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Cyclic loading of railway trackbeds with and without geogrid stabilization: Experimental design and instrumentation

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ABSTRACT: This communication presents the experimental design and instrumentation employed in a study investigating the behavior of railway trackbeds under cyclic loading, emphasizing the role of geogrid stabilization. Conducted at the Technical University of Darmstadt's Geotechnical Test Pit and within the framework of GEOLAB, the project advances understanding of trackbed mechanics through large-scale physical modelling under semi-realistic railway conditions. Two full-scale trackbed models were constructed: one with geogrid stabilization and one without. The models replicate in-service conditions, comprising a subballast layer over a weak subgrade represented by crushed aggregate and a crumbed rubber-sand composite, respectively. A large test pit (5 m × 5.4 m × 3 m) minimizes boundary effects, ensuring accurate mechanical response measurements. A comprehensive instrumentation scheme was implemented, including Distributed Fiber Optic Sensing (DFOS) at soil interfaces, strain gauges on the geogrid, and earth pressure sensors within the subgrade layer. Additionally, force and displacement sensors provide measurements on different layers during cyclic loading. The loading pattern simulates train speeds of 100–120 km/h, with 250,000 cycles applied to assess long-term deformation and load transfer under realistic traffic conditions. This study aims at setting a benchmark for large-scale physical modelling in railway geotechnics, contributing to the development of sustainable and resilient railway infrastructure solutions. This communication focuses on the design of the experiments and the instrumentation. Detailed analysis of the recent experimental campaign should offer unprecedented insights into load transfer mechanisms, geogrid-soil interaction, and trackbed deformation processes. The resulting data will inform numerical modelling and design optimization, addressing critical challenges in railway infrastructure maintenance and modernization.

KEYWORDS: Geogrid, trackbed stabilization, railway geotechnics, physical modelling.

1 INTRODUCTION

The essential role of railway infrastructure in Europe and worldwide is unquestionable, both for passenger and freight transport. To meet future and current demands, the network must be safe, efficient and affordable. In countries such as France, large investments must be devoted to maintaining and modernizing the existing rail network. One of the most cost-effective and environmentally friendly approaches to trackbed renewal is the use of geogrid stabilization (Sol-Sánchez and D'Angelo, 2017; Tutumluer et al., 2025). This technique allows to ensure trackbed performance under challenging environmental conditions such as increased water content and resulting reduced subgrade bearing capacity, or reduce trackbed thickness while maintaining similar performance to standard trackbed designs.

Geogrids are geosynthetics that have a planar structure formed by a regular network of tensile elements with apertures of sufficient size to allow interlocking with surrounding soil, rock, earth or any other geotechnical material to perform their functions (Carroll, 1988). Perkins (1999) formulated a comprehensive explanation of the geogrid stabilization mechanisms, based on stress spreading enhancement under vertical loading, initiated by soil-geogrid interlocking and tensioning of the grid strands.

However, the precise effects of geogrid stabilization on track service life and maintenance requirements are still poorly understood, and strongly depend on the context of implementation and use. In the particular case of the French rail network (like with German Railways), geogrids are typically placed within the subballast layer due to maintenance reasons. This differs from the configuration commonly adopted in experimental studies of geogrid stabilization mechanisms, where geogrids are often positioned in the surface ballast layer (Esmaeili et al., 2017; Horníček et al., 2017). While the reinforcing and stabilization effects of geogrids, as well as the separation and filter effects of geotextiles are in general well understood (e.g. Ruiken, 2013; Vollmert, 2017; Vollmert and Bräu, 2018), there is a need for further research to evaluate the effectiveness of subballast geogrid placement under realistic operating conditions (Dangeard et al., 2026).

The viability and effectiveness of geogrid stabilized trackbeds, relative to the needs of SNCF Réseau, has been assessed via laboratory cyclic loading tests (Yaba et al., 2022a) and validated in instrumented field track sections (Yaba et al., 2022b). These investigations led to the development of preliminary design guidelines. However, their practical applicability remains limited due to the limitations of the experimental setups. Specifically, the small dimensions of the laboratory test box, which may induce unquantified boundary effects and the presence of uncontrolled variables in the field study, such as driver behavior and weather conditions. Both limitations can be remedied by conducting new cyclic loading tests in a larger-scale experimental setting and with more extensive measurements.

Along this line, a collaborative project in the framework of the European Union's Horizon 2020 GEOLAB project, namely the CyLo RT Transnational Access project (Yaba et al., 2025), has been developed. The project aims to assess the long-term behavior of railway trackbeds under cyclic loading, with and without geogrid stabilization, in the controlled conditions at the Geotechnical Test Pit of TU Darmstadt (TUDa). The acquired experimental data will be integrated with the results of other ongoing research and used to improve the numerical modelling of SNCF trackbeds. This comprehensive approach is expected to inform and support the evolution of SNCF policies regarding trackbed design and service life.

This communication details the genesis of the project, and subsequently focuses on the methodology adopted for the design of the experimental set-up and its extensive instrumentation. It also describes the rationale behind the selected testing program, including the loading protocols designed to simulate the long-term behavior of railway trackbeds. Preliminary results are given to show that the tests were run successfully and that the instrumentation system was effective. A full extraction and detailed analysis of the recorded data are currently in progress.

2 TEST SET UP

2.1 *Objectives of the experimental campaign*

This research aims to enhance the understanding of interactions between the crushed aggregates of the subballast layer, the geogrid, and the underlying subgrade. It also seeks to quantify the influence of a geogrid on the mechanical properties of a trackbed subjected to rail traffic. This is achieved through full-scale physical modelling under controlled laboratory conditions, using a realistic loading pattern in a test pit large enough to minimize boundary effects. The loading system was designed to replicate the pressure footprint exerted by a bi-block sleeper, and the model was constructed at a 1:1 scale to ensure realistic stress conditions. While small-scale modelling of geogrids and interlocking mechanisms for controlled element tests like cyclic triaxial test provide reliable results (Bräunig and Weisemann, 2024), small-scale performance testing for applications remains particularly challenging (Stathas et al., 2017). Therefore, this approach has been ruled out right from preliminary physical modelling carried out at the 3SR laboratory in Grenoble (Yaba et al., 2022a).

The ultimate goal of the proposed experiments is to identify and quantify the hypothesized mechanisms of redistribution of forces (cf. Perkins, 1999) and to measure the corresponding deformations of the trackbed structure in the presence of a geogrid (Test 2). A preliminary control test without a geogrid (Test 1) was carried out for comparison. In addition to understanding these mechanisms, the acquired experimental data will be used to calibrate, validate and improve numerical models for the design and predictive maintenance of railway trackbeds.

2.2 *Physical modelling of the trackbed structure*

The model was constructed in a 5 000 mm long, 5 435 mm wide and 3 000 mm deep compartment of the TUDa Geotechnical Testing Pit. A schematic vertical cross section is given in Figure 1. It aimed at replicating a realistic trackbed structure.

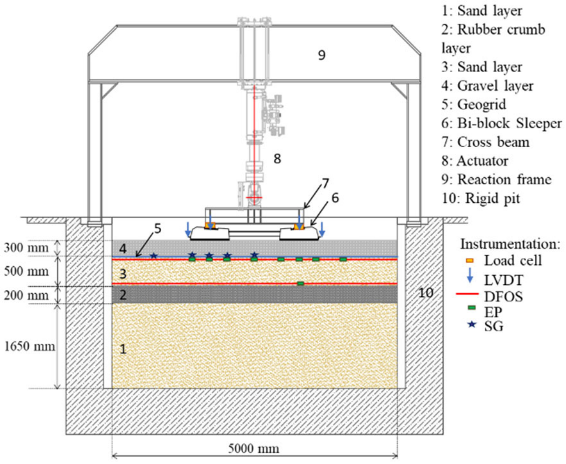

Figure 1. Schematic vertical cross-section of the test set-up.

From top to bottom, the model comprised a 300 mm thick subballast layer (Layer 4: gravel), which is a typical thickness value for this part of the trackbed in the French rail network. It was placed over a 700 mm thick soft subgrade, simulated using a composite structure comprising a 500 mm thick layer of Darmstadt sand (Layer 3) and a 200 mm thick layer of crumb rubber (Layer 2). This composite subgrade was designed to obtain a target plate load test modulus E_{v2} between 10 and 20 MPa following French standard (AFNOR, 2000). These modulus values are typical of soft to medium soils, which are considered particularly suitable for geogrid stabilization (Brown et al., 2007). This modelling of the subsoil does not represent a real subsoil in all its complexity, but it does have the advantage of being a well-known and reproducible parameter-set, ensuring the clarity of the material properties required as input values for subsequent numerical modelling.

Beneath the subgrade, a 1650 mm thick bottom layer (Layer 1) of Darmstadt sand permitted to adjust the surface level within the loading jack range. The different layers of the model were separated by a non-woven geotextile with no mechanical function. During the second test, the separation of the subballast and subgrade was provided by a geocomposite consisting of a geogrid and the same type of non-woven geotextile used for the first test.

The trackbed structure was modelled from the subballast layer, i.e. there was no explicit presence of the top ballast layer, as the studied soil-geogrid interaction mechanisms are not taking place in this part. However, the ballast layer presence was considered on the magnitude of the applied surface loading (layer self-weight).

The choice of load regimes was subject to the limitations of the overall project. In order to simplify the test procedure, the modelling of a train passing with rotating principal stresses was modelled as a monotonous cyclic load, as is also common in fatigue tests in the railway sector. After construction, the model trackbed was loaded vertically using a loading rig connected to a 500 kN hydraulic actuator. The loading rig consisted of a bi-block sleeper (type B 244 NP), with each block having a footprint of 290 mm × 680 mm and spaced 1563 mm apart (measured between the axes of the blocks). The applied force was evenly distributed between the blocks via a HEB 280 crossbeam (Figure 2). The entire rig was centrally placed in the pit. Hence, the minimum distance between the loaded surfaces and the pit vertical boundaries was about 1.3 m, to be compared with the vertical distance from the position of the geogrid, equal to 0.3m, allowing us to conclude that the side effects are limited. The actuator was firmly mounted on a rigid reaction frame, ensuring stable and precise vertical load application. The loading sequence is detailed in Section 3.4.

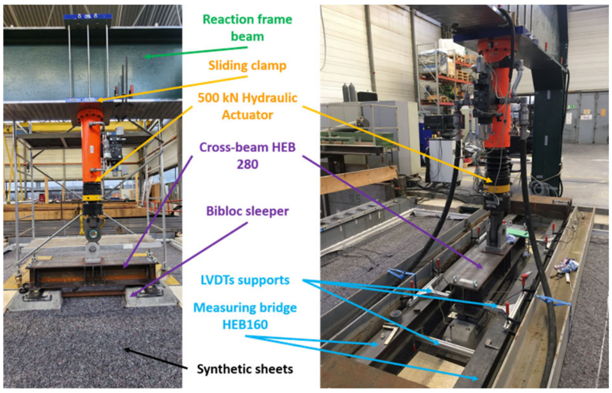

Figure 2. Surface loading system.

2.3 *Model instrumentation and data acquisition*

Numerous sensors (force, displacement, deformation, and pressure) were embedded in the model trackbed. In addition to traditional instrumentation, the standout feature of this setup was the use of Distributed Fiber Optic Sensing (DFOS) within the sand layer. This innovative technique permits high-resolution, continuous strain measurements, providing valuable insight into deformation patterns under the subballast.

All sensors have been strategically placed to capture the assumed behavior of the system and study specific mechanisms of interest. Their placement was informed by prior experience gained and observations made during a previous experimental campaign on a smaller-scale model at the 3SR laboratory in Grenoble (Yaba, 2022).

The instrumentation was structured into two complementary subsystems, enabling high-resolution monitoring of the trackbed response during cyclic loading, as detailed on Table 1. Within the first subsystem, Figure 1 and Figure 3 depict the positioning of the Earth Pressure sensors (EP) to assess the vertical stress spatial distribution beneath the loading system. Figure 4 shows the Strain Gauges (SG) glued on the geogrid to measure strains that develop in two orthogonal, horizontal directions. The strain gauges SG1.1 to SG 1.5 are placed along the sleeper axis and SG2.1 to SG2.4 are placed perpendicular to the sleeper axis. The data acquisition of this first subsystem was performed with a dedicated system that consisted of several synchronized chassis, at an acquisition frequency of 500 Hz.

Table 1. Sensors placed in the model.

Sensor	Nb in Test 1	Nb in Test 2	Capacity
Force sensor in the actuator	1		500 kN
Displacement sensors in the actuator	1		500 mm
Load cells into the loading rig	4		20 kN
Displacement transducers on the 2 blocks of the loading rig	6		200 mm
Earth Pressure sensors (EP) distributed in the subsoil (vertical stress)	14		100 kPa
Strain Gauges (SG) attached to the geogrid (two horizontal directions)	-	9	50,000 µm/m
Temperature sensors	2		0 - 100°C
Total subsystem 1	28	37	-
DFOS sensors	6 of ca. 40 m each; strain readings every 5 mm		4%

The second subsystem focused on distributed strain monitoring using 6 DFOS sensors, each approximately 40 m long. The sensors were embedded in a grid pattern at two distinct levels beneath the subballast layer (cf. L1 and L2 on Figure 1), with three sensors at each level. The placement of the top grid is illustrated in Figure 5. These innovative, monolithic DFOS sensors are made of lightweight polyester fibers and epoxy, have an outer diameter of 3 mm and an elastic modulus of 3 GPa. They enabled the detection of strain – either extension or shortening - along their entire length, with spatial resolution of 5.2 mm. Strain measurements were performed using reflectometer ODiSI 6100 by Luna Innovations, which allows data acquisition at frequencies ranging from 1.7 to 20 Hz. To improve the quality and relevance of the data, the total amount of measurements was optimized by implementing a targeted acquisition plan (not detailed in this communication). This plan defined which sensors were active at specific stages of the loading sequence, ensuring that data were collected during the most informative intervals. As a result, the DFOS technology could thus provide comprehensive insight into the strain evolution and deformation profiles of the subsoil.

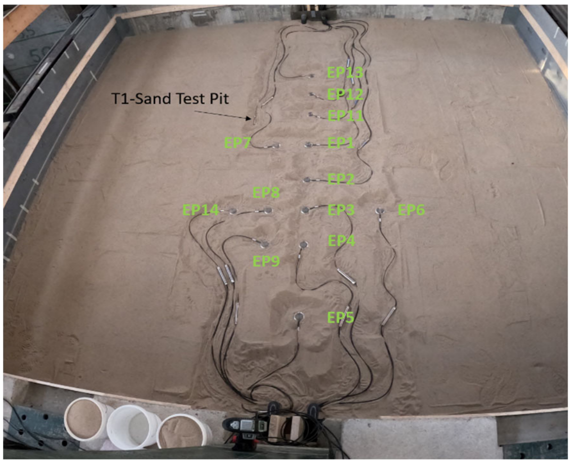

Figure 3. Placement of Earth Pressure sensors (EP) below the top gravel layer.

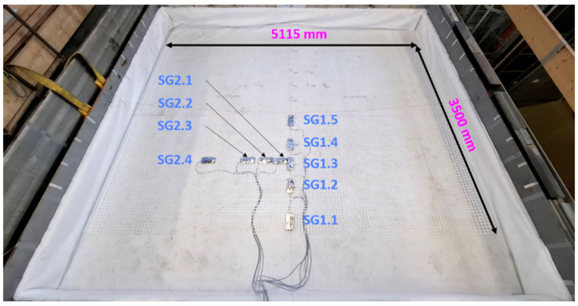

Figure 4. Location of the strain gauges glued on the geogrid.

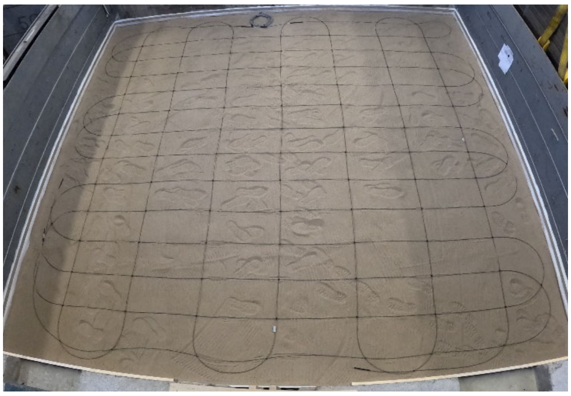

Figure 5. Placement of the DFOS cables on one of the two layers.

2.4 *Materials*

The 300 mm-thick subballast layer was composed of gravel sourced from an SNCF-approved quarry, in accordance with standard requirements for this type of trackbed construction. The material is similar to the gravel used in the previous small dimension experiments in 3SR laboratory in Grenoble (Yaba et al., 2022a). A well-graded crushed aggregate with a maximum size of 31.5 mm was specified, classified as D2 or D3 according to the French standard (SETRA-LCPC, 2000). A 0/20 calcareous crushed material was selected for the tests (Figure 6). Standard geotechnical laboratory tests were performed on the gravel material, including particle size distribution, Proctor, IBI, CBR, Los Angeles and Micro Deval (Yaba et al., 2025). The nominal grain size D_{50} was found to be 5 mm. The Proctor testing led to an optimum water content of 5%. In addition, large-sample triaxial tests are also scheduled on this material, especially to calibrate numerical models in future phases of the research.

Figure 6. Left: Subballast layer made of gravel (photo taken during density determination by sand replacement process). Right: Geotextile, geogrid and gravel.

Sand was used for the bottom layer and for the composite subsoil layer. The Darmstadt sand is a medium coarse river sand and is frequently implemented in large scale experiments performed at the TUDa Institute for Geotechnics. It has been thoroughly characterized by numerous tests, compiled in Beroya-Eitner et al. (2024).

The soft sublayer of the subsoil composite layer was made of granular crumbed rubber, obtained from recycled car tires (Figure 7). The particle size ranges from 1.5 to 5 mm and the specific density is 1160 kg/m^3. Detailed investigations are being performed to characterize the mechanical behavior of this material, in particular its deformability. Preliminary values of compressibility have been estimated at the stage of the composite layer design, to approach the target surface modulus. The experience gained from a previous project carried out at the TUDa (Schneider et al., 2024) has been used to estimate the reduction in layer thickness due to the installation of the upper layers, which is necessary for determining the quantity of compressible material to be installed in the model while controlling the final model level. It should be noted that rubber layer -which is highly compressible- does not constitute the entire subgrade, as this latter is represented by the multi-layer composite, so in combination with the sand layers above and below.

Figure 7. Rubber crumbs used for the subsoil composite layer.

Two types of geosynthetics were implemented in the experiments (cf. Figure 6):

- A non-woven geotextile, to separate the soil layers;
- A stabilization geogrid, used to improve track performance.

The geotextile is non-woven polypropylene sheet of thickness 3.9 mm, mass of 400 g/m² and a puncture resistance of 2500 N. It was used to separate the layers, mimicking real railway construction where such materials are placed at the interface between the subsoil and the subballast layers to prevent intermixing of materials.

The stabilization geogrid was only used in Test 2. A commercially available geogrid commonly used in stabilization applications was selected. This geogrid is a biaxial polypropylene product, made of stretched flat bars with welded junctions, forming square apertures with a center-to-center spacing of 40 mm. It has a nominal tensile strength of 40 kN/m at 7 % elongation and a tensile modulus of 800 kN/m at 1 % strain, in both grid direction. At this stage, only one type of geogrid has been implemented in the study. The effect of other types and stiffness properties of geogrid may be logically the subject of future studies.

3 TEST CAMPAIGN

3.1 *Tests performed*

Two test configurations were conducted: one without a geogrid (Test 1) and one with geogrid (Test 2), in order to precisely assess the influence of the geogrid. All other experimental conditions were kept as identical as possible, recognizing that natural and experimental variability cannot be entirely ruled out.

3.2 *Model preparation*

The bottom sand layer of 1650 mm thickness was placed in 17 sublayers of predetermined mass. The sand was deposited and spread evenly, without compaction.

A separation geotextile sheet was placed on top of the layer and the granular rubber layer was placed in two sublayers with a total mass of 120 kg/m², without compaction during installation, to reach a final total thickness of 200 mm after the installation of the upper material layers. The second sand layer of 500 mm was also placed without compaction, with additional care due to the presence of instrumentation (DFOS and EP, see Figure 1 for positioning). The DFOS sensor grids were first pre-assembled outside the pit following the model design. The assembly was then carefully transferred to the pit and positioned at the target level (cf. Figure 5). After placement, the cable ties used to prepare the grid were removed and the sensors were manually covered with sand, before proceeding with the installation of subsequent layers.

Again, a separation geotextile sheet was placed. For Test 2, the instrumented geogrid was placed immediately on top of it (Figure 4).

For the subballast construction, the gravel was installed in four 75 mm-thick sublayers, with a pre-determined mass to reach the target wet density of 2002 kg/m^3. The layers were compacted using a vibratory plate along a specific path, at a predetermined speed, and with manual compaction at the corners of the testing pit. Additional water had to be sprayed onto the gravel sublayers during the process to reach the optimum water content. Prior to installing subsequent sublayers, the surface of each of the first three gravel sublayers was roughened to ensure good interlocking between the grains at the interface.

Throughout the model construction process, the level of each layer was verified after compaction, with surface measurement on an 11×11 grid.

Under the sleeper of the loading rig, fine particles (< 2 mm) from the gravel were poured to ensure full contact with the subballast layer. Once the loading rig was placed in the center of the pit, the actuator was connected to the loading rig.

3.3 *Model characterization*

A series of Static Plate Load Tests (DIN, 2012), using a 300 mm diameter plate, and Dynamic Plate Load Tests DPLT (FGSV Verlag, 2012) were conducted during both tests to determine the deformation modulus (Ev) at two levels: i) on top of the composite subsoil layer and ii) on top of the subballast layer.

Dynamic cone penetration PANDA® tests were performed at 14 different points on the gravel layer, to assess compaction and bearing capacity of the structure (Benz-Navarrete et al., 2019), and its potential spatial variability.

The in-place density of the gravel layer was determined using sand replacement method, cf. Figure 6.

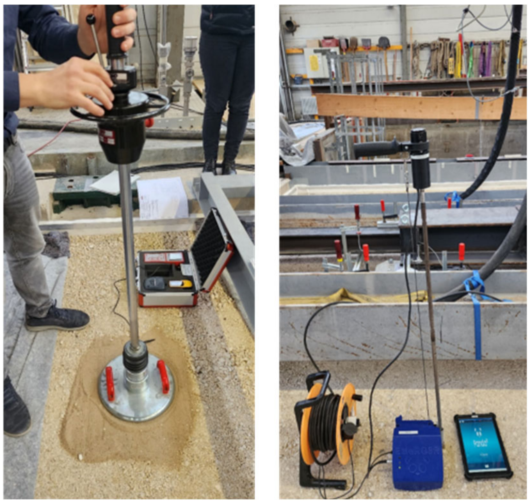

Figure 8. DPLT test (left) and PANDA® test (right).

3.4 *Loading sequences*

The aim of the project is to assess the long-term behavior of the trackbed structure, i.e. subjected to the repeated passage of trains. After model construction, the model trackbed was subjected to 250,000 loading cycles, corresponding to 50,000 train passes over 5 days, or 10,000 trains per day. This corresponds to 6 to 8 years of normal rail line operation.

The loading pattern applied on the loading rig is depicted in Figure 10, and corresponds to a simplified version of the loading pattern of a four-car passenger regional train (Figure 9). The corresponding vertical stress below the sleepers at subballast surface level ranged between 15 to 85 kPa. The residual 15 kPa mainly correspond to the permanent weight of the ballast layer which was not explicitly modeled in this study. These vertical stresses correspond to vertical forces to be applied between 3.54 and 31.15 kN.

For each test, the cyclic loading was applied in sessions of approximately 10 hours during 5 successive days. To enable the progressive adjustment of the control parameters of the hydraulic loading system, the cyclic loading was started with low frequency (equivalent to 1 train every 30 seconds), and gradually increased in three steps until reaching the target frequency of one train every 3 seconds. The corresponding loading patterns for the different frequencies are illustrated on Figure 11.

Exactly the same loading sequence was applied for both tests.

Figure 9. Bombardier Class B 81500 passenger train, 4-car variant: 10 bogies in pairs (SNCF).

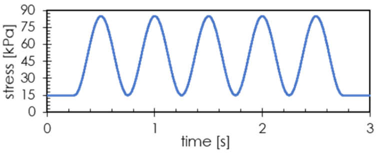

Figure 10. Applied loading path corresponding to one train passage at 120 km/h.

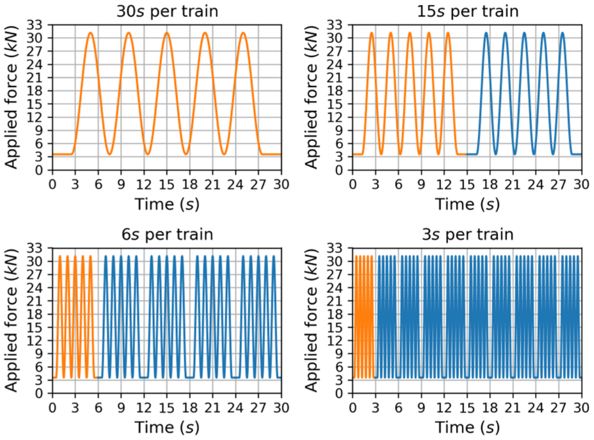

Figure 11. Loading pattern for a four-car passenger train passage at different speeds.

3.5 *Preliminary results*

Some preliminary results are given in this communication, not with the aim of detailed assessment or analysis of the trackbed behavior, which is beyond the scope of this paper, but rather demonstrate the effectiveness of the implemented instrumentation in capturing the trackbed behavior.

Figure 12 shows a progressive accumulation of surface settlement at the loading rig level over repeated loading cycles, with a higher accumulation at the start of the test.

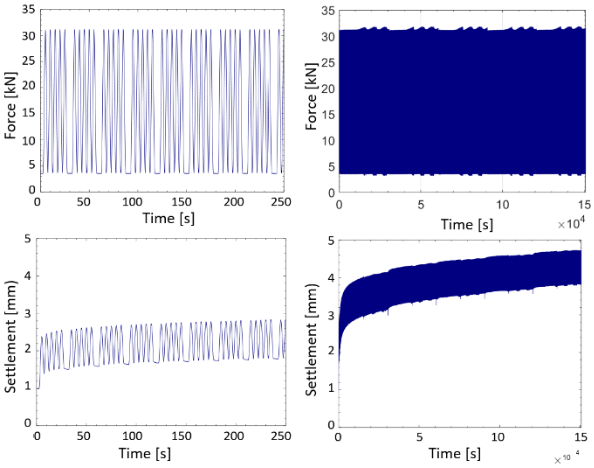

Figure 12. Evolution of the applied force and corresponding vertical displacement during the initial cycles (left) and over the entire duration of Test 1 (right).

Data extracted from the DFOS system, installed horizontally within the subsoil layer, demonstrate the instrumentation's responsiveness to loading, as illustrated in Figure 13. The results show tensile strain beneath the sleeper blocks and compressive strain in the adjacent lateral zones. This strain distribution is consistent with the observations of Perkins (1999) and Yaba et al. (2022a).

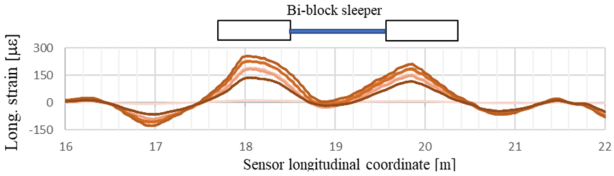

Figure 13. Distribution of strains in the DFOS under the sleeper, at different cyclic loading stages during Test 1 (examples).

A substantial amount of data was obtained throughout this project. All datasets were deposited as open-access on the Zenodo platform, accompanied by comprehensive documentation to facilitate for broad post-processing and analysis (Yaba et al., 2025).

4 CONCLUSIONS

The large-scale experimental campaign detailed in this communication was designed to evaluate the effectiveness of geogrid reinforcement in a realistic railway trackbed configuration under cyclic loading representative of regional train traffic. Recently completed, the experimental campaign procedures and results were published in a dataset on the Zenodo platform (Yaba et al., 2025). The large volume of data recorded during Test 1 and Test 2 as well as from in-situ characterization using the plate load tests and PANDA3® penetrometer measurements, is currently being processed and analyzed.

By employing a full-scale configuration and materials consistent with field conditions, the project overcame the typical limitations of scaled-down laboratory testing. The comparison between the two tests, one with geogrid and one without, explore the role of the geogrid in reducing vertical displacements and redistributing stress within the substructure, and analyze its stabilization potential in low to moderate bearing capacity soils.

Furthermore, the deployment of an extensive and innovative instrumentation system, including Distributed Fiber Optic Sensing (DFOS) technology, allows for an unprecedented level of insight into the internal mechanics of the unreinforced or reinforced soil. This wealth of high-resolution data enables a deep understanding of the interaction between the geogrid and the surrounding soil, and will serve as a valuable benchmark for future numerical modelling and design optimizations.

5 ACKNOWLEDGEMENTS

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