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1 **Analysis of railway ballasted track stiffness and behaviour**

2 **with a hybrid discrete-continuum approach**

3 Can Shi¹, Chunfa Zhao², Yang Yang³, Yunlong Guo^{4*}, Xu Zhang⁵

4 1. Ph. D. Candidate, State Key Laboratory of Traction Power, Southwest Jiaotong University, Chengdu
5 610031, China. E-mail: shican@my.swjtu.edu.cn

6 2. Professor, State Key Laboratory of Traction Power, Southwest Jiaotong University, Chengdu 610031,
7 China. E-mail: cfzhao@home.swjtu.edu.cn

8 3. Ph. D., China Railway Eryuan Engineering Group CO. LTD, Chengdu, Sichuan 610031, P.R. China.
9 E-mail: yyxnjd@163.com

10 4. Ph. D. Candidate, Faculty of Civil Engineering and Geosciences, Delft University of Technology, Delft,
11 2628CN, Netherlands. (Corresponding author). E-mail: yunlong.guo@tudelft.nl

12 5. Ph. D., School of Civil and Transportation Engineering, Guangdong University of Technology,
13 Guangzhou, Guangdong 510006, P.R. China. E-mail: xuzhang@gdut.edu.cn

14 **Abstract:** Railway ballasted track stiffness is an important indicator to identify supporting
15 condition that ensures the facility is well designed and functioned. Although many studies have
16 been performed on track stiffness based on experimental tests and finite element methods, the
17 factors influencing the track stiffness have not been completely confirmed yet, especially the
18 influences from ballast and subgrade layers at a mesoscopic level. To address this research gap, a
19 coupled the discrete element method (DEM) and the finite difference method (FDM) model is
20 utilised to study the factors influencing on the track stiffness from the particle level. Factors
21 (related to ballast layer properties) are bulk density, thickness and stiffness, and other factor
22 (related to subgrade properties) is elastic modulus. Additionally, the relationship between the track
23 stiffness and the mechanical behaviour of ballast is analysed. This study quantified the influences
24 of track components on the track stiffness and accordingly proposed how to improve it from the
25 ballast and subgrade layers at the mesoscopic level, which can provide the guidance for railway
26 ballasted track design and maintenance.

27 **Keywords:** Discrete element method, Finite difference method, Hybrid simulation, Track

28 stiffness, Railway ballasted track

29 **INTRODUCTION**

30 Railway ballasted tracks are widely used all over the world, and the main advantages of ballasted
31 tracks (compared to slab track) are low construction cost and easy maintenance work. The
32 performance of the ballasted track in terms of loading strongly depends on the track stiffness,
33 which is expressed by the ratio of the static load to the corresponding track deflection. Until now,
34 plenty of studies have demonstrated that the track stiffness has significant influences on the vehicle
35 ride quality (Lundqvist and Dahlberg 2005; Xu et al. 2020), the track dynamic behaviour (Frohling
36 et al. 1996; Li and Berggren 2010) and track long-term degradation (Milosavljević et al. 2012;
37 Grossoni et al. 2016). More importantly, some studies pointed out that track stiffness is a key
38 indicator for the demand of maintenance work (Sussman et al. 2001; Pita et al. 2004). Therefore,
39 understanding track stiffness more deeply can provide clearer guidance for assessing and
40 improving track performance.

41 To understand the track stiffness, many studies have been performed to confirm how various track
42 components influence track modulus and stiffness. Some researchers concluded that improving the
43 track substructure materials (ballast, subballast and subgrade layers) can enhance the track
44 stiffness performance (Selig and Li 1994; Khordehbinan 2010; Mosayebi et al. 2016; Sussman and
45 Selig 1999). Their theoretical models assumed the ballast layer with springs and dampers but
46 ignored the discontinuity, inhomogeneity and the randomness of ballast assembly. Particularly, the
47 effects of ballast layer characteristics (e.g. rearrangement) on the track stiffness cannot be revealed
48 by the model from ballast particle level (Qian et al. 2018).

49 Some other researchers performed experimental tests to study the track stiffness, and obtained the

50 macromechanical load-deflection characteristic of the whole track structure (Oscarsson and
51 Dahlberg 1998; Priest and Powrie 2009). However, the meso-mechanical characteristic of ballast
52 layer under the static load hardly can be investigated from experimental tests. In addition, the track
53 stiffnesses that are measured in the field are of great randomness (due to the existence of uncertain
54 factors), and experimental tests are not feasible to perform parametric study (due to difficulties in
55 variable control). Thus, the relationship between the track stiffness and the meso-mechanical
56 behaviour of ballast is rarely analysed, and the factors influencing the track stiffness have not been
57 completely investigated yet.

58 To address the limitation of earlier studies, the hybrid discrete-continuum approach is applied in
59 this study for the meso-analysis of track stiffness. The DEM is an effective and reliable approach
60 to present the granular material properties of ballast assembly, e.g. density, degradation, particle
61 size and particle shape (Guo et al. 2020a), and has been successfully applied in many
62 ballast-related studies, such as, under sleeper pads (Li and McDowell 2018), ballast particle
63 acceleration (Liu et al. 2019) and friction sleeper (Guo et al. 2020b). The hybrid
64 discrete-continuum approach has been proved to be an effective solution for the ballasted track
65 studies involving the subgrade (Shao et al. 2017; Ngo et al. 2017; Li et al. 2019; Shi et al. 2020a).

66 In this study, the DEM is utilised to build the ballast layer, sleeper and rail to study the track
67 stiffness. Ballast particles are modelled with irregular geometry shapes, and the compacted ballast
68 assembly under different sleepers had non-uniformly distributions (for different supporting
69 conditions). To analyse the influence of subgrade on the improving of track stiffness, the subgrade
70 layer is also considered. Considering the impossibility of numerical calculation of the subgrade
71 with huge amounts of soil particles in DEM, the subgrade is simulated with the FDM by
72 considering it as a continuous medium. The coupled DEM-FDM model of railway ballasted track

73 and subgrade is realized by exchanging the force and displacement data. Subsequently, the coupled
74 model is verified by comparing the numerical results of track stiffness to those in references, and
75 then the verified model is used to study the factors influencing track stiffness, as well as the
76 relationship between track stiffness and ballast behaviour.

77 **MODEL DESCRIPTION AND VERIFICATION**

78 *Model description*

79 Figure 1 shows the two-dimensional coupled DEM-FDM model of ballasted track and subgrade.
80 The coupled model has 13 sleepers with the length at 8.4 m, and the ballast layer thickness (under
81 the sleeper) is 0.35 m. Each longitudinal spacing between two adjacent concrete sleepers is 0.6 m.
82 Besides, the height of the sleeper is 0.19 m that is the size of the Chinese Type III mono-block
83 sleeper, and this type of sleeper can be found in (Guo et al. 2020b). The subgrade consists of three
84 parts as shown in Figure 1: the surface layer of subgrade (0.6 m), the bottom layer of subgrade (1.9
85 m) and the subgrade body (3.1 m). The FDM model of the subgrade is built according to the
86 Chinese standard for the heavy haul railway (National Railway Administration of P.R. China
87 2017). In the coupled model, the x-axis represents the longitudinal direction of the ballasted track,
88 and the y-axis represents the vertical direction of the ballasted track. For the subgrade boundary
89 conditions, in the plane of the model, at $y = -5.6$ m, the displacement of bottom boundary nodal
90 was fixed ($u_x, u_y = 0$); in the planes at $x = 0$ and $x = 8.4$ m, the displacement was constrained u_x (u_x
91 $= 0$).

92 As shown in Figure 1, the ballasted track (rail, sleepers and ballast layer) is built with the DEM
93 software, Particle Flow Code (PFC), in which the ballast particles can be built in irregular shapes.
94 More than 100 different shapes of ballast particles are applied in the ballasted track model, and the

95 modeling of irregular shapes ballast can be found in the reference (Zhang et al. 2016). The ballast
96 layer is built by compacting a certain number of particles with irregular shapes to an
97 adequately-compacted state. The particle size distribution of the ballast layer is the same as that in
98 the reference (Shi et al. 2020b), as shown in Table 1. The sleepers are built by combining 548 discs
99 as a Clump (rigid block), and the rail is built by bonding discs together as a beam with linear
100 parallel bonds. The linear parallel bonds present a physical performance similar to the cement,
101 which can glue together the two contacting discs (Guo et al. 2020a).

102 The subgrade is built by plane-stress solid elements in the FDM software, Fast Lagrangian
103 Analysis of Continua (FLAC), and the linear-elastic constitutive model is used to simulate the
104 subgrade. Table 2 and Table 3 summarize the main parameters used in the ballasted track and
105 subgrade models, respectively. Finally, a series of interface elements (walls) are created between
106 the FLAC and PFC to implement the coupling process of force and displacement exchanges. These
107 interface walls correspond to the nodal of the FDM subgrade surface and the wall positions update
108 at the beginning of each calculation cycle.

109 Specifically, the hybrid simulation is achieved by the exchange of contact forces and velocities
110 between the two kinds of software. Since both the PFC and FLAC are developed by the Itasca
111 company, they have a parallel configuration (I/O socket) that can transfer data between each other.
112 The data exchange between the two software packages is managed by the I/O socket using the
113 FISH function (computer language developed by Itasca). The boundary nodal velocities in the
114 FLAC (server) are outputted along with the updated coordinates, and then these data are inputted
115 into the PFC (client) through the I/O socket connections. The coordinates and velocities are used to
116 update the boundary wall coordinates, afterwards, the contact forces of wall-particle at the
117 boundary wall are calculated using the force-displacement law. Eventually, the contact forces are

118 converted to the nodal forces and applied to the boundary nodal in the FLAC. More detailed
119 descriptions about the discrete-continuum ballasted track and subgrade model can be found in (Shi
120 et al. 2020b).

121 *Support stiffness to sleeper*

122 In general, track stiffness is measured by the rail deflection under a static load, by which global
123 track stiffness can be measured. The global track stiffness can be further classified as two parts: 1)
124 above the sleepers (principally from the rail and rail pad) and 2) under the sleepers (from the
125 ballast and subgrade). Due to the rail and rail pad stiffnesses are easy to control, and the support
126 conditions of the sleepers have not been adequately studied. Therefore, the sleeper support
127 stiffness (the relationship between load and deflection of the sleeper) from the perspective of the
128 ballast and subgrade is focused in this study.

129 The secant stiffness (defined in Equation 1) is applied to calculate the sleeper support stiffness, as
130 this method can minimise the influences of poor ballast-sleeper contacts (Ebersöhn and Selig
131 1994). It is calculated based on the load-deflection test for a chosen load range (From F_a to F_b). It
132 is a common phenomenon that small gaps exist between sleeper and ballast, in other words, the
133 sleeper in most cases partially or completely lost contacts with ballast, causing the hanging sleeper
134 (Olsson and Zackrisson 2002; Augustin et al. 2003).

$$135 \quad k = \frac{F_b - F_a}{z_b - z_a} \quad (1)$$

136 where Z_b is the final sleeper elevation; Z_a is the initial sleeper elevation.

137 The range of loading for analysis is dependent on transportation and vehicle types (e.g. heavy haul
138 or high-speed railways). Because the stiffness of track components is non-linear (especially the

139 ballast), and the different static load ranges applied to the sleeper lead to different stiffness results.
140 In this study, the load range of heavy haul railway (freight vehicle) with an axis load of 22 t is used,
141 According to the field tests performed by Zhang et al. (2018), the maximum rail pad forces
142 induced by the locomotive with the axle-load of 22 t is between 58.2~79.7 kN. Thus, the secant
143 stiffness is calculated to be in the range of 10 - 80 kN to eliminate the effect of hanging sleeper.
144 Note that, the load value of 40 kN is used to apply on the sleeper in this half-track numerical
145 model, which is equivalent to the effect of applying a force of 80 kN to a three-dimensional track.
146 The preloading is carried out by applying a static force of 40 kN at the sleeper before the
147 measurement to eliminate the voids between the sleeper and ballast.

148 Figure 2 shows the schematic diagram of the sleeper positions to where the loads (F) were applied.
149 As shown in Figure 2, $F(t)$ are simultaneously applied on Numbers 1, 4, 7, 10 and 13 unfastened
150 sleepers (i.e. fasteners were removed), the corresponding sleepers' displacements are recorded at
151 the same time. The loads F are applied by the increment rate of 2 N/s until 40 kN, and the load F
152 is obtained:

$$153 \quad F(t) = 2000 + 2 \times t \quad (2)$$

154 Afterwards, using the same initial model, the Number 2, 5, 8 and 11 sleepers are performed the
155 same process, as well as on the Number 3, 6, 9 and 12 sleepers. Finally, the sleeper support
156 stiffnesses of all 13 sleepers are obtained.

157 ***Sleeper support stiffness verification***

158 As described above, the DEM and FDM are coupled by data exchange at the interface walls, and
159 the walls update according to the nodal of subgrade surface. Figure 3 shows typical
160 displacement-force curves of the sleeper, interface walls and the corresponding node of the

161 subgrade surface. From Figure 3, the displacements of the interface walls in PFC and
162 corresponding FLAC nodes show a high correlation, which implies the data are reliably
163 transmitted between the DEM model and the FDM model.

164 From Figure 3, it can be seen that the relationship between applied force and sleeper displacement
165 is not linear, which is consistent with the experimental tests performed by others (Frohling et al.
166 1996; Oscarsson and Dahlberg 1998; Sussman and Ebersöhn 2001). The initial stiffness (From 0
167 kN to 10 kN) is affected by the insufficient contacts between the sleeper and ballast, which is also
168 known as the seating stiffness. To further validate the coupled model in calculating sleeper support
169 stiffness, the calculated values of sleeper support stiffness and ballast layer stiffness are compared
170 with the previous measurement results, as shown in Table 4. The ballast layer stiffness is defined as
171 a vertical load divided by the ballast layer deflection (the sleeper displacement subtracts subgrade
172 surface displacement). The comparison shows that the simulation results are in consonance with
173 the measurements. Summarily, the coupled model for the sleeper support stiffness analysis is
174 validated.

175 **EFFECT OF TRACK COMPONENT PARAMETERS ON SLEEPER** 176 **SUPPORT STIFFNESS**

177 In this section, a parametric study with variable track component parameters is carried out to
178 confirm how much the factors influence on sleeper support stiffness. The parameters of track
179 components include the density, thickness and stiffness of the ballast layer and the elastic modulus
180 of different subgrade layers.

181 *Effect of bulk density on sleeper support stiffness*

182 Figure 4 shows the sleeper support stiffness and the bulk density of the ballast layer under each
183 sleeper, and the bulk density is measured at different areas (Area 1, 2 and 3). The “Area 1” and
184 “Area 2” mean the rectangles below each sleeper with a width of 0.15 m and 0.3 m, respectively.
185 The “Area 3” means an isosceles trapezoid with the sleeper bottom as its upper base and two
186 bottom angles at 45 degrees. In the following analysis, if no further description is made, the bulk
187 density value and other index values are measured from “Area 2”. From Figure 4, the sleeper
188 support stiffness is found to scatter between 50 MN/m and 63 MN/m. The bulk densities under
189 different sleepers are in the range of 1890 kg/m³ to 1950 kg/m³, which is consistent with the field
190 measurement results that the bulk density of fully-compacted ballast layer is about 1900 kg/m³
191 (Tutumluer et al. 2013). From Figure 4, it can be seen that the sleeper support stiffnesses
192 significantly varies from one sleeper to its adjacent sleepers, and the bulk densities under different
193 sleepers are considerably different. The conclusion can be drawn that the relationship between the
194 sleeper support stiffness and the bulk density under this sleeper is not obvious.

195 To further explore the influence of bulk density on the sleeper support stiffness, the ballast layer
196 with different compact states is analysed. Compaction states of “Tamp 1” to “Tamp 4” means the
197 compaction time, which is that more load cycles were applied on the ballasted track. The bulk
198 density of the ballast layer increases with the compaction time, as shown in Figure 5(a). From
199 Figure 5(b), the sleeper support stiffness also increases with the increase of the compaction time.
200 Summarily, improving the bulk density can increase the sleeper support stiffness to a certain
201 degree, which is also helpful to improve the carrying capacity of ballasted tracks.

202 Furthermore, Figure 6 shows the relationship between the sleeper support stiffness and the bulk
203 densities of different compaction states, where each point represents the average value of all 13
204 sleepers under different compaction states. From Figure 6, there is a good linear relationship

205 between the increment of bulk density and the increment of sleeper support stiffness. Thus, the
206 bulk density has significant influences on the sleeper support stiffness.

207 *Effect of ballast layer thickness on sleeper support stiffness*

208 The ballast layer supports the imposed wheel load and transmits the forces from the rail and
209 sleeper to the subgrade at an acceptable level. The design approaches of ballast layers from
210 different countries that are used to decide the thickness of the ballast layer were discussed and
211 compared in the reference (Burrow et al. 2007). In this study, ballast layers with a thickness of 0.4
212 m, 0.5 m and 0.6 m are chosen to analyse how the thickness of ballast layers influences the sleeper
213 support stiffness.

214 Figure 7(a) shows the initial bulk density of these ballast layers with different thicknesses. The
215 bulk densities of the ballast layers with the thicknesses of 0.4 m, 0.5 m and 0.6 m are about 1922
216 kg/m³, 1934 kg/m³ and 1930 kg/m³, respectively, which means their bulk densities were
217 approximately the same. As shown in Figure 7(b), increasing the thickness of the ballast layer is
218 also beneficial to improving the sleeper support stiffness, which is consistent with the studies
219 performed in the references (Gallego et al. 2011; Kim et al. 2019).

220 The mean values and the standard deviations of the sleeper support stiffnesses under different
221 ballast layer thicknesses are presented in Table 5. As the thickness of ballast bed increases from 0.4
222 m to 0.6 m, the sleeper support stiffness increases marginally by 17%, while the standard deviation
223 does not show a clear increasing trend. Besides, the conclusion can be drawn that the effect of bulk
224 density on the sleeper support stiffness is greater than the thickness of the ballast layer

225 *Effect of ballast layer stiffness on sleeper support stiffness*

226 According to the references (Ngo et al. 2016; Chen and McDowell 2016; Indraratna et al. 2016;

227 Zhang et al. 2016), when applying the DEM to simulate the ballast particles, the contact stiffness
228 between ballast particles varies from 1×10^8 N/m to 5×10^8 N/m. Hence, three different contact
229 stiffnesses (1×10^8 , 3×10^8 and, 5×10^8 N/m) are chosen for comparison to confirm the influences of
230 contact stiffness on the sleeper support stiffness.

231 At the beginning of the numerical simulation, three modeled ballast layers, each of which is made
232 by ballast particles with one of the three contact stiffnesses (1×10^8 , 3×10^8 and 5×10^8 N/m), are
233 stabilized, by performing cyclic loadings until the models reach a certain condition that the ratio of
234 average unbalanced force to average contact force reached 0.01. Subsequently, the numerical
235 simulations are carried out on how different contact stiffnesses influence on the sleeper support
236 stiffness.

237 Figure 8 shows that the sleeper support stiffness increases with the increase of the contact stiffness,
238 and the mean values of the sleeper support stiffness are 35.07 MN/m, 56.88 MN/m and 65.98
239 MN/m, respectively. Besides, Figure 8 shows the deviation of the sleeper support stiffness reduces
240 as the decrease of the contact stiffness, and the standard deviations are 2.49 MN/m, 3.69 MN/m
241 and 4.3 MN/m, respectively. Therefore, the conclusion can be made that the increase of contact
242 stiffness makes the sleeper support stiffness and the deviation of sleeper support stiffnesses
243 increasing.

244 ***Effect of subgrade elastic modulus on sleeper support stiffness***

245 To confirm the effect of different subgrade layer elastic modulus on the track performance, a
246 practical range of elastic modulus values for each subgrade layer is chosen. Table 6 presents the
247 elastic modulus of the variable subgrade used for parametric study.

248 Figure 9 shows the effects of subgrade elastic modulus on the sleeper support stiffness. From

249 Figure 9(a), it can be seen that the elastic modulus of the subgrade surface has insignificant
250 influences on the sleeper support stiffness. In this regard, the statistical analysis of the sleeper
251 support stiffness under different elastic modulus of the subgrade surface was carried out. The mean
252 values of the sleeper support stiffness are 55.66 MN/m, 56.88 MN/m and 56.92 MN/m,
253 respectively. As shown in Figure 9(b) and Figure 9(c), the sleeper support stiffnesses increase with
254 the increase of the elastic modulus of different subgrade layers. In general, the increase of
255 subgrade stiffness causes the sleeper support stiffness increasing. Furthermore, it can be seen from
256 Figure 9 that the part of subgrade influencing sleeper support stiffness most is the elastic modulus
257 of subgrade body.

258 **RELATIONSHIP BETWEEN SLEEPER SUPPORT STIFFNESS AND** 259 **BALLAST BEHAVIOUR**

260 The relationship between the sleeper support stiffness and the meso-mechanical behaviour of
261 ballast under vertical loading is presented below.

262 *Ballast particle behaviour*

263 Figure 10 shows that the sleeper support stiffness under the conditions that some degrees of
264 freedom of the ballasts were constrained. The “Fix spin” means the rotation of ballast particles is
265 constrained, and “Fix x-component displacement” means the movement of ballast particles in the
266 x-direction is restricted. As shown in Figure 10, the “Fix spin” has a greater influence on the
267 sleeper support stiffness than the “Fix x-component displacement”. Furthermore, the value of
268 sleeper support stiffness in the condition of fixing both ballast spin and x-component displacement
269 is almost the same as the condition of fixing ballast particles spin, which indicates that the
270 x-component displacement of ballast particles is mainly caused by the rotation of the ballast

271 particles.

272 To further prove the influences of ballast particles rotation on x-component displacement, the
273 average rotation angle and x-component displacement of ballast particles are presented. In
274 addition, the average azimuthal angle before and after loading is also presented, which indicates
275 the rotation direction of ballasts. The azimuthal angle is the angle between the long axis of ballast
276 particle and the vertical axis, and the long axis of ballast particle is the longest dimension of one
277 ballast particle among three dimensions (length, width and height), explained in Guo et al. 2019.

278 Figure 11(a) shows the average rotation angle and x-component displacement of ballast particles.
279 From Figure 11 (a), it can be observed that the change of ballast x-component displacement is
280 about 0.04 mm and the ballast particle rotation is about 0.9° after the force applied on the sleeper.
281 The average azimuthal angles of ballast particles before and after loading are shown in Figure
282 11(b). The results show that the directions of ballast rotation after applied forces increase the
283 average azimuthal angles, which indicates that the increase of ballast average azimuthal angles
284 will allow the ballast layer to withstand greater loads.

285 ***Contact forces and stress***

286 Figure 12 shows the relationship between sleeper support stiffness and the average contact force in
287 the ballast layer. It indicates that there is a good negative correlation between sleeper support
288 stiffness and ballast contact forces. The main reason is that the overlaps between ballast particles
289 increase as the contact forces increase, due to the contacts applied in the DEM models between
290 ballast particles are the linear contact with spring and dashpot. Therefore, a larger sleeper
291 deformation is formed by accumulating the overlap between ballast, and then bringing up small
292 sleeper support stiffness. As well knows, the greater the contact force between the ballast, the more

293 likely the ballast is to wear and break. Consequently, the results can be drawn that the ballast in the
294 areas with larger sleeper support stiffness is more prone to deteriorate.

295 To further investigate the mesoscopic contact force chain of ballast particles, Figure 13 shows the
296 distribution of the contact force chains in the DEM ballasted track and the vertical stress contour
297 σ_{yy} in the FDM subgrade. Each contact force is represented at the contact points by a red line
298 oriented in the direction of the force and with the thickness proportional to its intensity. As shown
299 in Figure 13, the force chain structure in the ballast layer and the stress concentration phenomenon
300 in the surface layer of the subgrade are obvious at the force-applied sleepers. For example, the red
301 force chains are wider under sleeper Number 1, 4, 7..., to which the forces are applied. The force
302 chains transmitting in the ballast layer approximately coincides with the cone distribution, which
303 is consistent with the assumption that the force is pyramid distribution in the ballast layer (Zhai et
304 al. 2004). Besides, the force chains (the contacts between ballast particles and the sleeper-ballast
305 contact) in the ballast layer are obviously different under the different sleepers, which can be the
306 reason of sleeper support stiffnesses significantly vary from one sleeper to its adjacent sleepers.

307 **CONCLUSIONS**

308 In this paper, the hybrid discrete-continuum approach is applied for the macroscopic and
309 mesoscopic analysis of sleeper support stiffness. After validating the coupled model, the factors
310 influencing the sleeper support stiffness are analysed, including the bulk density and thickness of
311 the ballast layer, the contact stiffness of ballast particles and the elastic modulus of subgrade.
312 Finally, the influences of ballast restriction on sleeper support stiffness and the mesoscopic
313 analysis of the contact force chains in the ballast layer are presented. The following conclusions
314 can be drawn for this study:

- 315 (1) There is a good linear relationship between the increment of ballast density and the increment
316 of sleeper support stiffness, and the best remedy technical of increasing the sleeper support
317 stiffness is increasing the density of the ballast layer.
- 318 (2) With the thickness of ballast bed increases from 0.4 m to 0.6 m, the sleeper support stiffness
319 increases from 57.43 MN/m to 67.21 MN/m, in general, the increase of ballast layer thickness
320 causes the sleeper support stiffness increasing slightly.
- 321 (3) The sleeper support stiffness and the deviation of sleeper support stiffnesses increase with an
322 increase of the contact stiffness, and the elastic modulus of subgrade body influence on the
323 sleeper support stiffness most among subgrade layers.
- 324 (4) Under the vertical force applied on the sleeper, the x-component displacement of ballast
325 particles mainly caused by the rotation of the ballast particles.
- 326 (5) The sleeper support stiffness is considerably related to the contact forces between ballast
327 particles, and the ballast in the areas with larger sleeper support stiffness is more prone to
328 deteriorate.

329 **DATA AVAILABILITY STATEMENT**

330 Some or all data, models, or code that support the findings of this study are available from the
331 corresponding author upon reasonable request (All data).

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Table 1 Particle size distribution of the ballast layer

Mesh size (mm)	22.5	31.5	40	50	63
Percentage passing by mass in Chinese design standards (%)	0~3	1~25	30~65	70~99	100
Percentage passing by mass of the ballasted track model (%)	0	13	45	88	100

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Table 2 Parameters in the DEM model of ballasted track

Parameters	Value	Unit
Disk thickness	1.3	m
Rail particle density	490	kg/m ³
Rail particle radius	75	mm
Fastener particle density	3184	kg/m ³
Fastener particle radius	20	mm
Sleeper particle density	3129	kg/m ³
Sleeper particle radius	5	mm
Ballast particle density	2600	kg/m ³
Ballast particle radius	4	mm
Rail particle parallel bond radius	37.27	mm
Rail particle normal parallel bond contact stiffness	1.427×10^{12}	N/m ³
Rail particle shear parallel bond contact stiffness	5.5297×10^{11}	N/m ³
Rail particle normal/shear parallel bond strength	1×10^{10}	N
Rail particle normal/shear contact stiffness	2.765×10^{11}	N/m
Fastener particle normal/shear bond stiffness	1×10^{10}	N/m
Fastener particle normal/shear contact stiffness	1.2×10^8	N/m
Ballast/Sleeper particle and vertical wall stiffness	3×10^8	N/m
Ballast particle friction coefficient	0.7	-

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Table 3 Parameters in the FDM model of subgrade

Components	Poisson's ratio	Young modulus (MPa)	Density (kg/m ³)	Thickness (m)
Surface layer of subgrade	0.25	180	1950	0.6
Bottom layer of subgrade	0.25	110	1900	1.9
Subgrade body	0.3	80	1800	3.1

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Table 4 Comparison of the simulation results and measured results

Parameters	Numerical simulation results (MN/m)	Measurement results (MN/m)	References
Sleeper support stiffness	50-63	25-85	Brough, et al. 2006
		46.48-51.29	Cano et al. 2016
Balast layer stiffness	105-163	71.98 -193.52	Ma, et al. 2016

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Table 5 Mean values and standard deviations of sleeper support stiffness

Ballast layer thickness (m)	Mean values (MN/m)	Standard deviations (MN/m)
0.4	57.43	3.45
0.5	60.93	4.57
0.6	67.21	4.04

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Table 6 Variable subgrade elastic modulus used for parametric study

Parameters	Nominal value	Values used to keep all other parameters at nominal value
		Modulus of elasticity (MPa)
Surface layer of subgrade	180	150(soft),210(stiff)
Bottom layer of subgrade	110	80(soft),140(stiff)
Subgrade body	80	50(soft),110(stiff)

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Figure 1 Coupled DEM-FDM model of ballasted track and subgrade

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Figure 2 Schematic diagram of force exertion

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Figure 3 Applied force versus measured displacements of interval walls, nodals and sleeper

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Figure 4 Sleeper support stiffness and bulk density of the ballast layer

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465 **Figure 5 Sleeper support stiffness and ballast layer density under different compaction states: (a) The density**
466 **of ballast layer; (b) Sleeper support stiffness**

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Figure 6 Relationship between sleeper support stiffness and bulk density

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471 **Figure 7 Bulk densities and sleeper support stiffnesses of ballast layers under different ballast layer**
472 **thicknesses: (a)bulk density; (b)sleeper support stiffness**

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Figure 8 Sleeper support stiffnesses of different ballast particle stiffness

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477 **Figure 9 Effects of subgrade elastic modulus on sleeper support stiffness: (a) surface layers of subgrade; (b)**
478 **bottom layers of subgrade; (c) subgrade body**
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Figure 10 Sleeper support stiffness of constrained ballast particles

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483 **Figure 11 Behaviour of ballast particles before and after loading: (a) x-component displacement and rotation;**

484 **(b)azimuthal angle**

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Figure 12 Sleeper support stiffness and ballast contact force

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Figure 13 Discrete-finite coupled model under the sleeper loads

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