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A Self-Levelling railway sleeper concept and its large-scale testing

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ABSTRACT

Railway track transition zones present engineering challenges due to their abrupt change in stiffness between structural elements such as embankments, bridges and tunnels affecting track geometry parameters. Although a variety of stiffness-based remedial measures have been widely applied, their implementation can be constrained by high capital cost, operational disruption, and the complexities associated with modifying the substructure. As a result, interventions in practice commonly focus on controlling permanent deformations and differential settlement, particularly related to the development of hanging sleepers. Thus, this study investigates the use of modular self-levelling sleepers (SLS) as a solution. To do so, two concept SLS systems are designed and developed: one employing a granular mechanism (SLS-G), and the other based on a horizontally acting wedge mechanism (SLS-HW). Both variants use the polymeric sleepers and are designed for compatibility with conventional ballasted track systems. Experimental laboratory testing is undertaken, and it is found that the SLS prototypes were able to restore the sleeper-ballast contact for voids up to 40 mm depth, while stress measurements at the interface indicated improved load distribution under the rails. The findings support the proof-of-concept that self-levelling sleepers have the potential to be a modular, low-disruption solution for mitigating track geometry degradation and reducing maintenance requirements at transition zones.

Introduction

Transition zones are sections of railway tracks where there is an abrupt change in track support stiffness, leading to a deterioration of vertical track geometry and even damage to the track components [1,2]. The problems associated with transition zones can be complex and can have different root causes. Two important variables at transition zones are track level and track stiffness, which can lead to increased dynamic forces when trains pass over them. In the longer term, these dynamic forces lead to accelerated track deterioration and additional demand for maintenance. In particular, hanging sleepers in transition zones cause significant disruptions. This happens when sleepers lose support from the underlying layers, causing uneven load distribution, accelerating track deterioration, and requiring more frequent maintenance to maintain acceptable track geometry. If hanging sleepers can be prevented at transitions, then the rate of deterioration will be greatly reduced.

Transition zones require frequent maintenance to ensure passenger ride comfort and avoid speed restrictions, resulting in high maintenance costs [3]. According to Sasaoka and Davis [4], US railways spend $200 million annually on track transition maintenance, while in Europe, the cost amounts to €85 million [5]. Hence, transition zones offer an opportunity to reduce maintenance costs in railway infrastructure. Over the years, various countermeasures have been proposed and implemented to address the problems encountered in transition zones [6,7].

The terms “open track” and “approaching zone” refer to the main components of the transition zone as illustrated in Fig. 1. Open track is the part ahead of the transition zone that is relatively far from the engineering structure and remains unaffected by its presence. The approaching zone is located close to the engineering structure and suffers from settlements in case of a poor performance of a transition zone. The engineering structure can be a bridge, culvert, tunnel or a level crossing.

Improvements for transition zones have been categorised in different ways in the literature. For instance, Sañudo et al. [6] grouped the solutions based on the location of the structure where the improvements

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are made: *(i)* substructure (subgrade), *(ii)* superstructure (rail, rail-pad, sleeper, ballast, sub-ballast), and *(iii)* mixed solutions combining *(i)* and *(ii)*. On the other hand, Kerr and Moroney [8] classified the remedies based on their main objectives which are five remedial actions: *(i)* smoothing the stiffness difference between the open track, approaching zone, and structure, *(ii)* reducing stiffness at the structure, *(iii)* improving the track foundation, *(iv)* limiting differential long-term displacements between the approaching zone and the structure, and *(v)* applying miscellaneous remedies. These categories are interconnected; for example, measures that smooth stiffness changes *(i)* or improve the foundation *(iii)* often help to reduce long-term displacements *(iv)*. Wang and Markine [1] divided the countermeasures for transition zones based on their application period, either preventive (design stage) or corrective (operation stage). In practice, multiple objectives are frequently addressed together. The present review focuses on solutions that can be applied without extensive reconstruction, as deep ground treatments are generally limited to the design stage.

Transition zones require carefully designed standards to ensure operational safety and efficiency, yet international guidelines remain underdeveloped, with current practices largely drawn from European Standards (EN), Dutch (OVS – Ontwerp Voorschrift Spoorbouw, PVE – Programma van Eisen), Czech (ČSN – Česká státní norma), Hungarian (MÁV Zrt. – Magyar Államvasutak Zártkörűen működő Részvénytársaság), and British (BS – British Standards) regulations [9]. These standards focus on four key areas: track geometry, transition zone geometry, train characteristics, and substructure requirements. Track geometry guidelines limit residual settlement (both differential and uniform) to prevent disruptive slopes and enforce alignment rules, such as curvature radius and rail inclination, linked to train speeds. Transition zone length is determined by maximum train speeds and permissible height differences between track segments. Train characteristics emphasise passenger comfort through a ride comfort index (calculated from vertical, lateral, and longitudinal accelerations) and dynamic axle load limits to avoid excessive stress. Substructure standards mandate subgrade stiffness and strength, tested *in-situ*, and prescribe construction methods like transition wedges or approach slabs, which vary regionally. While specific technical values differ by country, the core principles, controlling settlement, aligning geometry with speed, ensuring ride comfort, and maintaining substructure integrity, are universally applicable. The paper highlights these requirements but notes that broader regulatory frameworks for transition zones remain outside its scope.

Traditionally, the design of transition zones has focused on minimising the difference in track stiffness between the transition zone and the engineering structure. This is typically achieved by gradually increasing or decreasing stiffness along the transition zone. Various techniques have been developed to ensure a smoother stiffness transition, with specific methods recommended based on track requirements and regulatory standards. To achieve this transition, the stiffness of the upper railway track structure can be adjusted, or track foundation improvement methods can be used to distribute loads more effectively and enhance bearing capacity. However, deep soil modifications are impractical and must be incorporated at the design stage. In contrast, remedial measures targeting permanent deformation can be implemented without major reconstruction, allowing upper structure modifications to address differential settlement issues.

Before adopting a mitigation technique, it is crucial to first assess the severity of the problem, identify its underlying cause, evaluate suitable mitigation methods, and implement and monitor the chosen solution. When determining the cause, it is essential to quantify the contributions of differential track level and stiffness changes while considering their variations over time. This ensures the selection of an effective mitigation technique that directly addresses the specific issue.

This paper is organised as follows: Subparts in Section 1 present transition zone solutions and existing self-levelling technologies. Section 2 describes the development of self-levelling sleepers in this research. Section 3 outlines the experimental work, including the test setup, testing methodology, and data acquisition process. Section 4 presents and discusses the results. Finally, the last section summarises the key findings of this study and provides the main concluding remarks.

Stiffness-Based Remedial Measures

Several remedial measures have been proposed to address the stiffness differential among the open track, the approaching zone, and the superstructure. Transition zone with a wedge shaped backfill made of compacted layers of bound and unbound materials, so that a gradual transition from soft to stiff track sections can be achieved [10,11,12]. One must note that, this solution requires reconstruction of the track section, rather than a remedy for an existing track, thus, this solution is recommended during design process. Another approach involves modifying the dimensions and spacing of sleepers, notably by gradually increasing sleeper length to adjust stiffness. This technique is strongly

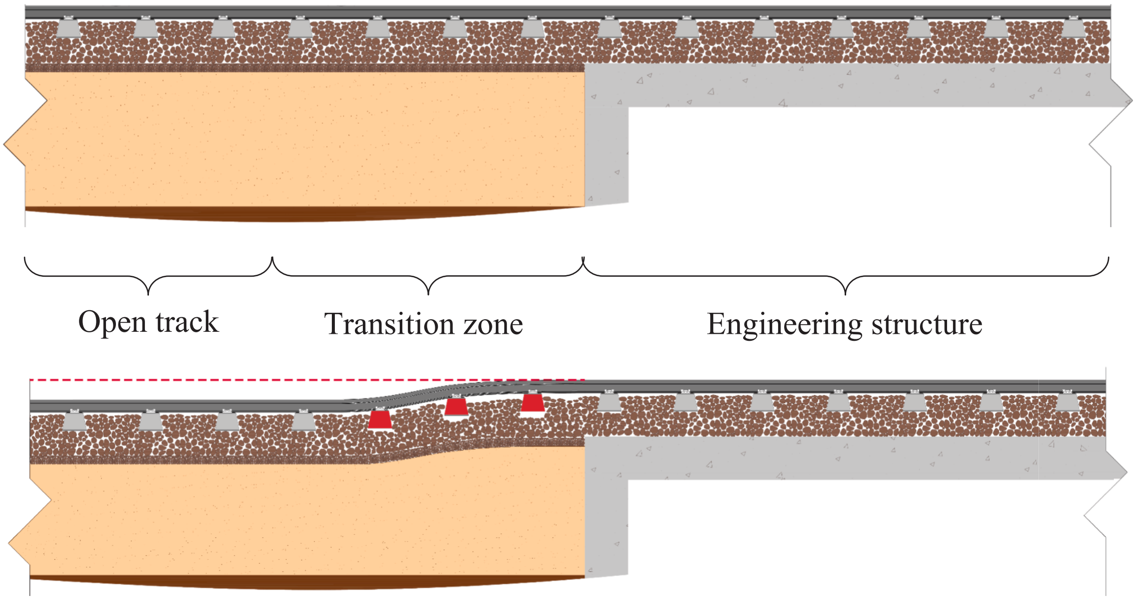


Fig. 1. Transition zone: schematic diagram of its components.

dependent on the uniformity and compaction of the ballast [13,14] and can be implemented on existing track infrastructure as a modular solution. Another method employs concrete approach slabs, which consist of reinforced concrete elements installed horizontally with a designed inclination to facilitate a smooth transition [15,16]. This solution, however, necessitates track reconstruction and is ideally incorporated during the design phase. A further solution is the use of a ribbed transition plate; a reinforced concrete element developed for the Hungarian State Railways (MAV Zrt.). This method is similarly recommended during the design stage rather than as a retrofit.

In terms of reducing stiffness within the superstructure, employing rail pads, under-sleeper pads (USPs), ballast mats, and baseplate pads allows for controlled variations in stiffness [17]. Additionally, sleepers fabricated from composite, plastic, or rubber materials have proven effective in achieving smooth transition zones [13,18]. The addition of extra or auxiliary rails, either placed between or adjacent to the main rails in the ballasted track section of the transition zone, serves to increase stiffness. This measure is considered a moderate remedy for tracks exhibiting low stiffness values [19,20]. These strategies offer modular solutions applicable to existing tracks.

Enhancing the track foundation is critical for distributing loads over the subgrade and embankment soils and for reducing peak stresses. This objective can be met through hydraulic, mechanical, and reinforcement methods designed to improve the load-bearing capacity of the embankment soils [6,21]with such improvements ideally planned during the design stage. Alternative methods, including the placement of a hot-mix asphalt layer, installation of geotextile, or the application of polyurethane grout technology or glued ballast [22,23,24], focus on strengthening the upper structure and can be implemented without reconstructing the existing track.

Improving the stiffness profile along a transition is desirable; however, it is often challenging to implement in practice. For example, foundation improvement methods are both costly and disruptive because they require significant reconstruction of the transition. As a result, unless these measures are integrated into the original design, they are rarely deployed as a remedial solution. Although substructure-level interventions have demonstrated measurable effectiveness, they are generally costly and difficult to implement within operational railway transition zones. Conversely, superstructure-based measures, including modifications to the rail, sleepers, rail pads, and under-sleeper pads, are comparatively easier to install [25].

An alternative and more attractive approach is to use a modular solution. Such solutions can be installed with minimal line closures and at a lower cost than extensive earthwork modifications. Typically, modular solutions focus on altering the stiffness of the upper track structure. While there are potential benefits to this approach, its design poses several challenges. Railway track structures exhibit complex dynamic stiffness behaviours, and this complexity is especially critical at transitions because sudden changes in stiffness generate high dynamic forces during train–track interactions. The high-frequency energy resulting from these interactions is confined within the upper track structure, meaning that without deeper remedial measures, any benefits will be limited to this frequency range. The propagation of dynamic energy is governed by the dynamic stiffness curve, which is particularly difficult to interpret at transitions because it varies along the length of the transition. Additionally, each type of rolling stock interacts with the transition in a unique manner, leading to the generation of differing frequencies. The dynamic characteristics of the transition can change over time, particularly when resilient elements such as railpads are incorporated, as their performance can be affected by factors such as temperature fluctuations and ageing.

Given these challenges and the numerous variables present at a transition, the design of stiffness remedial measures is inherently complex. In practice, only the most straightforward measures, such as the installation of auxiliary rails, are commonly deployed, even though they typically offer limited benefits. More frequently, remedial efforts focus on addressing high deflections and settlements, specifically through permanent settlement-based solutions, particularly those induced by hanging sleepers.

Permanent Settlement-Based Solutions

Minimising differential permanent displacements between the approaching zone and the structure can be achieved through several modular interventions that are applicable to existing tracks. Specifically, adjustable fasteners are employed to eliminate the gap beneath hanging sleepers, thereby enhancing track stability and mitigating further displacement [1]. Additionally, tamping, whether executed manually or mechanically, facilitates the compaction of ballast into the void beneath the sleepers, thus ensuring more uniform load distribution and improved track geometry [26]. Stone blowing is another remedial technique whereby stones are injected into the void under the sleepers. This method not only fills the existing voids but also serves as a rapid, minimally invasive approach to stabilising the track structure [1]. Furthermore, The Railway Technical Research Institute (RTRI) is based in Japan developed automatic irregularity-correcting sleepers (AICS) that address the issue of hanging sleepers. These innovative sleepers feature a baseplate that progressively fills any emerging void, thereby continuously correcting irregularities during service and reducing permanent deformations [27]. These modular solutions are considered cost-effective as they allow for targeted remediation without necessitating extensive reconstruction of the track.

Remedial measures that are based upon reducing permanent deformation at transitions are attractive for several reasons. Firstly, the track component(s) causing the high settlements are usually located within the upper track structure. Therefore, the remedial solutions do not require extensive earthworks which can cause significant line closures and expense. Secondly, they typically do not change the track stiffness across the transition. Consequently, assuming the original transition zone design was adequate, the stiffness will be restored close to the original design value. This is attractive because the design of track dynamics across a transition is challenging. In summary, it then avoids designs considering complex track dynamics and train-track interaction, all of which change with location and transition zone age. Therefore, the most commonly deployed remedial solutions are typically focused on restoring track settlements to an allowable range. This is usually done by eliminating ballast voiding in an attempt to prevent hanging sleepers. Thus, this type of approach is promising to explore for future remedial measures.

Most permanent vertical displacement occurs in the ballast layer, with factors such as hanging sleepers, increased ballast loads, poor drainage, wet fouled ballast, and damaged sleepers contributing to differential displacements in this region. This results in asymmetric bearing pressures and progressive damage in concrete sleepers [28,29]. Research indicates that even a single hanging sleeper with a void as small as 1 mm can lead to a 70 % increase in contact forces at adjacent sleepers [30]. Rail-seat deterioration, mid-span and centre cracking are also prevalent in these zones due to concentrated loads under repeated dynamic excitation. Cracking observed in prestressed concrete sleepers is generally induced by impact loads, with the most affected sections being the midspan and the rail-seat areas. Over the long term, time-dependent effects further influence the structural performance of prestressed concrete sleepers [31]. Sysyn et al. [32] investigated the mechanism of sleeper–ballast dynamic impact in void zones, showing through experimental in situ measurements of rail deflections that significant impact accelerations occur in these zones even under lightweight, slow-moving vehicles. Consequently, remedial strategies should focus on minimising these displacements to prevent impact forces and associated sleeper damage. One effective approach is designing transition zones that prevent or reduce the formation of sleeper-ballast gaps, thereby controlling permanent deformation and enhancing track stability.

To maintain track level and prevent hanging sleepers, various methods are available, including machine tamping. However, tamping may be challenging in transition zones with abrupt shifts from soft to stiff areas, such as those near bridges. A promising alternative is modular solutions that address minor vertical track geometry issues while preserving track stiffness. One such innovation is self-levelling sleepers (SLS or SL sleepers), also known as self-correcting sleepers, which help reduce maintenance needs by eliminating the high forces caused by train passage over ballast voids. SLS sleepers are particularly advantageous in transition zones, as they have the potential to automatically react and compensate for differential settlement and provide a modular, retrofitted solution.

Existing Self-Levelling Sleeper Solutions

The automatic irregularity-correcting sleeper (AICS) was invented by Nakamura & Muramoto [33] and Muramoto & Nakamura [34], which was followed by a short sleeper type of AICS (AICS-SS) proposed by Muramato [35] (Fig. 2). The AICS is made up of a fibre-reinforced polymer sleeper and two automatic subsidence compensating (ASC) mechanisms located under each rail. The automatic subsidence compensating device consists of two nested boxes, which allow for relative vertical movement (Fig. 3). The inner box, filled with the granular material (2 mm in diameter), is attached to the rail via the sleeper, while the outer one is placed on the ballast. When there is differential settlement in the track, the outer box sinks together with the ballast, with the granular material filling the gap between the inner and outer boxes. As a result, the granular material compensates for the unequal settlement. AICS-SS, on the other hand, is a short sleeper equipped with ASC that could be attached to a rail between existing sleepers. Because of the AICS-SS side, it does not require any alterations to the sleepers, potentially allowing for cost savings during construction [27].

The use of Automatic Subsidence Compensating Device, AICS, has been tested in full-size track models[27]. The experiments simulate the boundary between ballast and ballastless track. The outline of the track model can be seen in Fig. 4. Three cases have been tested: *(i)* a standard case where all sleepers are monoblock concrete sleepers, *(ii)* a low stiffness case where all sleepers are elastic sleepers and *(iii)* the AICS case where sleepers are equipped with the Automatic Subsidence Compensating Device. Fixed-point cyclic loading was performed on two points as shown in Fig. 4.

Fig. 5 shows the deformed shapes of the rail (under load, left and right rail average) for each tested case. The results in this figure show that the installation of AICSs in the transition zone is effective in reducing track settlement. Although an initial settlement of 3 mm was recorded after loading began, subsequent settlement remained marginal up to 1 million cycles and no hanging sleepers were observed.

A self-compensating sleeper (SCS) was developed by Insley and Sharpe [36] through Schwihag AG Gleis and Weichentechnik (Patent No: EP3608472A1, EP3608472B1). The SCS has conical shaped cavities from the top surface to the bottom Fig. 6. When the track is lifted, the granular material in the cavities falls into the holes under the sleeper, providing for automatic repacking. When the SCS is positioned at a location where voids would normally form, the SCS can pack itself, thus potentially compensating for void created beneath the SCS.

Another form of self-correcting solution is a sleeper with automatic, settlement compensating apparatus which can automatically correct ballast settlement caused by an inflating force of an air bag, proposed by Lee, et al. [38], with a European patent, ID KR101374526B1. The sleeper automatic settlement correcting apparatus is a hollow box with a sleeper connecting it to the rail side Fig. 7. An outer box is in touch with the ballast and is fastened to the inner box's outer peripheral surface. When the ballast settles, the air bag applies force to push the inner and outer cylinders in a vertical direction, while restricting movement in the opposite direction by air injection. It is feasible to automatically correct for ballast settlement and minimise gaps between the sleeper and the ballast using this technique. Embedded automatic differential settlement compensation apparatus is a sleeper embedded automatic track differential settlement compensation apparatus (Fig. 8). This apparatus is installed at a concrete sleeper and is capable of passively compensating for a track differential settlement due to a train load using oil pressure. By using the oil pressure, the apparatus can expand by means of a cylindrical rod to support a space which is generated by settlement of the track bed gravel or the asphalt roadbed underneath a concrete sleeper. This apparatus is proposed by Lee and Lee [39], with a European patent, ID EP3112533A1.

The Railway Engineering Group at the Technical University of Delft (TU Delft) also developed a solution to achieve vertical level self-correction in situations where a void occurs under the sleeper [40,41]. The solution involves using a sleeper with a wedge-shaped cross-section instead of a flat bottom, intended to stimulate the migration of ballast into any voids, thus reducing the occurrence of hanging sleepers, as shown in Fig. 9. The wedge-shaped bottom of the self-supporting sleeper aims to allow for the free movement of ballast particles, which can fill the void and provide support to the sleeper. This potential vertical level self-correcting effect is not possible with the traditional flat-bottom sleeper design. The sleeper's wedge-shaped bottom is crucial to its working principle. The angularity of the wedge allows ballast particles to move and rotate, using energy from each train passage, thus eliminating the need for complex internal mechanisms.

A series of scaled laboratory tests, along with 2D and 3D discrete element simulations, were conducted to examine various wedge-shaped geometries. These investigations compared a single long wedge to multiple mini-wedges and explored different wedge angles (30°, 45°, 60°). Initial scaled laboratory tests assessed the performance of various wedge geometries. Subsequent 3D DEM simulations analysed contact forces within the ballast layer across different designs, while 2D DEM simulations investigated settlement behaviour. The main findings indicate that a single long wedge performs better than multiple smaller wedges. When the wedge angle is larger than the ballast's natural angle of repose, particles can migrate into voids, enhancing support correction. However, a longer wedge also reduces the effective ballast height beneath the sleeper, which could pose challenges for retrofitting existing lines. Also, the wedge shape results in increased track settlement due to the sleeper cutting into the ballast.

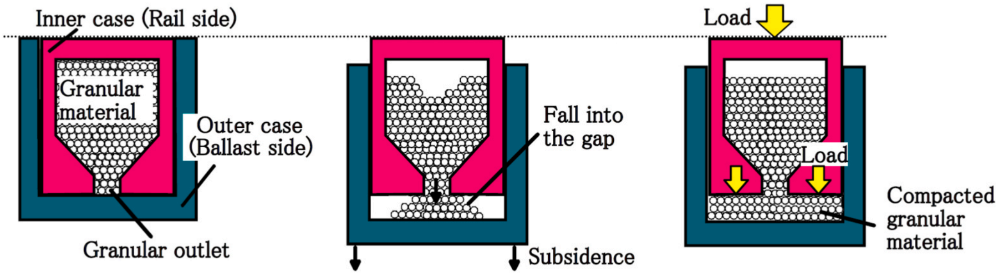


Fig. 2. Working principle of the Automatic Subsidence Compensating Device [27].

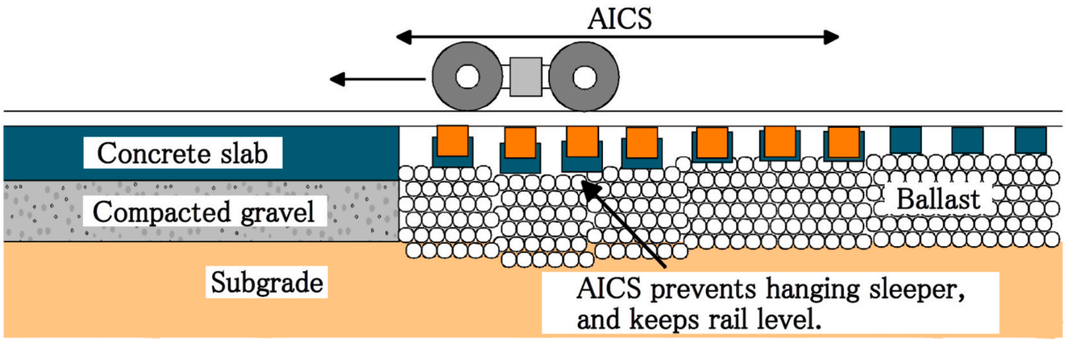


Fig. 3. Concept of hanging sleeper prevention with AICS [27].

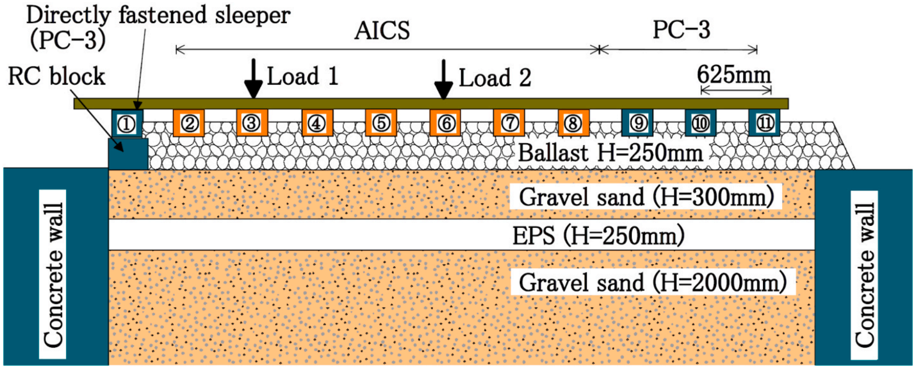


Fig. 4. Outline of the track model (after [27]).

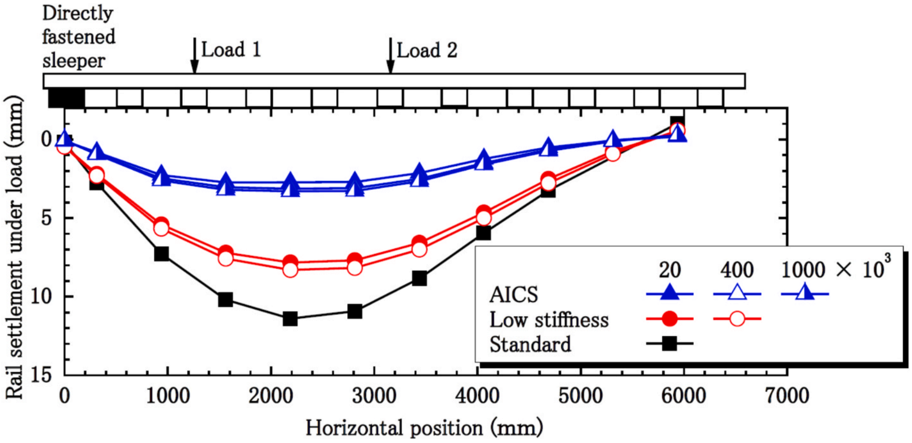


Fig. 5. Deformed shape of the rails after loading for different number of loading cycles [27].

Self-Levelling Sleeper Concept

This section outlines the full scope of the SLS design process. It includes an overview of the functional and structural requirements, definition of levelling capacity based on operational tolerances, and evaluation of various levelling mechanisms. Additional attention is given to material selection, modularity, maintainability, and environmental resistance, all of which inform the technical solution presented.

Design Principles

In the design of the new SLS, a range of fundamental requirements was addressed to ensure functionality under the operational and environmental conditions typical of railway transition zones. The levelling mechanism aims for precise vertical displacement correction, with millimetre-level resolution, to compensate for track settlement automatically and effectively.

The levelling mechanism was configured as a simplified system with a minimal number of components. This design choice supports both manufacturability and reduction of potential failure points. The system is modular, enabling straightforward integration into a variety of track configurations. Dynamic resistance was incorporated to prevent unintentional activation due to train-induced vibrations. Fatigue performance was addressed to manage repeated loading, and environmental durability was ensured through design features such as drainage capability, resistance to frost and moisture ingress, and thermal stability.

All primary functions of a conventional sleeper were retained. These include rail support at the designated inclination, gauge maintenance,

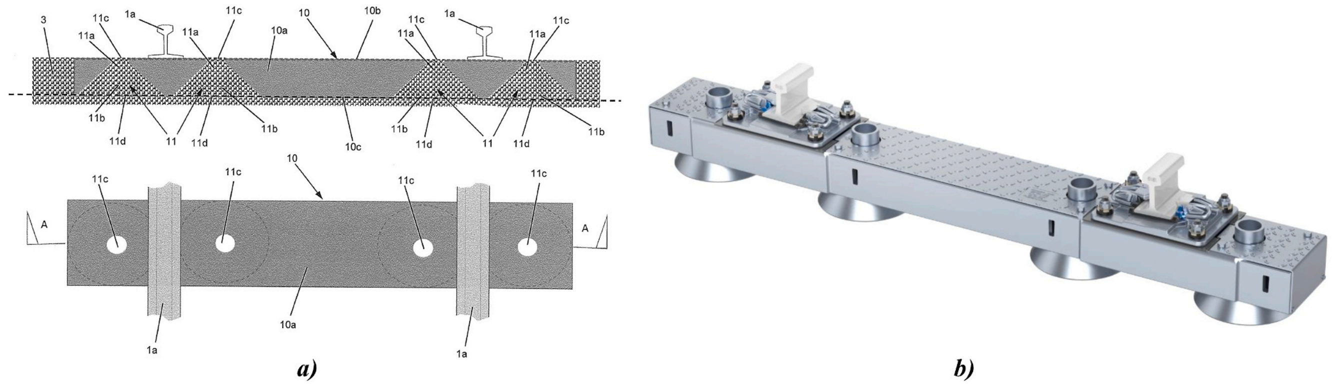


Fig. 6. Self-compensating sleeper a) sketches of Self-Compensating Sleeper (SCS) [36]b) SCS [37].

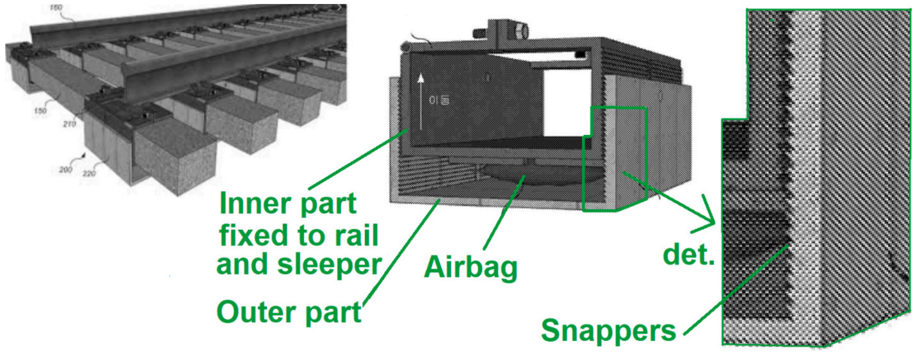


Fig. 7. Automatic subsidence correcting apparatus [38].

vertical load transmission to the subgrade with appropriate stiffness, and electrical insulation. Compatibility with standard ballasted track systems was preserved. The SLS accommodates conventional fastening systems, including screw spikes, baseplates, and guardrails. To prevent ingress of ballast fines, the levelling mechanism is enclosed within the sleeper body and isolated from direct contact with the ballast layer. The SLS sleeper functions similarly to a composite sleeper and can therefore be used in any ballasted track section where composite sleepers are applicable.

Maintainability formed a key part of the design approach. Although the SLS is intended to reduce the need for manual interventions by automatically maintaining track geometry, it remains compatible with conventional tamping equipment, especially the geometry of common tamper. The levelling mechanism can be mechanically locked during tamping or construction activities and reset to its reference position post-intervention. These features support lifecycle performance without introducing additional maintenance demands.

Although the initial manufacturing cost of the SLS may be higher than that of standard sleepers due to the embedded levelling technology, the aim is to reduce overall life-cycle cost (LCC). Reduced maintenance requirements, fewer tamping cycles, and avoidance of speed restrictions caused by geometric degradation in transition zones could contribute to cost efficiency.

Design Requirements and Functional Principles of the Self-Levelling Sleeper

This section defines the key design requirements and functional principles that guided the development of the self-levelling sleeper (SLS). It outlines the mechanical, geometric, and operational criteria necessary to ensure that the sleeper performs under the dynamic and environmental conditions typical of railway transition zones. Specific focus is given to the required levelling capacity, compatibility with existing track infrastructure, and integration with polymeric materials. The section also discusses structural durability, maintainability, and how the levelling mechanism aligns with safety and performance standards for modern railway systems.

Levelling Capacity and Track Geometry Considerations

Track geometry includes the longitudinal height of the rail, which is defined as the projection of the top of rail (TOR) in the track's vertical profile. Maintaining smoothness in the longitudinal height is essential for operational safety, riding comfort, and minimisation of mechanical wear. Deviation from this smooth profile typically occurs due to settlement, uneven loading, or inadequate maintenance, especially in transition zones between different track structures.

According to common operational standards, eg, EN 13848, acceptable limits for longitudinal height deviations are determined based on train speed. These are classified into three thresholds:

- **Alert Limit (AL)** – prompts condition monitoring.
- **Intervention Limit (IL)** – requires planned maintenance before the next inspection.
- **Immediate Action Limit (IAL)** – mandates urgent response, often including speed restrictions.

As line speed increases, these tolerances become more restrictive. For instance, at speeds up to 300 km/h, the IAL is ± 11 mm, while for lines with speeds under 60 km/h, the limit is ± 24 mm. To eliminate the need for frequent tamping, an operation that disrupts service and requires track possession, the SLS is designed to perform automatic levelling during early settlement phases.

Based on these standards and expected settlement behaviours, the design levelling capacity of the SLS was set at 40 mm, which includes a safety reserve above the maximum expected deviation of 24 mm. To ensure effective compensation of minor settlements, the system supports levelling steps as small as 2 mm, allowing for incremental correction.

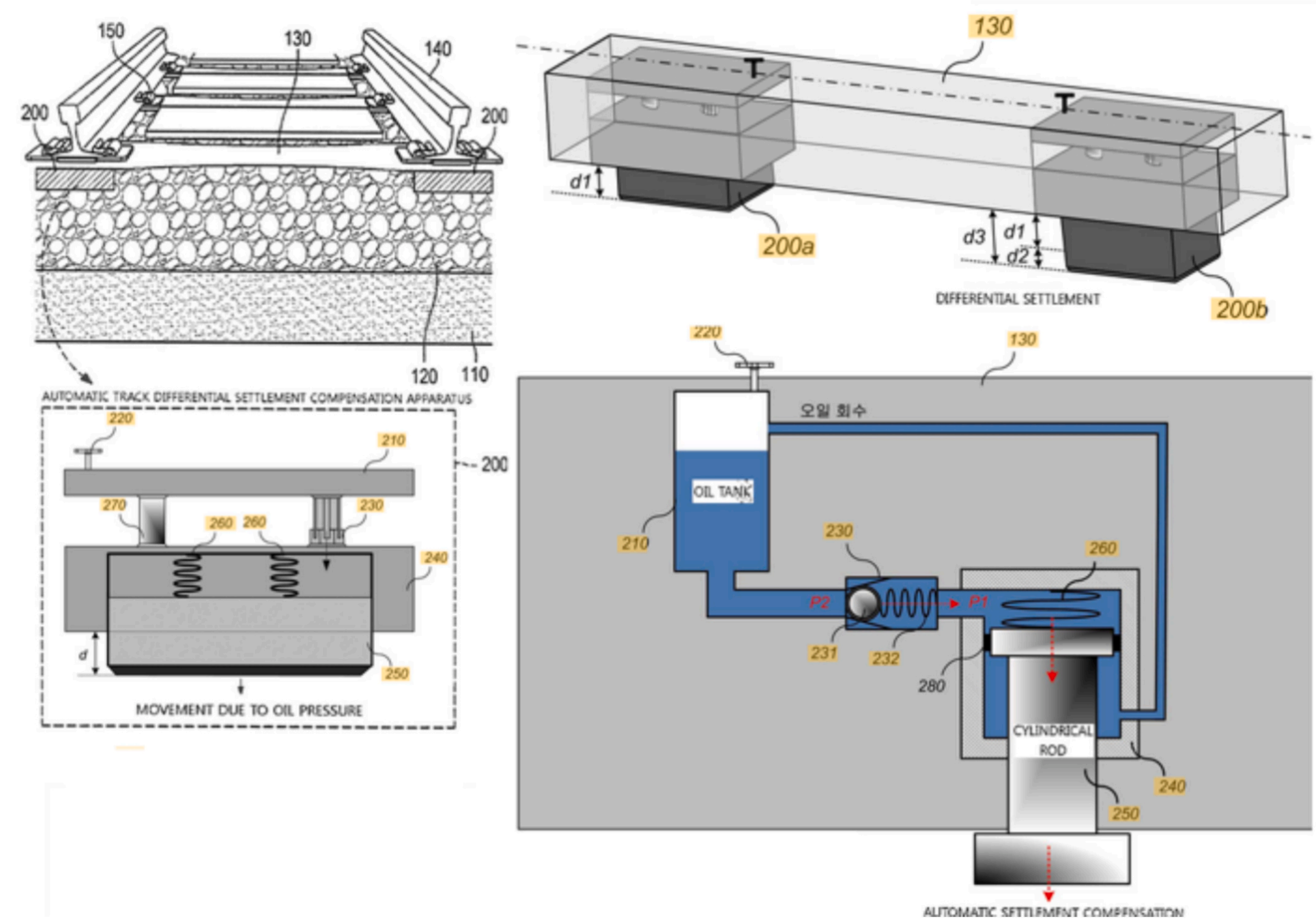


Fig. 8. Embedded automatic differential settlement compensation apparatus [39].

Modular Architecture and Polymeric Sleeper Material

The SLS was developed with a modular system architecture, with the aim of allowing it to be readily applied to different track sections and adapted to varying site-specific conditions. Modularity enhances maintainability, simplifies integration into both new construction and retrofitting scenarios, and supports production standardisation.

In addition to its modular design, the SLS is based on polymeric sleeper technology, using recycled plastic composite materials combined with discrete steel reinforcing over the length of the sleeper. The combination of these two materials in sleepers offers several strengths which were already investigated by Lojda & Krejčiříková [42] and Lojda et al. [43] in recent research of main track sleepers:

- Optimal bending stiffness comparable to timber sleepers
- Resistance to moisture, chemical, and biological degradation
- Limited environmental impact through the use of recycled materials
- Dimensional consistency and stability of track gauge under thermal cycling
- Durability under fatigue loading

The polymeric material also allows for wide design freedom and precise moulding of internal cavities, which is essential for housing the levelling mechanism without compromising structural performance. The polymeric matrix supports the integration of enclosed moving components and facilitates the modular assembly of internal systems such as wedges, valves, or granular silos.

Structural, Functional, and Environmental Design Requirements

The sleeper retains all critical functions of conventional sleepers: support of rail inclination, gauge maintenance, vertical load transfer and electrical insulation. The SLS design ensures compatibility with standard rail fastening systems, including screw spikes, baseplates, and guardrails. It is also fully compatible with ballasted track systems, both in new installations and as a replacement component.

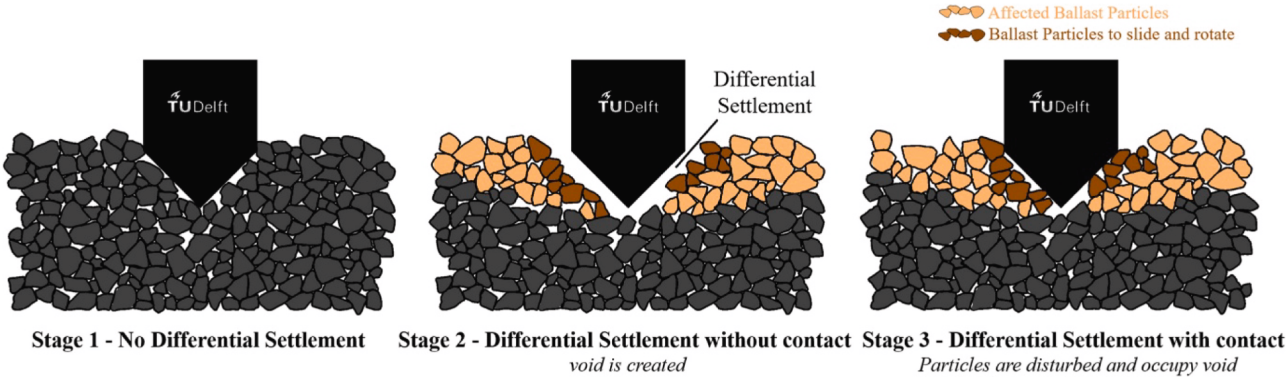
To protect the internal levelling mechanism, all moving parts are enclosed within the sleeper body, preventing ingress of ballast fines or environmental contaminants. The structure is designed to resist dynamic excitation, preventing unwanted activation under cyclic train loads. Fatigue resistance is accounted for in the material selection and mechanical configuration, and the design includes provisions for moisture drainage and thermal stability.

Maintainability and Life-Cycle Considerations

Although the SLS is intended to reduce the need for manual maintenance through passive levelling, the design also ensures compatibility with tamping operations. During tamping or construction activities, the levelling mechanism can be mechanically locked and subsequently reset to its reference state. This ensures that the sleeper remains fully functional throughout its service life without introducing new operational risks.

Conceptual Approaches to Self-Levelling Sleepers

A range of initial design concepts for self-levelling sleeper (SLS) systems were explored in collaboration with existing polymeric sleeper



(a)

(b)

Fig. 9. Wedge sleeper (a) Void correction concept using wedge sleeper, (b) Schematic of the scaled laboratory transition zone.

technologies, notably those developed by Lankhorst Engineered Products. The initial design principles were grouped into three categories based on their mode of operation: granular materials, hydraulic systems, or mechanical principle.

Each category represents a different principle for allowing the sleeper to adjust vertically when a void forms underneath. These early concepts focused on practicality, reliability, and whether they could be adapted to existing track systems.

From the conceptual phase, five technical solutions were selected for further technical development based on their functional viability, manufacturability, and potential application within track transition zones. These included:

1) A granular principle
2) A hydraulic system
3) A mechanical principle based on
a) ratchet mechanism
b) vertical wedge
c) horizontal wedge

Each design was modified in more detail to fit the production process for polymeric sleepers. The aim was to understand their strengths and weaknesses, and how well each one could perform the levelling function under realistic track conditions.

Granular Principle

In the granular system, the levelling function is achieved by allowing small particles to move inside the sleeper body (Fig. 10). The sleeper contains a silo and a chamber, and the particles flow from one to the other due to gravity & vibration, filling the space beneath the sleeper. The amount of levelling depends on the size of the granules and the slope of the internal surfaces.

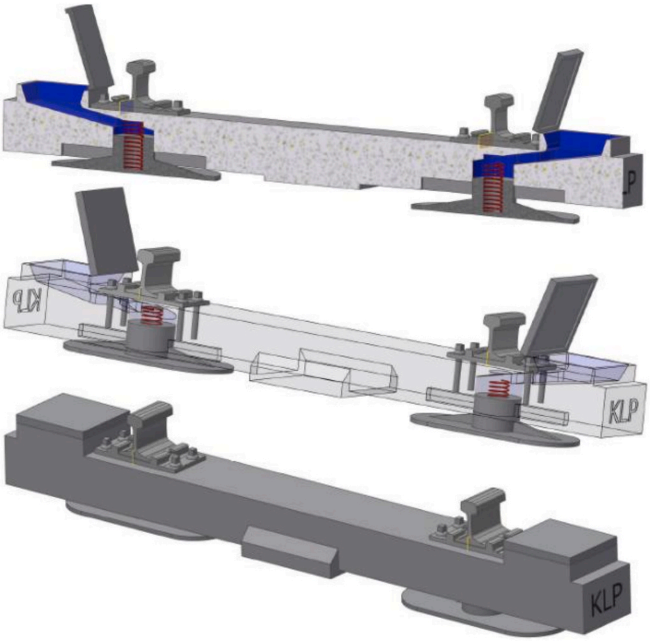


Fig. 10. Initial design of SLS based on granular levelling principle.

While this design is simple, with no moving parts that can fail, it poses several challenges. There is a risk that granules may move back into the silo during repeated train loading, which must be avoided.

There is also a chance that water or fine ballast particles could enter the chamber and interfere with the system. Resetting the sleeper to its original height requires special methods, such as vacuum suction or magnetic removal, if magnetic granular particles are used. Considering the extra silo volume, the sleeper must also fit within the limits of the track's clearance profile.

Hydraulic Principle

The hydraulic concept uses liquid and valves to control the levelling process. This allows for accurate vertical adjustment, and the sleeper can be designed to adjust in small steps. However, this system depends on how the fluid behaves. It could face issues if the liquid leaks or if small particles or dust enter the system (Fig. 11).

The type of fluid must also be carefully chosen to resist changes in temperature and moisture. A biodegradable oil is a potential option because it is already used by several railway operators. Sealing is a key part of the design, as oil leakage must be avoided. Although the system is promising in terms of precision, it is more complicated than other options.

Mechanical Principle Based on Ratchet

This design uses a ratchet mechanism where a series of teeth are built into the sleeper shoe, and spring-loaded pawls inside the sleeper engage with them (Fig. 12). When a void forms under the sleeper, the spring pushes the sleeper down, and the pawl locks it in place.

While this design allows for controlled adjustment, it has several limitations. The pawls and other small components may not be strong enough to carry repeated loads, and there is a risk that ballast could get into the mechanism and block it. The external parts are also at risk of damage during tamping or other track maintenance. Because of these problems, this concept is considered more suitable for lighter applications such as tramways, where loads and speeds are lower.

Mechanical Principle Based on Vertical Wedge

The vertical wedge system uses a simple wedge-shaped component that slides downward when a void appears under the sleeper (Fig. 13). This fills the gap and restores contact with the ballast. The system is protected inside the sleeper housing, which helps prevent contamination.

The wedge can be placed along or across the sleeper. Placing it along the sleeper length is better for spreading the load. Screws limit the depth of movement and can also show how much levelling has occurred. The wedge can be reset using rods attached to it.

Although the idea is straightforward and suitable for railway environments, calculations showed that the wedge could deform significantly under load.

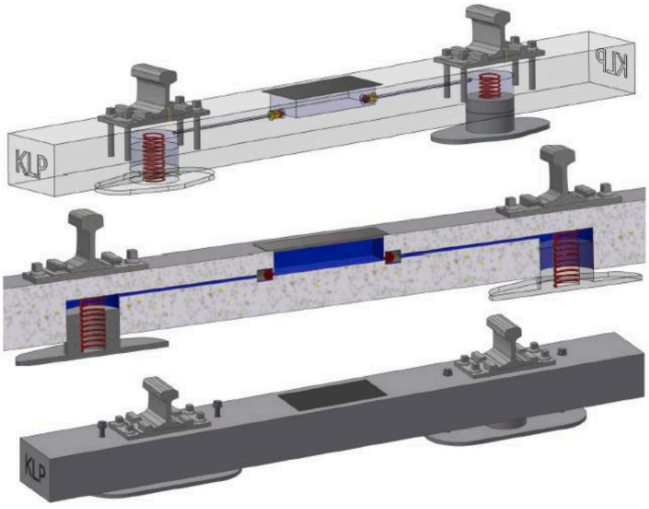


Fig. 11. Initial design of SLS based on hydraulic levelling principle.

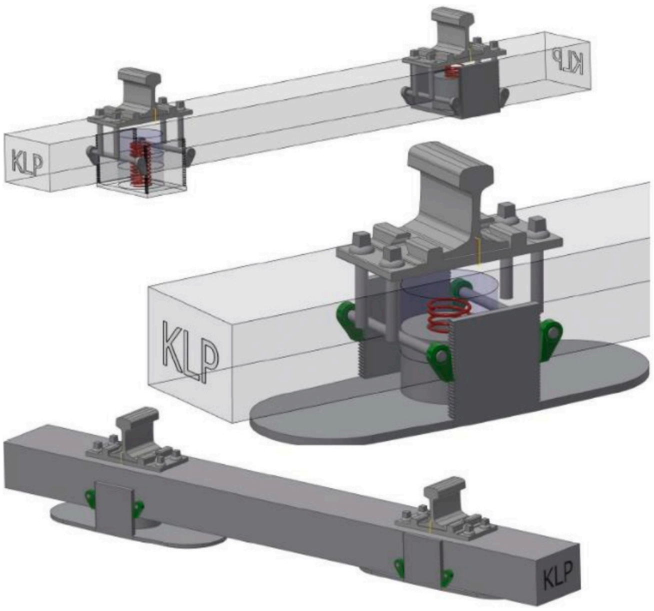


Fig. 12. Initial design of SLS based on mechanical levelling principle with ratchet.

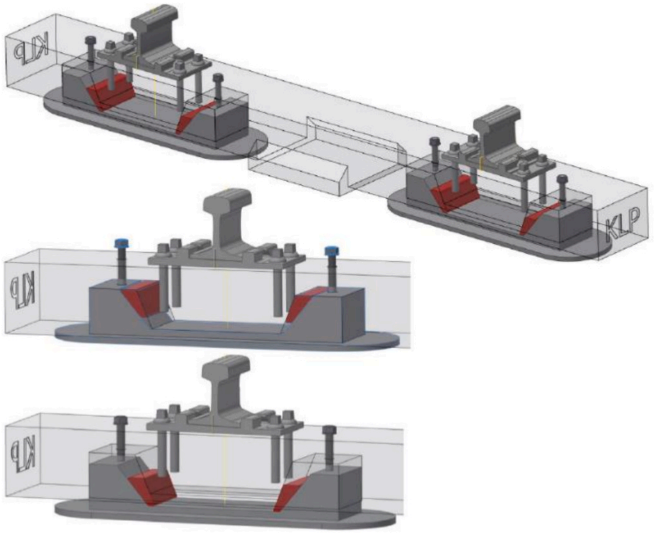


Fig. 13. Initial design of SLS based on mechanical levelling principle with vertical wedge.

Mechanical Principle Based on Horizontal Wedge

In this design, a horizontal wedge is pulled into the gap between the sleeper body and the sleeper shoe by springs (Fig. 14). The wedge fills the void and maintains the sleeper height. The entire mechanism is placed inside the sleeper casing, making it protected and easy to install.

This system is also compatible with tamping and other maintenance operations. However, its success depends on the spring design. The springs must be strong enough to pull the wedge into place and resist fatigue over time. If the spring weakens, the system may not function properly. With good design and testing, this concept appears to be practical and was identified as a candidate for further development.

Comparative Evaluation and Selection of Viable SLS Designs

All five SLS systems were assessed against key functional and

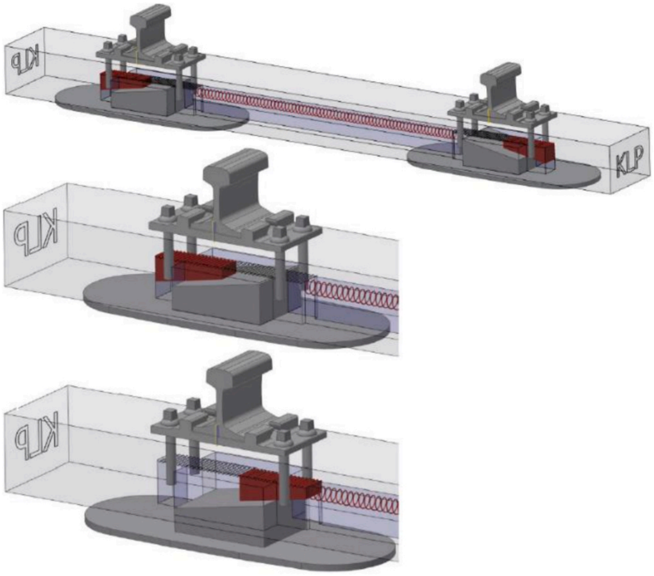


Fig. 14. Initial design of SLS based on mechanical levelling principle with horizontal wedge.

structural criteria. Despite differing mechanical principles, they shared a common design approach: levelling shoes that are extended either by gravity, hydraulic pressure, or mechanical displacement to fill voids and thus maintain vertical rail alignment. Several critical findings emerged from the evaluation:

- Risk of ballast ingress into the levelling mechanism remains a concern across designs. It must be mitigated through sealing or internal protection.
- Sleeper-ballast contact area must remain adequate even after levelling capacity is fully utilised, to avoid stress concentrations.
- All solutions must support tamping without mechanical interference or damage.
- Some designs may be implemented as modular short sleepers or half-length units to simplify replacement and installation.

IN2ZONE partners created a series of criteria to review the SLS designs and identify the most suitable solutions for further development. These criteria were selected to reflect not only the core functional requirements of self-levelling sleepers but also their practical applicability, durability, and ease of integration into existing railway infrastructure. A total of nine criteria were used in the evaluation process; each assigned a specific weighting to reflect its relative importance. These are summarised in Table 1. The most heavily weighted criterion was the levelling function, which accounted for 30 points. This criterion assessed whether the sleeper could effectively compensate for track settlement with a high degree of precision. Other fundamental requirements, such as the ability to transmit vertical loads, maintain track gauge, and provide sufficient stiffness, were grouped under basic functions and assigned 20 points. Similarly, track structure compatibility (20 points) evaluated the sleeper's ability to interface with standard components such as rails, fastenings, ballast beds, and track circuits. Additional considerations included manufacturability (20 points), assessing the feasibility of producing the sleeper using established materials and methods; and reliability (10 points), which favoured mechanically simple and failure-resistant solutions. The remaining criteria, each weighted at 10 points, were resistance to dynamic loading, weather resistance, maintainability, and estimated cost. Together, these criteria formed a comprehensive framework for comparing the various design concepts.

Five SLS concepts were evaluated: granular, hydraulic, ratchet, vertical wedge, and horizontal wedge mechanisms. The results of the scoring process are presented in Table 2. Among the five, the horizontal wedge design (SLS-HW) achieved the highest score of 105 out of 140. It performed particularly well in levelling function, manufacturability, reliability, and maintainability. The design's enclosed wedge mechanism demonstrated robustness against environmental factors and vibration, making it well-suited for the demands of railway transition zones. The granular concept (SLS-G) followed with a total score of 85. It was recognised for its simplicity and potential for modular construction, but its levelling function was rated lower due to uncertainties around the controlled movement of granular material. Concerns were also raised about the potential for blockage and inconsistent levelling under certain load or moisture conditions. The hydraulic design achieved a score of 73. It demonstrated strong levelling capabilities but was penalised for its complexity, sensitivity to temperature and contamination, and the challenges associated with maintenance and sealing. The vertical wedge design, with a score of 68, showed promise in simplicity and environmental resistance, but concerns about structural deformation under load reduced its viability. The ratchet mechanism scored the lowest, with 58 points. Its complex internal components, susceptibility to fouling by ballast, and limited fatigue resistance made it the least suitable for long-term use in dynamic and harsh railway environments.

Table 1
Evaluation Criteria and Weightings for Self-Levelling Sleeper Concepts.

Criteria	Criteria	Weighting points	Description of the criteria
a	Levelling function	**30**	Has the SLS the ability to level effectively i.e. compensates the track settlement precisely in [mm]?
b	Other basic functions	**20**	Is the SLS able to transmit the load (stiffness, strength), keep track gauge?
c	Track structure compatibility	**20**	Is the SLS compatible with ballasted track structure (rails, fastenings, ballast bed, track circuit)?
d	Manufacturability	**20**	Is the production of desired SLS structure and shape feasible?
e	Reliability	**10**	Is the occurrence of SLS errors prevented (e.g. by simple structure; as fewer parts as possible; grains do not block SLS)?
f	Resistance to dynamic load	**10**	Is the SLS resistant to vibrations and cyclic loading (fatigue)?
g	Weather resistance	**10**	Is the SLS well-drained (frost hazard) and free of sleeper thermal expansion hazard?
h	Maintainability	**10**	Is the SLS compatible with maintenance machines and actions?
i	Estimated costs	**10**	Is the design economic/ profitable (not too complicated/ expensive)?

Based on this evaluation, the horizontal wedge and granular designs were identified as the most promising candidates. These concepts were selected for detailed design, prototype manufacturing, and experimental testing. Their balance of functionality, reliability, and practicality aligns with the project's objective to deliver modular and effective solutions for improving performance in railway transition zones.

Details of Developed SLS Designs

This section describes the details of the two SLS prototypes that scored the best and were manufactured in full-scale and used for large scale testing.

Table 2
Comparative Scoring of Self-Levelling Sleeper Concepts Against Evaluation Criteria.

Design Principle	a. Levelling function	b. Other basic functions	c. Track structure compatibility	d. Manufacturability	e. Reliability	f. Resistance to dynamic load	g. Weather resistance	h. Maintainability	i. Estimated costs	**Total**
1. Granular	15	15	6	15	5	8	8	7	6	**85**
2. Hydraulic	20	15	6	10	5	6	6	3	2	**73**
3. Ratchet	10	10	6	15	2	2	4	3	6	**58**
4. Vertical Wedge	10	15	6	10	5	5	8	3	6	**68**
5. Horizontal Wedge	25	20	6	15	7	8	8	8	8	**105**

Self-Levelling Sleeper – Granular Principle (SLS-G)

The primary objective in the full-scale design of the self-levelling sleeper with granular system (SLS-G) was to optimise the internal silo and chamber to allow effective and controlled movement of granular material, while ensuring stable contact between the sleeper and ballast. To prevent localised stress that could cause the sleeper to embed into the ballast, particular attention was paid to the geometry and bearing area of the levelling shoes (Fig. 15). The final prototype comprised a polymeric sleeper body, two levelling shoes, a centre base section, silo lid, steel granules, ribbed baseplates, and conventional screw spikes.

The sleeper features a contact area of 0.88 m^2, distributed across the two shoes and the central part. Once the levelling capacity (40 mm) is exhausted, the sleeper rests primarily on the levelling shoes with a reduced contact area of 0.66 m^2. For reference, this is comparable to standard timber and concrete sleepers which are 0.64 m^2 and 0.68 m^2 respectively. The outer dimensions of the SLS-G (W1/W2 × H × L = 290/370 × 250 × 2600 mm) are similar to the German B70 or Dutch NS90 concrete sleepers, ensuring compatibility with track infrastructure and providing sufficient volume to house the granular mechanism. In terms of bending stiffness, the SLS, made of polyethylene with 25 mm reinforcement bars (290 × 250 × 2600 mm), has a flexural rigidity of $EI = 1800\ kN\cdot m^2$. By comparison, a reference concrete sleeper (220 × 190 × 2600 mm) has $EI \approx 5300\ kN\cdot m^2$, meaning the SLS achieves roughly 33 % of the stiffness of a conventional concrete sleeper.

The mechanical stability of the sleeper under load is critical; asymmetric bending or twisting could disrupt even flow and prevent proper

Fig. 15. Full-scale prototype of self-levelling *sleeper – granular principle (SLS-G)*.

levelling. To reduce production costs, the prototype was constructed by modifying an existing full-profile sleeper. Internal cavities were manually machined, and components were assembled using plastic elements joined by mechanical fasteners.

Levelling movement is restricted to a maximum of 40 mm. Two silos on the side of the sleeper contain steel balls that flows through a hole once a gap under the sleeper starts to occur.

The choice of steel ball size determines the levelling step because, once well compacted, the spheres arrange themselves into close-packed layers. Each new layer nests in the gaps of the one below. For the SLS prototype, the authors selected 3 mm diameter stainless steel polishing balls, resulting in each new layer providing a levelling increment of approximately 2.6 mm.

There are two reasons for this choice of sphere diameter. The first is functional: to achieve an optimal levelling step. Considering the sleeper levelling capacity of 40 mm and the chosen sphere size of 3 mm, the levelling steps, after rounding to convenient values, are 0, 3, 5, 8, 10, 13, 16, 18, 21, 23, 26, 29, 31, 34, 36, and 39 mm—practical correction steps for track settlements. The second reason is practical: to prevent possible blockage of the SLS moving parts by too small spheres. Testing confirmed that common dynamic effects (e.g. pre-axle rail lift) are significantly smaller than the levelling threshold, thus avoiding unintended activation. The spheres used are shown in Fig. 16. To protect the mechanism from contamination and moisture, the silo lids are sealed using screws.

The fastening system follows conventional arrangements used for polymeric sleepers, including screw spikes, ribbed baseplates, and elastic or rigid clamps. Resetting the levelling mechanism after tamping requires raising the sleeper by at least 50 mm and extracting the granular material either magnetically or with vacuum suction.

Installation of guardrails or auxiliary beams is common in bridge and transition zones. The SLS-G allows such installations, though restrictions exist near the rail seats due to guiding bolt placement. Suitable solutions include the use of extended baseplates or side-mounted counter plates. A minor design modification, such as repositioning the bolts, could facilitate standard guardrail attachment.

Self-Levelling Sleeper – Horizontal Wedge Principle (SLS-HW)

The Self-Levelling Sleeper – Horizontal Wedge Principle (SLS-HW) consists of a polymeric body, two levelling shoes, a centre section, horizontal wedges, stainless steel springs, ribbed baseplates, and four threaded steel counter plates. As with the granular version, the sleeper was fabricated from a modified existing type to reduce moulding complexity and cost. Individual components were assembled from machined plastic sections (Fig. 17). The SLS-HW has a bending stiffness similar to the SLS-G, with EI ≈ 1800 $\mathrm{kN \cdot m^2}$.

The SLS-HW provides a contact area of 0.64 $\mathrm{m^2}$ under the levelling shoes, comparable to that of conventional sleepers. The sleeper dimensions (W1/W2 × H × L = 290/370 × 250 × 2600 mm) match those of the SLS-G for design consistency. The levelling mechanism consists of two pairs of wedges; each pair composed of a fixed wedge in the shoe and a movable wedge inside the sleeper body. The wedge is driven forward by a spring aligned along the sleeper axis. The springs are constructed from corrosion-resistant stainless steel and are housed within a sealed cavity.

Levelling increments of 2 mm are achieved through interaction between the wedge teeth and internal notches in the sleeper body. The total levelling capacity is 40 mm. Eyebolts on the sleeper top act as travel limiters and position indicators. The initial and final wedge positions are shown in Fig. 18.

Resetting the levelling mechanism is required after tamping or for maintenance. A custom-designed hand tool connects through an access port in the sleeper (sealed with a plug during operation). Resetting involves lifting the sleeper, unlocking the wedges, and pulling them back to the top position. Steps include mechanical fixing of the levelling shoe in its reset state and restoring spring tension.

The fastening system mirrors that of the SLS-G, including ribbed baseplates and screw spikes. For improved anchorage, the sleeper includes embedded steel strips with threaded holes to accommodate fastening loads. Installation of auxiliary rails or guard beams requires modifications due to interference between guiding bolts and standard plates. Potential solutions include use of wider baseplates, external counter plates, or design adjustments to narrow the internal spring

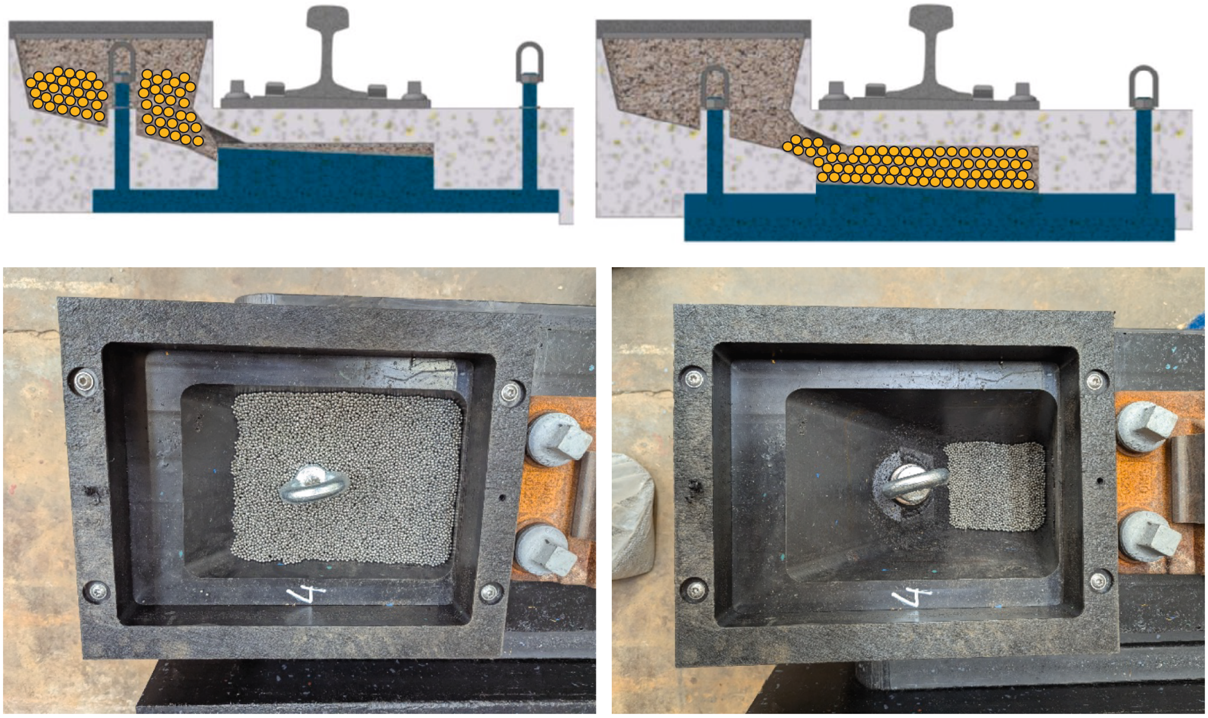


Fig. 16. Positions of levelling shoes of granular SLS: starting position (left) and end position after levelling capacity is depleted – balls in upper drawing not in scale (right).

Fig. 17. Full-scale prototype of self-levelling ***sleeper*** – ***horizontal wedge principle (SLS-HW)***.

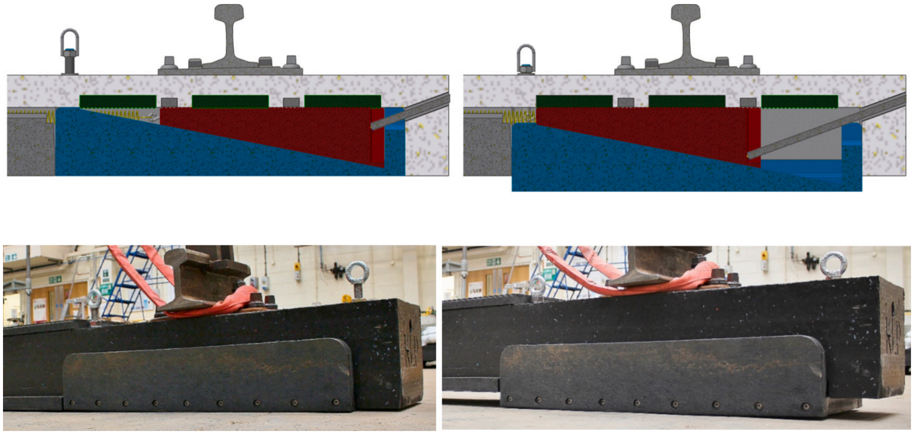


Fig. 18. Positions of levelling shoes of SLS-HW: starting position (left) and end position after levelling capacity is depleted (right).

cavity.

To prevent the problem of lifting the sleeper due to rail lift caused by passing trains, the free movement of the wedge is limited. This limitation is achieved through teeth on the top of the movable wedge and corresponding counter teeth on the surface of the sleeper body. The size and angle of these teeth allow levelling correction steps of 2 mm, dividing the levelling capacity of 40 mm into increments of 2 mm (e.g., 0, 2, 4, 6, 8, etc., up to 40 mm). Overall, the SLS-HW provides a mechanical solution for achieving self-levelling in railway sleepers, particularly in transition zones. Fig. 19 shows the scale of the SLS sleepers compared to the G44 concrete sleeper traditional in the UK.

Experimental Testing

The test setup comprised a single sleeper section of a ballasted track section placed on a compacted substructure. The setup is positioned in a metal testing box, with dimensions of 0.93 m in width, 3.8 m in length, and 0.685 m in depth, supported by a sturdy composite base. Hydraulic actuators, capable of applying individual loads of up to 150kN with loading frequencies of up to 15 Hz, and static loads of up to 200kN, were employed. The accelerated testing method for SLS prototypes facilitated the simulation of several years' worth of train loading in a condensed time frame based on continuous load cycles. For further testing, cyclic loading performed intermittently, introducing pauses between cycling to reduce heating, creep effects and to give track representative results,

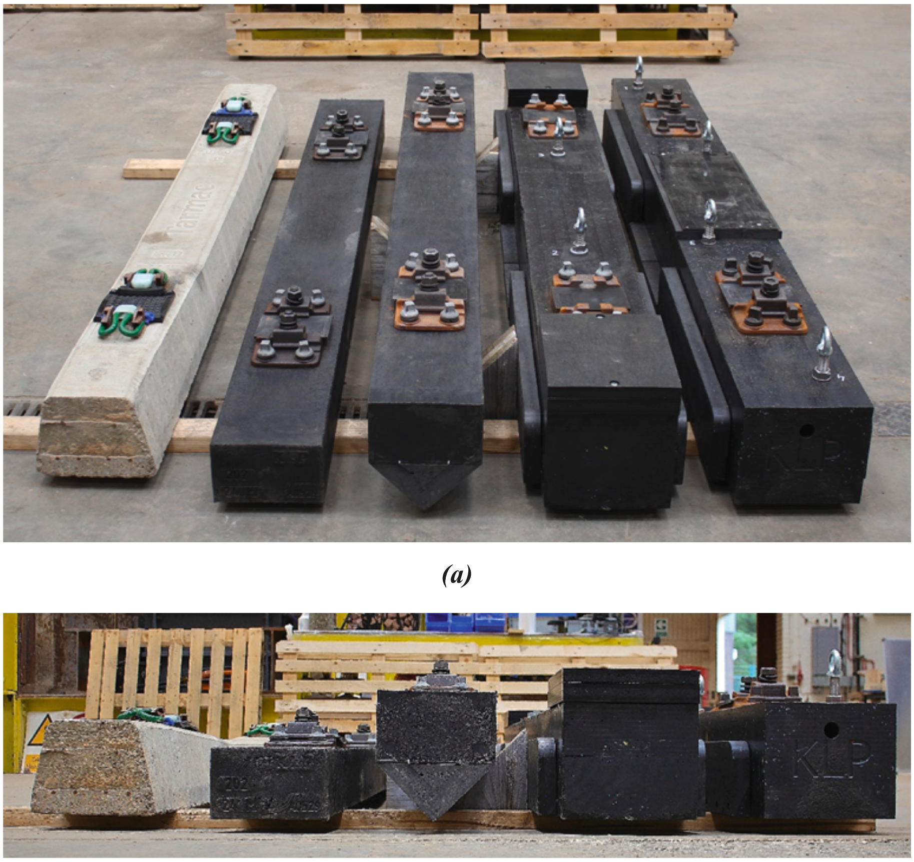


Fig. 19. Sleepers left to right Concrete Sleeper, Plastic Sleeper, TUD Wedge Sleeper, Self-levelling Sleeper – Granular Solution (SLS G), Self-levelling Sleeper – Horizontal Wedge Solution (SLS HW); (a) Top view (b) front view.

is recommended for polymeric sleepers [44].

Laboratory Setup

The specimen tested in this study comprised a section of subgrade, ballast, and a sleeper. The setup was installed in a steel testing box

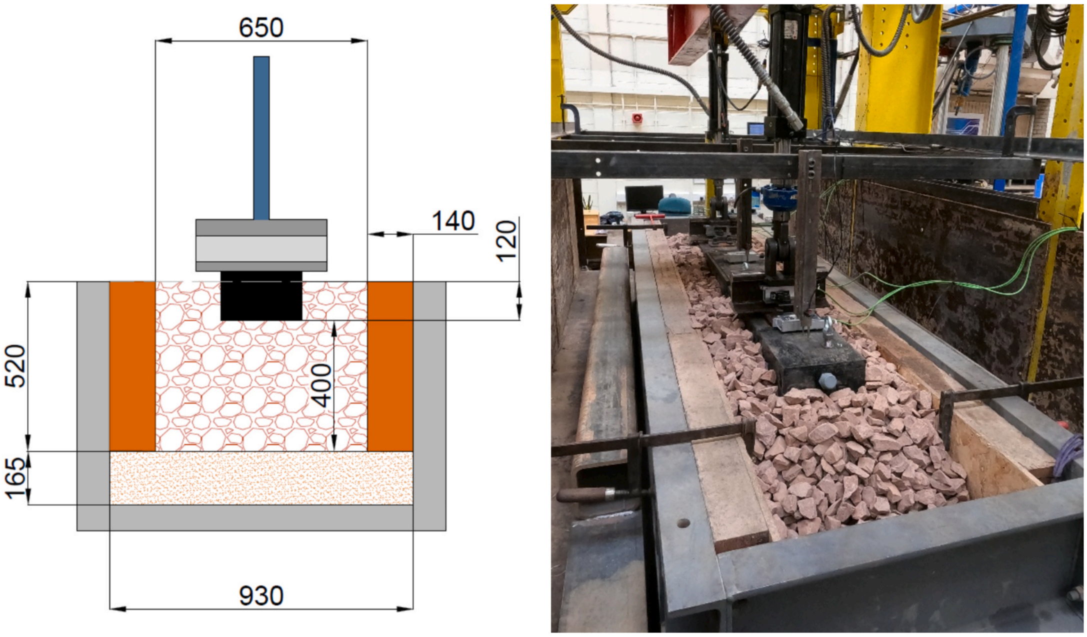


Fig. 20. Test Setup (a) sketch of the side view; (b) photo from the lab.

supported by a rigid composite base to ensure stability during loading. The box dimensions were 0.93 m in width, 3.8 m in length, and 0.685 m in depth, providing adequate space for the test configuration. The arrangement represented a single-sleeper track section with a sleeper spacing of 0.65 m (Fig. 20).

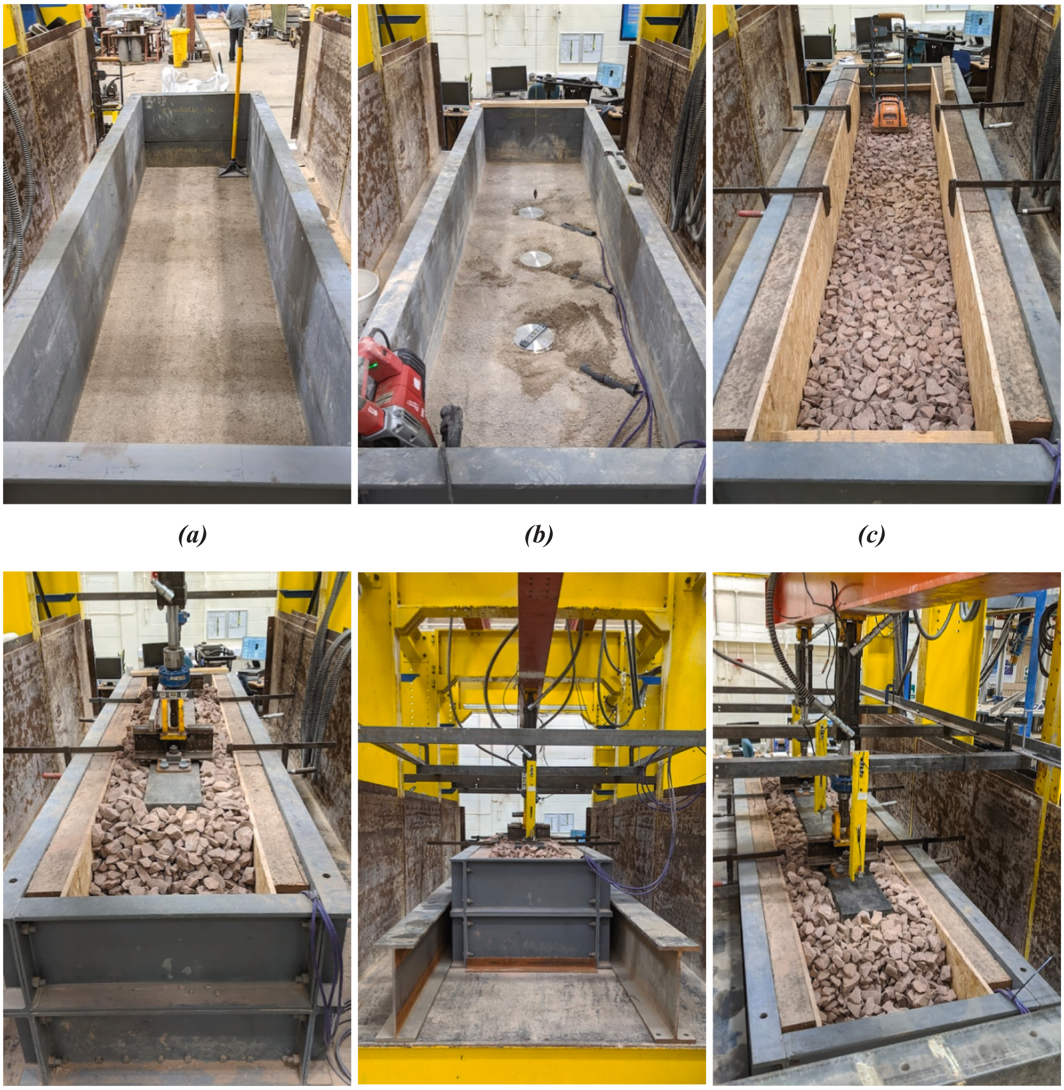
First, a 165 mm-thick subgrade layer was constructed using compacted sand consisting of 0–6 mm limestone (Fig. 21a). The sand was compacted at 5 % optimum moisture content using an electric forward compactor. Dynamic cone penetrometer (DCP) tests were performed to determine the California Bearing Ratio (CBR) values of the subgrade, which were targeted to be within 90–100. The subgrade served to bear the load transferred from the ballast, distribute pressure uniformly, provide an elastic support condition, and accommodate the installation of pressure cells. Upon completion of the subgrade, three pressure cells were installed: two aligned with the rail and one beneath the centre of the sleeper (Fig. 21b). Wooden blocks were then positioned along the sides of the box to simulate a 650 mm sleeper spacing. The ballast layer was placed to a depth of 400 mm beneath the sleeper and compacted in 100 mm intervals using a flat-bottom light electric compactor (Fig. 21c). The sleeper was then placed on the ballast and levelled using spirit levels (Fig. 21d). Subsequently, the actuators were connected to the rails, and the LVDT frame was positioned around the testing box, ensuring no contact between the frame and the test setup (Fig. 21e). The actuators were attached to the sleeper through short rail segments, allowing the use of real rail fastenings during the tests. Finally, LVDTs were installed on the sleeper to measure vertical displacements (Fig. 21f).

Loading Method

Static and cyclic loads were applied through independent actuators connected to the sleeper via short rail segments. In typical ballasted railway systems, analyses based on the beam-on-elastic-foundation (BOEF) model[45,46]indicate that a sleeper located directly beneath an axle carries approximately 50 % of the applied load. Accordingly, half of an axle load was considered in this study. “A 17-tonne axle load, identified by [47] as the maximum for passenger-exclusive high-speed lines, was selected, corresponding to 8.5 tonnes per sleeper after load distribution, or 4.25 tonnes per wheel. This equates to an applied load of approximately 41.7kN per rail seat, thus the actuator.

SLS Lifting Test

An additional testing procedure was conducted to assess the self-levelling limit of the SLS sleeper. In this method, an artificial gap was introduced beneath the sleeper and progressively enlarged during cyclic


(a) (b) (c)

(d) (f) (e)

Fig. 21. Test setup construction stages.

loading. Similar to the displacement-controlled test, the loading was applied under displacement control at a frequency of 0.2 Hz. After every 10 cycles, the sleeper's set point was raised by 0.5 mm. As illustrated in Fig. 22, a 5 mm displacement amplitude was initially applied in the first cycle to generate a force of 41.7 kN under full contact between the sleeper and ballast. The displacement amplitude of 5 mm was then kept constant throughout the test to represent the continuous cyclic motion expected under repeated train passages, while allowing the resulting load to vary as the support condition changed. Under displacement control, the load naturally decreased with increasing ballast settlement and reduced contact area, providing a realistic representation of the reduction in reaction force observed under hanging sleeper conditions in the field. Subsequently, the sleeper was lifted by 0.5 mm after every 10 cycles, gradually increasing the gap size (shown in light yellow in Fig. 22). The initial load of 41.7 kN corresponds to a typical wheel load acting on a single sleeper, thereby validating that the self-levelling system operates effectively under realistic service loads as well as under smaller loads that occur as contact diminishes. The self-levelling mechanism was expected to activate once a 2 mm gap formed, resulting in a total correction of 40 mm. Continuous contact between the sleeper and the ballast was anticipated until the SLS reached its levelling limit. One must note that this method was employed specifically to test the self-levelling function of the SLS rather than to replicate exact track loading conditions.

The corrective component of the sleeper is the base section, illustrated in blue in Fig. 16 and Fig. 18. The internal wedge mechanism moves horizontally, driving the sleeper base downward to achieve self-levelling. The sleeper can be easily reset by inserting a key into the designated slot and retracting the wedge to its original position.

Sensors and Data Acquisition

The tests were operated and monitored using the TIAB control software, which also managed data acquisition through two independent data acquisition cards with 16-bit and 14-bit resolution. The actuators were equipped with load cells (LC) and linear variable differential transformers (LVDTs) for load and displacement measurements. Three LVDTs were positioned on the sleeper, and all LVDTs and load cells were connected to the 16-bit data acquisition system. Three pressure cells (PC) were installed immediately beneath the ballast and connected to the 14-bit system. The sensor locations are shown in Fig. 23. A sampling rate of 250 Hz was used for all sensors. Sensor notations and descriptions are summarised in Table 3.

Model 3515 granular material pressure cells were used to measure vertical stresses. These semiconductor-type sensors featured a 9-inch diameter plate capable of measuring up to 250 kPa, with a sensitivity of 0.005 kPa. The pressure cells were embedded within the subgrade directly beneath the ballast. The load cell LVDTs were model DCTH6000, which measured both elastic and plastic displacements of the rail heads and controlled the actuator stroke. Their total measurement range was 300 mm with a sensitivity of 0.008 mm. The LVDTs positioned on the sleeper were model DCTH400. These sensors were more sensitive than those attached to the actuators, with a total range of 20 mm and a sensitivity of 0.001 mm. They recorded both elastic and plastic displacements of the sleeper.

Analysis and Discussions

In the SLS lifting test, an artificial gap was introduced beneath the sleeper and gradually enlarged. The loading was applied under displacement control at a frequency of 0.2 Hz. After every 10 cycles, the sleeper was lifted by 0.5 mm. An initial amplitude of 5 mm was applied to achieve a force of 41.7kN in the first cycle. The gap was then progressively increased by lifting the sleeper 0.5 mm after every 10 cycles. The self-levelling mechanism was activated once a 2 mm gap developed. Full loss of contact occurred when the sleeper was raised 44 mm on the right side (Fig. 24) and 45 mm on the left side (Fig. 26). The SLS was subsequently lowered by 14 mm until full contact between the sleeper and ballast was restored. The results presented here are based on SLS-HW, as tests with SLS-G indicated the need for further design refinements.

Each spike in the force signal indicates that the internal wedge of the SLS moved one increment, causing the sleeper base to move downward and fill the gap. Fig. 25 presents a zoomed view of the initial corrections. The orange line represents the rail displacement, which increased by 0.5 mm after every 10 cycles. After four such increments, adding up to 2 mm of cumulative lifting, the sleeper regained full contact with the ballast, and the target force was achieved. At every 2 mm of cumulative lifting, the sleeper's self-levelling mechanism was activated. The sleeper continued to be lifted in 0.5 mm increments until a total lifting of 44 mm, at which point full loss of contact with the ballast occurred and the self-levelling mechanism reached its limit.

In total, the sleeper corrected 30 mm and 34 mm on the right and left sides, respectively. After these adjustments, the sleeper remained fully functional. The self-levelling mechanism operated effectively, restoring full contact between the sleeper and the ballast, and maintained load transfer comparable to that of an intact sleeper. This demonstrates that the levelling mechanism possesses sufficient stiffness and strength to sustain the applied loads and maintain stable track support under repeated loading conditions. However, further settlement could lead to complete loss of contact, causing the sleeper to hang; full hanging was observed at approximately 40 mm of lifting. The stress measurements beneath the ballast also confirmed the function of the SLS. As shown in Fig. 27, the load was concentrated directly beneath the rails, while the centre of the sleeper experienced minimal loading. The continuous pressure between the sleeper and the ballast indicates that the sleeper

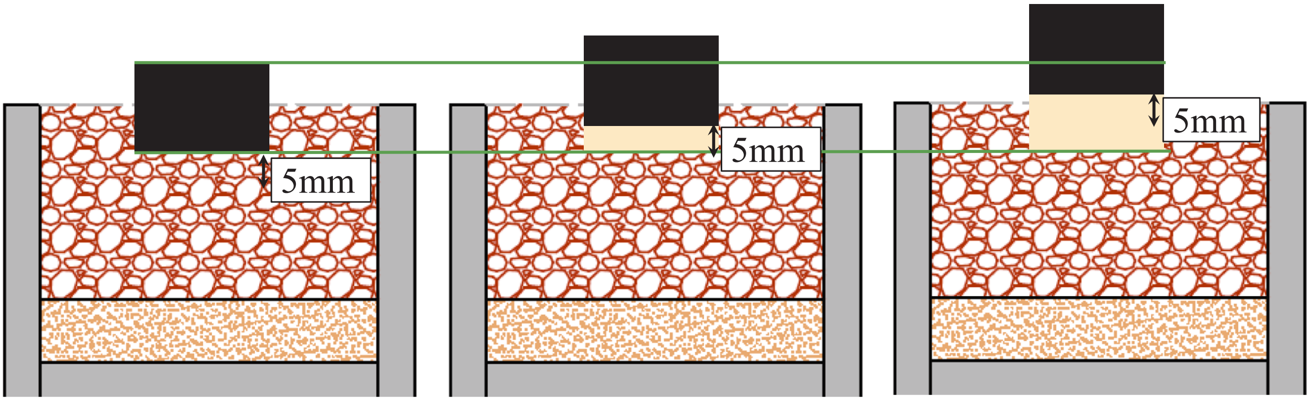


Fig. 22. Creating artificial gap with lifting the sleeper approach.

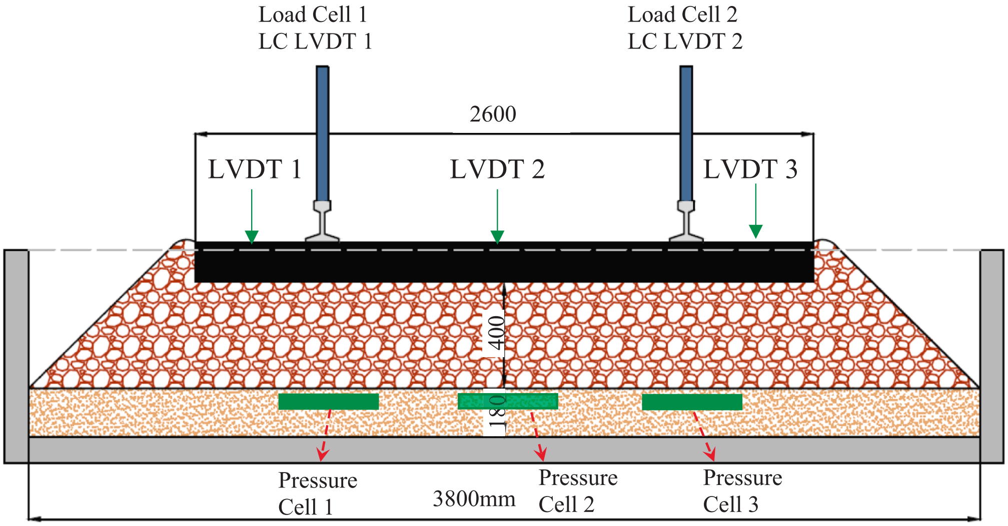


Fig. 23. Sensor positions on a cross-section of the facility (Dimensions are in mm).

Table 3
Sensor details.

Sensors	Notation	Info	Location
Pressure Cell 1	P_{Left}	• Geokon 3515	1st rail
Pressure Cell 2	P_{Centre}	• Under the ballast	Mid sleeper
Pressure Cell 3	P_{Right}	• 250 kPa	2nd rail
LVDT 1	$U_{Left,S}$	• DCTH400	Left side
LVDT 2	$U_{Centre,S}$	• On the sleeper	Mid sleeper
LVDT 3	$U_{Right,S}$		Right side
Load Cell 1	F_{left}	• In actuators	1st rail
Load Cell 2	F_{right}		2nd rail
LC LVDT 1	$U_{Left,R}$	• DCTH6000	1st rail
LC LVDT 2	$U_{Right,R}$	• On actuators	2nd rail

never lost contact, and consequently, no impact load was observed while the self-levelling function was active. The higher stresses observed beneath the rail seats are primarily due to the downward movement of the levelling shoe, while the central base of the sleeper remains relatively elevated, as shown in Fig. 28. Because the ballast was already in a compacted state, no significant additional settlement occurred during the test. Consequently, the stress distribution is governed mainly by the action of the levelling shoes rather than by ballast deformation. The total stress levels recorded beneath the ballast after self-levelling are comparable to those reported in field conditions [48], demonstrating that a hanging sleeper condition did not develop even after approximately 30 mm of settlement.

As it can be seen from Fig. 28, when the sleeper bases moved downward, the central portion of the sleeper lost contact with the ballast. Consequently, the contact area decreased from 0.88 m^2 before the correction to 0.66 m^2 after the correction, as the SLS rested on the sleeper base.

Under the displacement-controlled test, a 5 mm displacement was applied, which generated 41.7 kN on each actuator, corresponding to a total load of approximately 83 kN (8.5 t) on the sleeper. This

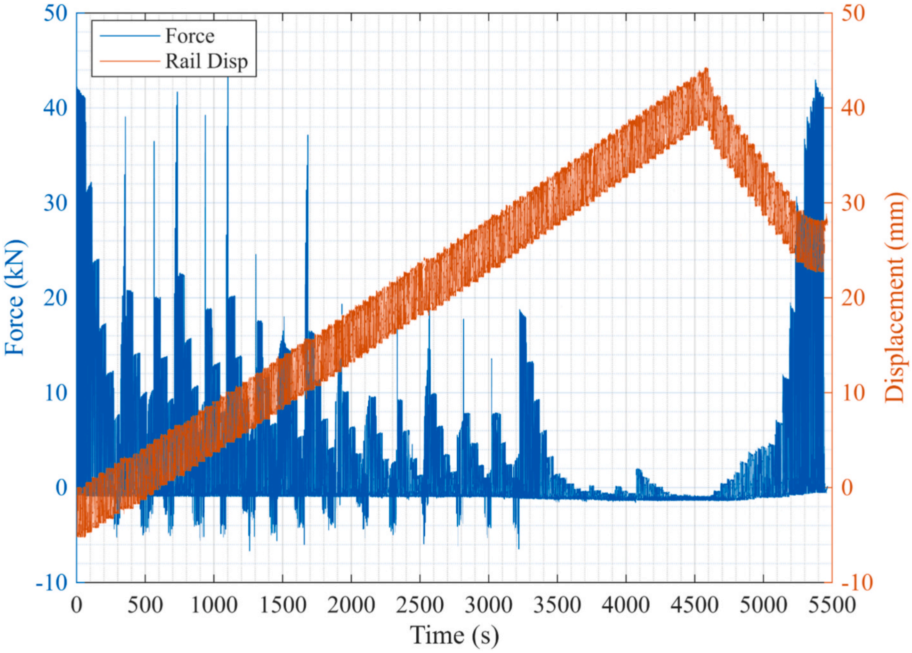


Fig. 24. Change of force (Load Cell 2) and lifting the right side of the sleeper (LC LVDT 2).

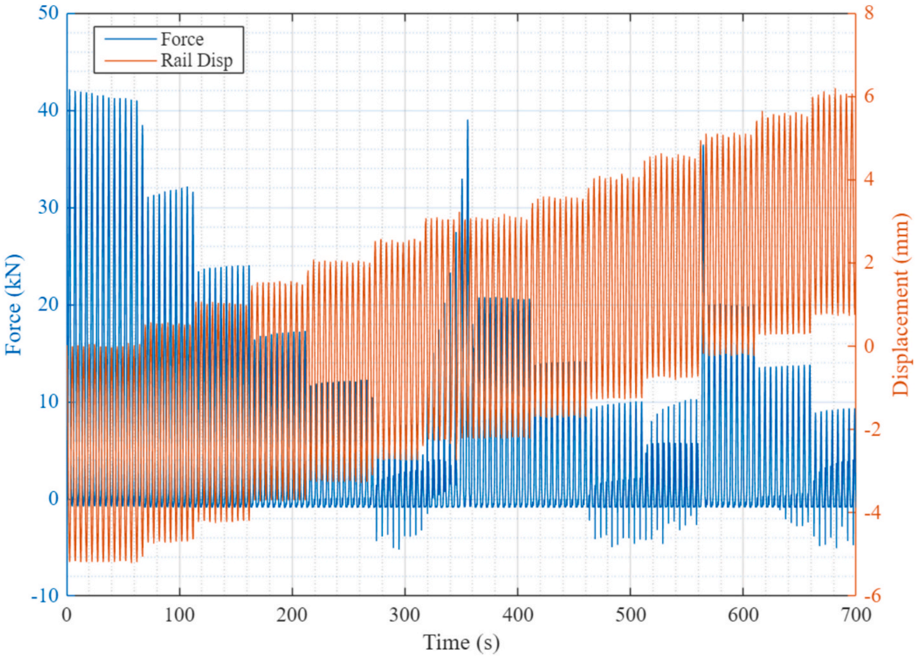


Fig. 25. Change of force (Load Cell 2) and lifting the right side of the sleeper (LC LVDT 2) (zoomed in to first 750 s).

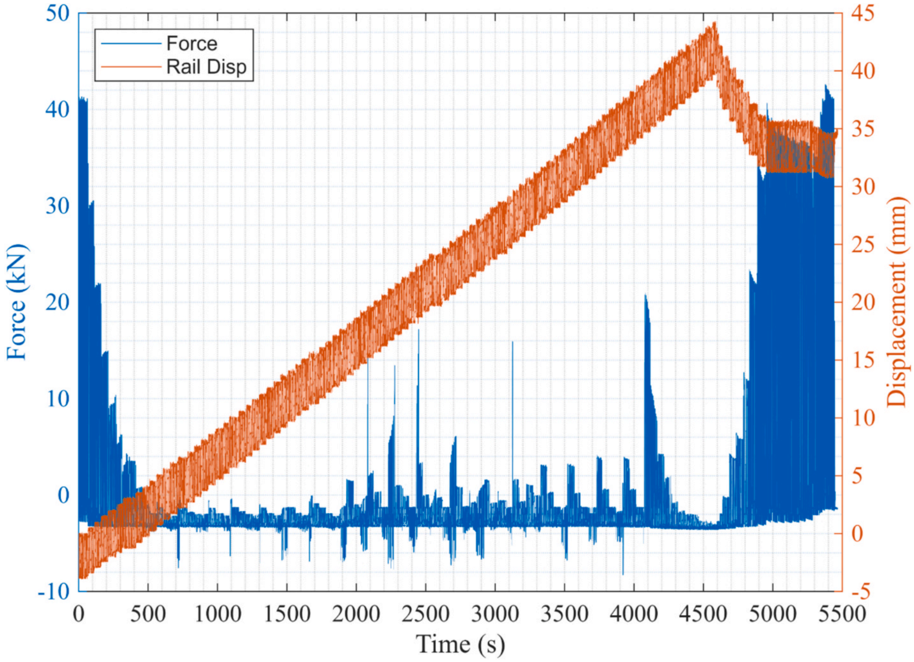


Fig. 26. Change of force (Load Cell 1) and lifting the left side of the sleeper (LC LVDT 2).

displacement was specifically chosen to ensure the sleeper experienced the target load. When the SLS corrected a 34 mm gap, the same 5 mm displacement produced a comparable force of around 42 kN per actuator, again corresponding to the full 8.5 t load. This demonstrates that the sleeper maintained its load-bearing capacity even after the self-levelling mechanism had been activated. Therefore, the displacement-controlled test was sufficient to verify the sleeper's structural integrity, bending stiffness, and load-bearing performance under the applied conditions.

It is acknowledged that the single-sleeper ballast-box configuration does not fully reproduce the complex dynamic interactions of a continuous track system under moving train loads. The primary purpose of this test was to evaluate the fundamental functionality and self-levelling response of the SLS under controlled boundary conditions, rather than to replicate full train–track interaction. The findings from this stage serve to verify the operating principle and reliability of the mechanism, forming the basis for advancing the SLS design toward higher Technology Readiness Levels (TRL) and subsequent field testing. Future investigations will focus on multi-sleeper track sections to evaluate the SLS performance under realistic dynamic and environmental conditions. To this end, it is proposed to install 8–10 SLS on an open (soft) track at a transition zone for in-situ testing. Future work will also include a cost–benefit assessment once the design reaches a higher TRL.

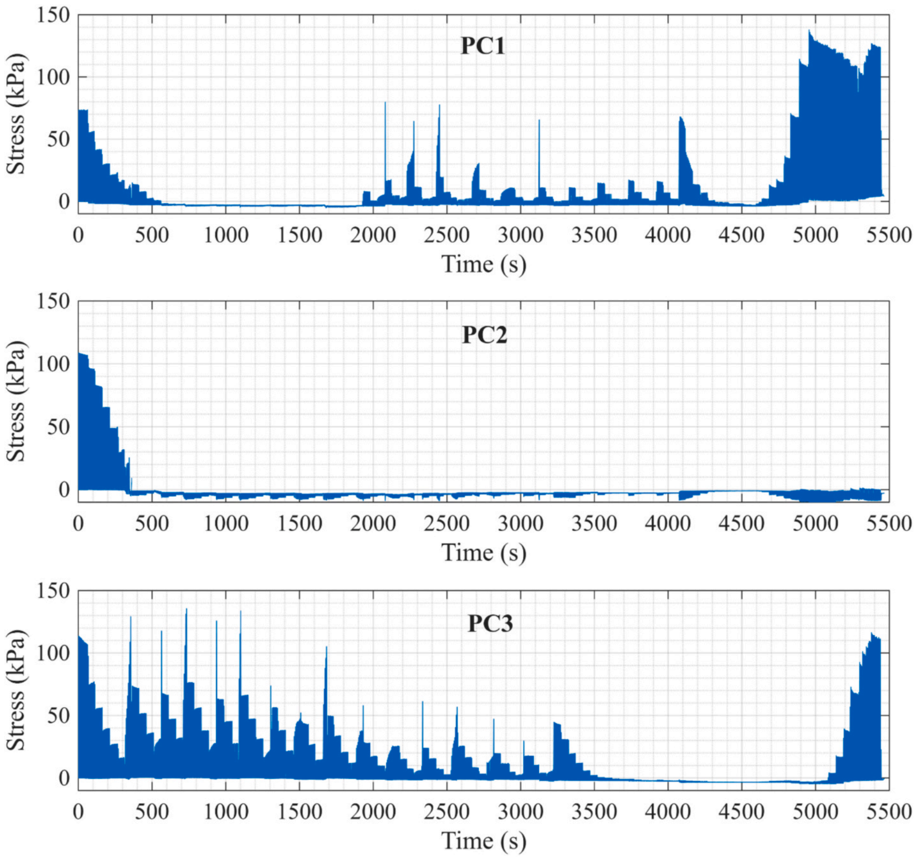


Fig. 27. The stress levels under the ballast after lifting the SLS gradually; PC1 – pressure cell 1 left side, PC2- pressure cell 2 centre, PC3- pressure cell 3 right side of the track section.

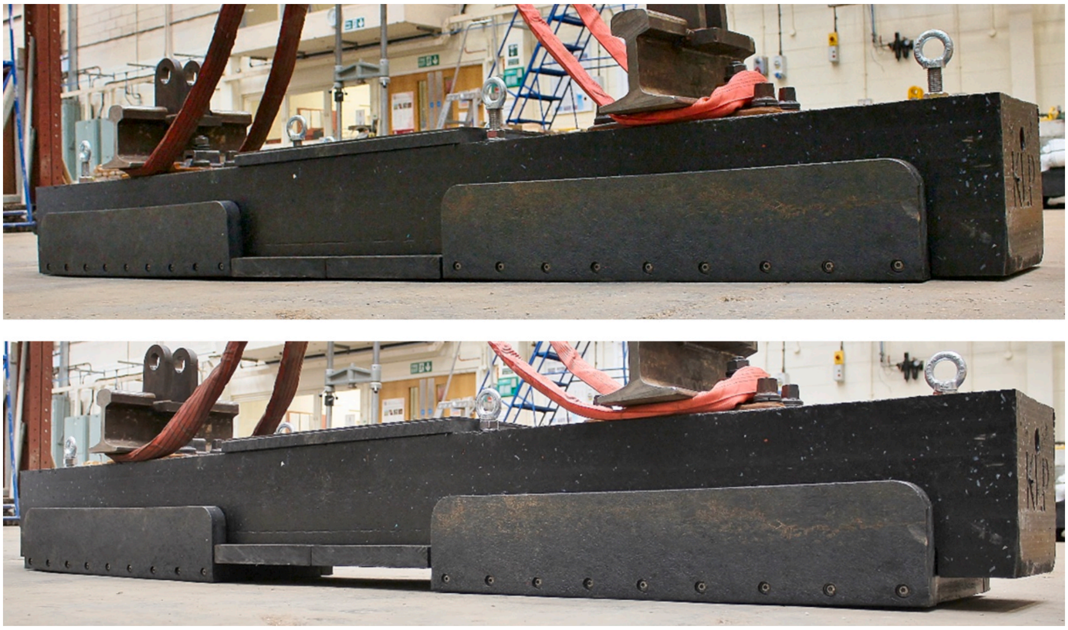


Fig. 28. Before and after levelling.

Conclusions

This study has presented the development, design, prototyping, and experimental testing of novel self-levelling sleeper (SLS) systems. The objective was to provide a modular solution to mitigate vertical track geometry deterioration at transition zones, where traditional stiffness-based remedial methods are often costly, complex, and disruptive to implement. Two full-scale SLS types were developed: a granular-based sleeper (SLS-G) and a horizontally acting wedge-based sleeper (SLS-HW). Both designs used polymeric materials, offering improved ballast interaction, reduced material degradation, and potential use of recycled plastics. These two concepts were shortlisted from an initial set of five, which also included hydraulic and ratchet-based systems, and were selected based on functional viability, manufacturability, and cost efficiency.

The study investigated the behavior of the SLS in the laboratory model of a transition zone when subject to an artificial gap created beneath them. The sleeper was gradually lifted, and the self-leveling mechanism reacted incrementally. The sleeper lost full contact with the ballast once it was lifted to predefined height levels, and the self-leveling mechanism was then used to restore contact by lowering the sleeper bottom; in other words, it changed its height. The SLS possessed a self-leveling function that allowed it to continue functioning until it reached its self-leveling limit, which was 40 mm. The experimental results indicated that after performing necessary corrections, the sleepers remained functional in terms of structural integrity, bending stiffness and ability to carry the load.

Stress measurements taken beneath the sleeper confirmed that vertical load transfer was concentrated primarily under the large sized rail seats of dimensions optimised for needed load distribution to railway ballast, with minimal loading observed at the centre of the sleeper. These findings demonstrate that the SLS-HW system operates as intended under progressive settlement, offering continued support and improved load distribution compared to conventional sleeper designs.

In conclusion, the SLS concepts developed in this study offer a potential solution to address settlement-related track deterioration in transition zones. The combination of modular construction, polymeric materials, and self-levelling functionality provides an alternative to traditional remedial measures which may be useful under certain circumstances. Laboratory testing confirmed the physical viability of the concept, particularly for the SLS-HW system, which has the potential to extend maintenance intervals, reduce lifecycle costs, and improve long-term track stability. The design of SLS-G requires further improvements to enhance its performance and reliability.

CRediT authorship contribution statement

A.F. Esen: Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **V. Lojda:** Writing – review & editing, Validation, Methodology, Investigation, Formal analysis. **A. van Belkom:** Supervision, Investigation. **V. Markine:** Supervision, Investigation. **D.P. Connolly:** Writing – review & editing, Supervision, Project administration, Methodology, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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