EXPERIMENTAL SETUP AND INSTRUMENTATION OF A FULL-SCALE BALLASTED RAILWAY TRACK TEST

Mehmet Ali Toprak[1], Niyazi Özgür Bezgin[2], Ercan Yüksel[1]
[1]*Istanbul Technical University, Turkey*
[2]*Istanbul University Cerrahpasa, Turkey*

Abstract

This paper presents the design, construction, and instrumentation of a full-scale laboratory experiment developed to investigate the vertical response of sleepers in ballasted railway tracks. The experimental setup features a comprehensive track segment comprising rails, seven concrete sleepers, ballast, and an under-ballast mat, facilitating a realistic representation of track components under controlled conditions. The experimental program encompasses both static and dynamic loading scenarios to characterize the track's structural response under diverse loading conditions. A primary contribution of this study is the development of a custom acceleration data-acquisition system. Accelerometers are strategically positioned on the sleepers and rails to capture vertical accelerations during dynamic testing. This modular system enables synchronized multi-channel data acquisition with adjustable sampling rates, offering a flexible and cost-effective alternative to commercial solutions. Furthermore, linear variable-displacement transducers (LVDTs) are used to monitor vertical sleeper displacements under both loading regimes. The integration of displacement and acceleration measurements allows for a comprehensive characterization of track behavior and enhances the reliability of the experimental findings. The proposed experimental configuration and instrumentation strategy provide a robust framework for full-scale laboratory investigations into the mechanical behavior of ballasted railway tracks. The primary aim of the study is to present the design, construction, and instrumentation of the experimental setup developed for future dynamic measurements of railway track behavior. While the system is designed to capture acceleration responses of the track structure, this paper primarily focuses on the experimental setup, loading configuration, and preliminary static validation results that demonstrate the reliability of the test facility.

Keywords: ballasted track, full-scale testing, vertical track response, acceleration

1 Introduction

Ballasted railway tracks remain the most widely used track system worldwide due to their cost-effectiveness and adaptability to varying ground conditions. The structural performance of such systems depends on the complex interaction between rails, sleepers, ballast, and subgrade layers. Among these components, the vertical response of sleepers plays a critical role in load transfer mechanisms, ballast degradation, vibration propagation, and long-term track performance. Accurate characterization of sleeper behavior under both static and dynamic loading is therefore essential for understanding the evolution of track stiffness and maintenance requirements. Several recent studies have demonstrated the potential of full-scale laboratory testing in railway research.

DOI: https://doi.org/10.5592/CO/CETRA.2026.2056

An advanced full-scale dynamic testing platform was developed for a ballasted high-speed railway track, incorporating multiple sensors to measure vibration velocities, dynamic soil stresses, and permanent deformations under simulated moving train loads. The study also introduced the use of "SmartRock" sensors for particle-scale monitoring and validated the experimental observations through Discrete Element Method (DEM) simulations [1]. Similarly, full-scale cyclic laboratory tests were conducted to compare the long-term settlement behavior of ballasted and concrete-slab tracks resting on compacted substructures representative of modern high-speed railway standards. Their findings demonstrated that ballasted tracks experienced significantly higher permanent settlement under phased cyclic loading, emphasizing the influence of track form and substructure stiffness on long-term performance [2]. A comprehensive full-scale model testing facility was simulated for ballastless high-speed railways subjected to simulated train-moving loads, highlighting the roles of dynamic soil–structure interaction and train speed in track vibration and soil stress distribution [3]. In addition, the improvement of ballasted track performance was investigated through ballast grading optimization and shoulder slope modification, demonstrating that geometric and material interventions can significantly reduce permanent settlement under cyclic loading [4]. Although previous studies have significantly improved the understanding of railway track dynamics and long-term behavior, comprehensive documentation of experimental setup design and instrumentation strategies for full-scale ballasted railway track systems remain relatively limited in the literature. Clear reporting of experimental configuration, boundary conditions, and instrumentation architecture is essential to ensure reproducibility and support subsequent analytical and numerical validation efforts. The present study addresses this need by developing and instrumenting a full-scale laboratory ballasted railway track segment designed to investigate the vertical response of prestressed concrete sleepers. The present paper focuses primarily on the design of the full-scale experimental setup and the instrumentation strategy developed for future dynamic measurements. Preliminary static loading tests are conducted to verify the system's stability and reliability prior to the dynamic testing phase.

2 Full-scale experimental setup

A full-scale ballasted railway track segment was constructed at the Structural and Earthquake Engineering Laboratory of Istanbul Technical University to investigate the vertical behavior of prestressed concrete sleepers under controlled laboratory conditions. The experimental assembly consists of seven sleepers, rail fastening systems, two continuous rails, ballast, and an under-ballast mat, which represents the substructure support layer. The track section was constructed using B07-type prestressed concrete sleepers and 60E2 rail sections. The sleepers are 2600 mm long. At the rail seat section, they have a bottom width of 320 mm and a height of 214 mm. Each sleeper weighs approximately 330–350 kg. Sleeper spacing was set to 600 mm, while the standard track gauge of 1435 mm was adopted. A detailed schematic representation of the experimental configuration is presented in figure 1.

To simulate realistic subgrade support conditions, an under-ballast mat was installed on the 1.2 m-thick testing floor. The floor provides a rigid and stable base while preventing excessive global deformation of the test system. A 350-mm-thick ballast layer was subsequently placed over the mat and mechanically compacted to achieve uniform support conditions. The sleepers were positioned on the compacted ballast and connected to the rails using the fastening system. Additional ballast was then placed and compacted up to the sleeper top surface. The shoulder ballast height was maintained at a constant width of 500 mm at the sleeper top level and subsequently reduced with a 1:1.5 slope toward the outer boundary. The installation stages of the test specimen are illustrated in figure 2. Vertical loading was applied to the middle sleeper (S4) using a specially designed steel load distribution beam.

The beam, manufactured to the track gauge, was attached to both rails. A hydraulic actuator transferred the applied load to the distribution beam, ensuring symmetric load transfer to both rails and minimizing torsional effects and eccentricities during testing. The load distribution beam is presented in figure 3.

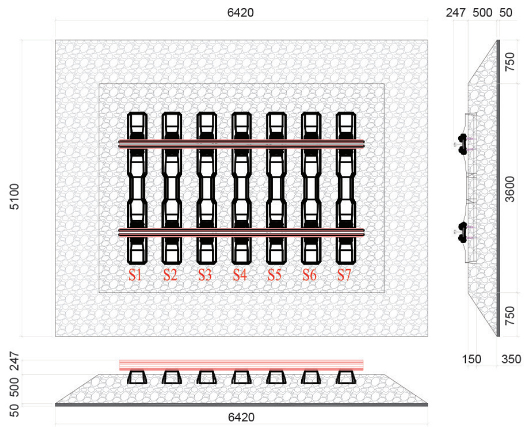

Figure 1 Experimental setup

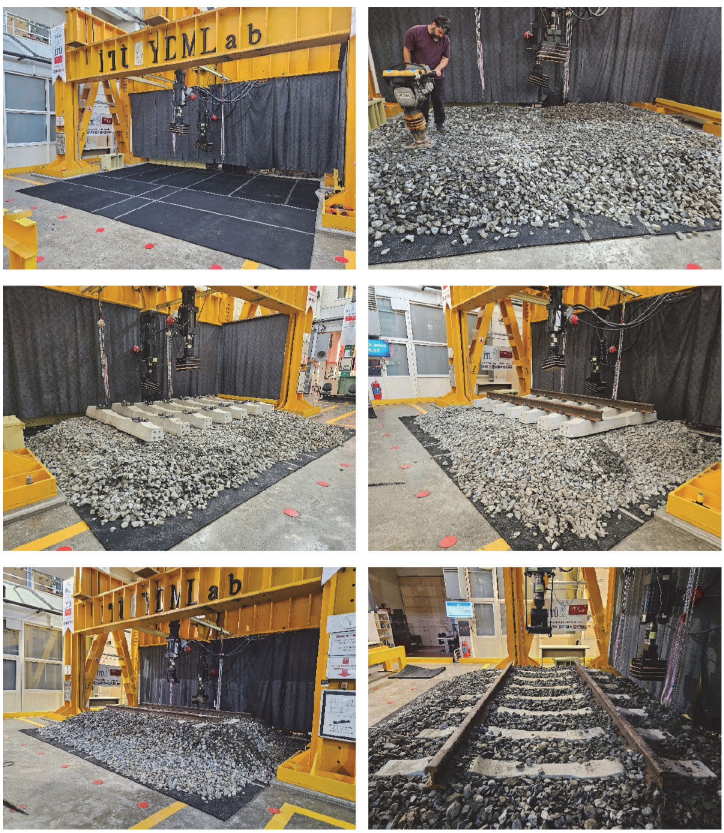

Figure 2 Installation of ballasted track

The constructed full-scale setup provides a controlled yet realistic representation of a ballasted railway track segment. The adopted configuration enables systematic investigation of vertical load transfer mechanisms, sleeper response characteristics, and ballast–rail interaction under both static and dynamic loading scenarios. The robustness of the setup forms the foundation for the subsequent instrumentation strategy and experimental program described in the following sections. The use of seven sleepers allows the middle sleeper (S4) to experience quasi-symmetric boundary conditions, thereby reducing edge effects and enabling a representative evaluation of vertical track response. Centralized loading further ensures that the measured behavior reflects structural response rather than boundary-induced artifacts.

Figure 3 Load distribution beam

3 Testing procedure and instrumentation

Static and dynamic loading tests were performed using a servo-controlled hydraulic actuator with a load capacity of ±500 kN and a displacement capacity of ±125 mm. The actuator enables load- and displacement-controlled dynamic and fatigue loading protocols under controlled laboratory conditions. In the static tests, load was applied monotonically at a rate of 2 kN/min until reaching peak load levels of 170 kN and 220 kN. The applied load levels were selected to simulate typical axle loads encountered in conventional railway operations. The maximum load corresponds approximately to the load transmitted to a single sleeper from a standard axle load distributed through the rail and fastening system. After attaining the target load, the specimen was unloaded at the same rate to evaluate elastic recovery and potential nonlinearity in the load–displacement response. This loading–unloading procedure was repeated three times for each peak load level to ensure repeatability.
For the dynamic tests, 200 loading cycles were applied at each load level. A sinusoidal load varying between 6% and 106% of the corresponding static peak load was imposed at a frequency of 4 Hz to maintain continuous compression. This loading protocol ensured sustained rail contact while reproducing realistic cyclic excitation conditions representative of railway traffic loading. A non-zero minimum load level of 6% was adopted to prevent separation between the rail and the loading beam during cyclic excitation. Maintaining continuous contact eliminated unintended impact effects and ensured stable load transfer throughout the dynamic tests. The upper limit of 106% of the corresponding static peak load was selected to preserve the intended load amplitude while maintaining symmetry around the reference static load level.

The loading frequency of 4 Hz was selected to represent typical axle passage frequencies encountered in conventional railway operations. Furthermore, the selected frequency ensured stable system behavior without inducing excessive vibration amplitudes or dynamic amplification that could compromise the integrity of the test assembly. Displacement and acceleration measurements were collected during experiments. The instrumentation layout, including sensor locations, is shown in figure 4. Displacement measurements were obtained using linear variable displacement transducers (LVDTs). At the loading section (S4), vertical displacements were measured at both edges of the sleeper and at both rails. At the remaining sleeper sections, displacement measurements were recorded from one edge of each sleeper to monitor the overall deformation along the track segment.
Acceleration measurements were conducted to characterize the system's dynamic response. At the loading section, accelerometers were installed at both edges of the sleeper, the sleeper center, both rails, the top surface of the under-ballast mat, and the laboratory floor. At the remaining sleeper sections, acceleration measurements were obtained from one edge of each sleeper. A custom-developed accelerometer and multi-channel data-acquisition system was used to enable synchronized measurements across all channels.

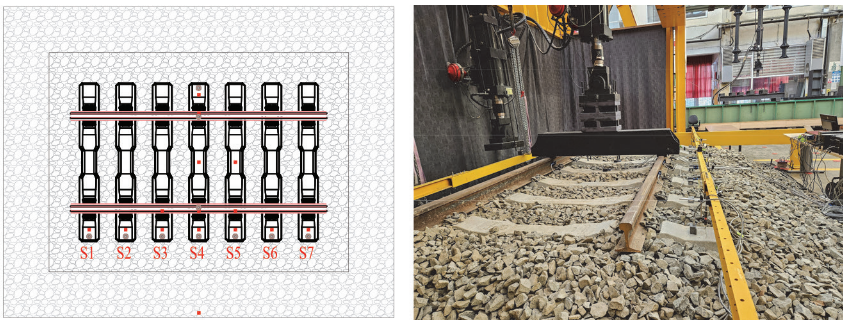

Figure 4 Instrumented track

During static tests, displacement data were recorded at a sampling rate of 1 Hz. In dynamic tests, displacement measurements were acquired at 100 Hz to ensure accurate capture of cyclic response characteristics. Acceleration data were collected at 200 Hz during dynamic loading to provide sufficient temporal resolution for frequency- and time-domain analyses. The combined displacement and acceleration measurement strategy enabled comprehensive characterization of both quasi-static and dynamic behavior of the track system. The distributed sensor configuration allowed assessment of local sleeper response, rail–sleeper interaction, load transfer mechanisms, and vibration propagation through the ballast and supporting layers. The adopted testing procedure and instrumentation framework, therefore, provide a reliable basis for evaluating the structural performance and dynamic characteristics of the full-scale ballasted track system.

4 Preliminary findings

The first phase of the experimental program aimed to verify the structural integrity, symmetry, and stability of the full-scale track segment under static loading. This preliminary assessment was necessary to confirm that the experimental configuration provides reliable and reproducible boundary conditions prior to detailed dynamic investigations. The static force–displacement responses obtained at the middle sleeper (S4) exhibited stable, repeatable behavior at both peak load levels (170 kN and 220 kN). The measured vertical displacements increased approximately linearly with applied load within the investigated range, indicating predominantly elastic system behavior.

No abrupt stiffness degradation or ballast instability was observed during loading or unloading. The unloading branches showed minor residual displacements, suggesting limited plastic deformation within the ballast layer. The overall response confirms that the ballast compaction and support conditions were sufficient to prevent excessive settlement during initial loading cycles. One of the primary objectives of the preliminary tests was to evaluate the system's symmetry under applied loading. Displacement measurements recorded at the edges of the sleepers (figure 5) demonstrated closely matched values, indicating symmetric load transfer and negligible torsional effects. Similarly, adjacent sleepers exhibited consistent deformation patterns, with displacement magnitudes decreasing progressively with increasing distance from the loading section. This behavior confirms that the seven-sleeper configuration successfully reduced edge effects and provided quasi-symmetric boundary conditions for the middle sleeper.

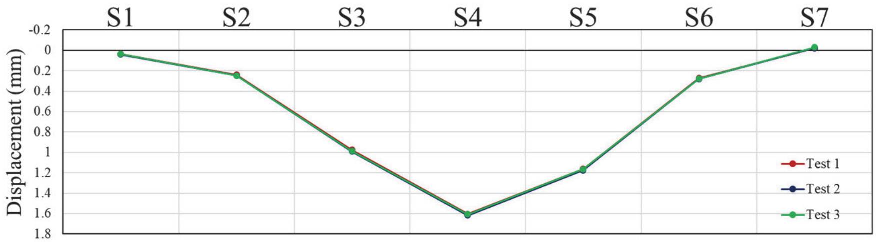

Figure 5 Displacement curve

The preliminary findings demonstrate that the experimental setup provides stable mechanical behavior, symmetric load distribution, and reliable measurement performance. No structural instabilities, excessive differential movements, or instrumentation inconsistencies were observed during static verification. These results confirm the suitability of the test assembly for subsequent dynamic investigations and for the extended three-phase experimental program aimed at characterizing the vertical response of ballasted railway tracks under cyclic loading conditions.

5 Conclusion

This study presented the design, construction, and instrumentation of a full-scale laboratory ballasted railway track segment developed to investigate the vertical response of prestressed concrete sleepers under controlled static and dynamic loading conditions.
A primary contribution of the study is the development of a custom multi-channel acceleration data-acquisition system. The adopted instrumentation framework enabled synchronized monitoring of local and global responses, allowing comprehensive assessment of load transfer mechanisms, sleeper deformation characteristics, and vibration propagation through the track system. Preliminary static test results confirmed the structural stability, symmetry, and repeatability of the constructed setup. The observed linear force–displacement behavior, minor residual deformations, and consistent response across sleeper locations validate the robustness of the experimental assembly and its suitability for subsequent dynamic investigations.
The proposed full-scale experimental configuration and instrumentation strategy provide a reliable and reproducible framework for detailed laboratory studies on the mechanical behavior of ballasted railway tracks. The validated setup serves as the basis for the remaining phases of the experimental program, which will focus on dynamic response characterization and the further evaluation of track performance under cyclic loading conditions.

References

[1] Feng, B., Basarah, Y.I., Gu, Q., Duan, X., Bian, X., Tutumluer, E., Youssef, M.A., Huang, H.: Advanced full-scale laboratory dynamic load testing of a ballasted high-speed railway track, Transportation Geotechnics, 29 (2021), 100559

[2] Čebašek, T.M., Esen, A.F., Woodward, P.K., Laghrouche, O., Connolly, D.P.: Full scale laboratory testing of ballast and concrete slab tracks under phased cyclic loading, Transportation Geotechnics, 17 (2018), pp. 33-40

[3] Abadi, T., Pen, L.L., Zervos, A., Powrie, W.: Improving the performance of railway tracks through ballast interventions, Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit, 232 (2018) 2, pp. 337-355

[4] Bian, X., Jiang, H., Cheng, C., Chen, Y., Chen, R., Jiang, J.: Full-scale model testing on a ballastless high-speed railway under simulated train moving loads, Soil Dynamics and Earthquake Engineering, 66 (2014), pp. 368-384