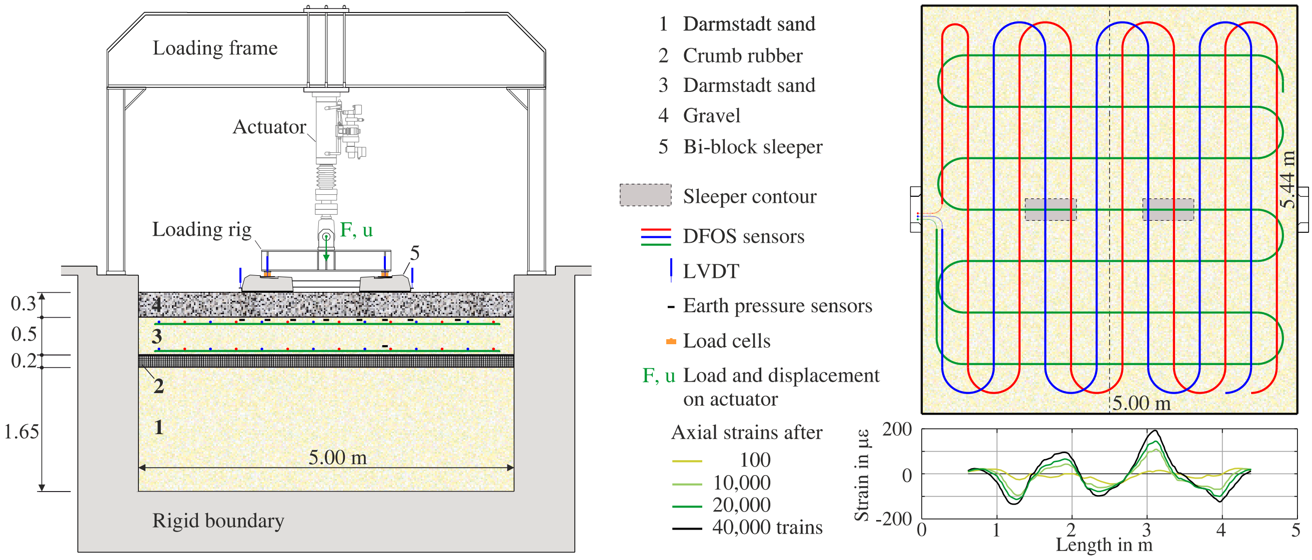

Figure 1. Schematic test setup at TU Darmstadt Geotechnical Test Pit (left) and DFOS layout with preliminary results (right).

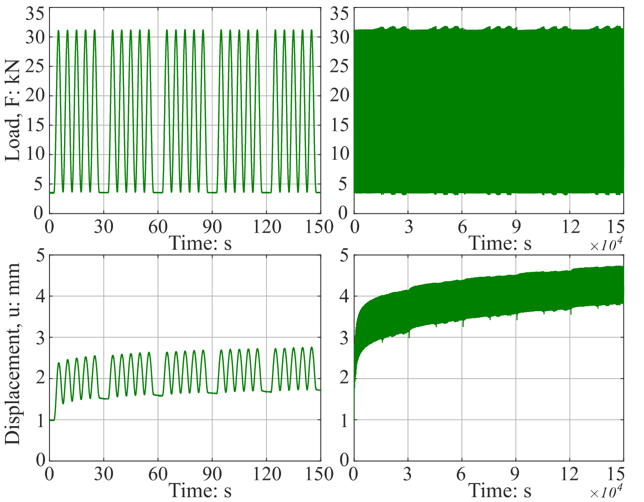

Figure 2. Load and corresponding vertical displacement for first five trains (left) and for the entire test (right).

3 DISTRIBUTED FIBRE OPTIC SENSING

Six EpsilonSensors were installed within the DFOS measuring system at two depths in the upper sand layer, with three sensors at each level, forming a rectangular sensor grid (Figure 1). The EpsilonSensor consists of single-mode SMF 9/125 fibres embedded in PLFRP (polyester fibres + epoxy) with bi-directional outer braid to ensure effective bonding with the soil. Each sensor, with a Young's modulus of 3 GPa and diameter of 3 mm, allows strain measurements up to ±4 % along its length. Using a Luna ODiSI interrogator, the sensing path of approximately 115 m per level yielded a total of around 44,230 data points with gauge length of 5.2 mm. Both sensor grids were pre-assembled outside the pit on a wooden frame with orthogonal lines marked, and cable ties used to fix all intersections. The grid was carefully placed at the target level in the pit. After positioning, the cable ties were cut, and the sensors were manually covered with sand to fix their position.

Figure 1 (right) shows the DFOS layout and example readings beneath the sleeper under applied loading. As vertical deformations accumulated, strain magnitudes recorded by the DFOS in the subgrade increased. Preliminary results indicate tensile strains directly beneath the sleeper blocks and compressive strains in the adjacent subgrade areas relative to the reference measurement taken immediately before the experiment started. The large dataset acquired is currently being evaluated.

4 CONCLUSIONS

The developed experimental setup enables long-term cyclic testing of railway trackbeds using DFOS alongside extensive conventional instrumentation. DFOS data provide detailed insights into strain distributions within the soft subgrade in relation to loading stages and settlement accumulation. The results of the experimental campaign are available in an open-access repository (Yaba et al., 2025).

ACKNOWLEDGEMENTS

This study received funding from the project "GEOLAB: Science for Enhancing Europe's Critical Infrastructure", as part of the European Union's Horizon 2020 research and innovation programme under grant agreement No. 101006512.

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