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A review of methods and challenges for monitoring of differential settlement in railway transition zones

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ABSTRACT: Differential settlement in ballasted railway tracks, particularly in transition zones between two track forms, poses a critical challenge for railway infrastructure. Such settlement, often exacerbated by a stiffness gradient due to changes in track superstructure and substructure, typically causes a local dip in the longitudinal track level a few metres from the transition, leading to higher dynamic traffic loading and reduced passenger comfort. Regular monitoring of transition zones is essential for safe operations and cost-effective maintenance. This paper reviews methods for monitoring differential settlement in railway tracks. To measure the properties and loading of the superstructure, potential methods include fibre Bragg grating (FBG) sensors, point receptance measurements, track geometry (and track stiffness) recording cars, and wheel load impact detectors (WILD). Characterisation of the subgrade can be carried out via a multichannel analysis of surface waves (MASW), dynamic cone penetration tests (CPT), interferometric synthetic aperture radar (InSAR), frost sticks for temperature monitoring, and total stations. Lessons learned from an in-situ measurement involving an extensive FBG-based system deployed in northern Sweden to monitor a transition zone in harsh weather conditions are presented. Integrating a combination of monitoring methods with a simulation model to verify and support the accurate prediction of differential settlement is a useful approach to addressing challenges associated with track stiffness gradients and guiding the improvement of transition zone designs.

KEY WORDS: Differential settlement, railway transition zone, condition monitoring, fibre Bragg grating sensors

1 INTRODUCTION

In transition zones between two different railway track forms, there is a discontinuity in the track structure, resulting in a gradient in track stiffness. Examples include transitions between different superstructures, such as slab track to ballasted track, and/or between different substructures, such as an embankment to a bridge or tunnel structure. Differences in the cyclic loading and supporting substructure on either side of the transition may lead to differential settlement of the ballasted track and an irregularity in longitudinal rail level soon after construction due to densification of ballast and consolidation of the subgrade layers. This results in an amplification of dynamic traffic loading along the transition, contributing to the degradation process of the foundation and further deterioration of the vertical track geometry. Historically, the design of transition zones has aimed to minimise the difference in track stiffness between the ballasted track on the embankment and the engineering structure [1–4].

Some researchers argue that the main causes of track deterioration in transition zones are the non-uniform stiffness and damping between different layers of subgrade materials, which are impacted by variations in moisture and other geotechnical factors [5,6]. In a field test conducted in Sweden [7], it was observed that the displacement of sleeper ends varied significantly from one sleeper to the next due to differences in support conditions. This highlights the importance of ballast and subgrade conditions in a railway network.

Various transition zone designs have been implemented to mitigate variations in loading and support conditions. Many of these solutions aim to achieve a gradual and smoother variation in track stiffness from one track form to another. Some approaches are designed to enhance the support of the subgrade, such as transition wedges and approach slabs, while others focus on the superstructure, including the implementation of track components such as wider sleepers, auxiliary rails, and elastic pads (including conventional rail pads with varying stiffness along the transition zone and/or under sleeper pads). A review of transition zone designs can be found in [5,6]. In parallel, advancements in real-time data acquisition, computational techniques, and the emergence of 'big data' approaches have enhanced the analysis and modelling of railway degradation, facilitating more comprehensive and precise evaluations [8].

Increasing frequency of traffic, higher axle loads and train speeds result in quicker deterioration of the infrastructure. Infrastructure managers need up-to-date information on both the current condition (diagnosis) and the expected future state (prognosis) of their assets to effectively plan maintenance and renewal efforts. Structural health monitoring (SHM) has emerged as a valuable tool for railway systems, enabling efficient asset management by providing real-time feedback on the condition of various components. By facilitating early damage detection, SHM enhances structural reliability and reduces life cycle costs. Condition-based maintenance means that system operators schedule maintenance based on the actual condition of the system and the anticipated deterioration rate. To achieve this, operators need to employ a monitoring strategy for recording the condition of their assets. The collected data can serve to develop or create regulations, such as acceptable condition thresholds [6], which are used to determine if maintenance should be performed.

2 LITERATURE REVIEW

Emerging sensing techniques, along with innovations in sensors and data analytics, present exciting opportunities in geotechnical, structural, and railway engineering to enhance the understanding of infrastructure performance during both construction and operation. A monitoring system could, and

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perhaps should, be integrated into the construction package to facilitate long-term, proactive operational monitoring, thereby contributing to quality control, maintenance, resilience against hazards, and reuse. Such a system should include techniques capable of capturing a wide range of data, ranging from low sampling rate parameters such as temperature, humidity, moisture, settlement, and inclination to high sampling rate data including acceleration, noise, rotation, wind velocity, and more.

In railway engineering, monitoring techniques can be categorised into trackside monitoring of both geotechnical and structural elements, onboard monitoring, and inspection. Trackside monitoring involves the use of instrumentation in or adjacent to the track to monitor the track, vehicles passing by, or the interactions between them [9]. For the track, this includes observing the status of various track layers, their geometry, and how they evolve over time [10]. Examples include assessing the condition of ballast and subgrade using methods such as ground-penetrating radar (GPR) [11] and cone penetration tests (CPT) [12]. GPR uses electromagnetic waves to scan and map subsurface features within the railway industry, offering geospatial data on subsurface conditions [13]. To evaluate the stiffness and stratification of the layered substructure at a test site, a multi-channel analysis of surface waves (MASW) can be used [14]. Furthermore, fibre optic sensors can be embedded in the track bed to monitor settlement and detect early signs of degradation and potential landslides in the embankment [15,16]. Research has also been conducted on technologies capable of accurately monitoring the average settlement of railway lines over extensive areas using synthetic aperture radar (SAR) and interferometric SAR (InSAR) techniques [17].

On the other hand, onboard track monitoring and inspection are generally carried out using in-service vehicles, as their regular passing over longer sections of track allows for efficient monitoring of track status. Onboard component monitoring is carried out by instrumentation on vehicles, evaluating their condition over time. Dedicated vehicles are equipped with advanced equipment that enables in-depth inspections, which are vital for railway safety. However, these vehicles require special scheduling and trained personnel, limiting their usage [18]. Measurement units on these vehicles use technologies such as laser imaging, image processing, GPR, ultrasonic sensors, vibration sensors, high-precision accelerometers, and electromagnetic sensors.

Several in situ investigations utilising trackside monitoring have been conducted to assess the dynamic behaviour of railway track using instruments such as accelerometers, strain gauges, and displacement transducers. In [19], results were presented from an extensive monitoring campaign of transition zones (embankment to culvert) in the Netherlands. Vertical displacement at various depths of ballast and subgrade, axle load, and average track stiffness were measured using geophones, uniaxial accelerometers (within the ballast), triaxial accelerometers (within the soil below the track), strain gauges, and a high-speed camera. It was concluded that voided sleepers in the transition zone, due to long-term differential track settlement, were the main sources of large track displacements that caused increased impact loading and accelerated track degradation. Zuada Coelho et al. [12] used CPT and borehole data to consider stochastic variations in support conditions on a network scale in the Netherlands when predicting track settlement using a two-dimensional model.

In [20], a track deflection and stiffness survey was carried out using micro-electro-mechanical-systems (MEMS) accelerometers. About 80 of these devices were placed on successive sleeper ends, primarily on the field side of the track, and then moved along the site during consecutive night-time possessions. This was done in two batches of 200 sleepers with an overlap of 50 sleepers, and measurements were repeated three months apart [21]. Additionally, a webcam mounted on a telescope was positioned at 6 m from the track to reduce the influence of ground vibration. It captured an image of the target, which was mounted on the sleeper for the measurement of peak-to-peak displacement. A key limitation of this method was that the video recording system could monitor the displacement of only one or two sleepers at a time.

Optical fibre sensors offer significant advantages over conventional and other smart sensors due to their high sensitivity, small size, and potential for short- and long-distance measurement. For example, Wang et al. [22] attached two FBG sensors on the rail web as a bi-directional device to measure longitudinal force in a high-speed railway line. Temperature compensation via calibration tests was conducted. Wheeler et al. [23,24] measured rail strains using Rayleigh backscattered, distributed optical fibre sensors. Their field test instrumentation included a 7.5 m long section of rail with nylon-coated single-mode fibres installed on the rail web at 20 mm and 155 mm from the bottom of the rail. The measured rail strains were used to determine shear forces, which, together with the known static wheel loads, were employed as part of the calibration to determine the rail seat loads for 14 consecutive sleepers as the train traversed the instrumented track. These data were then combined with measurements of dynamic rail displacement captured through high-speed imaging using digital image correlation (DIC) to process the rail seat load–deflection relationships for each sleeper.

On-board monitoring techniques have been investigated in research and used in infrastructure management [25]. This leads to better maintenance planning and reduces the delay between decision-making and the execution of maintenance actions. For example, in Finland, ballast degradation due to traffic and freeze-thaw cycles, leading to further particle breakage, settlement, or heaving, has been investigated using track geometry recording cars [26]. In Sweden, vertical track geometry degradation between 1999 and 2016 has been studied using regular monitoring by track geometry recording cars [27,28]. Furthermore, in Switzerland, an on-board monitoring policy is considered in infrastructure maintenance planning [29], and similarly in Australia [30].

This paper presents a review of methods and challenges associated with monitoring of differential settlement in railway transition zones. Specifically, it discusses the results and lessons learned from an extensive measurement campaign conducted under harsh conditions on a heavy haul line in northern Sweden. These measurements included both short-term dynamic and long-term static responses of the transition zone in different sleeper bays, using an FBG-based sensor setup and complementary measurements.

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3 MONITORING AND MEASUREMENT METHODS

Monitoring in a railway transition zone may involve numerous sensor types and measurement techniques, such as seismic, electrical, electromagnetic, and resistivity methods in geophysics. Brief descriptions and definitions of some of these are presented below. In Section 4, the practical use of many of these techniques will be discussed with reference to the challenges encountered during an extensive field test recently carried out in a transition zone on Malmbanan in northern Sweden.

3.1 MASW

The Multi-channel Analysis of Surface Waves (MASW) method is a cost-effective and non-destructive geophysical technique used to evaluate subsurface conditions (and to determine the location of bedrock) by analysing the propagation of surface waves, particularly the dispersion of Rayleigh waves. It provides shear wave velocity profiles down to a depth of up to 20 m, which are used to obtain small-strain stiffness and damping properties of the soil [31].

In this specific field test, an excitation source, such as a sledgehammer, weight drop, or specialised loading device, generates surface waves. An array of geophones, typically ranging from 12 to 48, is placed in a straight line on the ground at regular intervals. These geophones detect and record the waveform and arrival time of the seismic waves. The Rayleigh waves exhibit dispersion, meaning their velocity changes with frequency due to variations in subsurface material properties. Lower-frequency waves penetrate deeper into the ground, while higher-frequency waves provide information about shallower layers [31]. Typically, earth models are formulated using CPT data to distinguish the number of soil layers and provide a reasonable estimation of soil density. Consequently, shear wave velocity is fitted to the data at smaller strains.

3.2 CPT

The Cone Penetration Test (CPT) is a geotechnical investigation technique to provide a detailed soil profile by assessing the mechanical cone resistance of different layers of subgrade soils. The cone resistance is directly linked to the strength of the soils, and empirical relations are established to identify the soil type [32]. The data obtained from a CPT aids in designing track foundations, evaluating ballast and sub-ballast layers, and identifying soft soil layers that could lead to settlement or instability [32]. However, the density of data per square kilometre in railway infrastructure is generally relatively low due to the high cost of these boreholes [12].

The test is conducted by jacking or driving a steel cone into the ground at a controlled rate while continuously measuring cone resistance. Two primary types of CPT are used: Static Cone Penetration Testing (SCPT) and Dynamic Cone Penetration Testing (DCPT). In SCPT, the cone is jacked into the soil at 1 – 2 m intervals at a constant rate using a hydraulic system. This method records key parameters such as (1) cone resistance, which indicates soil strength, (2) sleeve friction, which helps to determine soil type, and (3) (excess) pore water pressure, which provides insights into soil drainage and consolidation behaviour. SCPT is frequently used in railway infrastructure to investigate embankment stability.

In DCPT, a steel cone is driven into the ground using a standardised weight dropped from a specified height. The number of weight drops required to penetrate a specific depth is recorded, providing an estimate of soil resistance and compaction quality. DCPT is widely utilised in ballast and subgrade assessment, as well as rapid evaluations of soil stability [32]. The data from CPT or MASW tests can be used to estimate dynamic subsoil stiffness and damping along the track using analytical approaches, such as the cone method from [33] and the analytical formulae in [34].

3.3 GPR

Ground-Penetrating Radar (GPR) is a non-destructive electromagnetic geophysical technique used to investigate and analyse subsurface structures. These systems can be mounted on track geometry recording cars, enabling continuous data collection at operational train speeds. This allows infrastructure managers to efficiently assess large sections of the track network and make data-driven decisions for maintenance planning. GPR operates by emitting electromagnetic waves (EM) into the ground and measuring their reflections using a receiving antenna to identify issues such as ballast fouling, moisture intrusion, and subsurface voids, as these can be linked to changes in electrical impedance [13]. GPR functions within a finite frequency range where the velocity and attenuation of the EM wave are independent of frequency (typically 1 MHz – 1 GHz) [13].

The receiving antenna captures the reflected signals, and the system measures the time delay and amplitude of these reflections. This data is then processed and visualised in radargrams, in the form of black-and-white, or coloured, waves and patterns, each corresponding to the radar signals reflected by different underground materials. These radargrams enable engineers to analyse subsurface conditions, detect hidden defects, and determine the thickness of different layers. The frequency of the radar waves plays a critical role in determining both the resolution and depth of penetration. High-frequency waves, typically above 1 GHz, provide detailed images but can only penetrate shallow depths, making them ideal for inspecting ballast conditions. Lower-frequency waves, in the range of 100 – 500 MHz, penetrate deeper but offer lower resolution, making them more suitable for analysing subgrade and deeper structural layers. Water-saturated or clay-rich soils tend to absorb radar waves, limiting penetration, while dry, coarse materials like gravel or sand allow for better wave transmission [13].

3.4 InSAR

Interferometric Synthetic Aperture Radar (InSAR) is a remote sensing technique that uses satellite-based radar imagery to measure ground surface deformation with millimetre-level precision. By analysing the phase differences between radar signals captured at different times, InSAR provides detailed information about land subsidence, uplift, and ground movement [32,35]. The precision of this technique is of the order of 3 – 5 mm.

3.5 FREE AND FORCED VIBRATION

Point receptance analysis in railways is a testing technique used to assess the dynamic properties of track by measuring its response to applied forces. A sledgehammer with a steel tip, or

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a falling weight of 8 kg, has been used in free vibration tests to generate an excitation impulse on the rail [36]. In a forced vibration test, a hydraulic actuator generates linear frequency sweeps with constant load amplitudes to stimulate various natural frequencies of a structure, such as a bridge [37]. The resulting accelerations are recorded using accelerometers or laser Doppler vibrometers at different positions, and the data is processed to compute Frequency Response Functions (FRFs). Measured FRFs can then be compared with corresponding calculated FRFs from a simulation model to identify the stiffness and damping of different parts of the structure [38].

3.6 PERMANENT DISPLACEMENT, SETTLEMENT

Various tools and instruments are available for measuring and monitoring settlement in track layers. These include the Multi-Depth Deflectometer (MDD), which is embedded in the track bed, uniaxial and triaxial accelerometers [39], settlement plates paired with total stations, vibrating wire-based measurement systems, liquid level sensors, inclinometers, Linear Variable Differential Transformers (LVDTs), Global Navigation Satellite Systems (GNSS), and FBG sensors.

The MDD is specifically designed to assess the mechanical response and deformation of soil layers. It is widely used at railway track sites to evaluate soil stiffness and condition. Primarily, the MDD serves as a reliable tool for accurately measuring the permanent deformation of different pavement layers. Additionally, it facilitates the calculation of the effective elastic moduli of multilayered pavement structures based on the collected data [40].

The LVDT is a displacement sensor used to detect linear movements in both the short and long term. It is commonly applied in railway infrastructure to monitor the displacement of components, such as sleepers, rails, bridges, and slabs [15].

A total station is an advanced electronic and optical instrument designed for precise measurement of angles, distances, and coordinates. In railway applications, it plays a crucial role in ensuring accurate track alignment, calculating gradients, and maintaining track conditions by detecting deviations and elevation changes [15].

The GNSS utilises satellite signals to determine the position of objects on Earth. It operates through a network of orbiting satellites that transmit signals to ground receivers, which process the timing and strength of these signals to compute position, altitude, and velocity. In railway systems, GNSS is used for continuous real-time monitoring of track settlement, enabling a better understanding of foundation changes at different stages and enhancing railway safety [41,42].

3.7 BALLAST INSPECTION

Ballast degradation occurs when fine materials or fouling agents accumulate in the spaces between ballast particles. This fouling can result from ballast fragmentation, contamination from external elements, or the infiltration of fines from the subgrade soil. Over time, as ballast continues to age, it becomes increasingly affected by fouling and degradation due to particle breakage and surface wear. These processes contribute to inadequate drainage, excessive settlement, track misalignment, and diminished lateral stability, all of which negatively impact railway track performance. In severe cases, excessive ballast degradation can lead to operational disruptions and safety risks [43]. Assessing ballast conditions typically involves visual inspections, manual measurements, and field sampling, which is often followed by sieve analysis. Additionally, automated methods such as the Ballast Scanning Vehicle (BSV) have been introduced to enhance evaluation processes. The BSV is capable of capturing field ballast images, video footage, and 3D height maps from both plan and depth profile perspectives, enabling a thorough assessment of ballast conditions [44].

3.8 WILD

Wheel flats and other forms of wheel out-of-roundness can be detected through acoustic or visual inspections, or by measuring vertical wheel–rail contact forces using wheel impact load detectors (WILDs). These detectors help operators monitor force levels, enabling proactive maintenance to prevent excessive wheel out-of-roundness. Commercial WILD systems use various types of sensors, including strain gauge circuits, fibre optic technology for measurements of rail bending, and load cells for rail seat loads [45].

3.9 FROST DEPTH

Extreme weather conditions in northern European countries may lead to recurrent issues with freeze-thaw cycles and seasonal variations in track geometry. Frost depth can be measured using frost sticks [15].

3.10 TRACK GEOMETRY AND TRACK STIFFNESS RECORDING CAR

Track geometry recording cars are specialised rail vehicles equipped with advanced measurement systems such as laser profilometers, accelerometers, and ultrasonic sensors. Track geometry is evaluated based on band-pass filtered indicators, such as longitudinal level, horizontal alignment, cant, curvature, gauge, and twist. These indicators are assessed based on the specific wavelength intervals defined in EN13848-5, see Table 1 [46].

Table 1. Wavelength ranges according to EN 13848–5[46].

Longitudinal level	Wave type	Wavelength range (m)
D_0	Short wave	1 – 3
D_1	Mid wave	3 – 25
D_2	Long wave	25 – 70

3.11 POINT MEASUREMENTS

Strain gauges (traditional or FBG-based), accelerometers, and contact pressure cells [39] are widely used in railway measurements to monitor track and vehicle dynamics, ensuring safety and performance. Strain gauges are installed on rails, sleepers, and train components to assess strain, stress, load distribution, and deformation under varying operational conditions.

4 CASE STUDY: THE GRANSJÖ TEST SITE

In 2022–2023, an extensive field measurement campaign was carried out in a transition zone at *Gransjö*, north of Boden, on the Swedish heavy haul line *Malmbanan* [15]. The transition zone was between a conventional ballasted track on embankment and a Moulded Modular Multi-Blocks (3MB) slab track. An FBG-based long-term monitoring arrangement, with a high temporal resolution, was used for both short-term and long-term condition monitoring of the operational railway track in the harsh conditions of northern Sweden. The test set-

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up was limited to measuring the response in four selected sleeper bays.

Figure 1. An overview of the test site including a transition zone between ballasted track and 3MB slab track at Gransjö, north of Boden, Sweden.

4.1 TEST SITE

Traffic on the line is dominated by iron ore freight trains with axle loads up to 32 tonnes, operating from the mines in Kiruna and Malmberget to the ports in Narvik and Luleå. The speed of the loaded heavy haul trains is 60 km/h. The line is also used by passenger trains at maximum speed 135 km/h and by other freight trains. The annual traffic load is of the order of 14 MGT (mega gross tonnes).

The track design includes 60 kg/m rails, rail fastenings with 10 mm rubber rail pads, and concrete sleepers designed for axle loads of 35 tonnes at a sleeper distance of 0.6 m. The 3MB track at Gransjö was constructed in September 11 – 15, 2022, as part of the Horizon 2020 Shift2Rail EU project In2Track3. [15]. It was decommissioned in August 2023, see Figure 1.

4.2 GEOTECHNICAL SURVEY

Prior to the construction of the 3MB track, geotechnical tests in the form of CPT and MASW were conducted to determine the stiffness and stratification of the layered substructure. The results indicated that the subgrade at the site consists almost exclusively of moraine, mixed with large blocks of rock, with a maximum depth of 5 m to bedrock [47]. The embankment height varies between 2 and 2.5 m. Due to years of maintenance involving tamping and re–ballasting of the track, the thickness of the ballast layer (nominally 30 cm) has increased to 80 cm. This necessitated additional excavation depth to remove the ballast layer (and large blocks) during the construction of the 3MB slab system.

In the MASW survey [47], the dispersion of Rayleigh waves on the ground surface, acquired using vertical geophones, was used for the interpretation of small strain shear stiffness. See Figure 2 for an example of measured distribution of wave speed in a cross-section of the subgrade at the test site.

Track geometry was measured using a track geometry recording car. For reference, in another study conducted on Malmbanan, track geometry car recordings from 1999 to 2016 were analysed to investigate rates of vertical track geometry degradation. This analysis indicated some correlation between track stiffness gradient and differential settlement, providing insights into how variations in substructure stiffness can lead to local track irregularities. As expected, it was concluded that the settlement rate along Malmbanan varies significantly depending on the local conditions and properties of the subgrade. For a poorly supported section of the track, the standard deviation of the longitudinal level (1 – 25 m), evaluated over a 50 m track segment, increases by approximately 1 mm per annum [27,28].

Track stiffness at rail level, measured using the same track geometry recording car before and after construction of the 3MB track, is presented in Figure 3. A large gradient in stiffness is observed at either end of the 48 m slab track. The mean value of the track stiffness is particularly low for the slab track due to the softer elastic pads and the poor compaction of the backfill material after the excavation carried out during construction.

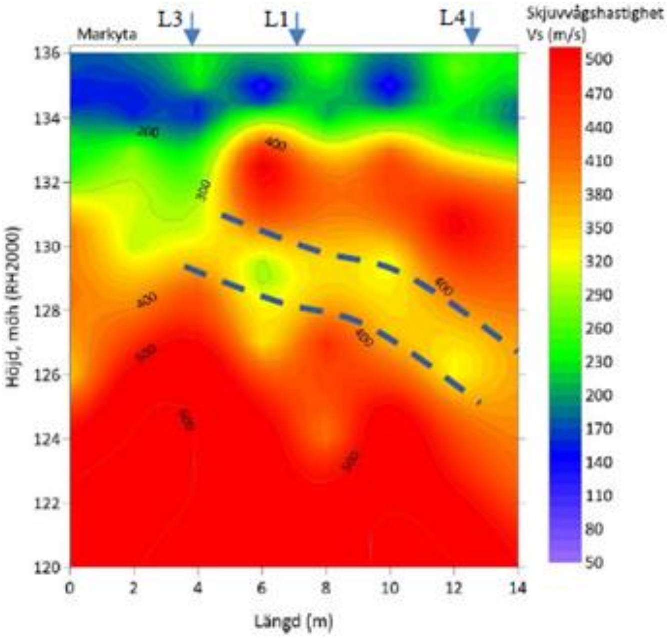

Figure 2. An example of measured shear wave speed distribution of layered soil at the test site [47].

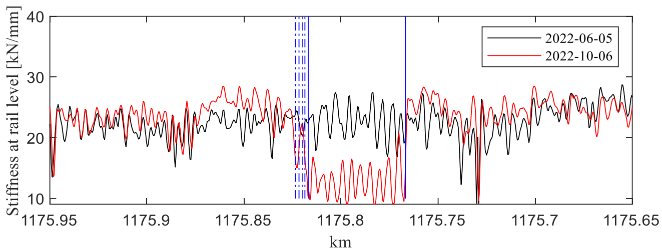

Figure 3. Track stiffness at rail level for ballasted track on embankment, two transition zones, and 48 m of slab track at Gransjö, measured by a track geometry recording car before and after construction. Blue vertical solid lines indicate the positions of two transitions (slab ends). Blue vertical dashed-dotted lines show the positions of instrumented sleepers 3, 5, 8, and 11, numbered from the slab.

4.3 FROST DEPTH AND INSAR

The extreme weather conditions at the test site, with temperatures down to -40°C during the winter and relatively warm summers, result in recurrent issues associated with freeze-thaw cycles and seasonal variations in track geometry.

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The Swedish Transport Administration monitors frost depth using frost sticks, which record the temperature in the subgrade at various levels down to a depth of a few metres, thereby generating a temperature profile. The variation in frost depth over a period of eight months, recorded at a station near the test site, is shown in Figure 4. It is observed that prior to the end of October 2022, the ground was not frozen at all. By mid-December 2022, the ground had commenced freezing gradually down to a depth of 2 m. From mid-December 2022 until the beginning of May 2023 more than 2 m of the ground remained frozen.

Frost penetrating to a certain depth may induce the expansion of the subgrade, resulting in ground uplift. This phenomenon, known as frost heave, poses a significant issue on Malmbanan. To evaluate the average settlement at the test site, InSAR data was used, providing the average settlement over a specified surface area at various times. It was found that the average settlement at a track point near the test site is about 1 – 2 mm per year [31], see Figure 5.

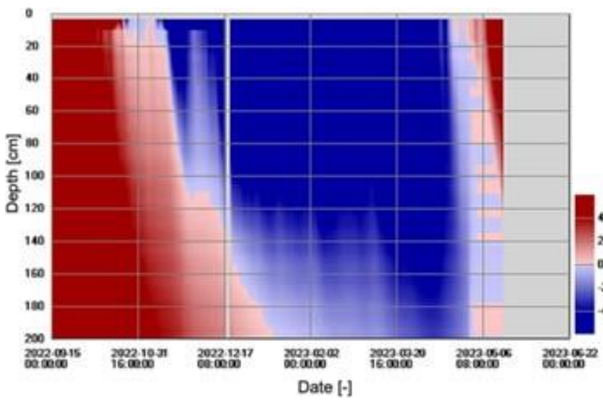

Figure 4. Temperature profile of subgrade down to 2 m depth at a measurement station near the test site [15].

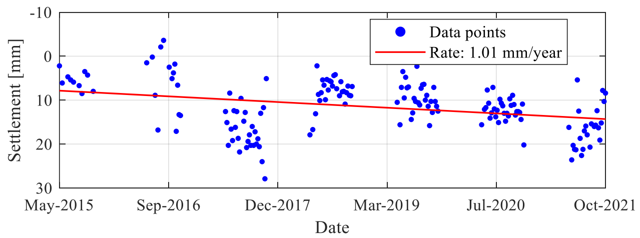

Figure 5. An example of InSAR long-term settlement measurements at a track point near the Gransjö site, covering the period from 2015 to 2021 [48]. Positive settlement numbers indicate downward permanent displacement.

4.4 TRAFFIC LOAD

Information regarding traffic loading is crucial for evaluating railway infrastructure. In this campaign, data from a nearby wheel impact load detector was used to assess the range of mean wheel–rail contact forces for a specific train passage traversing the test site [15].

Additionally, to evaluate the influence of the stiffness gradient and to detect potential voids beneath sleepers, the wheel–rail contact force was measured within the transition zone. Temporary electrical strain gauges were used to measure the contact forces in sleeper bays 3, 5, and 8 from the transition. A Wheatstone bridge comprising two waterproof strain gauges, each with a sensing area of 6 mm × 2.2 mm, was glued to the neutral axis of the rail within a specified span between two adjacent sleepers, oriented at ±45° relative to the horizontal and vertical coordinate axes, see Figure 6. Shear deformations of the rail web were measured on two occasions, with a six-month interval.

It was concluded that the wheel–rail contact force in sleeper bay 3 was higher than in sleeper bays 5 and 8. The higher load could be attributed to vehicle dynamics when traversing the transition between two track forms with a stiffness gradient and potentially voided sleepers on the ballasted side. Consequently, the greater settlement of sleeper 3 could be a result of the higher loading. Additionally, it was observed that the wheels were generating forces, on average, about 5 kN higher in May 2023 than in October 2022 due to the evolving irregularities in the longitudinal level along the transition. The magnitude of forces derived from WILD data for the same train was consistent with the measured wheel–rail contact forces.

Figure 6. Full Wheatstone bridge mounted on the neutral axis of the rail web

4.5 TRACK FORM DYNAMICS

Vertical point and cross receptances (frequency response functions) of both track forms were measured by exciting the rail using an instrumented impact hammer and recording the track response with accelerometers. The rail was excited either above a rail seat or at the centre of a sleeper bay. Apart from the hammer excitation, the track was in unloaded conditions. Accelerations were measured at locations sufficiently far from the transition to mitigate any boundary effects resulting from the change in track form.

For the ballasted track, see Figure 7, three resonance peaks can be observed in the measured receptance at 30, 290, and 950 Hz. The first peak corresponds to a vertical in-phase vibration of the rail and sleepers, characterised by high damping due to the propagation of waves in the ballast and subgrade. The second peak corresponds to an out-of-phase motion between the rail and sleepers, influenced by the flexibility of the rail pads. The third peak represents the pinned-pinned resonance mode, which is a vertical bending mode with a wavelength twice the sleeper span.

4.6 SHORT-TERM TRACK RESPONSE

The instrumentation setup included sensors for measuring axial rail strains to assess rail bending moment and rail seat load, vertical sleeper displacement, and vertical acceleration at the sleeper ends. The setup consisted of four clusters placed in sections between two sleepers in sleeper bays 3, 5, 8, and 11, numbered from the transition. Each FBG-based cluster consisted of one accelerometer, one displacement transducer, and one strain array with four strain gauges. In total, 30 FBG sensors were installed. Aluminium covers and cable conduits

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were added to protect the sensors and cables from mechanical damage and harsh weather conditions.

The interrogator was housed in a heated cabinet to maintain operational temperatures (0 – 60 °C) and positioned near a power source and data connection. Additional site equipment included a field computer, hard drive, junction box, temperature sensors, thermostat, fan, 4G antenna for backup, and a network switch. The interrogator continuously recorded sensors data at a 2 kHz sampling rate, distributing data via a network socket to a computer. A custom LabVIEW-based program, FemtoGateway, processed and stored the data locally before synchronising it with a server at Chalmers.

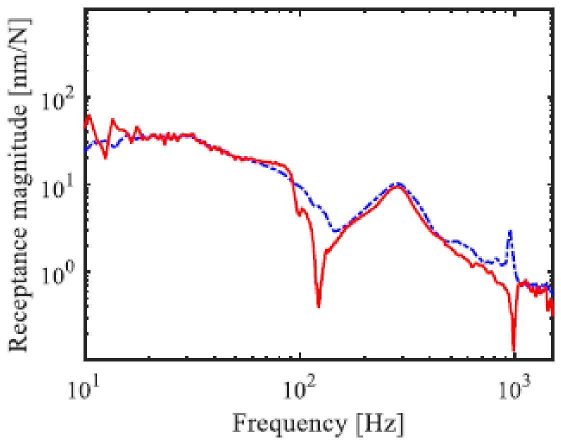

Figure 7. Magnitudes of measured rail receptances for the ballasted track. Vertical hammer excitation on the rail at midspan. Response measured on the rail at midspan (point receptance shown using a blue line) or on the rail at railseat (cross receptance shown using a red line).

Figure 8. Overview of the four clusters (C1 – C4), and strain sensor numbering for each cluster.

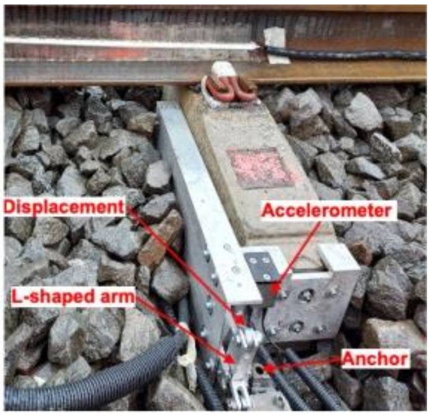

Figure 9. Detail of an instrumented sleeper equipped with a vertical base plate, an L-shaped mechanism, one accelerometer and one displacement transducer.

Axial rail strains were measured using strain gauges at the positions indicated in Figure 8. Based on the measured strains and assuming Euler-Bernoulli beam theory, examples of the evaluated time histories of rail bending moment above sleepers 5 and 11 for part of a loaded iron ore train are shown in Figure 10. Each peak corresponds to a passing axle. It is observed that the rail bending moment above sleeper 11 is higher than that above sleeper 5, indicating that sleeper 11 has softer support conditions. This was confirmed by comparing the corresponding measured sleeper displacements.

Based on the elongation of the displacement transducer, the vertical displacement of the sleeper was measured relative to a fixed anchor embedded deep into the ground (fixed reference), as indicated in Figure 9. Additionally, vertical accelerations were measured using six FBG-based accelerometers. Five of these were placed at the sleeper ends (3, 5, 8, 11, and 31), while one was positioned on the first block on the slab track side.

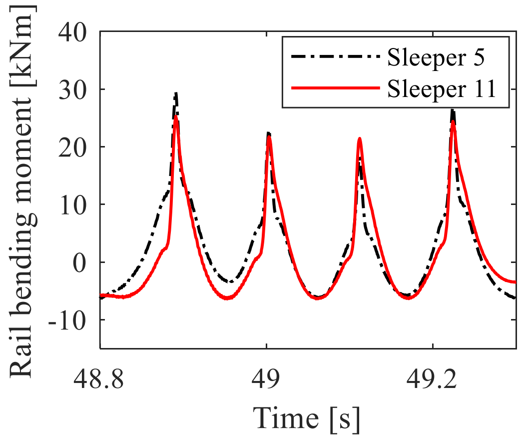

Figure 10. Rail bending moment above sleepers 5 and 11 along the transition.

4.7 *LONG-TERM TRACK SETTLEMENT*

Permanent displacements of the track structure were determined by extracting the at-rest positions of the instrumented sleepers from intervals between train passages. The resulting long-term track settlements for sleepers 5 and 11, evaluated over a period of about 11 months, including one winter, are shown in Figure 10. It is observed that the initial settlement rate immediately after the installation of the slab track and transition zone was very high, but it slowed down after a few weeks of traffic. For sleeper 11, there was a reversal in the permanent displacement during the winter due to frost heave.

To verify the trend in measured permanent sleeper displacements, a sleeper level survey was conducted using a Trimble SX12 self-levelling, automatic-scanning total station with an active prism. The survey was carried out on six occasions over a period of ten months. Overall, the long-term sleeper displacement data aligned well with the total station survey results for the ballasted track until the end of December. Subsequently, the relative measurement from the FBG system, which was referenced to a ground anchor, indicated less upward movement of sleeper 5 due to frost heave compared to the total station survey results. This discrepancy may be due to the short (2 m) length of the anchor that did not extend below the frozen ground layers, see Figure 4. To obtain a fixed

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reference, longer anchors extending beneath the frozen layers would have been necessary. For sleeper 11, the total station survey results were consistent with the relative track displacement measurements since the anchor length exceeded 4 m.

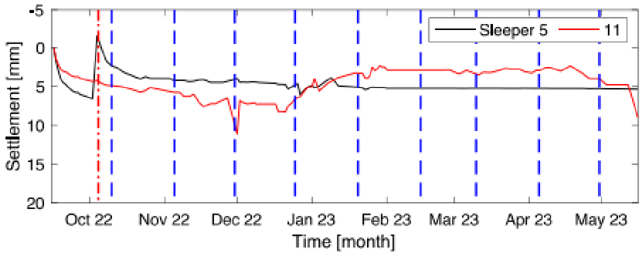

Figure 11. Evolution of permanent sleeper displacement (settlement) over time for sleepers 5 and 11. Sleeper 5 was tamped after 20 days of operation.

The Swedish Transport Administration utilises frost sticks to monitor frost depth. These instruments are capable of measuring temperature profiles to a depth of a few metres. Based on these measurements it was concluded that the ground remained unfrozen until late October, at which point it gradually froze to a depth of 2 m by mid-December. This depth was exceeded until early May 2023, cf. Figure 4. As air temperatures declined below -10 °C and frost depth exceeded 2 m, sleeper settlement at positions 5 and 11 ceased and initiated a reverse process. This indicated that frost heave was the probable cause of this uplift.

5 CONCLUSIONS AND LESSONS LEARNED

In this paper, various methods for measurement and monitoring of differential settlement in railway infrastructure have been reviewed. The case study presented, conducted in a transition zone between ballasted track and a short demonstrator section of 3MB slab track at Gransjö on Malmbanan, aimed to integrate existing data, such as geotechnical surveys and InSAR measurements, with observations from an extensive FBG-based instrumentation system that captured both short-term dynamic track responses and long-term static settlements (permanent displacements) of selected sleepers.

Given the sensor requirements, harsh weather conditions at the test site on Malmbanan, operational railway track with heavy haul train traffic, and budget constraints, FBG sensors were selected. This system reduced the installation time, which was critical due to the narrow installation window during the construction of the 3MB slab track. Another benefit was the simplified routing of optical cables, allowing the interrogator to be placed in a heated cabinet to maintain operational temperatures (0 – 60 °C), as well as to be near the available power source and data connection provided by the track owner.

FBG-based sensors have a higher initial cost than traditional sensors but offer superior performance, including multiplexing capabilities, reduced installation complexity, and greater durability in harsh environments. Their high sensitivity and immunity to electromagnetic interference enhance reliability, making them a more efficient and sustainable choice for advanced monitoring applications despite the higher upfront investment.

The measured data have been used for a long-term assessment of the transition zone and the new slab track design, as well as for the calibration of track models for further simulation studies [38]. It was concluded that most implemented sensors performed reliably. The FBG-based strain gauges enabled the setup to successfully detect the type of vehicle, train speed, and the number of axles in each train. The spatial and temporal resolution of the observed rail curvature distribution were found to be sufficient for analysing rail bending moments.

A considerable variation in measured displacements between the selected adjacent sleepers in the transition zone was observed. These displacements depend on the initial and evolving support conditions of each sleeper and their distance from the transition. For example, sleeper number 3, located near the transition, became voided shortly after installation, while sleeper 8 appeared to be supported by a very stiff foundation, leading to minimal settlement. Good agreement was observed between the displacement data from the FBG sensors and the total station survey.

Unfortunately, the conditions and available time window during the construction of the transition zone and slab track at Gransjö were far from optimal. The excavated volume of ballast and subgrade was replaced with insufficiently compacted backfill material before the construction of the slab, leading to significant settlement of the slab track soon after installation. Due to the excessive settlement of the slab track, the fasteners on the slab side had to be adjusted to their desired height by sliding shims after 20 days of operation. At the same time, the first six sleepers on the ballasted side were tamped to restore the longitudinal level. Still, the substantial settlement of the slab track continued, albeit at a lower rate. This had a significant effect on the support conditions also for the sleepers near the transition, particularly indicated by the measured short-term displacements and settlement of sleeper 3.

The signal-to-noise ratio of the acceleration data was too low because the delivered accelerometers were designed to measure higher acceleration levels than anticipated, preventing the use of the acceleration data for reconstructing sleeper displacements [49]. This issue could not be resolved, as the sensors were deployed in clusters, and replacing them in the field was not feasible. To address this issue, it is recommended to implement more rigorous quality control tests prior to installation.

Furthermore, based on Euler-Bernoulli beam theory and the measured difference in rail bending moment across the width of the rail pad [23], the plan to evaluate time histories of rail seat loads failed due to inconsistent data from different strain gauges.

The test site was distant from the university, leading to high travel costs in the event that anomalies needed to be addressed during the measurement period. For example, the displacement sensors and anchor arrangements needed adjustments on a few occasions due to the unexpectedly high levels of settlement. The measurements were conducted during winter, with heavy snowfall and low temperatures, which further complicated access to the sensors and made the process more challenging.

Nevertheless, it is argued that the combination of the described FBG-based test set-up (improved with accelerometers with higher signal-to-noise ratio and more

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consistent strain data) with existing geotechnical and traffic load data is a powerful approach that can be employed by infrastructure managers to justify, test, and evaluate transition zones and new track designs across their network.

This study has focused on the heavy haul track on Malmbanan in northern Sweden, but insights discussed here are relevant to railways operating in other climates. Accurate monitoring of differential settlement in railway infrastructure is a common challenge worldwide, regardless of the type of loading and climate. It is argued that elements of the setup used here will assist infrastructure managers across the network in justifying, testing, and assessing new track designs.

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