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Evaluation of Lateral Stability of Railway Tracks due to Ballast Degradation

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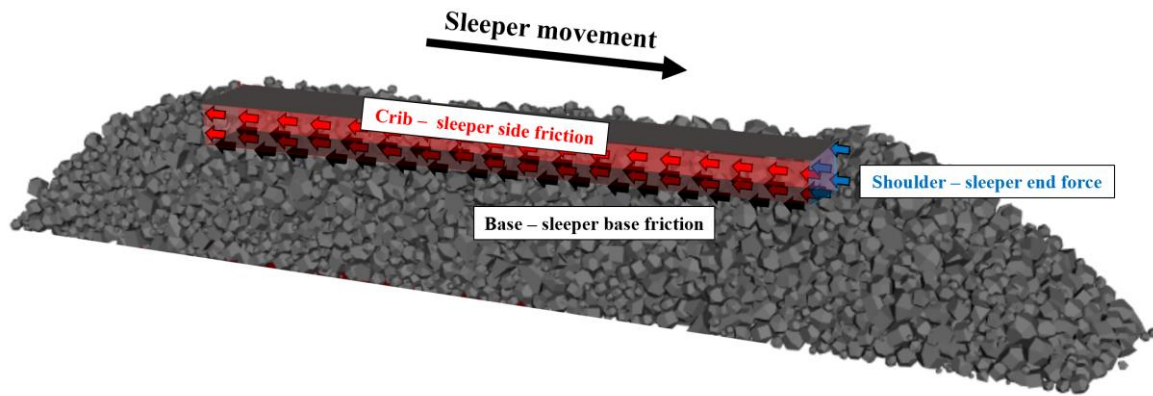
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Abstract

Track lateral stability is one of the most critical considerations for safe and reliable railway infrastructures. With increasing exposures to high temperatures globally, a greater expansion in continuous welded rails can induce higher risk of track buckling, especially when track defects exist. In ballasted track structures, ballast layer holds sleepers in place and provides lateral support and stiffness to the track. When ballast deteriorates in services, to what degree a railway track's lateral resistance is compromised has not been fully investigated. Note that the fouling conditions can be due to the accumulation of ballast breakage or outside contamination, such as subgrade intrusion or coal dust, and difficult to inspect in the field. It is evidenced that track buckling can incur even if the railway track and ballast seem to be in a good condition by visual inspection. Therefore, this paper presents a more realistic model to study Single Sleeper (Tie) Push Test (STPT) conditions using the Discrete Element Method (DEM) with the objective to evaluate ballasted track lateral resistance considering different fouling scenarios. The lateral force-displacement curves of sleepers are analysed. The lateral force is derived from the sleeper-ballast contact forces obtained from three main components: sleeper bottom friction, sleeper side friction, and sleeper end force. The fouling conditions are employed by adapting appropriate model parameters in the DEM simulations. The results indicate that fouled ballast can significantly undermine the lateral stability of ballasted tracks by more than about 50%. Track lateral stiffness may be reduced significantly due to fouled ballast layer conditions that cannot be inspected visually in the field. This may reduce track restraint and increase the likelihood of track buckling even though the degraded ballast does not have a direct contact to the sleeper. Finally, the study will enrich the development of inspection criteria for ballast lateral resistance and support conditions, improve safety and reliability of rail network, and mitigate the risk of delays due to track buckling leading to unplanned maintenance.

1. Introduction

Railway track buckling has become a serious concern due to higher than average summer temperatures observed globally and the increasing risk of track buckling noted around the world [1]. The increase in global temperatures can induce higher rail temperatures and build up the compression force in the continuous welded rail (CWR). Although CWR provides a smooth ride and has lower maintenance cost, CWR still suffers from drawbacks in which the track tends to buckle easily when the rail temperature reaches a certain limit. Many research studies have indicated that track buckling has been one of the major causes of train derailments associated with huge losses of life and assets [2, 3]. It has been found that the track components developing resistance to rail buckle are the sleeper and the supporting ballast. Lateral ballast resistance not only resists track buckling but also helps to maintain lateral track alignment which is one of the reasons for the lateral force in the rails. Ballast providing lateral resistance can be stated as the most significant factor to resist the buckling forces during the expansion of rail. Lateral resistance of ballast consists of three main components: bottom friction of sleeper, side friction of sleeper and ballast shoulder restraint, as shown in Figure 1. The resistance force is calculated from the summation of ballast-sleeper contact force in lateral plane to encounter the sleeper movement.



45

46

Figure 1. Contributions of different frictional components.

47 As evidenced in the UK and worldwide, railway track buckling can still occur even if the railway tracks
 48 are fully supported and the ballast layer seems to be in good condition by visual inspection. In fact,
 49 degraded ballast particles and the accumulation of ballast breakdown or outside contamination, such as
 50 subgrade intrusion or coal dust, often may not be seen visually [4, 5]. Their presence undoubtedly would
 51 have a negative impact on the vertical stiffness of the railway tracks and cause potential track geometry
 52 defects. No quantifiable data currently exist on the extent degraded ballast could influence the lateral
 53 stiffness of ballasted track and what percent the fine particles generated in a fouled ballast would
 54 decrease the lateral support through direct contact with the sleeper. Accordingly, there is a need to study
 55 and quantify the effect of the progressive degradation of ballast influencing lateral resistance by
 56 properly considering the contributions of the different frictional components in a ballasted track.

57 According to previous research on track buckling simulations using the Finite Element Method (FEM)
 58 [6-8], railway tracks were mostly modelled using a series of beams and springs to represent track
 59 components. The nonlinear tensionless springs of ballast have been applied at the sleeper ends to
 60 represent the actual behaviour of ballast. The elastoplastic curve of lateral resistance has been also used
 61 in modelling of track buckling. It is noted that the properties of lateral springs of ballast connected to
 62 sleepers are derived from the contact force between sleeper and ballast, and displacement of sleeper
 63 subjected to lateral load from Single Sleeper (Tie) Push Tests (STPTs) [9, 10]. This method has been
 64 proven to be the most suitable method to quantify the lateral resistance of tracks recommended by
 65 AREMA [11]. There has been much research conducted on the STPTs of sleepers to obtain the lateral
 66 resistance-displacement curve of sleepers for ballasted track. This method can measure the lateral
 67 resistance of sleeper-ballast interaction.

68 To model the STPT, researchers considered ballast layer as a continuum model represented by a
 69 homogeneous material consisting of connected uniform elements of infinitesimal size [12]. The three-
 70 dimensional FEM models were developed for sleepers embedded in the homogeneous ballast [13, 14].
 71 The friction coefficient between sleeper and ballast was then varied to study the lateral resistance of
 72 ballasted track. The results showed good trends and were reasonable. However, some of the modelling
 73 aspects, such as friction and boundary conditions, in these previous studies were mostly based on certain
 74 assumptions which made the results often questionable. Most importantly, it is a wrong assumption to
 75 treat railway ballast as a continuum due to the particulate nature of a ballast layer assembly which, in
 76 fact, consists of aggregate particles, each approximately 40-75 mm [15] in size. A more realistic
 77 numerical simulation approach has been the Discrete Element Method (DEM), which is nowadays
 78 widely used for simulating load-deformation behaviour of ballast layer granular materials. DEM for
 79 granular material was first introduced for rock and soil particles [16]. This approach is a numerical
 80 method for computing the deformations of individual particles with interactions in a granular assembly.
 81 DEM can provide insight into the micro-mechanical behaviour of railway ballast. Recent research
 82 studies have proposed to use different DEM approaches to analyse the lateral resistance of ballasted

83 track including STPT simulations and considered different types of ballast particles used as discrete
84 elements [17-21].

85 The lateral resistance of ballasted track is commonly reduced with usage due to long-term degradation,
86 maintenance activities and ballast disturbance. There are several methods that can potentially improve
87 the lateral resistance of ballasted track such as using different shapes of sleepers [20, 22], ballast gluing
88 [23], ballast reinforcement [24], and track maintenance or renewal. The effects of ballast particle shapes
89 and tamping activity on the lateral stability of ballasted track have also been studied [25]. Tamping
90 activities have been found to impact lateral resistance by loosening the compacted state of the ballast
91 layer. It is also known that angular ballast particles have higher shear resistance than rounded ones and
92 the ballast degradation is directly related to the crushed stone type aggregate source and particle
93 morphology [26]. The shapes of deteriorated ballast particles tend to become more rounded than sharp
94 cornered. The round gravel ballast can reduce the lateral resistance by about 30-35% [27].

95 Railway track is progressively degraded with usage making the improvement of ballasted track
96 necessary. Most importantly, lack of ballast support can significantly undermine the capacity of railway
97 track [28, 29]. For instance, in a track which is in poor condition, large voids and gaps can easily be
98 observed between sleepers and the ballast, usually caused by the wet track beds (highly moist ground)
99 from natural water springs or poor drainage. The strength and drainage aspects of ballasted tracks are
100 compromised due to the increasing level of ballast fouling. This leads to larger particle movement
101 resulting in more severe loss of support conditions. Since it is not clear to what extent progressive ballast
102 degradation and fouling may decrease lateral resistance of ballasted tracks, the research study described
103 in this paper was therefore intended to quantify major contributions of frictional components of a sleeper
104 on track lateral resistance through a realistic DEM modelling approach for ballast behavior.

105 This paper presents results of DEM simulations of push tests of single timber and concrete sleepers by
106 considering different levels of fouling within the ballast depth profile. The study compares the effects
107 of progressive ballast fouling conditions that start with accumulating finer particles from the bottom
108 and consider different heights all the way to the top to finally represent the full-depth fouled ballast
109 profile. Such effects of ballast condition and vulnerability influencing track lateral resistance are
110 quantified through DEM simulations. The results presented are discussed in relation to allowable
111 magnitudes of rail buckle forces that can be resisted and safe temperatures that the tracks can withstand
112 under these ballast conditions. The findings presented are intended to help track engineers to better
113 evaluate how different fouled ballast conditions can be related to performance and hence to develop
114 inspection criteria related to ballast layer maintenance and renewal associated with the level of ballast
115 degradation.

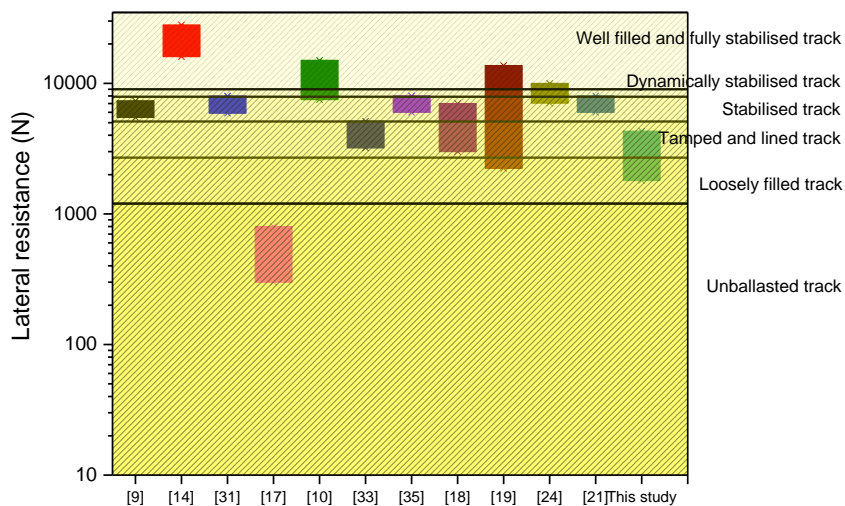
116 **2. Lateral resistance of ballasted tracks**

117 Researchers in the past have conducted both numerical and experimental studies to obtain the lateral
118 resistance of track. As for numerical, different methods have been applied for quantifying lateral
119 resistance force through FEM and DEM approaches considering different contact parameters and types
120 of particle shapes. Several parameters were assumed especially for FEM [13, 14] and DEM spherical
121 shapes [18]. In addition, spherical clump and polyhedral particles have been previously used for STPT
122 simulations in DEM [17, 19-21]. These studies mostly considered the tracks when ballast was well
123 compacted and the ballast shapes were assumed as clumps of spherical particles. Both the textured
124 sleepers [13, 17] and ladder sleepers [22] were shown to improve the lateral resistance of ballasted
125 track. Further, many researchers also studied the effects different dimensions and profiles of ballast
126 layer [19, 30]. It was found that the frictional components of the sleeper bottom and sides had a major
127 role in determining track lateral resistance. Also, widening the ballast shoulder could help increase the
128 lateral resistance. Nonetheless, only few studies using DEM focused on the effect of ballast particle
129 shape, i.e., the angularity [17]. It was found that ballast with angular aggregates provided better shear
130 resistance than ballast with round particle shapes, however, the results were not fully indicative since

131 only sleeper base friction was considered [17]. Different geometries of ballast layer were factored only
 132 for the ballast thickness and shoulder length [19].

133 Measurements for lateral resistance have been widely conducted through field experiments [9, 10, 19,
 134 20, 31-33]. Although the STPTs were carried out in both laboratory and field experiments, it was found
 135 that the lateral resistance of track in the laboratory experiments was generally less than that in the field
 136 due to the different compaction levels [32]. Note that the lateral resistance in the field tends to be larger
 137 since the tracks have been operated at some point before the tests take place. Most of the previous
 138 studies with field experiments focused on the effects of sleepers on lateral resistance of ballasted track
 139 with clean ballast. The methods of improving lateral resistance using more detailed sleeper geometries
 140 and dimensions, such as in the types of frictional sleepers, ladder sleepers, etc., were studied in the field.
 141 No doubt these different sleeper types and features could significantly improve the lateral stiffness of
 142 railway track [21, 22, 24, 34]. As for the ballast layer contribution, some kind of ballast particle gluing
 143 has been applied to railway tracks to improve the lateral stability [23, 24]. Moreover, different types of
 144 ballast materials, i.e., limestone and steel slag, with a similar gradation were also considered in the field
 145 measurements [35], and the steel slag was found to provide better lateral resistance than limestone
 146 ballast due to its higher bulk specific gravity.

147 A recent European review provided benchmarked STPT results for the lateral resistance of ballasted
 148 track during different ballast construction and in-service stages [27]. Based on this benchmarking,
 149 Figure 2 presents a comparison of the results from various STPT research studies for mono-block
 150 concrete sleepers only. The different track conditions and ballast construction and in-service stages
 151 correspond to unballasted track or lying free, loosely filled track, tamped, and lined track, dynamically
 152 stabilised track, and well filled and fully stabilised track according to [27]. The typical values of lateral
 153 resistance of ballasted track with concrete sleeper are presented at the sleeper displacement of 2 mm,
 154 which tends to be over the yielding point [27]. Note that this yielding point is when lateral stiffness is
 155 reduced after the sleeper displaces and was reported in the literature to be between 0.5 and 2 mm. The
 156 lateral contact force only has a very slight change and is likely to be constant after yielding point or
 157 elastic limit. Figure 2 indicates the lateral resistance of ballasted track to fall within the stage of loosely
 158 filled and tamped and lined track when track buckling might occur in reality.



159

160 **Figure 2 Lateral resistance of ballasted track at sleeper displacement of 2 mm with**
 161 **benchmark values [27].**

162 **3. Discrete element modelling**

163 This paper considers the cross-section of typical single ballasted track with the mono-block timber and
 164 concrete sleepers laid on ballast layer. Timber sleeper with dimensions of 250x150x2600 mm and
 165 concrete sleeper with dimensions of 260x235x2600 mm are separately constructed on top of a 300 mm
 166 thick ballast layer. The material properties and dimensions of sleepers are presented in Table 1. The
 167 physical models of the ballast layer geometry were first constructed without ballast shoulder and crib
 168 as shown in Figure 3. The dimensions of the established ballast layer model are presented with sleeper
 169 dimensions. Full width of the track is modelled with 400 mm wide ballast shoulders and a 1:1.5 shoulder
 170 slope. The longitudinal dimension of the track is 600 mm which is equal to the typical sleeper spacing.
 171 Hence, the model boundary area is set as 600 mm in length and 4600 mm in width.

172

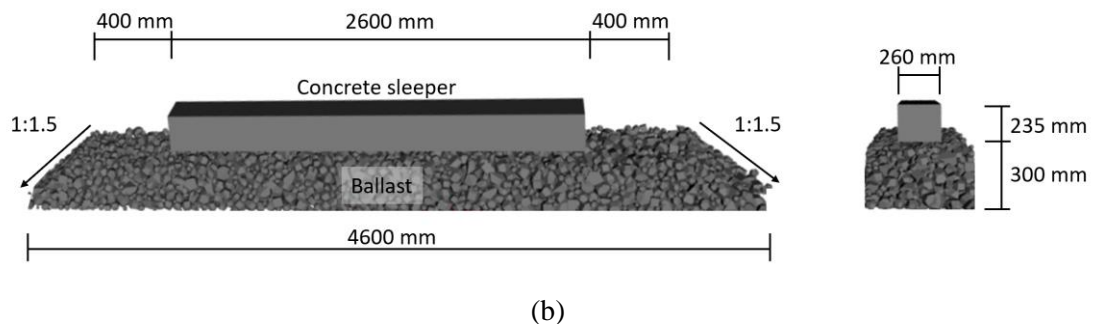
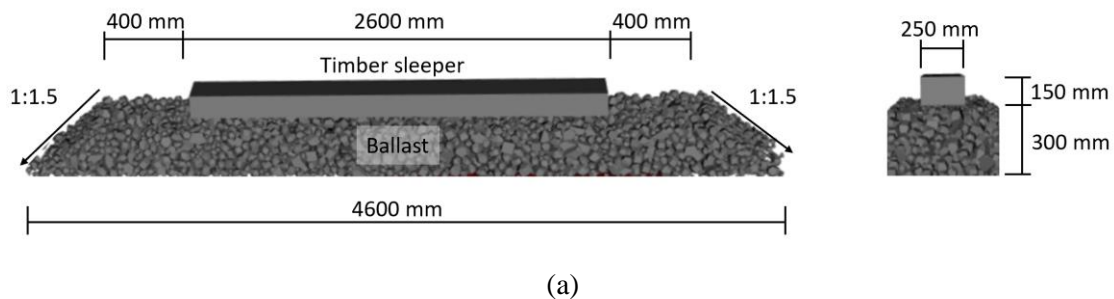
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Table 1 Sleeper characteristics.

Sleeper types		Value	Unit
Timber sleeper (Hardwood)			
Density		1100	kg/m ³
Elastic modulus		16000	MPa
Poisson's ratio		0.25	
Dimension	Length	2600	mm
	Height	150	mm
	Width	250	mm
Concrete sleeper			
Density		2740	kg/m ³
Elastic modulus		37500	MPa
Poisson's ratio		0.2	
Dimension	Length	2600	mm
	Height	260	mm
	Width	235	mm

174

175

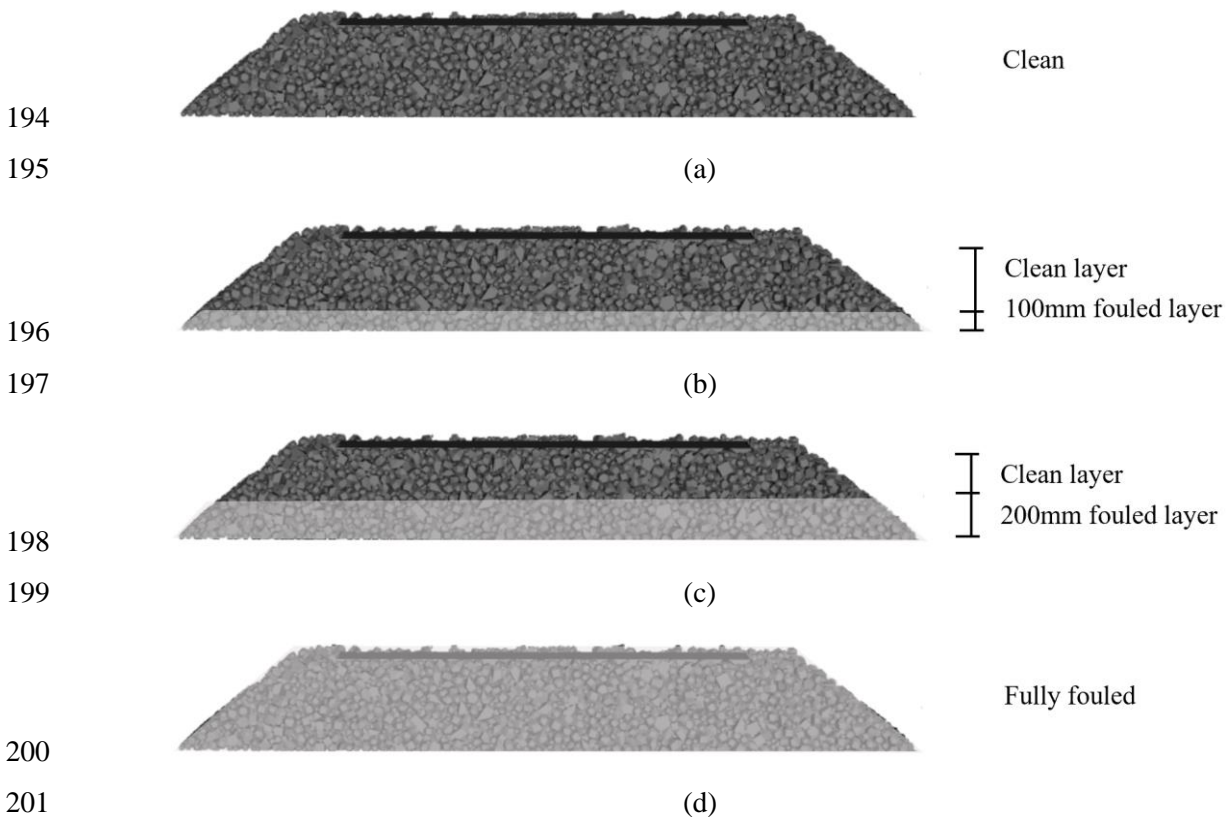


180 **Figure 3. Sleeper and ballast layer geometry studied: (a) timber sleeper, (b) concrete sleeper.**

181

182 The DEM models were then extended for sleeper with full ballast components including ballast crib
183 and shoulder. This study considers the following three ballast fouling conditions within the layer depth
184 profile: (1) 100-mm fouled layer at the bottom, (2) 200-mm fouled layer at the bottom, and (3) full-
185 depth fouled ballast layer, as shown in Figure 4. It was assumed that the breakdown of ballast material
186 due to the load from the sleeper generated ballast fines which migrates from top to bottom and starts to
187 accumulate at the bottom of the ballast layer [5]. Note that this may not be the case if soft subgrade
188 causes mud pumping and subgrade soil fines intruded may be collected and observed at any depth
189 profile in the ballast layer [36, 37]. This phenomenon is represented in the DEM simulations here with
190 the whole ballast layer fouled. The details of the progressive ballast fouling conditions with fines
191 accumulating from bottom to top, i.e. most observed ballast material breakdown, are explained in the
192 next section.

193



202 **Figure 4. Schematic view of a) clean ballast layer b) 100 mm fouled ballast layer c) 200 mm**
203 **fouled ballast layer e) fully fouled ballast layer.**

204





205 To create realistic shapes of railway ballast crushed aggregate particles, polyhedral elements need to be
206 used in ballast DEM simulations. This approach can generate non-spherical particles and potentially
207 provide better insight into interparticle contacts by properly accounting for corners and sharp edges of
208 the particles, which are essentially needed to simulate correctly dilatancy angles in angular particle
209 assemblies. In this study, the ballast shapes and their morphological properties are analysed using the
210 Enhanced University of Illinois Aggregate Image Analyzer (E-UIAIA) [38]. The E-UIAIA is the
211 imaging technology to capture the realistic 3D shapes of ballast particles from three orthogonal views
212 to quantify detailed shapes and measurements of each particle including surface texture (ST) index,

213 angularity index (AI) and flat and elongated (F&E) ratio. The ballast particles obtained by E-UIAIA
 214 were imported to BLOKS3D DEM software developed and extensively used at the University of Illinois
 215 at Urbana-Champaign in the last three decades [39, 40]. Note that AI simply presents an average of the
 216 Angularity values of all the particles weighted by the particle weight, which measures overall degree
 217 changes on the boundary of a 2D particle silhouette. The flat and elongated (F&E) ratio illustrates the
 218 ratio of the longest dimension of the particle to its shortest dimension from the three orthogonal views;
 219 for each 2D silhouette the shortest Feret dimension is perpendicular to the longest Feret dimension.

220 The shapes and geometric properties of the ballast particles used in this study are presented in Table 2.
 221 The percentages of particles and the average AI values used in this simulation are also presented. It
 222 should be noted that even though the particles are randomly generated, the ballast proportions of all
 223 cases are constantly controlled to make the DEM models consistent. The proportions and AI of each
 224 particle are calculated using the E-UIAIA to match the field-collected ballast sample database [29]. The
 225 average AI is calculated by taking a weighted average of the AI of each ballast shape, weighted by the
 226 percentage of number of particles. It should be noted that the average AI is around 430 which is
 227 considered as a low angularity value mostly representing more of round shaped particles [17]. This
 228 generally presents the ageing of railway ballast with the particles having less angularity. Moreover, air
 229 voids considered is roughly 38% of the volume of the ballast layer and thus making the ballast layer in
 230 somewhat loose condition since the expected air voids for compacted ballast should reach 35% in the
 231 field [36]. The particle distribution curve of the ballast sample studied herein is shown in Figure 5. The
 232 ballast gradation conforms to the American Railway Engineering and Maintenance-of-Way Association
 233 (AREMA) No. 24 standard specification.

234

235 **Table 2. Imaging based shape indices of ballast particles used as discrete elements in DEM**
 236 **simulations.**

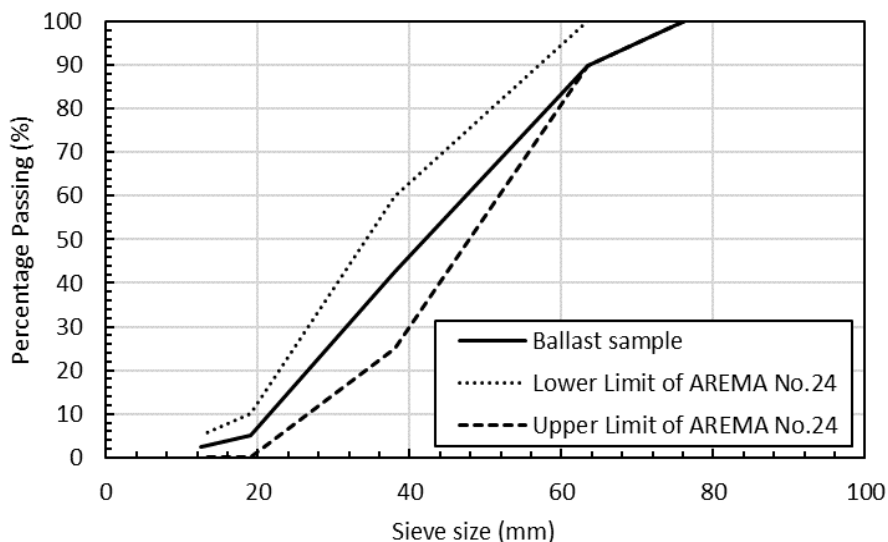
No	Ballast shape	Percentage of number of particles (%)	Angularity Index (AI)	Flat & Elongated ratio (F&E)
1		3.56	720	1:1
2		10.20	570	1:1
3		19.30	448	1:1
4		66.94	390	1:1
Average			430	1:1

237

238 The DEM model parameters consist of normal stiffness, shear stiffness and surface friction. The DEM
 239 model parameters used are presented in Table 3. Note that the model parameters used for ballast have
 240 been validated with the previous experimental results based on direct shear and triaxial tests [41].
 241 Accordingly, the surface friction angle between two individual ballast particles is set as 31 degrees.
 242 Note that these DEM model parameters in Table 3 gave good predictions when compared to the
 243 experimental results obtained in the laboratory [36]. In terms of contact between sleeper and ballast, the
 244 surface friction angles for both timber and concrete sleepers to ballast are assumed equally to be 30
 245 degrees, which is a value obtained previously for contact between concrete sleeper and ballast. It should
 246 be noted that the surfaces of concrete sleepers are relatively smooth in comparison to timber sleepers.
 247 This may slightly affect the results on the contact between sleeper bottom and ballast. However, the

248 effect is probably negligible since the total lateral resistance increases by about 5% when the surface
 249 friction angle increases from 30 to 40 degrees. Accordingly, the surface friction angle of 30 degrees is
 250 used in this study for both the timber and concrete sleeper cases.

251



252

253 **Figure 5. Ballast particle size distribution conforming to AREMA No. 24 standard ballast**
 254 **specification.**

255

256

Table 3 DEM ballast layer simulation model parameters.

Parameters	Value	Unit
Normal stiffness	20	MN/m
Shear stiffness	10	MN/m
Surface friction angle (for clean layer)	31	°
Surface friction angle (for fouled layer)	27	°
Global damping	0	
Contact damping	0.4	

257

258 For the ballast layer preparation, 5 infinite planes, consisting of bottom, left, right, front, and back, are
 259 first built to create the global boundary area to prevent the ballast particles going through. Then, inclined
 260 rigid blocks are used to provide the layer features and dimensions (shown in Figure 3) for the
 261 constructed ballast with the indicated shoulder slope. For the clean ballast, approximately 12,805 ballast
 262 particles are generated and randomly dropped into the boundary area to generate the ballast layer. The
 263 particles above the target height are removed and the non-deformable compaction plate is then pushed
 264 downward on top of the particles applying the normal pressure of 100kN to compact the ballast layer
 265 until it reaches the target void ratio and no particle movement observed. Sleeper, which is modelled as
 266 a non-deformable master block, is applied on top of the ballast layer. It should be noted that the flexural
 267 behaviour of the sleeper is not considered so that the non-deformable master block can be properly
 268 considered in this study. Two types of sleepers (concrete and timber) are considered.

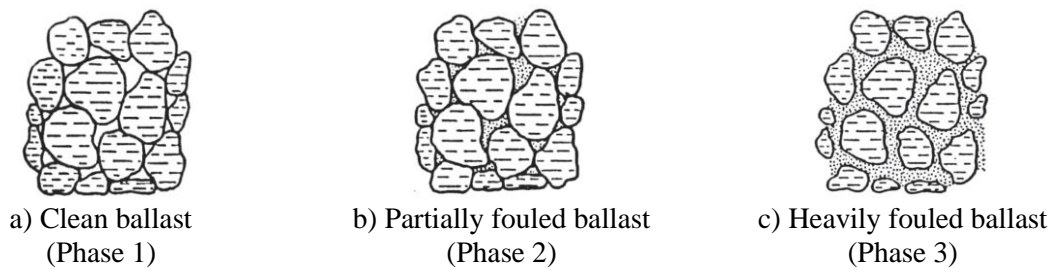
269 Next, the STPT test is conducted first for ballasted track with no ballast shoulder and crib. As for the
 270 layer with ballast crib and shoulder, more ballast particles are added later to generate ballast shoulder
 271 and crib. It is noted that the ballast is randomly dropped so that the ballast particles, which have the

272 centroid over the depth of sleeper, are removed. Thus, ballast crib and shoulder height are set as a depth
273 of sleeper. Also, the height of ballast shoulder above the sleeper top does not play a significant role in
274 influencing the lateral resistance as evidenced in previous studies [14, 31]. After layer preparation, a
275 transverse velocity of 0.5 mm/s is applied to the sleeper. The sleeper is displaced laterally for about 3
276 mm. It should be noted that after reaching this point, the slope of force-displacement representing lateral
277 stiffness is almost constant. The resistance forces are calculated from the total contact force between
278 sleeper and ballast against the movement of sleeper combining three different locations: sleeper bottom,
279 sleeper crib, and sleeper end force.

280 **Ballast fouling mechanism**

281 Generally, ballast is progressively fouled over time as the voids among particles are filled with finer
282 materials. The major source of ballast fouling is ballast breakdown, which is about 76% of all sources
283 as found in North America [42]. Other sources are infiltration from underlying layers and ballast surface
284 which make up 13% and 7%, respectively. They are followed by subgrade intrusion (3%) and sleeper
285 wear (1%) [42]. Ballast fouling has been emphasized to greatly undermine the stability and strength of
286 railway track by many researchers [36, 43]. Further, ballast fouling may cause drainage issues in
287 ballasted track since the voids are filled up and water is blocked, leading to higher levels of moisture
288 accumulating in the track substructure [44]. Figure 6 presents the ballast fouling phases and their
289 mechanisms. Phase 1 presents clean ballast where each particle is in contact with others. Since there
290 are voids between particles, finer materials easily fill those voids. The contacts between particles are
291 still maintained while the contact strength can be reduced significantly. In phase 3, the ballast is heavily
292 fouled leading to the elimination of particle contact. Note that many of the ballast particles shown in
293 Figure 6 phase 3 are not as large as in the case of clean new ballast composition due to the significant
294 breakdown and the movement of each particle is constrained by finer materials filling the voids. In this
295 situation, the ballast undoubtedly requires improvement and maintenance. This normally happens when
296 the percentage of fouling particles in the ballast layer is higher than 50% [45].

297



298

Figure 6. Critical ballast fouling phases [46].

299

300 According to the previous experiments [46], three types of fine materials: coal dust, plastic clayey soil
301 and mineral filler were added to the dry and wet ballast conditions. Coal dust was chosen as the fouling
302 agent due to being commonly found in coal lines with its poor mechanical properties and it was reported
303 to cause the most significant decreases in aggregate assembly strength compared to other fouling agents
304 [41].

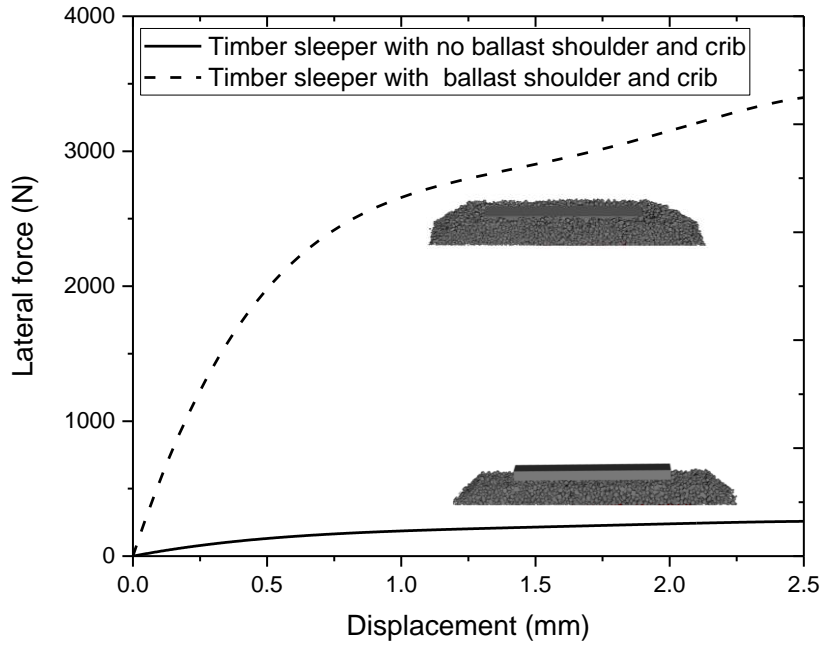
305 In DEM simulations, there are two approaches to represent the fouled ballast conditions. The direct
306 approach is used to apply the new size distribution of fouled ballast so that more particles are
307 represented. This approach may take longer computational time and larger memory consumption due
308 to the larger number of particles included in DEM simulations. Another approach is to assume fouled
309 ballast will still have large aggregate particles contacting each other, such as in the case of new ballast

310 gradation, but individual particles having much lower surface friction angles, which is adopted here as
311 the modified DEM model parameter. This approach is based on previous experiments using coal dust
312 as a fine material in direct shear tests [41]. It is noted that the coal dust acts as a lubricant which can
313 reduce the friction between particles and assigning a lower surface friction angle between two discrete
314 ballast particles/elements in contact, which is the approach adopted herein for DEM simulations. This
315 method still allows dealing with new ballast type uniform gradations having much fewer particles than
316 for degraded ballast particle size distributions and provides better simulation time. However, this is
317 based on the assumption that the void ratio and compaction characteristics are completely similar in
318 both clean and fouled ballast conditions while, in fact, when ballast layer is fouled, the void volume
319 must be reduced [36].

320 For the fouled ballast DEM simulations shown in Figure 4b, 4c, and 4d, the surface friction angle is
321 reduced to 27 degrees in the fouled layer to match the laboratory results for fouled ballast in case of
322 15% dry coal dust fouling as resulted in [41]. The normal and shear contact stiffness values are kept the
323 same based on the assumption that the coal dust does not greatly affect the contact stiffness. As for the
324 simulation approaches for partially fouled conditions, the ballast layer can be divided into two layers:
325 fouled and clean layers. The fouled ballast particles with a surface friction angle of 27 degrees are firstly
326 dropped in the boundary area. The particles over the target of fouling level are then removed to generate
327 an exact depth of fouled ballast layer. After that, the second layer, which represents the clean ballast
328 layer, is made by dropping the particles with a surface friction angle of 31 degrees. These cases represent
329 the partially fouled conditions where fine aggregates are accumulated at the bottom layer. Lastly, the
330 completely fouled condition is taken into consideration by reducing the surface friction angle on the
331 whole ballast layer (see Figure 4d). The simulation approaches of this case are like that for completely
332 clean layer but with a surface friction angle of 27 degrees.

333 **4. Results and Discussion**

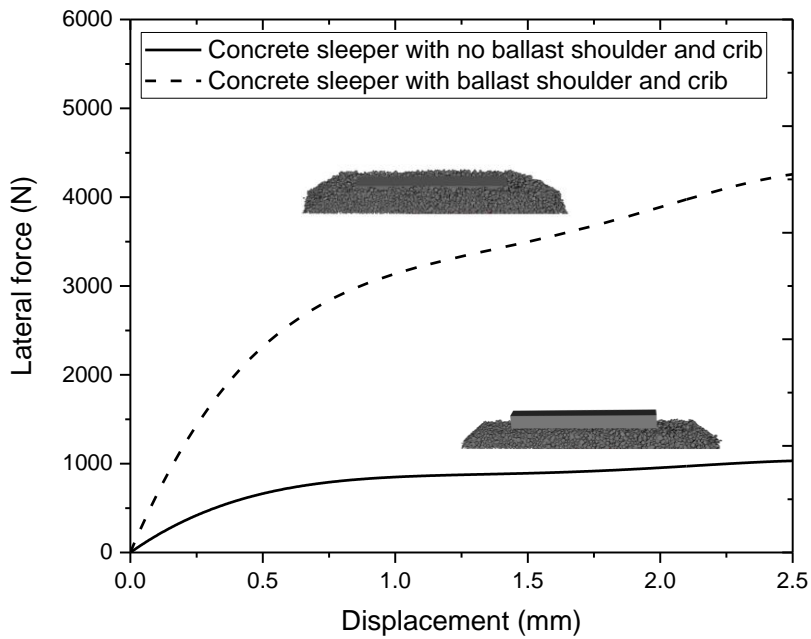
334 The lateral resistance of ballasted track with timber and concrete sleepers are shown in Figures 7 and 8,
335 respectively. The lateral force is computed by the summation of contact forces between sleeper and
336 ballast in transverse direction. It should be noted that the raw data results have been smoothed using
337 an adjacent-averaging method to remove the spikes from signals. It is well known that adding ballast
338 shoulder and crib can significantly increase lateral resistance of ballasted tracks with both timber and
339 concrete sleepers. A similar trend of lateral force-displacement of sleepers can be found in both timber
340 and concrete sleepers. The slope of this curve presents the lateral stiffness of ballasted track due to
341 sleeper-ballast contact. It is noted that the curves are likely to be bilinear which can be fit to the original
342 ones. The lateral resistance increases as the sleeper displacement increases until reaching a certain value
343 or displacement limit. At that certain point, sleeper displacement yields, and lateral stiffness tends to be
344 reduced. From the results presented in Figure 8, the lateral force at 2mm concrete sleeper displacement
345 is about 3.8kN. According to the benchmarking models [27], it implies that the lateral resistance of
346 concrete sleeper cases in this study matches well and falls within the loosely filled (lateral resistance <
347 2.5kN) and tamped stages (lateral resistance < 5.1kN) as expected in this study. This value is lower for
348 timber sleeper to be just above 3 kN (see Figure 7).



349

350

Figure 7. Lateral force - displacement graph for timber sleeper.



351

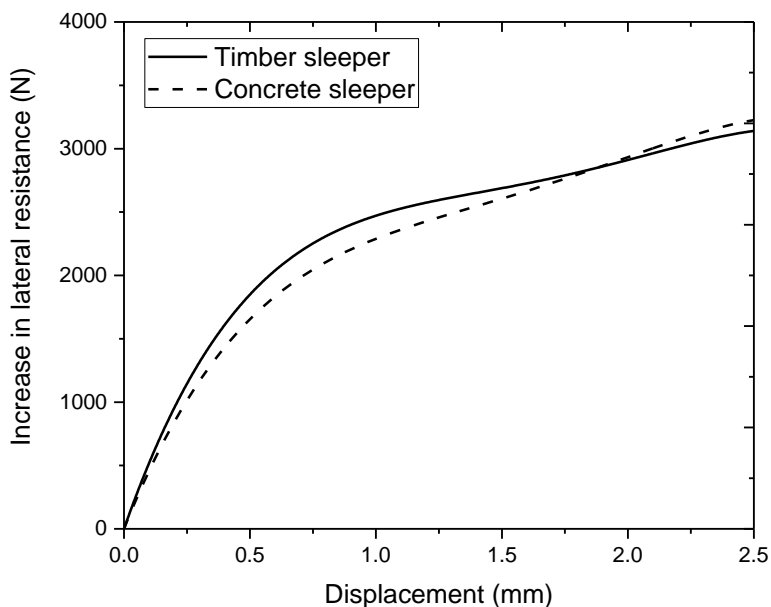
352

Figure 8. Lateral force - displacement graph for concrete sleeper.

353

354 The increases in lateral resistance after the addition of ballast shoulder and crib are presented for timber
 355 and concrete sleepers in Figure 9. This indicates that adding a ballast shoulder and crib can significantly
 356 increase the lateral resistance even though the sleeper displacement has reached a certain yield point.
 357 After this certain sleeper displacement, the ballast and crib can still improve the lateral resistance of

358 ballasted track but in lower rate. The lateral stiffness after this yield point depends on the ballast
 359 shoulder and crib properties. However, the results for both timber and concrete sleepers tend to be
 360 similar in magnitudes with a slight difference which may be due to the effect of surface friction angles
 361 that are assumed to be the same for both cases.



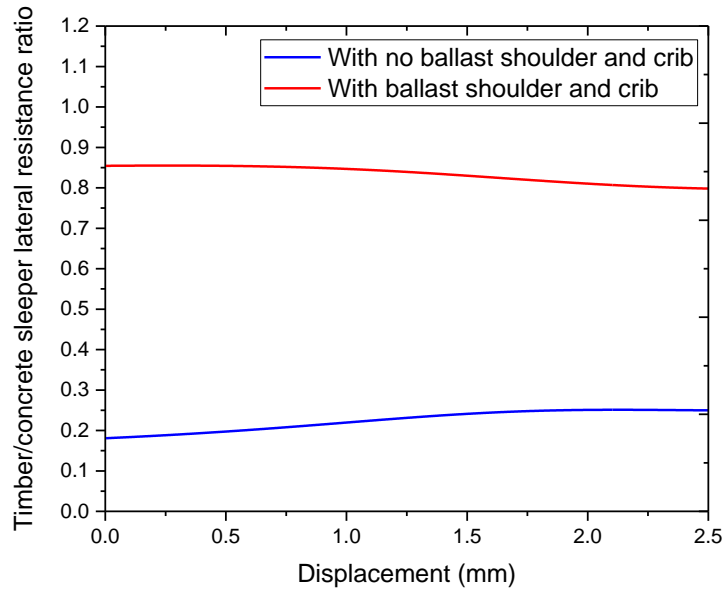
362
 363 **Figure 9. Increase in lateral resistance after adding ballast shoulder and crib.**

364
 365 The lateral resistance ratio over sleeper displacement of timber sleeper to concrete sleeper is presented
 366 in Figure 10. It is shown that, as for ballasted track with no ballast shoulder and crib, lateral resistance
 367 of ballasted tracks with timber sleepers is about 20-30% of that of tracks with concrete sleepers as the
 368 sleeper weight and shape are changed. It is noted that this is directly related to the weight and shape of
 369 a sleeper. While the ratio of lateral resistance of ballasted track with ballast shoulder and crib is between
 370 0.80-0.85. This is because the sleeper side friction and ballast shoulder also help to increase the lateral
 371 resistance and these parts are not influenced by sleeper weight.

372 The lateral resistance values of ballasted tracks under fouled conditions are presented for timber and
 373 concrete sleepers in Figures 11 and 12, respectively. The displacement limit, which is also known as
 374 the yield point, is established between 0.5mm and 1mm. It is observed that the lateral resistance is
 375 gradually reduced when the fouled layer becomes thicker and the ballast fouling tends to reduce not
 376 only lateral resistance but also the lateral initial stiffness. The initial stiffness is decreased as the fouled
 377 ballast thickness is increased.

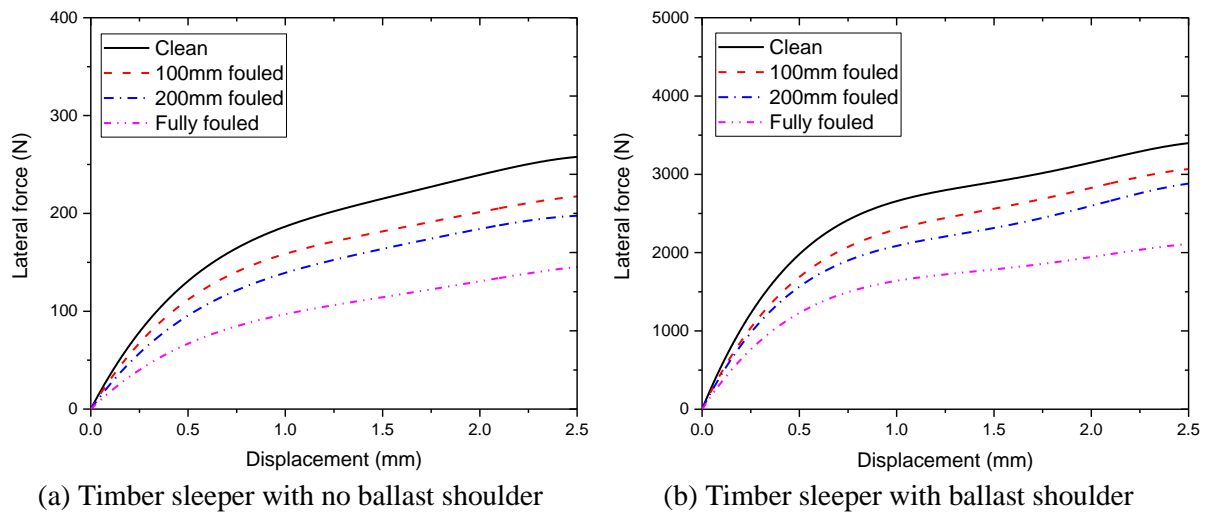
378 The reduction of lateral resistance of ballasted tracks are presented in Figure 13. This reduction of lateral
 379 resistance is calculated based on the difference between the lateral resistance of track with clean ballast
 380 and that with different fouled ballast layers ($\frac{R_{clean}-R_{fouled}}{R_{clean}} \times 100$, where R is the resistance). Note that
 381 the resistance is measured when the sleeper displaces by 2mm. The thicker the layer of fouled ballast,
 382 the lower is the lateral resistance. For the timber sleeper, the reduction rates are 13-15%, 21-25%, and
 383 38-48% for tracks with the fouled ballast thicknesses of 100mm, 200mm, and 300mm, respectively.
 384 While the reduction rates of tracks with concrete sleepers tend to be higher than timber sleepers since
 385 17-21%, 23-38%, and 39-64% reductions are observed for tracks for the fouled ballast thicknesses of

386 100mm, 200mm, and 300mm, respectively. Tracks without a ballast shoulder and crib are likely to be
 387 more sensitive since reduction rates in lateral resistance will be higher than those with ballast shoulder
 388 and crib.



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Figure 10. Timber/concrete sleeper lateral resistance ratio.

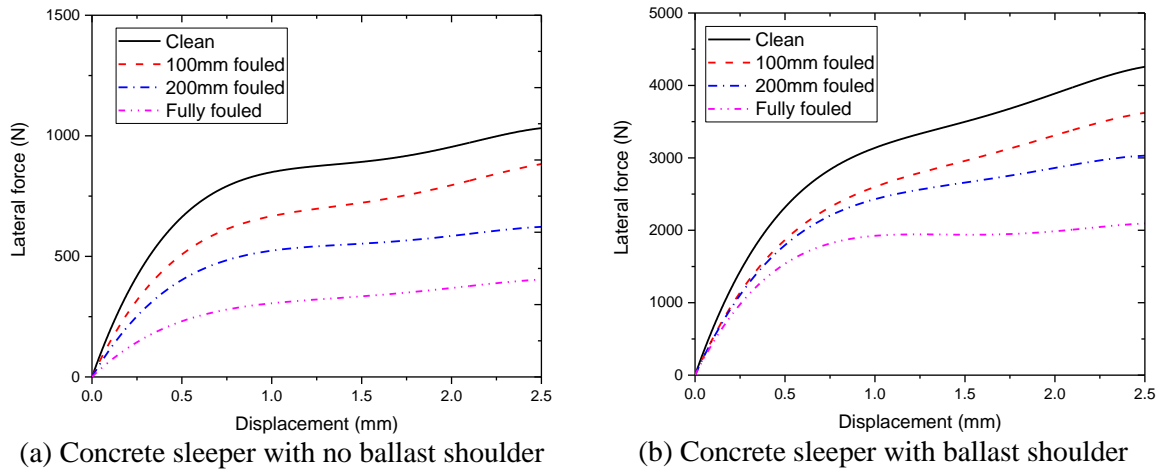


(a) Timber sleeper with no ballast shoulder

(b) Timber sleeper with ballast shoulder

393
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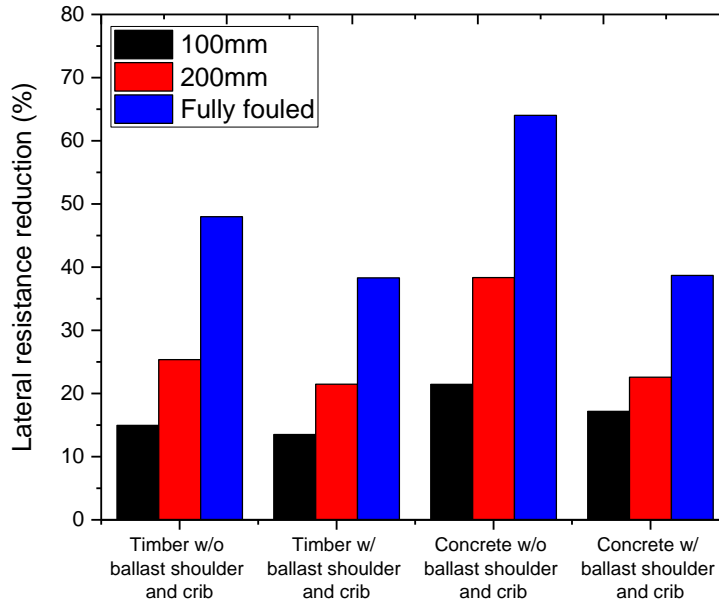
Figure 11. Lateral force - displacement graph for timber sleeper considering fouled ballast.



395 **Figure 12. Lateral force – displacement graph for concrete sleeper considering fouled ballast.**

396

397



398 **Figure 13. Lateral resistance reduction due to ballast fouling.**

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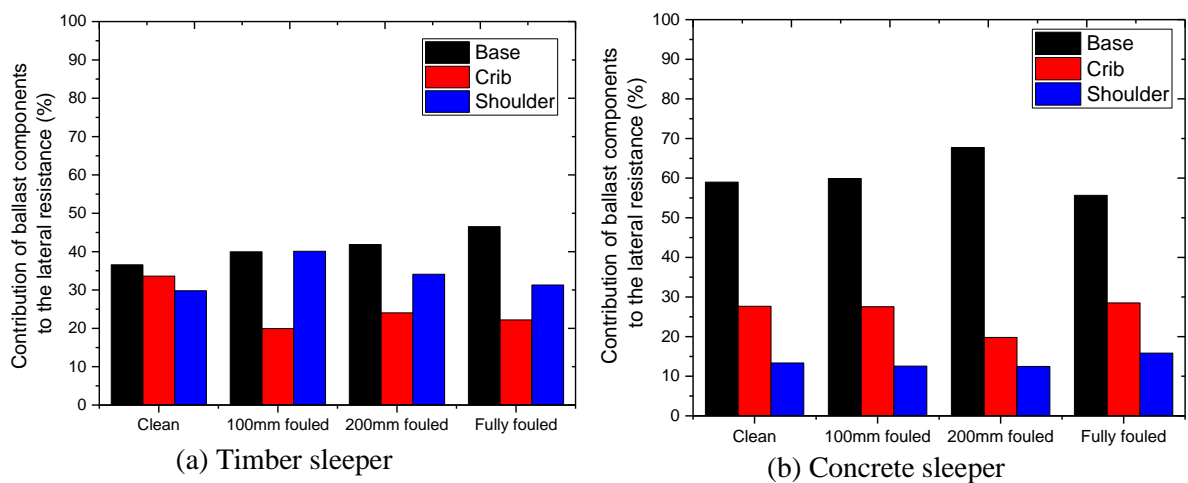
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401

402 Figure 14 presents the lateral resistance contribution of each frictional component. The results are
 403 derived from the case when sleeper is placed on ballast bed with ballast crib and ballast shoulder. Note
 404 that the contributions are provided by sleeper base, ballast crib, and ballast shoulder as previously
 405 presented in Figure 4 and they are calculated from the percentage ratio of the component resistance to
 406 the total resistance ($\frac{R_{component}}{R_{total}} \times 100$). In Figure 14, the contributions were computed when the
 407 displacement of the sleeper was equal to 2mm. As for the timber sleeper, the percentage ratios are 37-
 408 47% for the sleeper base, 20-34% for the ballast crib and 30-40% for the ballast shoulder. Whereas the
 409 sleeper base plays a higher percent contribution for ballasted track with the concrete sleeper and the
 410 percentage ratios are 56-68% for the sleeper base, 20-28% for the ballast crib and 12-16% for the ballast
 411 shoulder. This is because the concrete sleeper has a greater weight and larger dimensions resulting in

411 higher normal forces and frictional resistance at the base contact area. It is also noticeable that ballast
 412 crib of concrete sleeper case has a bigger contribution in lateral resistance than the ballast shoulder
 413 while it is less for the timber sleeper case. These results match well with the previous studies on the
 414 lateral resistance of ballasted track with concrete sleeper. Note that the boundary area in longitudinal
 415 direction of the rail was set as 600mm for both the timber and concrete sleeper cases. This slightly
 416 affects the number of ballast particles in the crib area as the number of ballast particles in contact with
 417 the concrete sleeper are probably fewer than that for the timber sleeper case due to the larger width of
 418 concrete sleeper. In accordance, the sleeper spacing also plays a role in the lateral resistance as it
 419 changes the contact with particles in crib ballast. Reducing the sleeper spacing can increase the lateral
 420 resistance due to ballast crib. In conclusion, the lateral resistance contributions provided by ballast in
 421 the crib and shoulder mainly depend on the ballast layer geometry and number of ballast particles in
 422 contact.

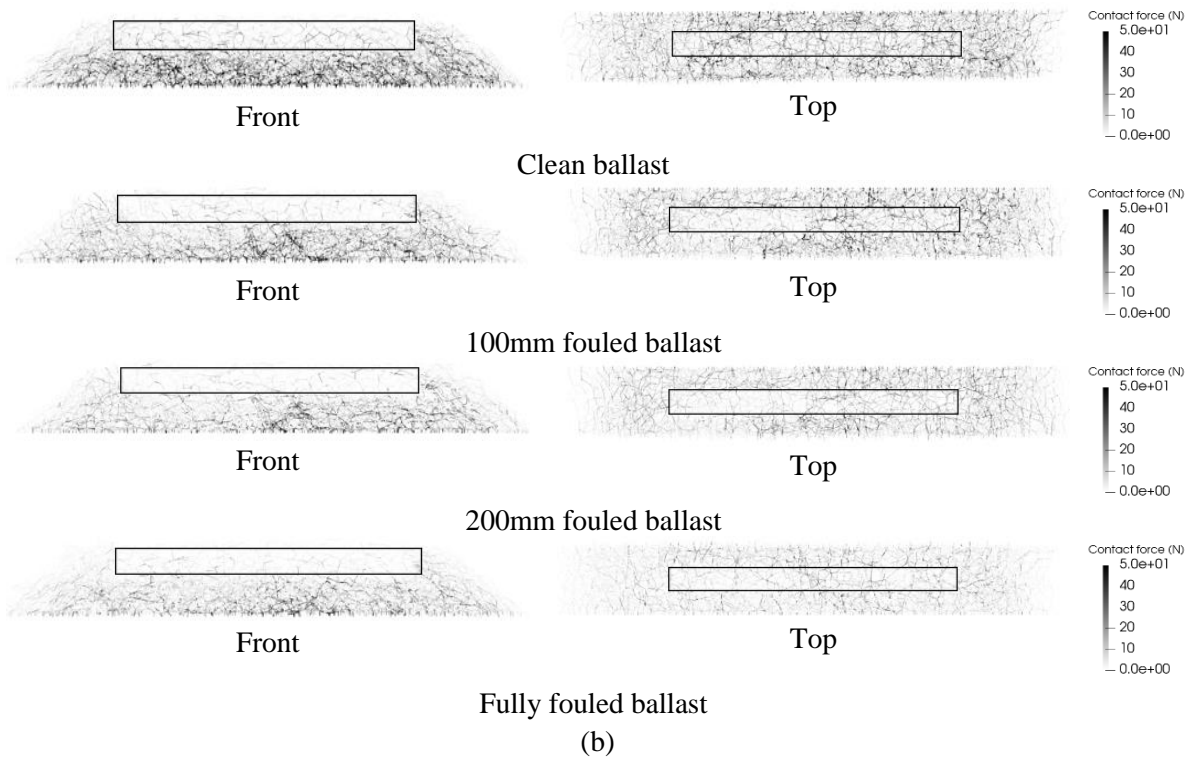
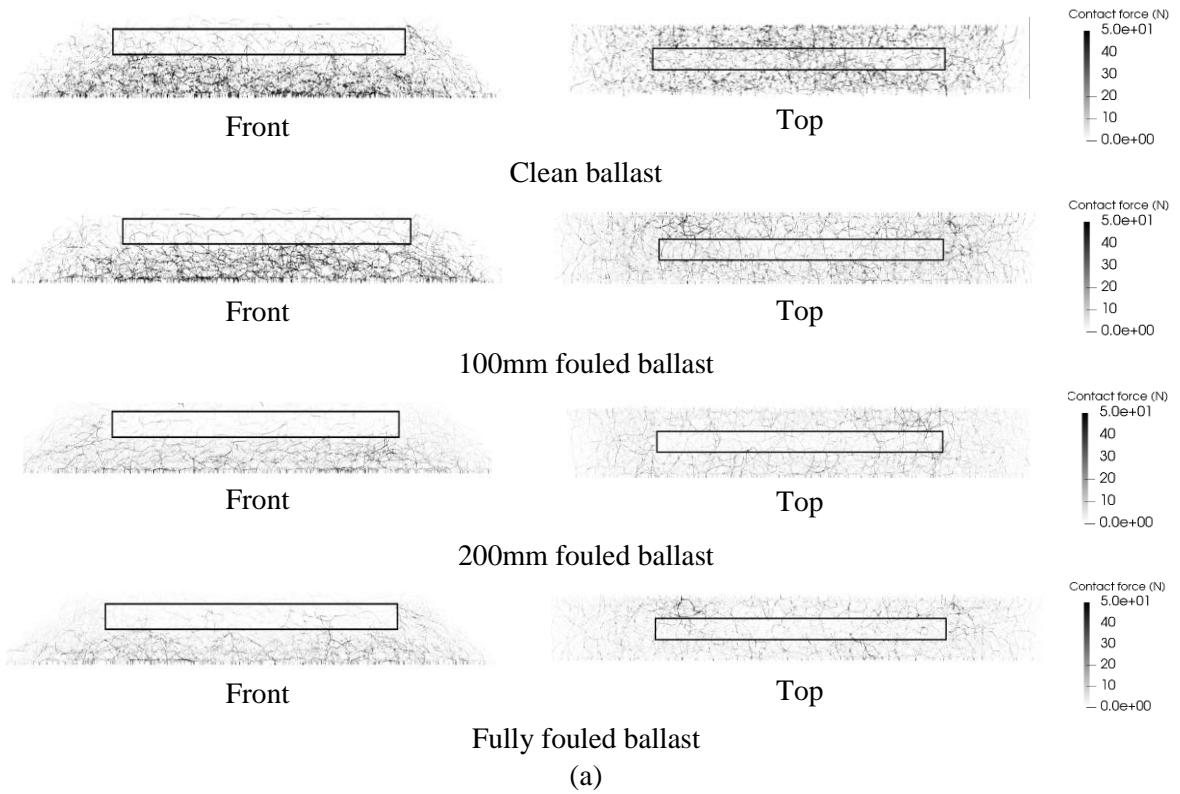
423



424 **Figure 14. Contributions of different frictional components.**

425

426 Figure 15 presents contact force distributions illustrating the force chains in the ballast layer of tracks
 427 and visualised for the different fouling conditions when the lateral displacement of sleeper reaches
 428 2mm. The ballast layer contact forces are shown for the full longitudinal width of the ballast with no
 429 concern about ballast particles in the front obstructing the view of the ballast particles in the back. In
 430 this figure, the sleeper is pushed from left to the right. The darker and thicker areas represent the larger
 431 contact forces between particles while the lighter areas represent lesser ballast particle contact force. It
 432 should be noted that the larger contact force areas result in better support condition or resistance while
 433 the lighter areas represent insufficient support or poor resistance. In accordance, for all the cases
 434 analysed, the larger ballast contact forces are generated at the bottom of sleeper and near sleeper end
 435 while the ballast around crib area has less contact forces in comparison to ballast below the sleeper and
 436 ballast shoulder. The contact force chain intensities for the track with the timber sleeper, however, the
 437 contact forces are generally less than those for the concrete sleeper. Also, the clean ballast case has the
 438 highest contact forces between ballast particles and is followed by 100mm fouled, 200mm fouled and
 439 fully fouled, respectively, due to sleeper movement. This trend can be seen in a similar fashion for both
 440 the timber and concrete sleeper cases. In other words, the more severe are the fouling conditions, the
 441 lesser are the contact forces, and the ballast particles provide relatively lower lateral resistance for the
 442 sleeper movement. In summary, when ballast is degraded and fouling starts to accumulate from bottom
 443 up, the ballast support becomes much less sufficient to provide the needed lateral restraint to arrest the
 444 movement of sleeper.



447 **Figure 15. Contact force chains of ballast layer with different conditions: (a) timber sleeper and**
 448 **(b) concrete sleeper.**

449

450 **5. Conclusions**

451 This study focused on conducting ballasted track numerical simulations using the Discrete Element
452 Method (DEM) to study Single Sleeper (Tie) Push Tests (STPTs), which essentially are performed in
453 the field to quantify track lateral resistance associated with new clean and degraded (or fouled) ballast
454 conditions. The result of ballast breakdown and fouling with usage on track lateral vulnerability has not
455 been fully investigated in the past. Previous studies which considered coal dust filling the voids of new
456 ballast layers could be modelled successfully in DEM simulations by adjusting the surface friction angle
457 related to the ballast particle contacts. In a similar fashion, the fouled ballast layer conditions were
458 created by adopting DEM model parameters, which have been calibrated previously against the direct
459 shear and triaxial tests, to indicate each particle interaction has less friction when ballast layer is fouled.

460 In the DEM simulations of STPTs in this study, fouling was considered to start from the bottom of the
461 ballast layer in different zones and was applied all the way to the top to represent the completely fouled
462 ballast layer condition. Both timber and concrete sleepers were considered with proper weights and
463 geometries in the simulations. Note that the sleeper base plays a significant role in lateral resistance
464 especially for heavier and larger concrete sleepers.

465 The DEM simulation results in general matched well with findings from previous studies; ballast bed
466 and crib had more contribution than ballast shoulder for concrete sleeper. However, for timber sleeper,
467 ballast shoulder had higher influence than ballast crib due to the smaller width of sleeper. The DEM
468 simulation results showed that ballast fouling significantly reduced the lateral resistance of ballasted
469 track by up to about 48% for timber sleepers and 64% for concrete sleepers. In accordance, a depth
470 profile fouling investigation of the ballast layer is therefore very important as ballast fouling conditions,
471 often unseen or noticed from the ballast surface, can undermine the lateral stability of railway track.
472 This may shift the buckling failure mode from snap-through to progressive buckling, due to the
473 reduction in lateral resistance in the same track profile, and increase the risk of track buckling. The
474 results can be used further for the full track buckling analysis to potentially evaluate the buckling
475 temperature and phenomena of railway track under these conditions. The insights will enhance the
476 inspection of lateral stiffness in railway systems and mitigate the risk of delays due to unplanned
477 maintenance, thus paving a robust pathway for improved safety and a practical impact on societies.

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482 and advanced sensing in extreme environments (www.risen2rail.eu) [47].

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