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Ballast Mechanical Performance with and without Under Sleeper Pads

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Abstract: With the train speed and axle load increasing, excessive stresses are produced and transmitted to the ballast layer, inducing rapid ballast degradation. To solve this issue, the under sleeper pads (USPs) have been widely applied between sleepers and ballast particles as the elastic layer. In this research, laboratory tests using half-sleeper track were carried out to study the ballast bed performance with or without the USPs under static and cyclic loading. Results show that applying the USPs reduces the track stiffness and can decrease the settlement. However, installing the USPs increases the ballast bed acceleration and the sleeper vertical acceleration. The contact areas of sleeper-ballast with USPs are over 5 times as those without USPs. The USPs assist reducing ballast degradation mainly by avoiding the ballast particle breakage at the sleeper-ballast interface and can increase the stress distribution at the longitudinal direction.

Keywords: Ballast, USPs, Cyclic loading, Settlement, Breakage

1 Introduction

The increasing train speed and axle load lead to the several degradation and deformation of ballasted tracks. It is already known that the track settlement is significantly affected by ballast degradation (Guo et al., 2019,Li et al., 2002). Consequently, mitigating ballast degradation is urgent and necessary not only for improving the track capacity and performance but also for reducing maintenance costs and increasing track service time (Xiao et al., 2017).

Recently, the geo-inclusions have been successfully applied in ballasted tracks, such as polyurethane, geogrid and geocell (Indraratna et al., 2018,Indraratna et al., 2013,Jing et al., 2019). The main purpose of applying these geo-inclusions is to improve performance and reduce degradation of the ballast layer by restricting the ballast relative movements. Additionally, it has been demonstrated that these geomaterials are able to enhance track stability (lateral and longitudinal sleeper resistance) and decrease the plastic deformation (Chen et al., 2015,Indraratna et al., 2014,Jing et al., 2018,Qian et al., 2015). However, maintenance and material costs are the main concerns when applying these materials.

Alternatively, some other new materials (elastic elements) have also been utilised in ballasted tracks by increasing the track damping and absorbing the vibrations, e.g. rail pads, under sleeper pads, tire-derived aggregates and ballast mats (Guo et al., 2019,Jayasuriya et al., 2019,Kaewunruen and Remennikov, 2006,Lima et al., 2018,Nimbalkar et al., 2012). Among them, the USPs are the most potential one and at present have been applied as a standard component in some countries (e.g. France, German, Austria) due to the following reasons (Schilder, 2013): 1) vibration and noise reduction; 2) ballast degradation mitigation; 3) rail surface damage reduction; 4) ballast layer thickness reduction; 5) track irregularity compensation. It needs to note that the reduction of the vibration and the ballast layer thickness are crucial for the high speed railway, because they induce problems in the ballast degradation, ballast layer compaction and further the track irregularity (e.g. hanging sleeper) due to the discrete nature of ballast assemblies (Sun et al., 2016).

Earlier studies have been performed and demonstrated that the USPs contribute to track resilience improvement, ballast degradation reduction and excessive energies dissipation (Jayasuriya, et al., 2019). Further the USPs are applied for in some special track structures under impact loadings, e.g. transition zones, turnouts and rail joints (Kaewunruen et al., 2017,Steenbergen, 2013,Wang et al., 2018). Particularly, the study in (Navaratnarajah and Indraratna, 2017) confirmed that the USPs cause an average of 15%, 20%, and 40% reduction in vertical plastic strain, ballast degradation, and vertical stress at the sleeper-ballast interface. Similar results were also presented in (Navaratnarajah et al., 2018), which shows that the application of USPs reduces ballast breakage, vertical stress at the sleeper-ballast interface and vertical plastic strain at an average of 50%, 10% and 40%, respectively. For the aspects of life cycle cost and sustainability of the USPs, the ballast and sleeper degradation reduction contribute to reduce the track geometry irregularity, thus reducing the maintenance and prolonging the track service life. This can further reduce the life cycle cost and increase the track sustainability (Le Pen et al., 2018,Paixão et al., 2018,Schneider et al., 2011).

From the above introductions, the advantages of using the USPs can be observed. However, studies on some aspects are still not sufficient, and some controversial conclusions were made due to research limitations.

Most of the USPs studies were performed in the field and mainly focused on the dynamic responses of the superstructures (i.e. sleeper, fastening system and rail) (Ali Zakeri et al., 2015,Kaewunruen, et al., 2017,Le Pen, et al., 2018,Paixão et al., 2014,Schneider, et al., 2011,Steenbergen, 2013). The dynamic performance of the ballast layer has not been fully revealed. Due to the complex field conditions, it is not easy to control the same test configurations, the ballast acceleration is not easy to measure and the ballast degradation is uneasy to evaluate. These limitations may lead to some result differences. For instance, the study in (Larsen and Løhren, 2016) shows that the USPs have negligible influences on improving the track quality, and the conclusion is drawn based on a few years of field measurements . Results in (Kaewunruen, et al., 2017,Paixão, et al., 2014) show that the USPs affect the track dynamic performance, inducing large amplitude vibrations under high frequency loadings. Furthermore, the USPs increase the track vertical flexibility and cause larger rail movements and higher sleeper accelerations.

Some laboratory tests were performed for studying the USPs effects on the ballast degradation and settlement, additionally, they compared the influences of the USPs stiffness on the settlement (Abadi et al., 2019,Jayasuriya, et al., 2019). However, some aspects can be modified as a further study based on these studies, e.g. considering the ballast layer dynamic performance (ballast acceleration measurement).

Although enhancing the sleeper-ballast interaction is the main effect factor of the USPs performance, inadequate studies were performed from the viewpoint of the load distribution. The USPs mainly increase the sleeper-ballast contact area, further enhancing the track performance by uniformly and widely distributing the loading. As reported in (Jayasuriya, et al., 2019), the USPs can increase the ballast volume for supporting the sleepers, thus reducing stresses on ballast (Fig. 1). Additionally, due to uniform deformation and stress distribution, the elastic behaviour of USPs decreases the vertical stress on ballast bed by 10-25% (Remennikov, 2015).

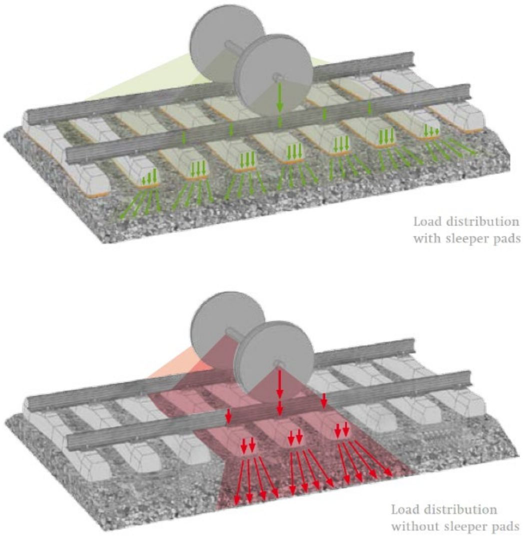


Figure 1 Stress distribution with and without the USPs (figure reproduced from (Kaewunruen, et al., 2017))

The cyclic loadings are applied in most of the earlier studies with laboratory tests, which did not consider the impact loadings. Because in some special track structures (e.g. turnouts), the main loading type is the impact loading.

To further study the application feasibility of USPs, the half-sleeper track laboratory tests (under impact, static or cyclic loading) are performed with the presence of shoulder ballast. By the tests, the feasibility of the USPs is examined on the following aspects: 1) ballast degradation; 2) sleeper-ballast interaction; 3) the vertical and lateral stresses of the ballast layer; 4) dynamic performance of ballast bed. The test results are presented and discussed concerning the vertical settlement, vertical and lateral pressure stresses in ballast layer, the ballast bed stiffness with and without the USPs, ballast bed and sleeper accelerations, sleeper-ballast contact areas and ballast degradation. This study is with the purpose of optimising ballasted track design by intensifying some characteristics, e.g. damping capacity, energy dissipation, and settlement reduction. The study conclusions are able to help scholars or engineers on railway engineering with more safe and sustainable tracks with the USPs.

2 Experimental study

2.1 Test materials

2.1.1 Ballast

The fresh ballast particles used in this study were predominantly crushed volcanic basalt, provided by

Tangshan Quarry, Hebei Province. Ballast physical properties were tested according to the British standard, including the durability, mineralogy and particle shape (British Standards Institution, 2013). The physical properties of the ballast particles are given in Table 1. Based on the British standard, the ballast particles were sieved to obtain the required particle size distribution (PSD, Grade A) as shown in Table A.10 and Table A.11, and the ballast density was 2930 kg/m^3 (British Standards Institution, 2013). Ballast particles were washed and dried at the room temperature (about 16 degrees centigrade).

Table 1 Ballast physical properties sourced from Tangshan Quarry

Property	Standard	Result	Maximum specification value
Los Angeles abrasion loss (%)	BS EN 1097-2	11.70	20.00
Micro-Deval loss (%)	BS EN 1097-1	5.20	7.00
Flakiness index (%)	BS EN 93-3	2.20	35.00
Elongation index (%)	BS EN 93-3	0.90	4.00
Fine particle content (%)	BS EN 933-1	0.30	0.60
Fines content (%)	BS EN 93-3	0.20	0.50

2.1.2 Sleeper and under sleeper pads

The applied sleepers were half sleepers derived (by sawing) from a full-size sleeper. Two sides of the sleeper are sawed and the middle part of the sleeper was used, which was a simplification of the real track. The sleeper was Chinese Type Ⅲ Mono-block sleeper with the weight at 375 kg, whose configuration can be found in Fig. 2. The sleeper configuration was different from (Abadi, et al., 2019). The applied sleeper for testing was a typical-utilised one in Chinese railway. The USPs applied in this study was with the thickness at 6.0 mm and they were made from polyurethane and elastomeric inclusions. The USPs stiffness was 0.212 N/mm^3 and it was attached to the sleeper bottom with the size at 1000 × 300 mm.

It is crucial to select the USPs with suitable stiffness and in terms of static stiffness they are classified into four groups (Table 2). For example, the study in (Abadi et al., 2015) shows the softer USPs, the higher contacts between the sleeper base and ballast particles. Additionally, according to the International Union of Railways report (Remennikov, 2015), the medium or stiff USPs are suitable for improving the track quality, reducing the track stiffness and the ballast layer thickness, while the soft USPs are more appropriate to reduce the vibrations and noises. In this regard, the medium stiff is chosen in this research for studying the dynamic performance improvement of ballast bed.

Table 2 USPs classification according to stiffness (Esmaeili et al., 2016)

USPs	Stiffness (N/mm^3)
Stiff	0.25-0.35
Medium stiff	0.15-0.25
Soft	0.10-0.15
Very soft	≤ 0.10

2.1.3 Pressure-sensitive paper

The pressure-sensitive paper was a Fuji film that can accurately measure pressure magnitude and distribution. Red patches appear on the paper when applying contact pressure and the colour areas indicate the corresponding contact pressure magnitude (Abadi, et al., 2015). In this paper, the pressure-sensitive paper was placed at the interface of the USPs/ballast to measure the contact locations and contact areas after the whole loading period.

2.2 Test setup and procedure

2.2.1 Painted ballast particles

The applied ballast particles at different layers were painted with different colours to distinguish them and more easily to evaluate the ballast degradation at different layers. The particles directly under the sleeper were painted in yellow and the particles around the sleeper were not painted, as shown in Fig. 2. In the figure, the positions of the red and green ballast particles were observed.

The spray paint was a non-oil-based one, which covered the ballast particles with a very thin coating. Therefore, after painting, the ballast surface texture was almost the same as before. Heap tests were performed on unpainted ballast particles and painted ballast particles, and the repose angle results are given in Table A.1. From the table, it can be observed that the repose angles of the green ballast and red ballast increase 1.4 and 1.1 degrees, respectively. The test results demonstrate that painting the particles has few influences on the interparticle friction. This conclusion was also proved in the study in (Navaratnarajah, et al., 2018) using the direct shear tests.

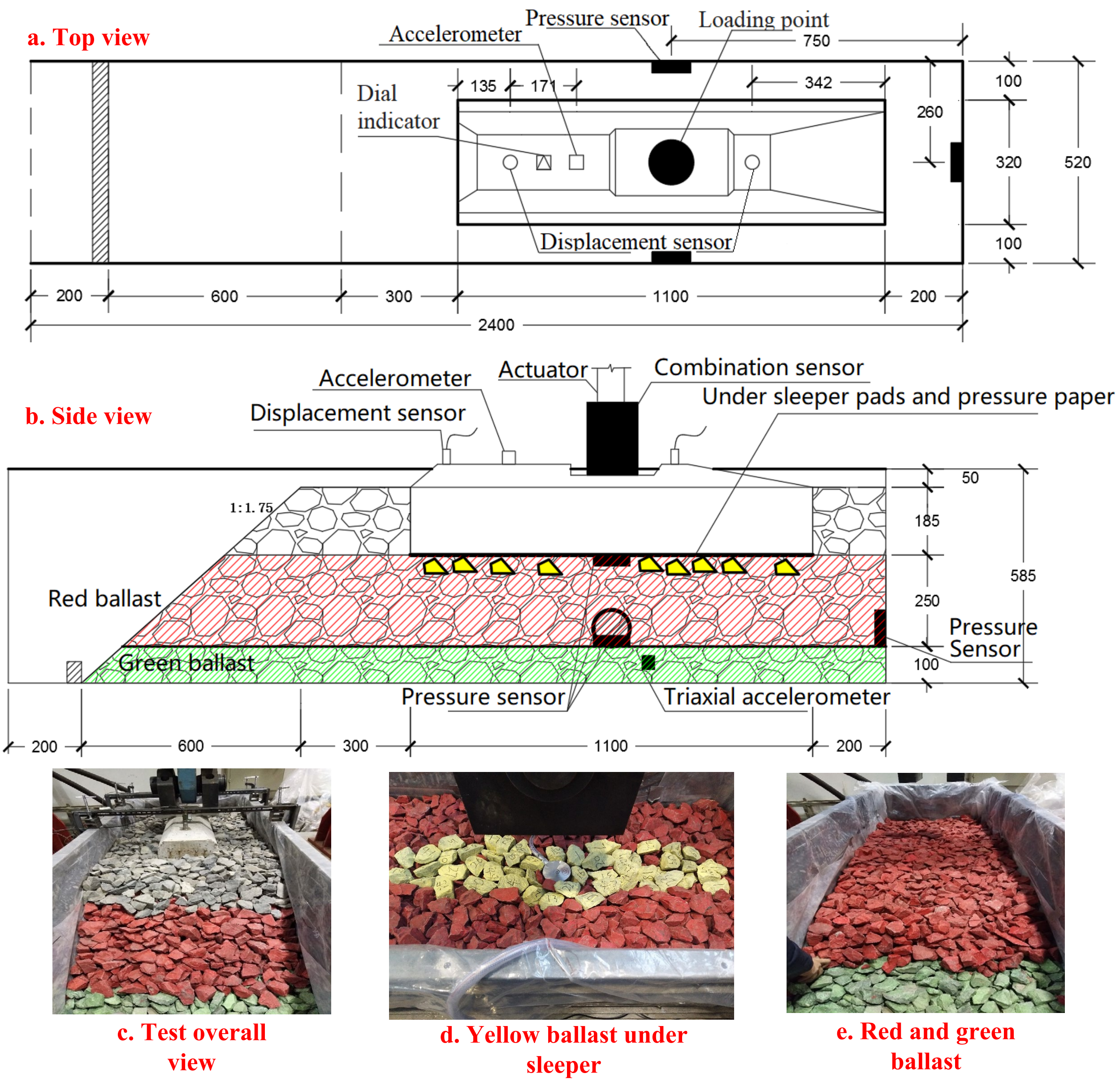


Figure 2 Test instruments and test setup

2.2.2 Test setup and Procedure

In (Abadi, et al., 2019), it shows that in traditional ballasted track around 50% of the loading was directly transmitted to the sleeper. Therefore, the maximum vertical loading of 125 kN matches the 25 ton axle load. This value can be acceptable for the freight axle loads, which in China is around 25 ton at most. The frequency was according to the length of the bogie (2.02 m), the distance between two bogies and the train speed. The frequency was in the range of 1-15 Hz at the train speed of 100 km/h. The average value of the range (8 Hz) was chosen for this study, which was slightly arbitrary. Nevertheless, the effect of the loading frequency was not a variable in the current study, and keeping the loading comparability in each test to test was sufficient for this study.

The impact loading was also considered in this study. The loading was decided after dropping steel plate at different weight and height. The main reason for deciding these two factors was to provide enough excitation that can shock the sleeper with a reasonable vibration. Comparing the acceleration difference was the main focus in this study, consequently, the impact loading (i.e. weight and height selection) was chosen from a reasonable range. It needs to note that the height is the lowest height that can provide enough excitation, because it is necessary to avoid damaging the sleeper when dropping the weight.

After the material preparation, the setup and procedure of the cyclic and static loading tests are given as follows:

1. The ballast particles were put into the container with three walls and one side free (for ballast shoulder). The container was filled with green ballast particles at 100 mm, and ballast particles were compacted to a typical field bulk density (2.05 g/cm^3) with a compactor.
2. Afterwards, the red ballast particles and yellow ballast particles were placed and compacted in the container (250 mm) with half sleeper placed on them. Finally, the unpainted ballast particles were placed around the sleeper as the ballast crib and the ballast shoulder was made to the upper sleeper surface.
3. During placing the ballast particles, the instruments (data acquisition) were set and placed at the appropriately-designated positions, including the triaxial accelerometer, pressure sensor, dial indicator, displacement sensor and accelerometer (Fig. 2). The pressure-sensitive paper was affixed under the USPs.
4. Before applying loadings, the pressure sensors were calibrated. Specifically, pre-loadings were applied that started from 0 kN until 125 kN and one force-displacement curve can be obtained. Afterwards, the actuator and the data acquisition system were calibrated to the same. Finally, when the pre-loading was from 50 kN to 200 kN, little error was observed. Until the pre-loading reached 250 kN, the difference was 1.0%. The values are given in Table A.12 (Appendix).
5. Afterwards, the sinusoidal cyclic loadings were applied at 8 Hz with the magnitude between 40 kN (minimum) and 125 kN (maximum). The total 1,000,000 cycles were applied. Before and after the cyclic loading tests, the static loadings were applied for measuring the static ballast bed stiffness. The static loading was applied with the magnitude at 0 to 120 kN.
6. The impact loading test was performed after the cyclic loadings. The impact loading was

provided by a steel plate with the dimension at 240 × 150 × 40 mm and the weight at 15 kg. The steel plate drops at 300 mm height to produce the impact loading, and two loading positions were selected, i.e. at the sleeper side and in the middle.

2.3 Instruments and data acquisition

As shown in Table 3, the applied instruments and how they get data are introduced, including the triaxial accelerometer, pressure sensor, dial indicator, displacement sensor and accelerometer (Fig. 2).

Table 3 Instruments and data acquisition

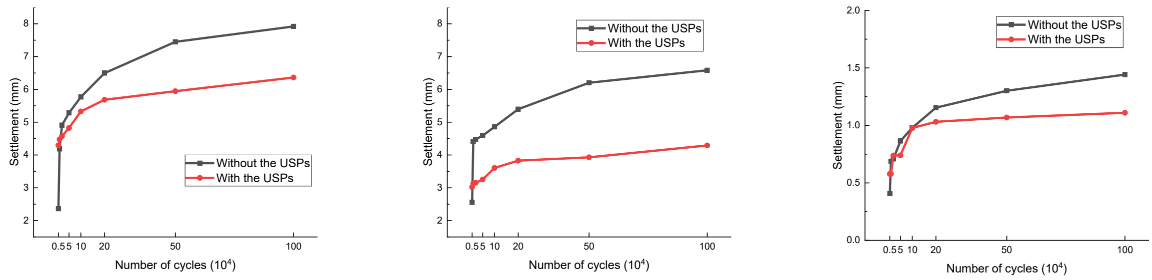
Instrument name	Specification	Data acquisition explanation
Triaxial accelerometer	Range: 0-20 g	Ballast bed acceleration at three orthogonal directions, placed in the green ballast layer
Pressure sensor	Range: 0.0-3.0 MPa, 0.0-5.0 MPa; Diameter: 100 mm	Vertical and lateral pressure stress measurement, placed 1) at three side walls, 2) under the sleeper, 3) between the red ballast layer and green ballast layer
Dial indicator	Range: 0-50 mm	Settlement measurement, placed at the sleeper upper surface
Displacement sensor	Range: 0-25 mm	Displacement measurement during the static loadings and settlement during cyclic loadings, placed at the sleeper upper surface
Accelerometer	Range: 0-50 g	Sleeper acceleration measurement, placed at the sleeper upper surface
Pressure-sensitive paper	Sensitivities: 0.5-2.5 MPa; Thickness: 0.2 mm	Contact areas, placed between the USPs and the ballast layer
Actuator	Range: 0-500 kN; Piston stroke: ± 150 mm; Loading frequency: 0.1-10.0 Hz;	-
Electronic level meter	-	Repose angle measurement
Sieve	Aperture size: 63, 50, 40, 31.5, 22.4 mm	Particle size distribution measurement for degradation analysis

3 Results and discussions

3.1 Permanent settlement and static ballast bed stiffness

The long-term performance of ballast bed is determined by the permanent settlement, particularly, the differential settlement is an important reason for the track geometry deterioration, affecting passenger comfort and safety. Consequently, the permanent settlement under cyclic loading with and without the USPs are measured after each designated cycle (i.e. $0.5/1/2/5/10/20/50/100\times10^4$) as shown in Fig. 3. The evolution of ballast bed load-displacement with and without the USPs are also studied by comparing the stiffness results before and after cyclic loadings, and the results are shown in Fig. 4. The two figures are drawn based on the data (Table A.2-A.4) in the appendix.

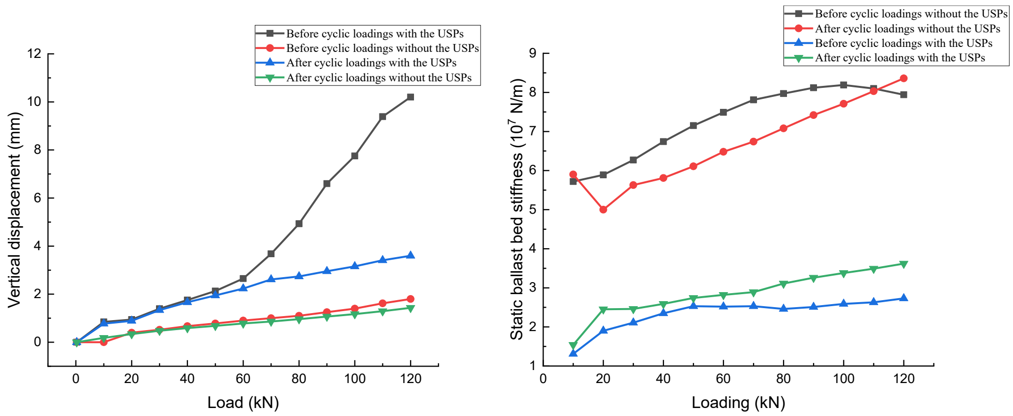
Settlements at three sleeper positions are illustrated with and without the USPs (Fig. 3). The positions for displacement measurement are 1) at the sleeper middle, right side of the actuator, 2) at left side of the actuator using the dial indicator and 3) at the left edge of the sleeper. From Fig. 3, it can be seen that the settlements with the USPs are smaller than these without the USPs at all the three positions. The settlements at the three positions with the USPs are 6.4, 4.3 and 1.1 mm, respectively. Comparing with the settlements without the USPs (7.9, 6.6 and 1.4 mm), the reduction of settlements are 19.6%, 34.8% and 23.1%, respectively. This proves that the USPs can reduce the settlement (ballast bed deformation), further improving the long-term ballast bed performance.



a. Settlement measured in the sleeper middle b. Settlement measured at the left side c. Settlement measured at the left sleeper edge

Figure 3 Settlements measured at three positions of the sleeper

Fig. 4(a) shows the load-displacement of the ballast bed with and without the USPs before and after the cyclic loadings. From the figure, it can be observed that before the cyclic loadings the vertical displacement with the USPs has the fastest increment. However, after cyclic loadings its load-displacement becomes stable increment. This means the USPs initially soften the interaction of the sleeper and ballast particles, and they reduce the overall ballast bed stiffness. Nevertheless, the ballasted track with the USPs has better long-term performance after the ballast assemblies are compacted.



a. Load-displacement of the ballast bed

b. Static ballast bed stiffness

Figure 4 Load-displacement and static stiffness of ballast bed with and without USPs

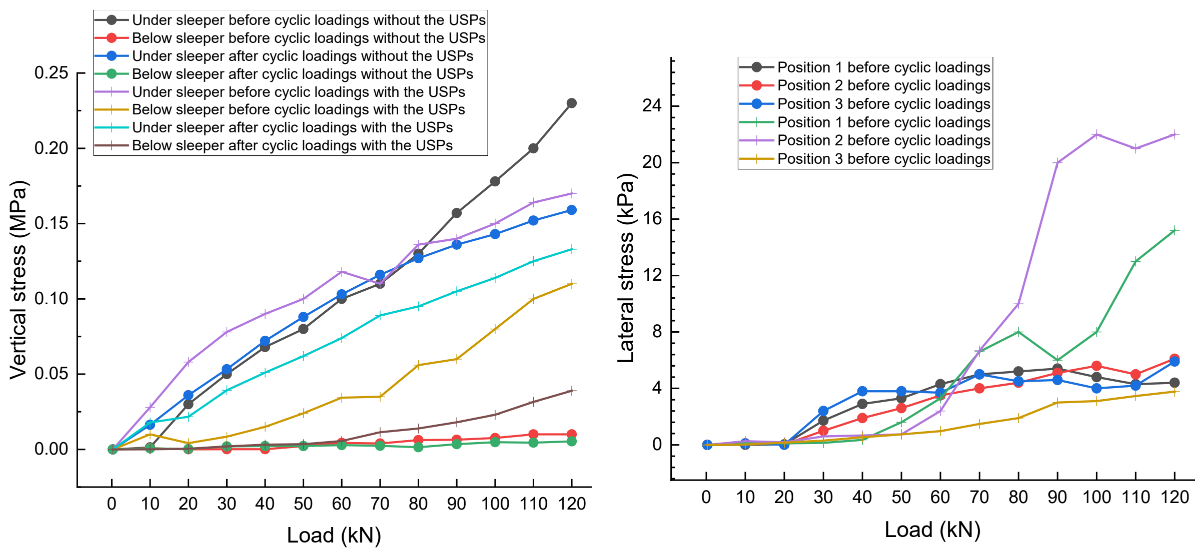
Fig. 4(b) illustrates the static ballast bed stiffness values with the USPs are less than these without the USPs in most cases. When the load reaches 120 kN (before cyclic loadings), the maximum stiffness without the USPs is 7.94×10^7 N/m, which is higher than that with the USPs by 46.6% (4.24×10^7 N/m). After applying cyclic loadings, the maximum stiffness without the USPs is 8.36×10^7 N/m, which is higher than that with the USPs by 56.7% (3.62×10^7 N/m). This proves that the ballast bed with the USPs has lower static ballast bed stiffness than that without the USPs. However, the static ballast bed stiffness with the USPs slightly increases after cyclic loadings, whereas the static ballast bed stiffness without the USPs decreases after cyclic loadings. This demonstrates the USPs can enhance the compaction during the cyclic loadings.

In Fig. 4(b), the red curve goes down from 0-20 kN, afterwards it goes up. It is possibly due to the ballast bed was loosened after cyclic loadings, and some ballast particles had very big movements when applying larger loads (0-20 kN). However, after the ballast bed was loaded, the contacts between ballast particles became stronger after 20 kN, and then the curve went up steadily.

3.2 Vertical and lateral stresses

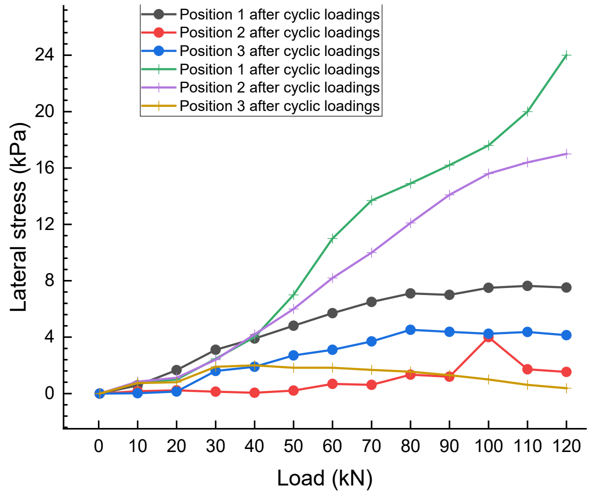
As shown in Fig. 1, the USPs can improve stress distribution, further assist in transmitting the vertical and lateral stresses. In order to check the effects of the USPs on stress transmission, five pressure sensors are placed at five different positions. Position 1 is at the front wall; Position 2 is at the back wall and Position 3 is at the side wall (Fig. 2). At Position 1-3, the pressure sensors were placed vertically to measure the lateral stresses. Position 4 is under the sleeper and Position 5 is 250 mm below the sleeper between the red ballast and green ballast, as shown in Fig. 2. The two pressure sensors horizontally placed at Position 4, 5 are utilised for measuring the vertical stresses. It needs to note that the pressure sensors have the diameter at 100 mm, which can be big enough to reflect the pressure of the area.

The vertical and lateral stresses are measured before and after the cyclic loadings under static loading from 0 to 120 kN, as shown in Fig. 5. The figure is obtained based on the data given in Table A.5–A.8. From Fig. 5(a), it can be observed that the vertical stresses (under or below the sleeper) without the USPs before cyclic loadings are close to those after the loadings. Dissimilarly, the vertical stresses with the USPs show variability to each other. However, after the ballast bed was compacted by the cyclic loadings, using the USPs can reduce the stresses at the sleeper-ballast interface. This can be observed and proved by that the vertical stress curve (under sleeper after cyclic loadings with the USPs) is lower than the vertical stress curve (under sleeper after cyclic loadings without the USPs). Moreover, the stress curve (below sleeper after cyclic loadings with the USPs) gets lower and become close to the stress curve (below sleeper after cyclic loadings without the USPs). This means after ballast bed compacted the USPs have few influences on the stress magnitude at the layers below sleeper.

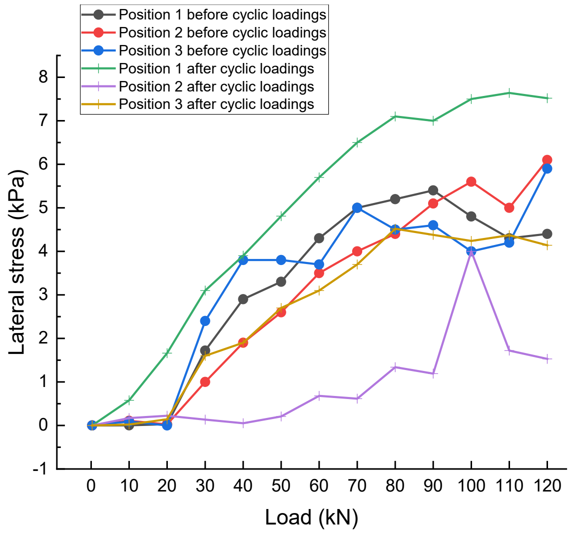


a. Load-vertical stress

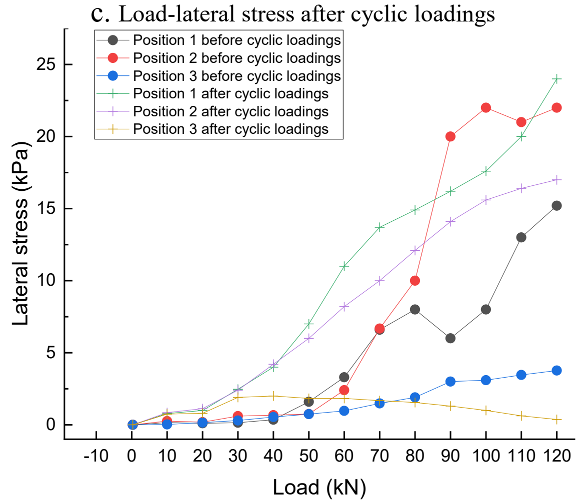
b. Load-lateral stress before cyclic loadings



c. Load-lateral stress after cyclic loadings



d. Load-lateral stress without the USPs



e. Load-lateral stress with the USPs

Figure 5 Load-vertical stress curve and lateral stress-load in the ballast bed with and without USPs

Fig. 5 (b)-(e) present the load-lateral stress curves before and after cyclic loadings with and without the USPs. From Fig. 5 (b)(c), it can be seen that the USPs can increase the lateral stress at the longitudinal directions (Position 1, 2), while without the USPs the stress curves at three positions are close. Since the only condition difference between the two test is the USPs, it can prove that installing the USPs can improve the stress distribution.

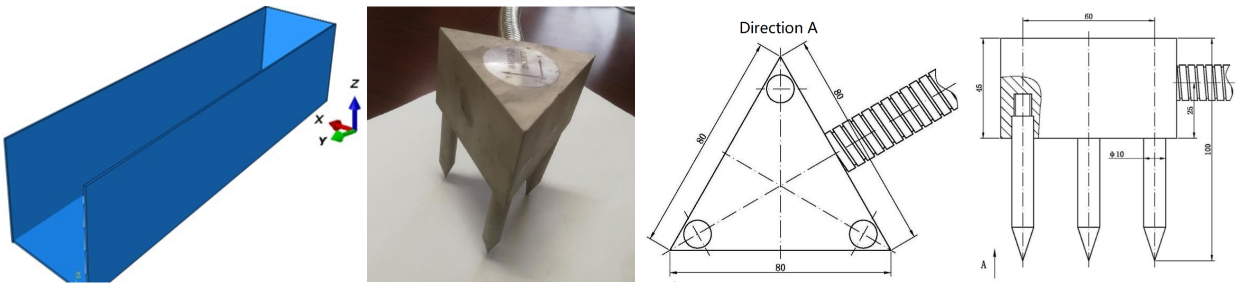
It needs to note that the stress curve at Position 3 is lower than Position 1, 2 because it has a longer distance to the walls than the other two positions (Fig. 2), which are 200 mm (Position 3) and 100 mm (Position 1, 2) respectively. However, the lateral stress curve with USPs in the lateral direction (Position 3) is close to the curve without the USPs. This means the USPs have few effects on the lateral stress transmission in the lateral direction. Additionally, from Fig. 5 (d)(e) it can be observed that without the USPs the lateral stress curves after the cyclic loadings are slightly different from those before the cyclic loadings, while with the USPs the curves before and after cyclic loadings have a great difference. This demonstrates that the USPs cannot provide consistent performance.

3.3 Ballast bed and sleeper acceleration

The ballast bed and sleeper accelerations are measured in order to study their dynamic performance, as well as the energy dissipation of the ballast bed under cyclic loadings and impact loadings respectively. The triaxial accelerometer was placed between the red ballast layer and green ballast layer, and an accelerometer was placed on the sleeper (Fig. 2).

3.3.1 Acceleration under cyclic loadings

The triaxial accelerometer is utilised to measure the accelerations at three orthogonal directions (i.e. X, Y, Z). The X direction is longitudinal, the Y direction is lateral and the Z direction is vertical as shown in Fig. 6(a). Fig. 6(b)(c) present the applied triaxial accelerometer and its configuration. It was fixed during the tests by inserting the three sharp feet into the green ballast layer. This is for avoiding its movements during the cyclic loadings, which may cause incorrect results.



a. Three accelerometer directions b. Triaxial accelerometer c. Triaxial accelerometer configuration

Figure 6 Information of the triaxial accelerometer

The accelerations of the ballast bed were measured at the cycle number 0.5/1/2/5/10/20/50/100 $\times 10^4$. To be more specific, when the cycles reached the designated number, the accelerations started to be recorded for 10 minutes. The maximum accelerations (X/Y/X directions) at different cycles are given in Table A.9. Based on the results in Table A.9, the figure of maximum accelerations at different cycles are obtained, as shown in Fig. 7(a)-(c). From the figures, it can be seen that the accelerations at X and Y directions with the USPs are smaller than those without the USPs, however, the acceleration with the USPs at Z direction increases to 4.03 m/s^2 after 10^6 cycles, which is larger than without the USPs (2.95 m/s^2).

The sleeper acceleration also increases to 1.33 m/s^2 when applying the USPs, whereas sleeper acceleration without the USPs is 0.72 m/s^2, as shown in Fig. 7 (d). The sleeper acceleration increment ratio is 85.6%. The results demonstrate that using the USPs can enhance the ballast-sleeper interaction, but cannot guarantee dynamic performance. The phenomenon of the sleeper acceleration increment when the USPs are applied was also found in the study (Kaewunruen, et al., 2017).

The accelerations of both sleeper and ballast increase can be observed in this test. The reason of acceleration increment is that installing the USPs can soften the interaction (contact) between the sleeper and ballast. In other words, the situation is similar as hanging sleeper. The increased sleeper acceleration cannot be absorbed sufficiently by the USPs, consequently, the ballast layer acceleration increases.

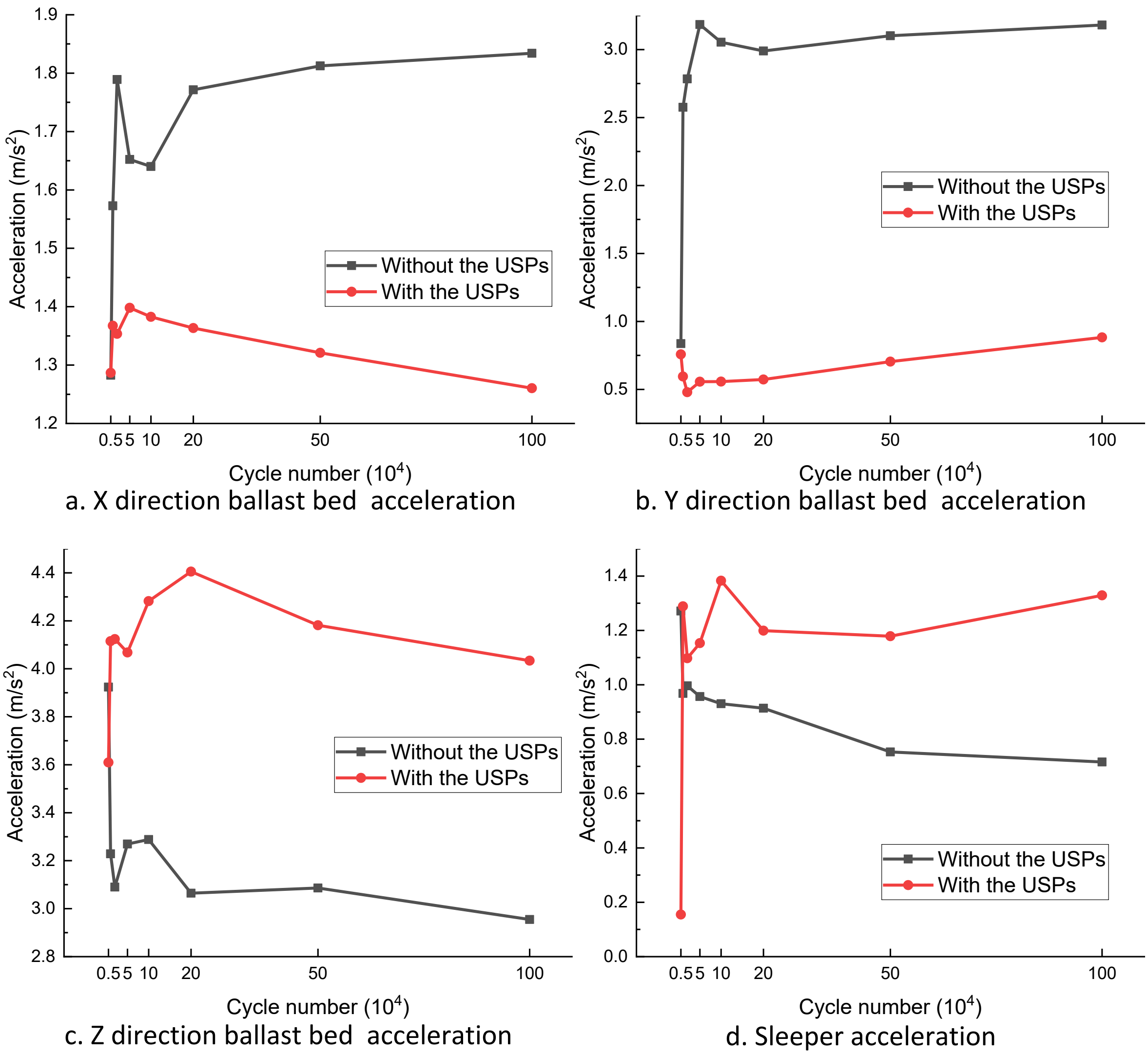


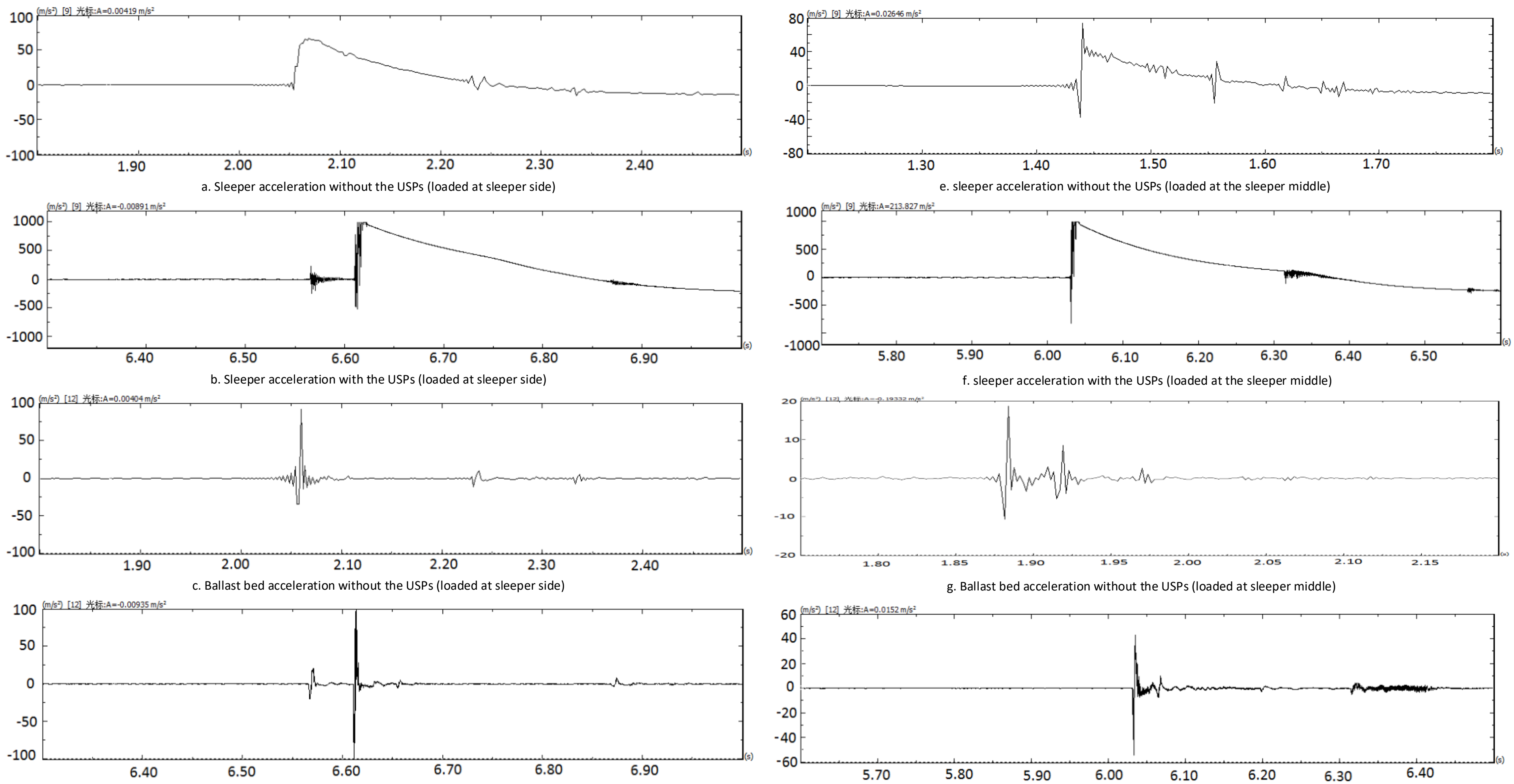
Figure 7 Ballast bed and sleeper accelerations under cyclic loadings

3.3.2 Acceleration under impact loading

The impact loading was applied to the sleeper to study the dynamic performance of the ballast bed and sleeper. The measured accelerations are utilised to present the dynamic performance, as shown in Fig. 8.

From the Fig. 8 (a)-(f), it can be observed that the sleeper accelerations with the USPs are around 10 times higher than those without the USPs. Fig. 8(c)(d) show that the peak accelerations of the ballast bed with and without the USPs are both around 100 m/s^2. whereas Fig. 8 (g)(h) show that the peak acceleration with the USPs is 60 m/s^2, which is 3 times higher than without the USPs. This is due to the accelerometer was placed below the sleeper, and the higher loadings from the sleeper (with the USPs) cannot be sufficiently and rapidly dissipated at position (250 mm below the sleeper).

More importantly, the energy dissipation with the USPs is weakened, which may result from the high-resilience of the USPs. This is reflected from that the accelerations have more large-amplitude cycles, as shown in Fig. 8 (b). It needs to note that the time for the sleeper stabilisation is longer when applying the USPs (6.5 seconds), while it costs 2.3 seconds without the USPs. This means the USPs may slow down the energy dissipation under the impact loadings. More importantly, Fig. 8(d)(h) illustrate that two peak acceleration values are shown with the USPs, whereas without the USPs only one peak acceleration value is shown in Fig. 8 (c)(g).



a. Sleeper acceleration without the USPs (loaded at sleeper side)

e. sleeper acceleration without the USPs (loaded at the sleeper middle)

b. Sleeper acceleration with the USPs (loaded at sleeper side)

f. sleeper acceleration with the USPs (loaded at the sleeper middle)

c. Ballast bed acceleration without the USPs (loaded at sleeper side)

g. Ballast bed acceleration without the USPs (loaded at sleeper middle)

d. Ballast bed acceleration with the USPs (loaded at sleeper side)

h. Ballast bed acceleration with the USPs (loaded at sleeper middle)

Figure 8 Ballast bed and sleeper accelerations under impact loadings

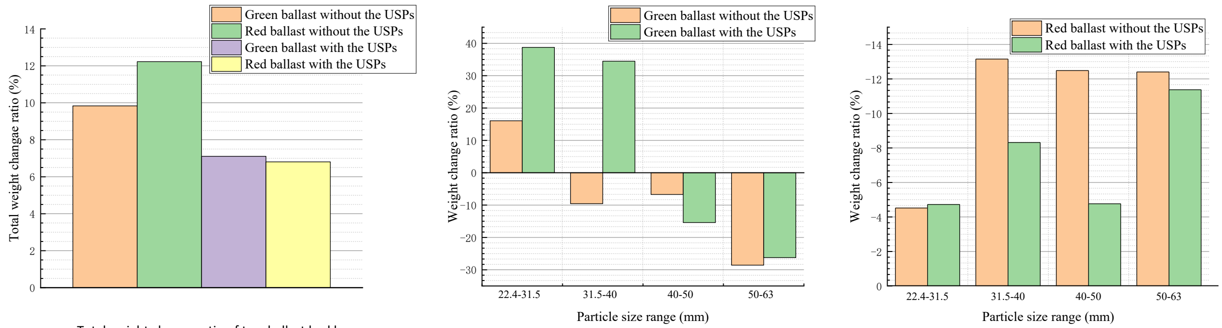
3.4 Ballast degradation and contact areas

Ballast degradation happens progressively during cyclic loadings. The abrasion and angularity loss are the initial degradation types, which mainly occur at sleeper–ballast interfaces or the particle contacts. After the ballast assemblies are compacted, ballast breakage starts to appear and it depends on ballast materials and applied stress magnitude. Ballast breakage contributes to the PSD changes, further increasing ballast bed deformation and also causing the differential track settlement.

The USPs can reduce ballast degradation by increasing the contact areas between ballast and sleeper. The ballast degradation with and without the USPs is evaluated, and the contact areas are measured sing the pressure-sensitive paper.

3.4.1 Ballast degradation

The results of the PSD before and after the cyclic loadings are given in Table A.10 and Table A.11. It needs to note that the ballast particles smaller than 22.4 mm are sieved out according to the classification of the PSD in British standard (British Standards Institution, 2013). Based on the two tables, Fig. 9(a) shows the total weight loss percentage comparison of two ballast bed layers with and without the USPs. From the figure, it can be seen that using the USPs can reduce the weight loss of ballast bed. Fig. 9(b) shows the weight change ratio of the green ballast layer, and it presents that using the USPs increases the weight of particle size ranges at 31.5-40 and 22.4-31.5 mm. Whereas, without the USPs only 22.4-31.5 mm weight increases and the increment value (16.07%) is much lower than that with the USPs (38.75%). This means that without the USPs large ballast particles are prone to crush into pieces, producing smaller particles. Fig. 9(c) presents the weight change ratio of the red ballast layer. From the figure, it can be seen that the weight change ratios with the USPs are lower than these without the USPs except the size range of 22.4-31.5 mm (almost same value). This means the USPs provide good performance for reducing the ballast degradation at the layer under the sleeper.



a. Total weight change ratio of two ballast bed layer with(out) the USPs

b. Weight change ratio of green ballast with(out) the USPs

c. Weight change ratio of red ballast with(out) the USPs

Figure 9 Weight change ratio of the ballast bed with and without the USPs

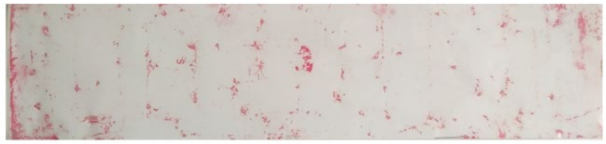
The green ballast layer has incremental weight at some particle size range (i.e. 22.4-31.5, 31.5-40 mm), whereas for the red ballast layer the weights at all size ranges reduce. This may be due to the red ballast layer has a much higher vibration than the green ballast layer. Further study should be performed to understand this phenomenon.

The material is an important factor when analysing the ballast degradation. The ballast material in this study is the basalt, which is different from the ballast material (granite) used in (Abadi, et al., 2019). The ballast degradation is to a large extent depends on the ballast material, and the granite has higher strength than the basalt. Consequently, severer degradation was observed in this study.

It needs to note that quantifying the ballast degradation with the weight change and PSD change is not very accurate due to the sieving is sometimes subjective and the results in most cases rely on the sieving duration. Therefore, more sensitive and accurate methods are expected to create in the future study. This is crucial for correlating in-depth geological knowledge with ballast degradation.

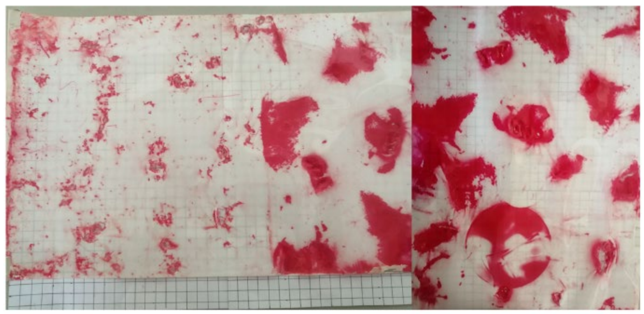
3.4.2 Contact areas

The contact areas of the sleeper-ballast with and without the USPs are shown in Fig. 10 (a)(b), and the calculation method of contact area is measured by summing the covered meshes up, as shown in Fig. 10(c). The results show that the contact area with the USPs is 16.2%, while the contact area without the USPs is 2.9%. This means the contact area increase over 5 times after applying the USPs.



a. Sleeper-ballast contact area without the USPs

b. Sleeper-ballast contact area with the USPs



c. Calculation method of contact area using the mesh area summation

Figure 10 Sleeper-ballast contact area and its calculation method

The contact area with the USPs is much bigger than that of the study in (Abadi, et al., 2019), which presents the value at 1.05-4.75%. This is due to the simulated track configuration is different, furthermore, the applied cyclic loading (frequency, amplitude) is different.

4 Conclusions

In this paper, the dynamic performance of the ballast bed with the USPs under cyclic or impact loadings is explored. Additionally, the effects of the USPs are also studied, including on the permanent settlement, static ballast bed stiffness, the vertical and lateral stress of the ballast layer, the sleeper-ballast interaction and ballast degradation. According to the above results and discussions, the following conclusion can be made.

1. Applying the USPs help to reduce the permanent settlement with the maximum percentage at 34.8%, and enhance the ballast bed compaction during the cyclic loadings.
2. After the ballast layer is compacted, the USPs become effective to transmit the stresses in ballast

bed, specifically, the stress distribution at the longitudinal direction is increased. However, the vertical stresses of the ballast bed with and without the USPs are almost the same after compacted. In addition, the USPs cannot provide consistent performance.

3. Utilising the USPs increases the sleeper and ballast bed accelerations, however, it reduces the ballast degradation. Because despite higher ballast bed and sleeper vibration the sleeper-ballast interface is the main area causing ballast degradation. The increased contact areas (6 times) protect the ballast breakage, and the abrasion (particle-particle) is slight and has few contributions to the ballast degradation.

When performing the laboratory tests, some variables are extremely to control, e.g. compaction, particle size distribution and particle shape. In addition, the different samples are very difficult to control the same. Therefore, the Discrete element modelling for the USPs performance studies are needed in further research. Moreover, the half-sleeper track test is still performed in a ballast box, which is without the presence of the rail, fastening or subgrade. More realistic tests should be performed to avoid boundary effects. It needs to note that the stiffness of the whole track system is changed by the USPs, while the other elastic materials (e.g. railpads) also contribute to the system stiffness. Therefore, a multi-body model with combination of every part (vehicle-track model) can be built and used to analyse their dynamic performance.

The steel plate was used create impact loads at same heights, because we want to keep the same condition. By doing so, the only variable is the USPs, which is the focus point in this study. Because doing this is only for creating impact load, and the impact load cannot simulate real track situations. In the real situations, the impact loads are totally different at different structures in different locations, such as the transition zone and switch and crossing. Therefore, applying the loadings that can simulate one situation in the real track is the next step research, such as, the transition zone. The impact loads and accelerations can be measured at the transition zone, and steel plates (with different masses and heights) are dropped to compare the results with the measured ones.

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