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IN2ZONE Research project towards the Next Generation of Railway Transition

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Abstract

IN2ZONE is an EU Funded project of Shift2Rail under Innovation Programme 3. The aim is to develop a next generation transition zone solution which is able to self-correct issues such as hanging sleepers, thus offering a step-change reduction in maintenance requirements compared to existing solutions. Firstly, to create a proof-of-concept design, three- and two-dimensional discrete element sleeper-ballast models were developed. The results obtained from numerical simulations were then used to guide the manufacture of full-scale prototypes for full-scale lab testing. A single sleeper section of a ballasted track was built and tested. Displacement transducers, load cells, pressure cells and accelerometers were positioned to investigate the occurrence of hanging sleepers. The elastic and plastic deformations, stress distribution, and accelerations in the track were obtained.

Keywords: Railway transition zone; Hanging sleeper; Discrete element method; Self-levelling sleepers; Plastic sleepers; Full-scale testing, Railway monitoring

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1. Overview and motivation

The average cost of building a railway line in Europe is between €13-40 million per kilometre. After construction and/or several years of operation in some circumstances, there could be high infrastructure maintenance due to heavy traffic, high speed, poor quality of construction, poor subsoil etc. A major source of track maintenance costs are the transition areas, as a high level of maintenance is required here to maintain the desired track geometry, ensuring passenger comfort and avoiding speed restrictions, and reducing degradation speed of the constructions. Transition areas should allow smooth train movement and minimise the effects of changes in stiffness of the track supporting layers along the track. When a train moves from an embankment towards a stiff structure such as a bridge, culvert and tunnel, there is an abrupt change in support stiffness, which increases dynamic wheel loads and causes increased track stresses. At the same time a differential settlement between the embankment track and structure starts to occur, generating differential track geometry, which causes an increase in the interaction forces between the train wheel and rail. Moreover, due to differential settlements, some of the sleepers lose contact with the ballast, leading to a phenomenon called hanging sleepers.

To reduce the need for maintenance, self-correcting sleepers have been proposed. Nakamura and Muramoto (2009) and, Muramoto and Nakamura (2010) invented an automatic irregularity-correcting sleeper (AICS), which was followed by Muramato (2012) in Japan's Railway Technical Research Institute (RTRI). The AICS is made up of a fiber-reinforced polymer sleeper and two automatic subsidence compensation (ASC) mechanisms located under each rail. AICS-SS, on the other hand, is a short sleeper with ASC that can be easily attached to rail and placed between existing sleepers. Because the AICS-SS is so simple to attach and detach from the rail and requires no sleeper modifications, it allows for significant cost savings during construction (Muramoto, et al., 2012). A self-compensating sleeper (SCS) was developed by Insley and Sharpe (2020) with the applicants Schwihag AG Gleis and Weichentechnik (Patent No: EP3608472A1). The SCS has conical shaped cavities from the top surface to bottom. When the track is lifted, the granular material in the cavities falls into the holes under the sleeper. The SCS provides for an automatic repacking. When the SCS is positioned at a location where voids would normally form, the SCS can effectively pack itself, thus compensating for any void created beneath the SCS. Another form of self-correcting solution is a sleeper automatic settlement compensating apparatus which can automatically correct ballast settlement caused by an inflating force of an air bag, proposed by Lee, et al. (2012) with the application of Korea Railroad Research Institute (KRRI) and has a European patent with ID KR101374526B1. Embedded automatic differential settlement compensation apparatus, on the other hand, concerns a sleeper embedded automatic track differential settlement compensation apparatus. This apparatus is installed at a concrete sleeper and is capable of automatically compensating for a track differential settlement due to a train load by using oil pressure. This apparatus is proposed by Lee and Lee (2014) with the Korea Railroad Research Institute (KRRI) application and has a European patent with ID EP3112533A1.

There is a lack of data on self-levelling concepts. These solutions require a thorough short- and long-term performance investigation in terms of elastic and plastic deformations as well as life cycle behaviour. Some solutions are reported to be costly and incompatible with common maintenance approaches. To further investigate this, IN2ZONE will design and test a prototype next generation transition zone solution that improves track support conditions with the aim of reducing maintenance interventions. To achieve this, new Self-correcting sleepers will be designed, formed from synthetic material, with optimised properties for transition zones. This will enable the transition zone solution to self-correct minor vertical track geometry irregularities/faults. The self-levelling sleeper will be developed using recycled plastics, which will be reinforced with steel bars, a technology with which Lankhorst Engineered Products has experience. Bending stiffness and details about polymer rectangular sleepers can be found, for example, in Lojda et al. (2019).

2. Methodology

The new design will be optimised with recent advances in discrete and finite element numerical simulation tools. Then the transition zone solution will be built and tested in a controlled laboratory environment.

2.1. Numerical modelling

The numerical modelling method, discrete element method (DEM) has been applied to explore sleeper optimisations. Models of ballast box tests with cone sleepers (2D & 3D) and self-correcting with granular solution are built, based on which, the cone shapes are analysed and optimised, while the design for self-correcting sleeper is validated.

DEM. Discrete element method is one of the modern numerical methods that allows to describe the motion of a large number of small particles and to analyse their interaction. The method becomes extremely useful when it comes to analysis of the dynamic behaviour of the systems involving granular materials, such as bulk material handling equipment and railway systems. As a research methodology, the discrete element method has been used in plenty of ballast-related studies and proved to be an effective numerical method (Guo et al. 2020a). To analyse the interaction between the sleeper and ballast, where the settlement is initiated, the DEM model is necessary. The interaction between the ballast particles depends on several factors such as the material and morphology of the ballast particles as well as the particle size distribution in the ballast bed, etc. These factors together with the particle contact and wear/breakage mechanisms can be taken into account using DEM models, which is impossible to do using the typical track models (e.g., spring and/or solid elements). Track settlement is often occurred in transition zones, e.g., the locations on interface with engineering structures like bridges and tunnels, and creates a serious problem for the track safety.

3D cone sleeper track model. The model has 3 parts. A box (wall element) was built as the boundary of track bed, with the dimension of 600*600*600 mm. In the box, the ballast particles (clumps) were filled in at 500 mm height. Sleepers (wall element) with different bottom angle were built, including a 300*300*250 mm cuboid box and a rectangular pyramid (Figure 1). The pyramid bottom can produce a slope in ballast layer, by which ballast particles can fall and fill the void more easily when settlement occurs, thus providing better support to the cone sleeper.
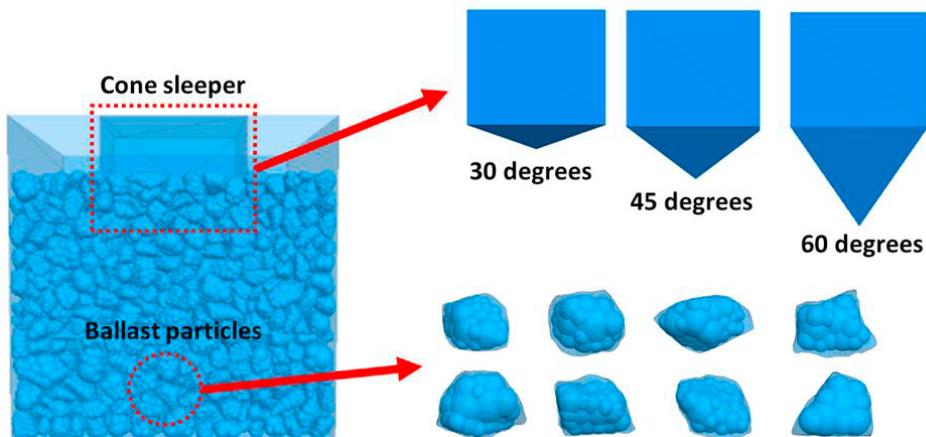

Figure 1. 3D cone sleeper track model

2D cone sleeper track model. A series of 2D simulations was used to analyse the performance of cone sleeper under cyclic loading, as shown in Figure 2. Cone sleeper with bottom angle at 45 degree was chosen, and mono-block sleeper was used as a reference. The sleeper in 2D model was built with Wall element, according to the cross section of KLP sleeper type 202, with the height of 150 mm and 250mm width. The ballast was built with Ball element to save the computational costs. In order to compensate that the interlock between balls is lower than between complex shaped particles, a liner contact model with rolling resistance was employed. This means has been proved effective in the study (Guo et al. 2020b).
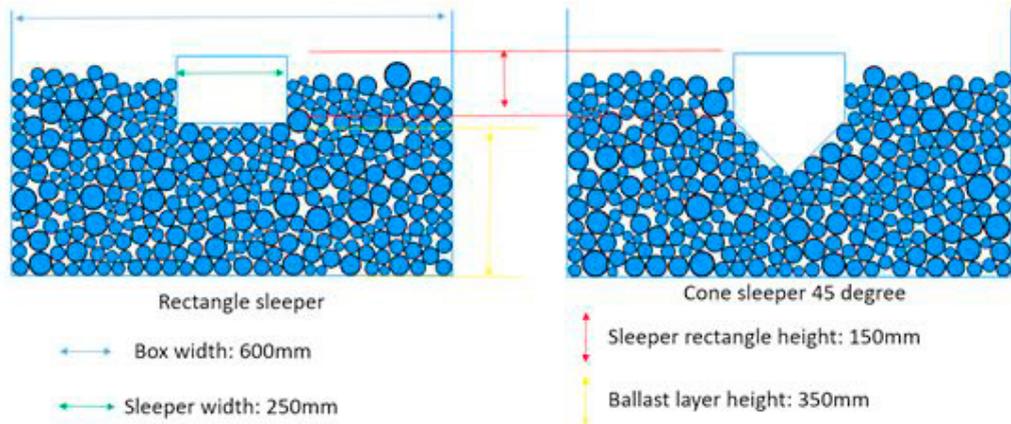
Figure 2. 2D cone sleeper track model and mono-block sleeper track model

2.2. Laboratory tests

The numerical results were used to inform the lab tests. A full-scale laboratory-based testing is used to assess the short and long-term performance of a ballasted track section resting on a compacted substructure. A single-sleeper-section of a track is placed in a 0.93m wide, 3.8m long and 0.685m deep metal testing box with which is supported by thick composite base. The testing rig operates via hydraulic actuators which are individually capable of loading 150kN at loading frequencies up to 15 Hz, and up to 200kN statically. To better understand the behavior of sleepers at transition zones and to assess the proposed solutions, two different testing methods have been proposed (Figure 3). Each method requires only one-sleeper-section of a track. Single sleeper is positioned above the ballast. Benchmark tests on a traditional concrete or plastic sleeper shall be performed for both methods in addition to a self-levelling sleeper test. A standard KLP 202 plastic sleeper is tested for benchmark purposes, which is followed by the self-levelling sleepers.

Method 1- Hanging sleeper test with displacement control: A displacement control test is a fixed deflection excitation in which the loads are applied via a displacement. A displacement value oscillates sinusoidally between a fixed minimum and maximum displacement value, defining the load delivered to the sleeper.

Method 2- Transition zone test with force control: A force control test is a load-controlled test in which the rate of loading is controlled to maintain a constant load increment per unit of time. The force provided to the sleeper via actuators oscillates in a sinusoidal pattern between fixed minimum and maximum loads.
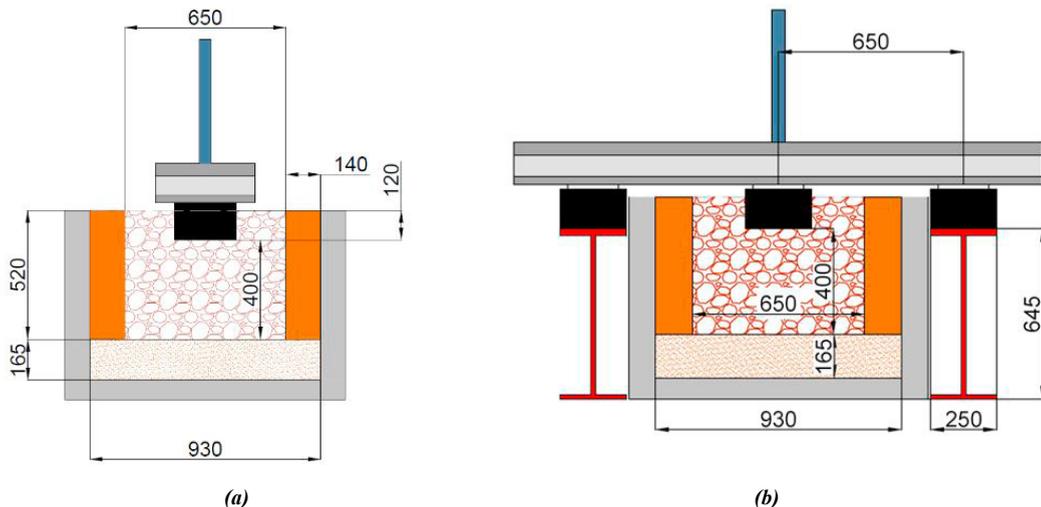

(a)   *(b)*

Figure 3. (a) Method 1: Hanging sleeper test with displacement control, (b) Method 2: Transition zone test with force control

Method 1 test of plastic sleeper have been completed. The actuators are attached to a sleeper via short rail segments (Figure 3). Real rail segments are used to utilise the fastenings during the tests. The load is applied in displacement control for certain number of cycles. Due to the nature of the displacement control, the sleeper oscillates at the certain location, thus permanent settlement is not the main concern of this method. After a number of cycles, the ballast settles and starts losing the full supporting condition. A gap starts to develop under the sleeper.

Firstly, the half of a 17t-axle load is applied statically. It is followed by the cyclic test. A displacement magnitude is introduced to the actuators which will generate the wanted axle load oscillation. The load will stand for 50% of the axle load. The cyclic test will be in displacement control. This test will be performed for 500,000 to 1,000,000 cycles. Then, first static test is repeated. It is expected the pressure under the ballast and reaction force on the sleeper should decrease after numerous cyclic loadings owing to the appearance of gap under the sleeper. However, self-levelling sleepers are designed to correct the gap while it starts to develop. Once the SLS sleeper corrects the track automatically, the pressure drop under the ballast and the reaction force on the sleeper is expected to be less than standard sleepers. This method will prove the working principle of SLS sleepers. The development of hanging sleeper i.e. size and occurrence speed of the gap.

Regarding the measurement system used for laboratory tests, efforts were focused on two objectives: first, to setup and deploy a data acquisition system to support laboratory tests; second, to specify and design a resilience-based monitoring system suitable for field applications ensuring a relatively maintenance free system. The measurement system used for the laboratory test was based on Evopro's modular vibration measurement solution shown in Figure . The system was developed with the expected harsh environmental conditions of railway field applications in mind, enabling high reliability and availability. It consists of a data acquisition module (eITG) and up to 8 sensor modules (eRVM), where each module is equipped with a three-dimensional accelerometer. The data acquisition module includes a high performance industrial embedded computer and various communication/networking interfaces supporting wireless and wired protocols (Ethernet, USB, RS-485, CAN, as well as WiFi and 4G) and can be battery or mains powered. Data acquisition and processing can be carried out by either a stream-based, continuous data acquisition or a batch-based, triggered approach. In addition to store measured data, the acquisition module provides support for real-time monitoring of the measurement, and it sends real-time calculated measurement characteristics to a cloud storage location via a network connection.
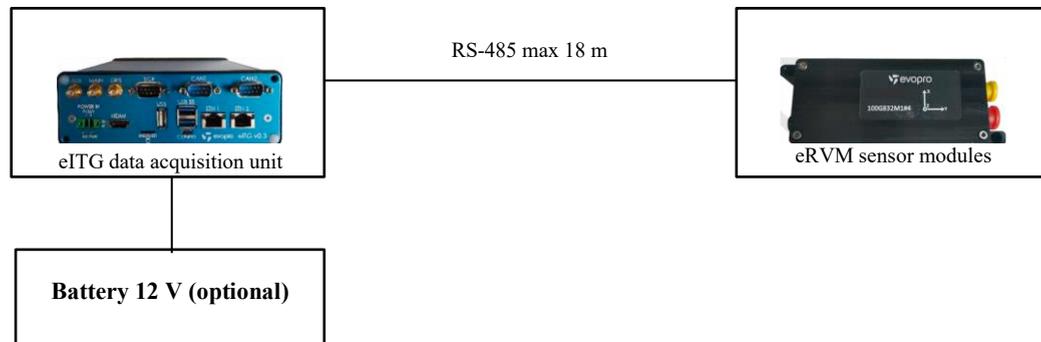

Figure 4. Data acquisition system

The sensor modules were placed at different locations on the test track; along the rail segments and on the middle sleeper, as shown in Figure 5.

(a)   *(b)*

Figure 5. Laboratory test setup and sensor positions a) Method 1: Hanging sleeper test (b) Method 2: Transition zone test

2.3 Design optimisation

The key results from 3D cone sleeper track model are given in Table 1. The table reflects the support correction function of cone sleepers. Specifically, the lowest contact force under zero is caused by the friction between crib ballast and sleeper side. When sleeper bottom has contacts with ballast particles, the forces acted on sleeper begin to increase rapidly. At this point, the sleeper has been supported by ballast particles. With the cone angle increased from 30 degree to 45 degrees, the sleeper displacement (until supported by ballast particles) increases from 0.86mm to 1.51mm. When the cone angle goes to 60 degrees, the sleeper displacement (until supported by ballast particles) is 2.36mm. These results demonstrate that the bigger cone angle leads to better settlement correction, however this is dependent upon the friction angle used in DEM simulations.

Table 1 Key results from 3D cone sleeper track model

Cone angle (degree)	Biggest frictional force (Z-direction) (N)	Displacement when sleeper begins to get support (mm)	Force incensement in last 1 mm (kN)	Peak sleeper contact force (Z-direction) (kN)
30	-0.14	0.86	1.56	39.31
45	-0.32	1.51	74.95	80.12
60	-0.34	2.36	21.88	284.33
Mono-block sleeper	-0.29	0.98	11.71	13.49

The results from 2D cone sleeper track model are shown in Figure 6. The correction effects and contact distribution forces are shown.
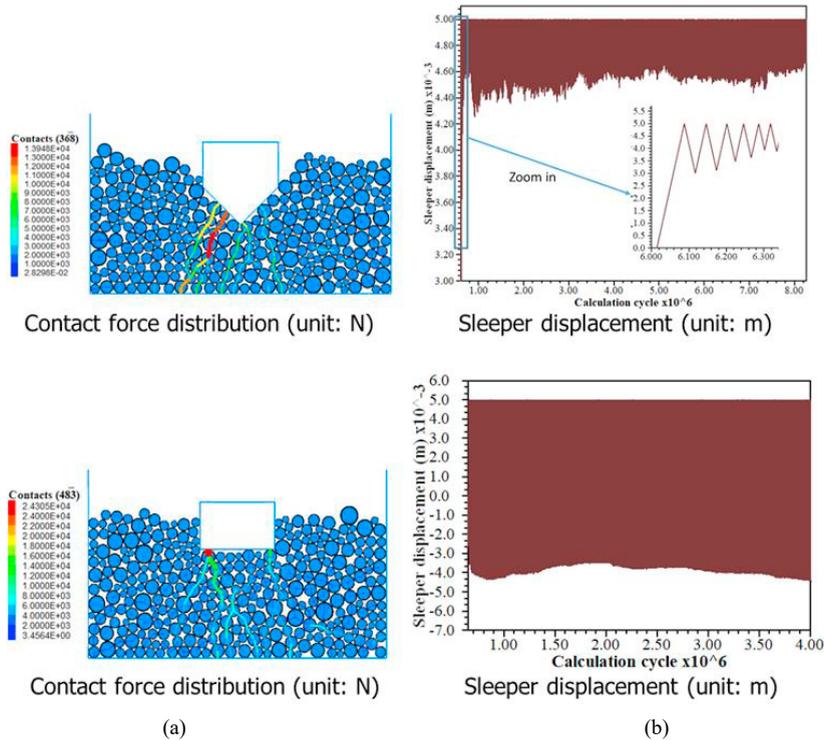
Figure 6. Comparison of (a) mono-block sleeper and (b) cone sleeper track under cyclic loading

The post-processing of the laboratory results is still ongoing. Some of the results from the tests are indicated in Figure 7. The early cycles are obtained from the initial 10 cycles where the sleeper is in full contact with ballast, while the late cycles were obtained around 600,000th cycle. It indicates the reaction forces on the left rail. As it can be seen, the reaction force dropped below zero at the final cycles suggesting sleeper loses contact with the ballast during the sinusoidal displacement-controlled movement.
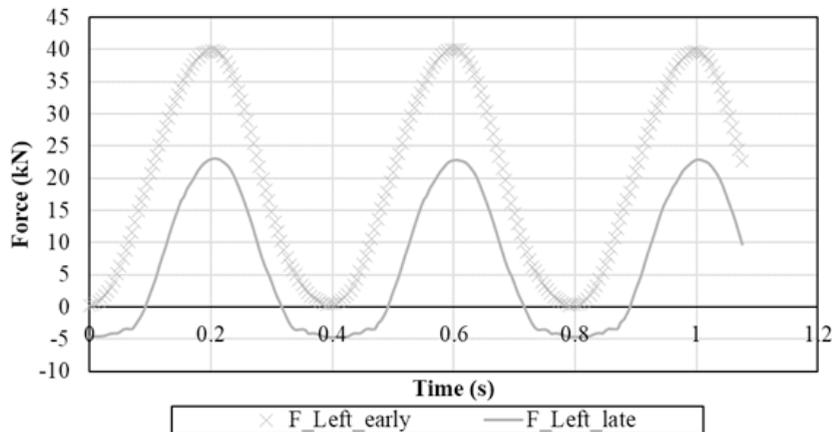

Figure 7. The comparison of reaction forces between the ballast and the sleeper at the beginning and end of the cyclic loads

3. Conclusion and future works

To achieve a high-performance transition zone, new automatic irregularity correcting sleepers are being explored, that are formed from synthetic material, with optimised geometry and stiffness keeping capacity for

transition zones. This will enable the transition zone solution to self-correct minor track geometry irregularities/faults, meaning maintenance activities are less frequent. These novel sleepers will be part of a holistic design, which also uses novel ballast stabilisation, soil improvement and resilient elements to optimise the change of stiffness across the transition. An advanced resilience-based monitoring specification for transition zones will also be designed.

3.1 Laboratory test

A steel box that can accommodate single sleeper section of railway track is used for the large-scale test setups. The hanging sleeper experiment in displacement control is proven to be a useful tool to test self-levelling sleeper. The standard sleeper test showed a gap occurring under the sleeper. In the future tests with self-levelling sleeper, the gap expected to be compensated with the self-levelling mechanism.

3.2 DEM

The DEM simulation results of cone sleeper show that it has the support correction function and reduce contact forces in ballast layer. Furthermore, the 45-degree cone sleeper shows a good performance on support correction under cyclic loading (long-term performance). Compared with mono-block sleeper, the advantage of cone sleeper is that it reduces the contact force between sleeper and ballast due to bigger contact area.

3.3 Field tests and transition zone monitoring

In the framework of the present project, in line with the planned resilience-based monitoring specification for transition zones, a novel eRTD (evopro Railway Track Diagnostics) system will be developed, which will be a dedicated design to serve special functionalities of the transition zone monitoring. Based on the experiments and results of the laboratory test, the eRTD system will support new type and configuration of sensor modules developed as a next generation electronics of the current sensor modules. Due to the various and different structures and materials used for transition zone construction, the monitoring system shall provide a flexible, modular, and scalable approach to fulfil different physical, timing, and various application aspects and requirements. As a general approach, the monitoring system will fuse measurements from multiple sensors, collect and aggregate data through one or more field communication devices (edge computing) and apply different edge- and cloud-level processing and evaluation. The digital twin framework will also be supported.

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