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Effect of Sleeper Bottom Texture on Lateral Resistance with Discrete Element Modelling

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Abstract: The lateral stability of ballasted track becomes more important because of the safety requirement under the demand of higher train speed and heavier axle load. To increase the lateral resistance of ballast bed, this paper proposes three types of new sleepers, frictional sleepers. The frictional sleepers are sleepers with different shapes of textures attached at the sleeper bottom. To study the application feasibility of the frictional sleepers, experimental tests (single sleeper pull-out test) and numerical simulation (discrete element modelling) are performed. The lateral resistances of the three types of frictional sleepers are compared with the traditional sleeper based on the experimental test, and the mechanism of the lateral resistance increase is revealed according to the numerical simulation. The results indicate that the frictional sleepers can increase the lateral resistance by 32% (maximum), due to the enhanced interaction between sleeper and ballast particles. More importantly, different types of frictional sleepers have different performances, and the optimal friction sleeper is confirmed. This study is helpful for the further research on sleeper design.

Key words: Fictional sleeper; Lateral resistance; Discrete element modelling; Ballasted track; DEM

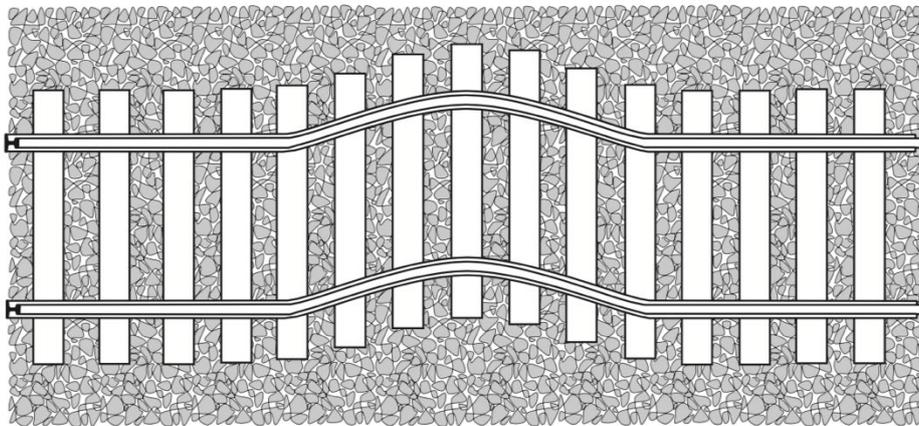
1. Introduction

An important function of ballast layer is providing sufficient lateral resistance to prevent rail lateral movements. Specifically, the ballast layer provides the lateral resistance to sleeper to resist the forces from the rail thermal elongation (due to temperature change) and excessive axial forces (train loads) [1]. Rail buckling may occur when the lateral resistance of the sleepers is not sufficient, as shown in Figure 1. This issue attracts more attention since the continuous welded rails (CWR) has been widely applied [2]. Lateral CWR buckling is a dangerous phenomenon, which will cause rail and wheel damages and even derailment [3]. The track lateral resistance is utmost important indicator for the track stability and the safety, which helps to quantify the possibility of preventing temp expansion and track buckling [4, 5].

With the increasing of the train speed and axle load, the lateral resistance insufficiency is still an unsolved problem for the traditional ballasted track. For example, the operating train speed in China has increased to 320-360 km/h, and some operating lines even reach the speed 400 km/h. In addition, heavy haul railway

36 increases the axle loads to above 35 tons [6]. As railway system is developing towards higher speed and
37 heavier axle load, the lateral resistance enhancement is becoming a more and more urgent issue, especially
38 when the vibrational characteristics and resistance-evolution law are considered [7].

39 Earlier studies have been performed on the ballast bed lateral resistance from the interaction of the ballast
40 and sleeper [8-12] with the Single Sleeper Pull-out Test (SSPT). The SSPT is a widely-used method for
41 measuring ballast bed lateral resistance [13]. Ballast bed lateral resistance is provided primarily by the
42 sleeper-ballast contact interfaces at the base, shoulder ballast and crib ballast [4, 5, 14]. The lateral
43 resistance is considerably dependent on the sleeper characteristics, such as type, weight and spacing [8].
44 Moreover, it is significantly influenced by the ballast bed properties, such as shoulder ballast size,
45 compaction and degradation stage [14-17]. Based on the effect factors of ballast bed, the optimisation
46 means have been developed in depth, e.g. enlarging the shoulder ballast size, applying steel slag ballast,
47 laying geogrids and spraying ballast glue [5, 11, 18, 19].



48
49 **Figure 1 Schematic view of lateral instability of ballasted tracks (figure reproduced from [20])**

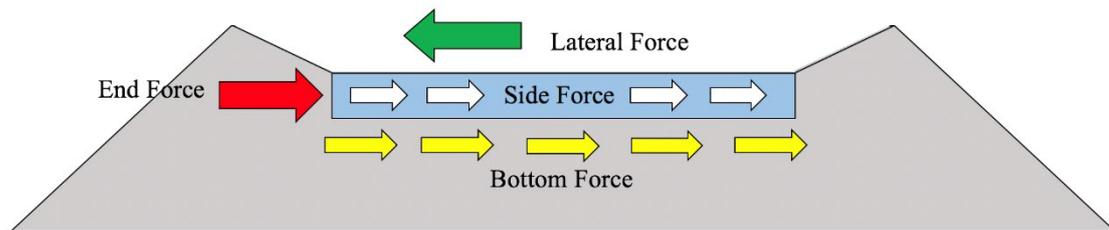
50 However, optimization means for the ballast bed have reached a bottleneck due to several reasons. Firstly,
51 the ballast fly (high speed train) limits the ballast bed size. For example, in French railway, the crib ballast
52 is around 6 cm lower than the sleeper, and the shoulder ballast height is reduced. Secondly, tamping and
53 maintenance are difficult for the specific ballast bed (ballast glue or geogrids). Finally, the higher cost of
54 new materials applied in ballast bed is one critical concern. Towards this, sleeper optimisation has become
55 a new better solution and research hot spot to increase the lateral stability of ballasted track.

56 For instance, in [21], the sleeper shape is designed as mono-block sleeper with wings on the bottom, end
57 side and middle side. From the finite element modelling results, it indicates that winged sleeper can
58 increase the lateral resistance around 50%. In [20], similar optimization was performed and the similar
59 conclusions were draw according to the laboratory tests. Specifically, both sides of sleeper were set two
60 wings making the sleeper “H-shape”. Afterwards, the SSPTs and track panel pull out tests (1:5 scaled) were
61 carried on the H-shape sleepers. In [22], the nailed sleeper is proved as an effective solution that can
62 increase the lateral resistance more than 200%. These studies illustrate that lateral resistance can be
63 enhanced by increasing the contact area of sleeper and ballast bed, however, there are still limitations such
64 as installation difficulty, and tamping maintenance process when applying these kinds of sleepers.

65 The frictional sleeper makes it possible to increase the lateral resistance without interruption or setback for
66 tamping operations and installation, and the lateral resistance of the frictional sleeper can increase by 64%

67 as concluded in [16]. The frictional sleeper is the sleeper with its bottom attached with some textures. Many
68 studies evaluated the portion of the base, crib, and shoulder ballast on the lateral resistance (Figure 2) [5,
69 23-25]. All the studies indicated that the base ballast contributes a majority of lateral resistance, even
70 though the portion results were not similar. For instance, in [5], the contribution of different components
71 (base, crib, and shoulder ballast) are 26–35%, 37–50%, and 15–37%, respectively. In [26], it was proposed
72 the contributions are 45–50, 10–15, and 35–40%, respectively. Therefore, enhancing the sleeper bottom
73 could be an effective means for increasing ballast bed lateral resistance.

74 In addition, the following advantages of the frictional sleeper can be noted, 1) without influence on sleeper
75 spacing and maintenance operation, 2) less investment in sleeper fabrication and transportation 3) and
76 microscopic interface improvement with ballast particles.



77
78 **Figure 2 Contribution of the lateral resistance**

79 However, until now, the frictional sleeper studies were performed only with one type of sleeper, and more
80 importantly all the studies were based on the laboratory tests. More types of friction sleeper should be
81 developed to find out the optimal type that can provide the highest lateral resistance. Additionally, before
82 applying the frictional sleeper in the field, the numerical simulations should be performed to check the
83 application feasibility. More importantly, understanding the mesoscopic mechanism (contribution, contact
84 force) of the lateral resistance of frictional sleeper is necessary for further sleeper design. Furthermore, most
85 of the numerical simulations utilised the finite element methods. Limited studies on frictional sleeper were
86 performed with the Discrete Element Method (DEM), which has been demonstrated as an effective tool for
87 railway ballast study e.g. [25, 27-33].

88 Towards the research gaps, this paper focuses the enhance lateral stability of ballast bed using different
89 types of frictional sleepers (three kinds of bottom texture). The commercial DEM software, Particle Flow
90 Code in three-dimensional is utilised. A set of laboratory SSPTs were performed on the Chinese IIIc type of
91 mono-block concrete sleeper and the three types of frictional sleepers. Based on the test configurations, the
92 DEM ballast bed-sleeper models were built and validated. Based on the DEM models, the effects of bottom
93 texture shape of frictional sleeper to lateral resistance were studied and analysed in mesoscopic level. The
94 results are helpful for further development of sleeper shape towards the track stability enhancement.

95 **2. Laboratory Test**

96 **2.1. Materials and Methods**

97 **2.1.1. Ballast Bed**

98 The SSPTs were performed upon a 10-meter length ballast bed, and the ballast depth (thickness under

99 sleepers) is 0.35m with the slope grade at 1:1.75 according to the Chinese ballast bed standard for high speed
 100 railway [34]. Firstly, the ballast bed was built in four times by layers (four layers in total), and each layer
 101 was compacted 5 times by a vibrating compactor. Afterwards, the track panel was placed on the ballast bed,
 102 and ballast were filled in the crib and made the shoulder. Finally, the ballast bed was compacted by
 103 vibrating compactor a second time. It should be noted that the sleepers spacing was 600 mm for all tests.

104 The ballast shoulder height and width are set as different values based on different test configurations (Table
 105 1). In the table, the test number R1-R3 are tests on mono-block sleeper, and the test number A, B and C are
 106 tests on the frictional sleeper, which will be introduced in Section 2.1.2.

107 Traditionally, the ballast shoulder width is supposed to be in the range of 300-500 mm [9]. In addition, it is
 108 suggested that an appropriate ballast shoulder width is in the order of 300 mm for conventional ballasted
 109 tracks [35], however, the optimal ballast bed size for high speed railway has not been confirmed. Therefore,
 110 the SSPTs were performed on different types of sleepers with different dimensions of shoulder width (SW)
 111 and shoulder height (SH) as shown in Table 1. It should be noted that crib ballast was filled up to the top level
 112 of the sleeper and fully compacted with the vibrator before each test.

113

Table 1 Single sleeper pull-out test configurations

Test number	Sleeper type	Shoulder width (mm)	Shoulder height (mm)
R1	Mono-block	500	0
R2	Mono-block	500	150
R3	Mono-block	300	0
A1	ST-sleeper	500	0
A2	ST-sleeper	500	150
A3	ST-sleeper	300	0
B1	RT-sleeper	500	0
B2	RT-sleeper	500	150
B3	RT-sleeper	300	0
C1	GT-sleeper	500	0
C2	GT-sleeper	500	150
C3	GT-sleeper	300	0

114

Table 2 Ballast physical properties of the ballast bed

Property	Standard	Result	Maximum specification value
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

115 The ballast material is basalt that is provided by Tangshan Quarry in Hebei Province. Ballast physical
 116 properties were tested according to the British standard, including the durability, mineralogy and particle
 117 shape as shown in Table 2. The material is suitable to be used for ballast bed. Additionally, the particle size
 118 distribution (PSD) of ballast particles are also according to British standard, as shown in Figure 3 [36].

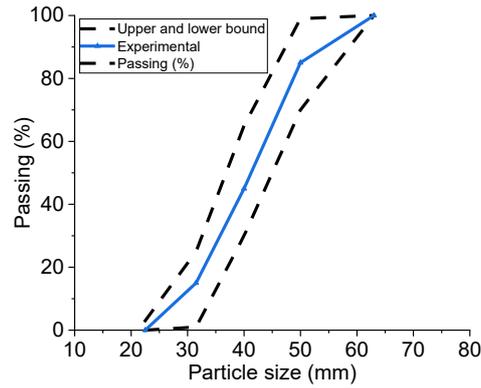
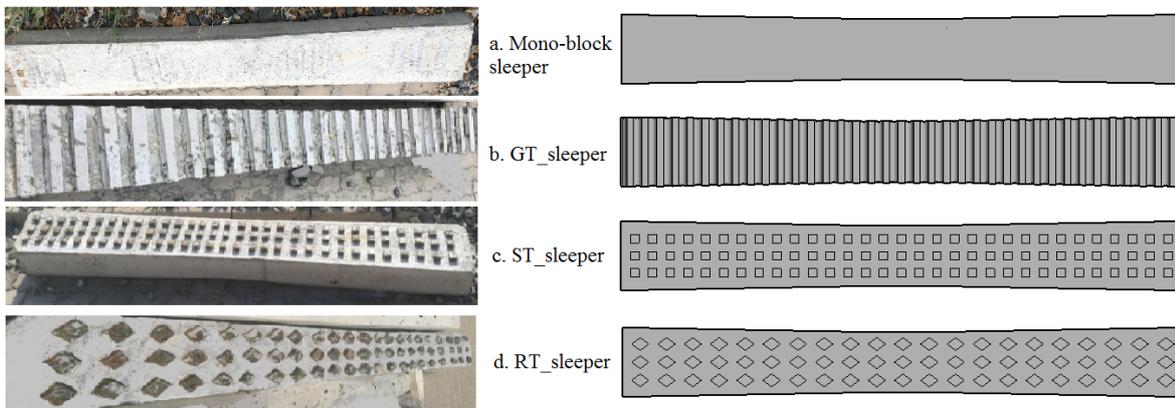


Figure 3 Particle size distribution

119
120

121 2.1.2. Sleepers

122 Three types of frictional sleepers are designed and produced based on Chinese IIIc mono-block sleeper by
 123 attaching texture to the sleeper bottom, as shown in Figure 4. The specifications of the sleepers are as
 124 follows: 1) Grooves texture sleeper (GT-sleeper): grooves texture is on the sleeper bottom and the shape of
 125 texture block can be found in Figure 4(c). The interval between two blocks is 60 mm. 2) Square texture
 126 sleeper (ST-sleeper): this type of sleeper applies the square texture, and the shape of texture block can be
 127 found in 3(a). The interval between two blocks is 40 mm. 3) Rhombic texture sleeper (RT-sleeper): the
 128 sleeper had rhombic texture, and the shape of texture block is showed in Fig. 3(b). The interval between two
 129 blocks is 40 mm.



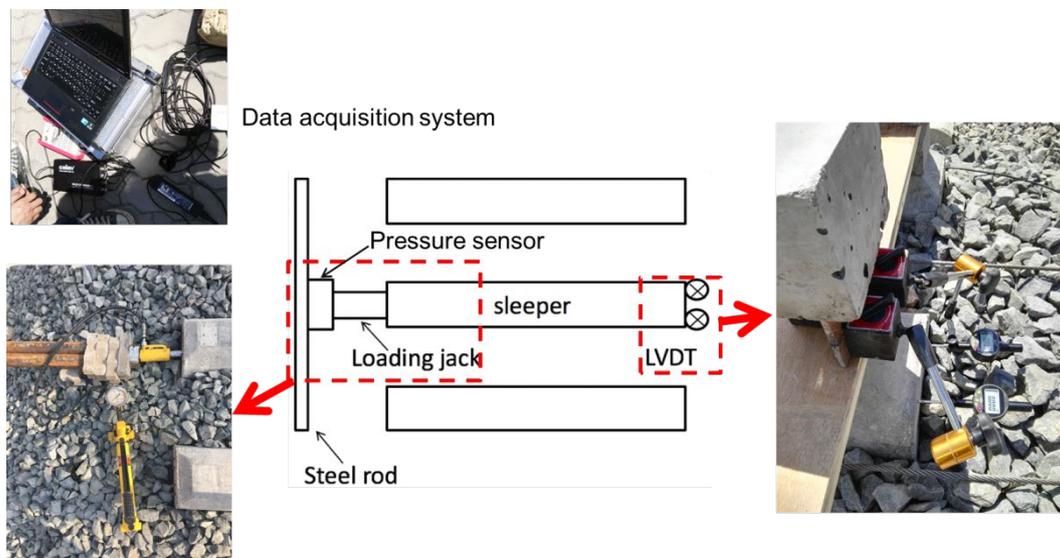
130
131

Figure 4 Different types of frictional sleepers: (a) mono-block sleeper, (b) GT-sleeper, (c) ST-sleeper, (d) RT-sleeper

132 2.1.3. Lateral resistant test setup

133 The applied test equipment is shown in Figure 5, including the Linear Variable Differential Transformer
 134 (LVDT), hydraulic jack, pressure sensor and data acquisition system. The two LVDTs, with the precision at
 135 0.001 mm and measuring range at 0~30 mm, were placed at the sleeper end to measure the lateral
 136 displacement of sleepers. The lateral displacement of the sleeper was calculated by the mean value from
 137 LVDTs. The hydraulic jack can provide the maximum loading at 10 ton, and the jack actuator stroke is 10
 138 cm, which is long enough to reach the peak resistance value. The hydraulic jack was installed between steel
 139 rods and the sleeper end (Figure 5), and the steel rods were used to provide enough resistance. The jack
 140 loading was the step-loading that was carried out with 30s intervals. The pressure sensor is with the
 141 measuring range at 0~10 ton, and it was placed between the hydraulic jack and the steel rods. Every forces

142 corresponding to every 2 mm displacements were considered as the lateral resistance of the sleeper. The
143 data acquisition system is IMC, INV3018A that was used to record the resistance force at the sleeper end.



144
145

Figure 5 Single sleeper pull-out test setup

146 2.2. Tests Results

147 2.2.1. Shoulder height and width

148 Figure 6 presents the lateral resistance of four types of sleepers at displacement of 2 mm, and it can be seen
149 that the geometry of the ballast bed plays an effective role in the track stability. Specifically, the figure shows
150 that lateral resistance increases significantly with the increase of the shoulder height. In the figure, for
151 example, the SW500_SH150 represents that the shoulder width (SW) is 500 mm and the shoulder height (SH)
152 is 150 mm.

153 By increasing the shoulder height from 0 to 150 mm (500 mm shoulder width), the resistances of the
154 GT-sleeper, RT-sleeper, ST-sleeper and Mono-block sleeper increase by 23.3%, 27.4%, 24.0% and 33.9%,
155 respectively. In [12], it concluded that the lateral resistance of sleepers increased faintly with the increase of
156 the shoulder width. However, in the presented results, it can be seen that increasing the shoulder width has
157 certain influences on the lateral resistance, which can increase the resistance 11.4% (GT-sleeper), 12.6%
158 (RT-sleeper), 13.8% (ST-sleeper) and 17.4% (mono-block sleeper), respectively.

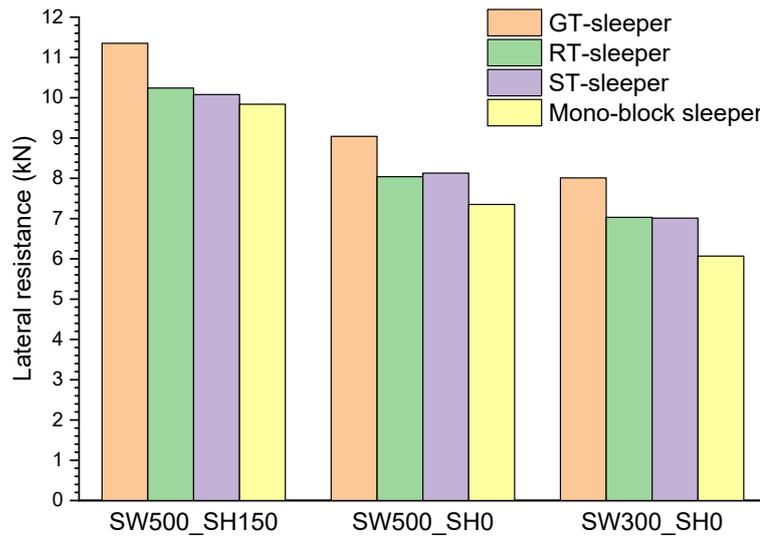


Figure 6 Lateral resistance of four types of sleepers at displacement of 2 mm

159
160

161 2.2.2. Influence of Sleeper types

162 The lateral resistance of three sleeper types were measured to find the optimal sleeper type. Three types of
 163 frictional sleepers are compared with the mono-block sleeper, as shown in Figure 6. From the results, it can
 164 be seen that all the frictional sleepers have higher lateral resistance than the mono-block sleeper. Using the
 165 GT-sleeper has the lateral resistances at 11.15 kN (SW500_SH150), 9.04 kN (SW500_SH0) and 8.01 kN
 166 (SW300_SH0), which are respectively 13.3% and 23.0%, 32.0% higher than the mono-block sleeper
 167 resistances. The reason of lateral resistance differences among different types of the frictional sleepers is the
 168 different contact forces at the sleeper bottom, which will be demonstrated in the following DEM simulation
 169 part.

170 In addition, according to the test results, it should be noted that the lateral resistance of the RT-sleeper and
 171 ST-sleeper are much lower than GT-sleeper. Consequently, the application of GT-sleeper is recommended in
 172 ballasted tracks.

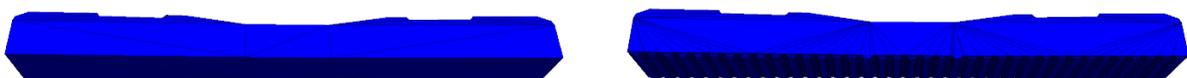
173 3. DEM Simulation

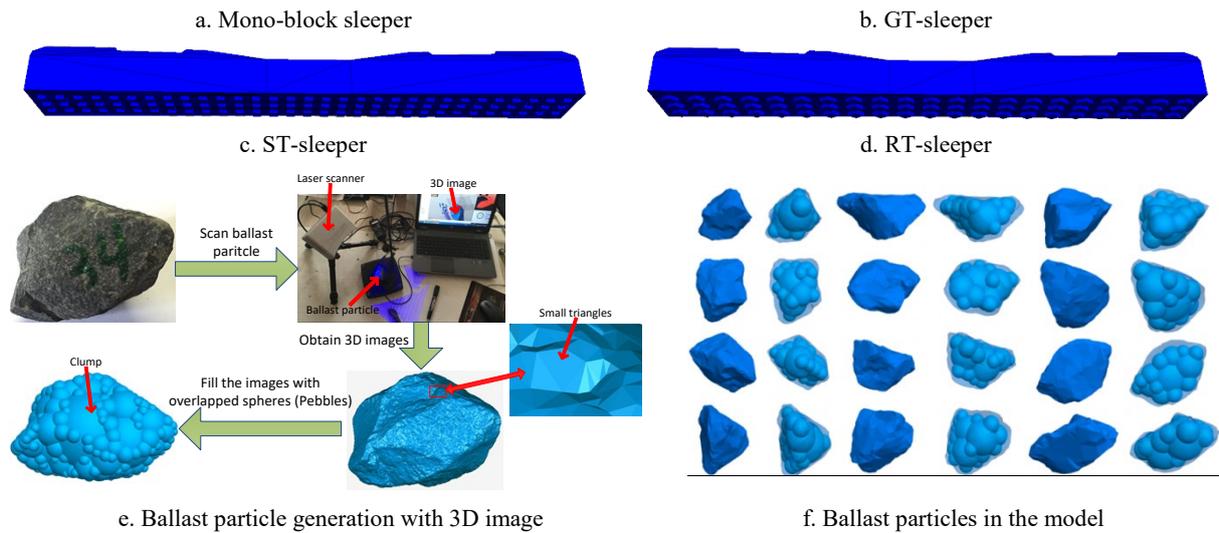
174 The commercial DEM software, PFC3D, is utilised for the numerical study the frictional sleeper lateral
 175 resistance at mesoscopic level. Particularly, the following aspects are studied, including the contribution of
 176 different parts (base, crib and shoulder ballast), contact force chain and sleeper bottom interface.

177 3.1. Model description

178 3.1.1. Sleeper model

179 Four types of sleepers were drawn with the AutoCAD, afterwards, according to the drawn sleeper
 180 configurations the Wall elements were used to create the sleepers in the PFC3D, as shown in Figure
 181 7(a)-(d).





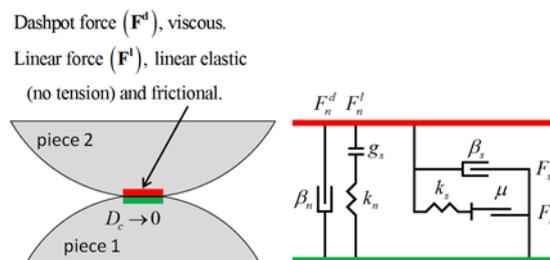
182 **Figure 7 Four types of modelled sleepers and ballast particle generation method**

183 **3.1.2. Ballast Particles model**

184 Ballast shape is very important for producing reliable results, and using the digital image correlation
 185 technology for ballast particle generation has been widely accepted [37]. The ballast particles in the PFC3D
 186 are created with the 3D images that are obtained by laser scanning technique, as shown in Figure 7(e). The
 187 3D images are made of small triangle meshes. Using laser scanning can produce the ballast geometry, and
 188 with the geometry the uncrushable particle was generated as the Clump. The Clump is made of spheres (the
 189 spheres used to create the Clump are named the Pebble), using the Bubble Pack algorithm of Taghavi [38], as
 190 shown in Figure 7(e)(f). The pebble number for making one Clump is in the range of 20-30, and 21 types of
 191 Clump are used in the SSPT model.

192 **3.1.3. Contact Model**

193 The linear contact model (LCM) is applied in this study, which needs to define the parameters: normal
 194 stiffness, shear stiffness, friction and damping, as shown in Figure 8. In addition, the material parameters
 195 should also be defined in the PFC models, i.e. the density. The ballast density is given according to the real
 196 density, and the parameters are calibrated according to the experimental results and given in Table 3. The
 197 LCM utilises two components (a spring and a dashpot) for kinetic energy transmitting and dissipation at
 198 normal and shear directions. The spring provides the no-tension linear elastic force and the shear stiffness
 199 together with friction are used to provide shear forces. For the ballast particles, there is no viscos between two
 200 ballast particles. Because of this, the dashpot is not active in almost all the earlier studies. The damping
 201 applied in the model is the restitution coefficient that is used deciding the particle velocity after acted by a
 202 contact force.



203

204

Figure 8 Linear contact model (reproduced from [39])

205 The spring component is the combination of normal and shear forces ($F_l^n; F_l^s$), and they can be expressed as
 206 shown in Equation 1 [39, 40]. In the equation, the k_n and k_s are the normal and shear stiffness, respectively.
 207 The δ_n and $\Delta\delta_s$ are the contact overlap at normal direction and the tangential overlap increment,
 208 respectively. The $(F_l^s)_0$ is the previous timestep shear force. The μ is the friction coefficient.

209 **Equation 1** (a) $F_l^n = k_n \delta_n$
 210 (b) $F_{l^*}^s = (F_l^s)_0 + k_s \Delta\delta_s$
 211 (c) $F_l^s = \begin{cases} F_{l^*}^s & \text{if } F_{l^*}^s \leq \mu F_l^n \\ \mu F_l^n & \text{if } F_{l^*}^s > \mu F_l^n \end{cases}$

212 3.1.4. SSPT Model creation

213 In this section, the SSPT model creation is introduced. The modelled ballast particles (from 3D images) were
 214 used to make the ballast bed, and the ballast particles were generated with a self-developed method for faster
 215 model creation (introduced later). Before the generation of ballast particles, the sleeper (Wall elements) was
 216 generated and fixed at the certain position until the ballast bed stabilised. The detail steps of the model
 217 creation are as follows.

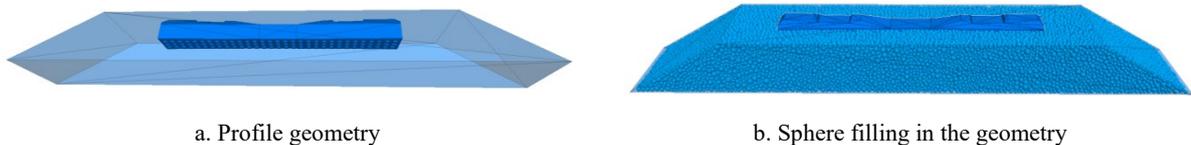
218 Firstly, a profile geometry is created for containing the ballast particles with the Wall command, as shown in
 219 Figure 9 (a). The two side walls were made into slopes, which is the same slope grade (1:1.75) as the ballast
 220 shoulder.

221 Afterwards, the spheres are generated in the profile geometry with the same PSD as the experimental tests.
 222 The sphere generation keeps on until the required porosity (0.34) is reached. During the generation process,
 223 the sleeper is fixed at the certain position. Due to the sphere is randomly generated in the geometry, there are
 224 many overlaps between spheres. Therefore, the model should be stabilised with high damping forces until the
 225 ratio of unbalanced contact forces to average contact forces is below 0.01. This stage is named the initial
 226 equilibrium state.

227 Finally, the spheres are replaced with Clumps with the self-develop algorithm, which can make that the
 228 Clump has the correct volume, density and position. More importantly, the algorithm guarantees a little
 229 change at the contact forces between particles. Specifically, as shown in Equation 2, a scaling factor (β) is
 230 confirmed based on the contact force. The scaling factor is a factor used to expand the clump size.

231 **Equation 2** (a) $\beta = -1 \cdot \lambda \cdot V_b \cdot \Delta\sigma \cdot k_{sum}^n$
 232 (b) $\Delta\sigma = \sigma_{in} - \sigma_m$
 233 (c) $k_{sum}^n = \sum_i (k_i^n \cdot (R_i^a + R_i^b) \cdot R_i)$

234 In the equation, R_i^a , R_i^b are the radiuses of i th contact between two sphere (a, b); R_i is a constant related
 235 with sphere radius and contact; λ is the dimension (3 for 3D); V_b is the ballast bed volume; σ_{in} is the desired
 236 stress of ballast bed; σ_m is the current average ballast bed stress; k_i^n is the normal stiffness of the i th contact.





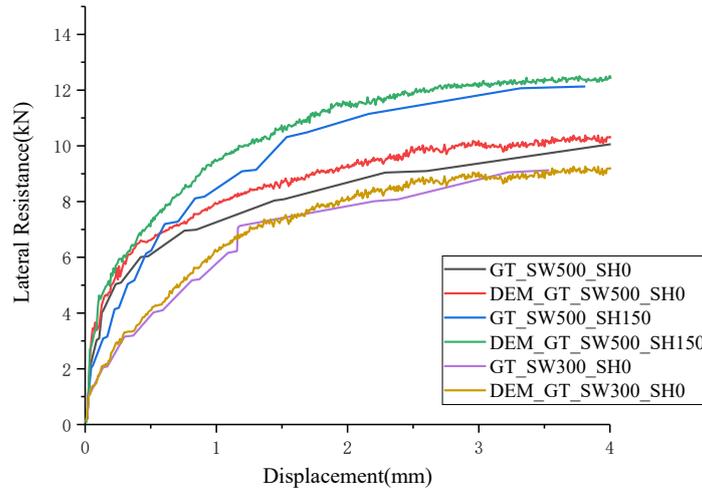
c. Replacement and stabilisation

Figure 9 SSPT model creation procedure

237

238 3.2. Model validation and calibration

239 The numerical and experimental results of GT-sleeper are compared for model parameter calibration, due to
 240 the GT-sleeper can increase the lateral resistance most. It needs to note that after the SSPT model is created,
 241 the sleeper is moved laterally at the speed 0.4 mm/s. As shown in Figure 10, the results of experimental
 242 SSPTs are in good agreement with the DEM simulation results. At the displacement of 2 mm, the differences
 243 of the results were 2.1% (SW500_SH0), 3.2% (SW500_SH150) and 3.3% (SW300_SH0), respectively. The
 244 correlation coefficients are 0.94 (SW500_SH0), 0.94 (SW500_SH150) and 0.96 (SW300_SH0), respectively.
 245 The difference is acceptable, and it may be caused by the lack of interlocking of particles. The porosity of the
 246 experimental test is difficult to measure. Even though the ballast bed as compacted several times, the
 247 compaction is still lower than the DEM model. A set of micro-mechanical parameters adopted for the DEM
 248 simulation of ballast can be validated and given in Table 3 based on the comparison results. These parameters
 249 will be used in the following simulations.



250

251 Figure 10 Results of SSPT experimental tests and DEM simulation of GT-sleeper

252

253 Table 3 Parameters for the SSPT models

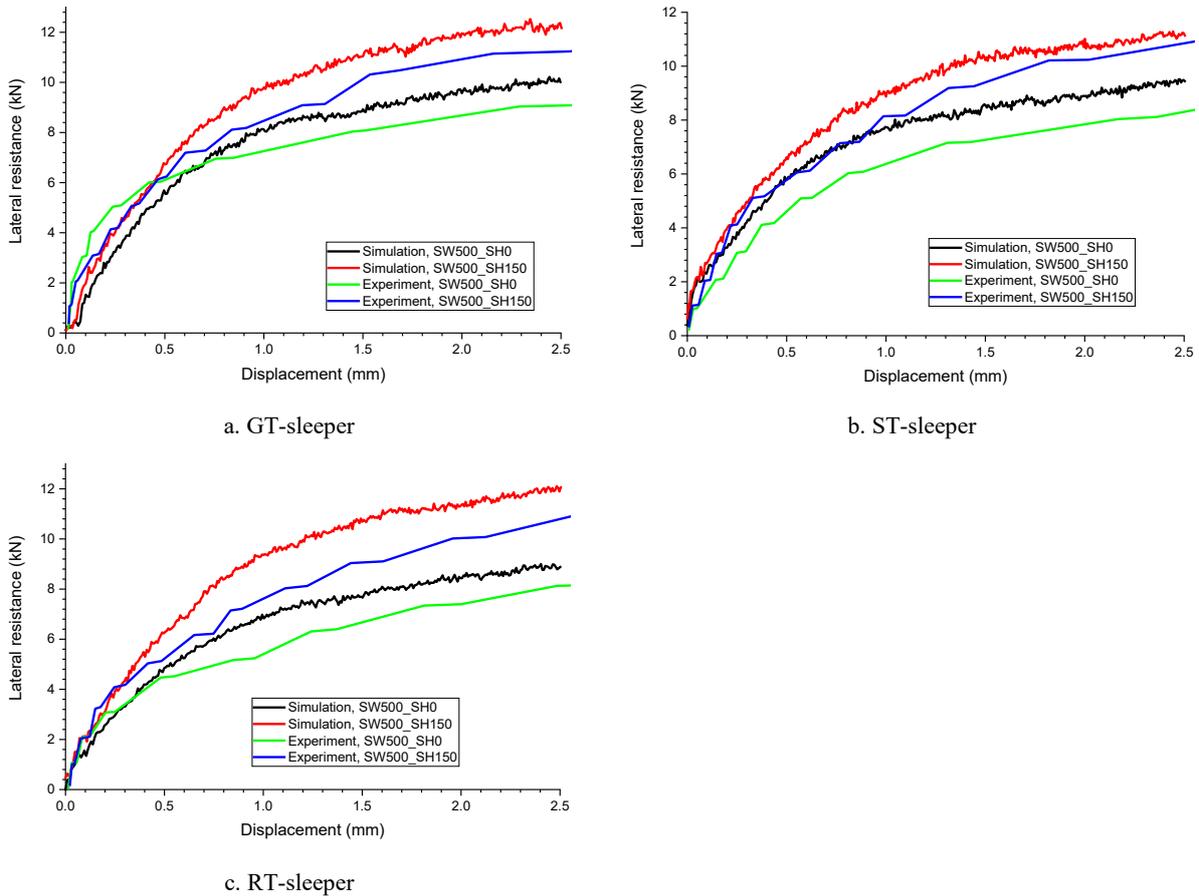
Parameters	Clump	Wall
Normal stiffness, k_n (N/m)	5e9	1e9
Shear stiffness, k_s (N/m)	2e9	1e9
Friction	0.55	0.55
Density (kg/m ³)	2700	-

254

255 **3.3. Results and discussion**

256 **3.3.1. Lateral resistance development**

257 The relationships between lateral resistance and the horizontal displacement of the sleepers obtained from the
258 DEM simulation of SSPTs are shown in Figure 11. From the figure, it can be observed that the lateral
259 resistance increases with and sleeper displacement at the beginning, and after the displacement about 2 mm,
260 the lateral resistance becomes stable.



261 **Figure 11 Results of SSPT experimental tests and DEM simulation of three types of frictional sleepers**

262 In addition, all the simulation results are slightly higher than the experimental results. This is due to the field
263 test control is very difficult, especially the compaction, and the DEM model porosity may be a little higher
264 than the experimental test porosity. The difference is within the tolerance and acceptable, and the mesoscopic
265 analysis on the contact force chain, contribution and ballast-sleeper interaction will be performed in the
266 following sections.

267 **3.3.2. Lateral resistance contribution**

268 In Table 4, the contribution of the lateral resistance is given. From the results, the presence of the sleeper
269 bottom texture can increase the base ballast percentage from 37.3% to 52.3% (ST-sleeper), 58.2%
270 (RT-sleeper) and 65.1% (GT-sleeper). This means with the surface texture on the sleeper bottom can increase
271 the lateral resistance at the sleeper bottom. To reveal the mechanism, the contact forces between the sleeper
272 and ballast particles are analysed in the following section.

273

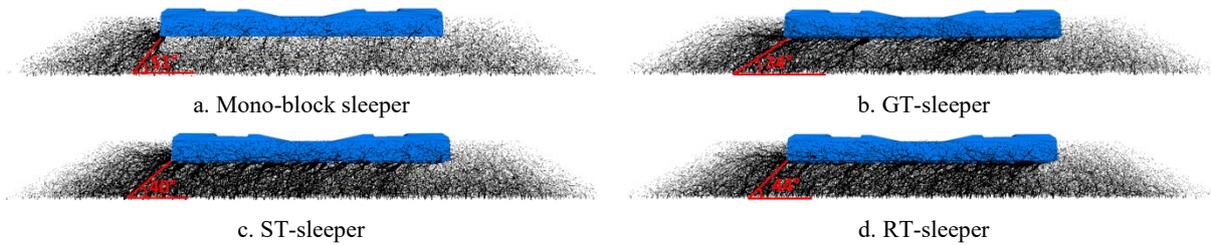
Table 4 Contribution of different parts for the lateral resistance (SW500_SH0)

Test panel	Base ballast (%)	Crib ballast (%)	Shoulder ballast (%)
Mono-block sleeper	37.3	30.5	32.2
GT-sleeper	65.1	16.3	18.6
ST-sleeper	52.3	23.7	25.0
RT-sleeper	58.2	19.3	22.5

274

275 3.3.3. Contact force chain

276 The contact force chain between the sleeper and ballast particles can show which frictional sleeper is optimal.
 277 Figure 12 presents the distribution of contact forces of four types of sleepers. From the figure, it can be
 278 observed that using the frictional sleepers can enhance the contacts under the sleeper to provide more lateral
 279 resistance. Moreover, the frictional sleepers have smaller contact force chain angle than the normal sleeper,
 280 and the GT-sleeper is the optimal one with the smallest angle at 34 degrees. This means more ballast particles
 281 can provide forces for the GT-sleeper.



282

Figure 12 Contact force chain and distribution of four types of sleepers (SW500_SH0)

283 3.3.4. Sleeper bottom interface

284 Table 5 presents the results of four types of sleepers with the shoulder width at 500 mm and height at 0 mm.
 285 By comparing the results, it can be concluded that the frictional sleepers have more contact number at the
 286 sleeper bottom, 183 (GT-sleeper), 211 (ST-sleeper) and 208 (RT-sleeper) which are at least three times
 287 higher than the normal sleeper (61). The contact number increase can be the reason of the lateral resistance
 288 increase. The reason of contact number increase is that the bottom texture of frictional sleeper enlarged the
 289 effective contact area between sleeper and ballast bed. The enlargement of effective contact area makes the
 290 ballast contact number increased at a prominent growing rate.

291 The average force changes with the type of sleeper, where mono-block sleeper gained the biggest value at
 292 130 N. Although the mono-block sleeper provides the lowest lateral resistance, the contact number of
 293 mono-block sleeper is much fewer than frictional sleepers. This leads to higher forces to limited particles.
 294 In contrast, the average force of GT-sleeper is small, but its contact number is much more than mono-block
 295 sleeper. As a result, the total force of GT-sleeper is the highest.

296 From the results, it can be concluded that the effect of frictional sleeper can be reflected in two aspects:
 297 contact number and average force. By adding bottom texture to the sleeper, the contact number increased
 298 significantly while the average force decreased, and the lateral resistance improved eventually. More
 299 importantly, the average force decreased when applying the frictional sleepers, which may infer a new
 300 method to reduce the stresses at ballast particles for degradation reduction.

301

Table 5 Contact number and contact force of sleepers

Sleeper type	Mono-block sleeper	GT-sleeper	ST-sleeper	RT-sleeper
Contact number	61	183	211	208
Total force(kN)	7.73	9.33	8.47	8.39
Average force(N)	130	50	40	40

302 4. Conclusions and perspectives

303 In this paper, a set of Single sleeper pull-out tests and DEM simulations were performed to study the lateral
 304 resistance of normal concrete sleeper (mono-block sleeper) and innovated frictional sleepers (three types).
 305 In the experiments, the shoulder ballast height and width were considered as the effect factors. Particularly,
 306 the lateral resistance of four types of sleepers were compared to confirm the optimal type. The DEM
 307 simulations were used to further analyse the meso-mechanism of ballast-sleeper interaction, revealing the
 308 reason of the lateral resistance increase. Based on the results and discussion, the following conclusions are
 309 given.

- 310 1. Frictional sleepers can increase the lateral resistance. For example, the grooves texture sleeper can
 311 increase the resistance by approximately 32.0% compared with traditional concrete sleeper.
- 312 2. DEM analysis and results could be served to illustrate the micro-mechanism of ballast-sleeper lateral
 313 interaction. Bottom texture of frictional sleeper could provide more contact number, and less average
 314 force.
- 315 3. The frictional sleepers have better contact force distribution than the traditional sleeper, which means
 316 more particles can contribute to the lateral resistance. This leads to the ballasted track more stable.

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