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# Transportation Geotechnics

## Large-scale Testing Facility for Heavy Haul Track

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<b>Abstract:</b>	<p>Given the substantially increased demand for increased axle loads of heavy haul trains, there is an imperative need to develop sustainable track infrastructure. When subjected to heavy axle loading, ballast aggregates rapidly break down, compromising the particle friction and associated load bearing capacity. Therefore, understanding the deformation and degradation (breakage) of ballast subjected to various boundary and loading conditions is crucial for improved track design and performance monitoring. Ideally, field testing should be carried out in real-life tracks to avoid laboratory scale and boundary effects, but field tests are often expensive, time-consuming and may disrupt rail traffic, hence not always feasible. A prototype test facility that can simulate appropriate axle loading and boundary conditions for standard gauge heavy haul tracks is presented in this paper. In collaboration with more than a dozen Universities and Industry organisations, Australia's first and only National Facility for Heavy-haul Railroad Testing (NFHRT) has recently been constructed and is now fully operational. This new facility enables a real-size (1:1 scale) instrumented track section to be subjected to continuous cyclic loading simulated via two pairs of dynamic actuators in synchronized operation. The results of a typical test are presented in this paper including the measured track settlement and lateral deformation, transient vertical and lateral stresses, rail and sleeper accelerations, resilient modulus and breakage of ballast. The test results show that an average track settlement of about 14 mm and lateral displacements up to 9 mm are recorded after 500,000 load cycles. Subjected to a 25-tonne axle load, the maximum vertical stress measured at the sleeper-ballast interface is about 225 kPa and this attenuates with depth. The test results of this iconic facility are generally consistent with actual field measurements obtained in heavy-haul tracks located in the towns of Singleton and Bulli in the state of New South Wales, Australia.</p>
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**Declaration of interests**

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:



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Dear Editor,

Enclosed herewith is a re-revised manuscript of the above technical paper for your consideration publishing in the Transportation Geotechnics.

Yours Sincerely,

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# Large-scale Testing Facility for Heavy Haul Track

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**Abstract:** Given the substantially increased demand for increased axle loads of heavy haul trains, there is an imperative need to develop sustainable track infrastructure. When subjected to heavy axle loading, ballast aggregates rapidly break down, compromising the particle friction and associated load bearing capacity. Therefore, understanding the deformation and degradation (breakage) of ballast subjected to various boundary and loading conditions is crucial for improved track design and performance monitoring. Ideally, field testing should be carried out in real-life tracks to avoid laboratory scale and boundary effects, but field tests are often expensive, time-consuming and may disrupt rail traffic, hence not always feasible. A prototype test facility that can simulate appropriate axle loading and boundary conditions for standard gauge heavy haul tracks is presented in this paper. In collaboration with more than a dozen Universities and Industry organisations, Australia's first and only National Facility for Heavy-haul Railroad Testing (NFHRT) has recently been constructed and is now fully operational. This new facility enables a real-size (1:1 scale) instrumented track section to be subjected to continuous cyclic loading simulated via two pairs of dynamic actuators in synchronized operation. The results of a typical test are presented in this paper including the measured track settlement and lateral deformation, transient vertical and lateral stresses, rail and sleeper accelerations, resilient modulus and breakage of ballast. The test results show that an average track settlement of about 14 mm and lateral

39 displacements up to 9 mm are recorded after 500,000 load cycles. Subjected to a 25-tonne axle load,  
40 the maximum vertical stress measured at the sleeper-ballast interface is about 225 kPa and this  
41 attenuates with depth. The test results of this iconic facility are generally consistent with actual field  
42 measurements obtained in heavy-haul tracks located in the towns of Singleton and Bulli in the state of  
43 New South Wales, Australia.

44 *Keywords: Ballast, Rail geotechnics, Heavy hauls, Breakage, Prototype test*

45

## 46 **1. Introduction**

47 The current track infrastructure in various parts of Australia cannot sustain the increasing demand to  
48 transport freight to and from ports in regional and rural areas. This growth in demand for faster and  
49 heavier trains leads to an increase in the frequency and load intensity on track substructure. As a result,  
50 ballasted tracks settle differentially, particularly on weak subgrades with poor drainage, they become  
51 fouled due to clay pumping and ballast breakage, and the rail tracks buckle due to insufficient confining  
52 pressures from the shoulder ballast aggregates (Suiker and Borst 2003, Zhai *et al.* 2004, Indraratna *et*  
53 *al.* 2016, 2020a, Sayeed and Shahin 2017, Sol-Sánchez *et al.* 2020, Powrie *et al.* 2019, Guo *et al.* 2020).

54 Upon repeated train loading, fouling of tracks occurs along with ballast degradation. Fouling agents  
55 could decrease the shear strength of ballast and reduce the drainage capacity of ballasted track  
56 (Indraratna *et al.* 2011, Touqan *et al.* 2020). Huang *et al.* (2009) studied track problems associated with  
57 fouling issues in Wyoming, US and found that coal dust was the worst fouling agent for its impact on  
58 track substructure and roadbed. When the coal dust fouling percentage increased, the ballast shear  
59 strength steadily decreased. In particular, wet fouling was found to exacerbate this trend. Bian *et al.*  
60 (2017) investigated track problems related to the hanging of sleepers and showed that a hanging tie  
61 would lead to an increase in dynamic impact loading on the ballast and therefore further deteriorate the  
62 track substructure. Another track problem receiving increasing attention worldwide is associated with  
63 the transition zones between a ballasted track and a concrete bridge deck leading to enhanced dynamic  
64 load, differential settlement and accelerated track degradation (Hu *et al.* 2019, Mishra *et al.* 2014,  
65 Paixão *et al.* 2016).

66 Previous research carried out worldwide over the past decades has shown that ballast breaks down and  
67 progressively deteriorates under freight train loading. Over the years, heavy trains and faster passenger

68 services have caused progressive deterioration of ballast which in turn results in loss of track geometry;  
69 this compromises safety and leads to more frequent maintenance (Selig and Waters 1994, Priest *et al.*  
70 2010, Esveld 2014, Bian *et al.* 2020). In response, Australian railway companies are now emphasising  
71 on high-speed train corridors (5 routes across NSW) and heavier freight operations (Brisbane-  
72 Melbourne Inland rail) to achieve more efficient and cost effective services, particularly in the mining  
73 and agricultural sectors. One of the major challenges in delivering heavier and faster trains in Australia  
74 is not the immediate cost, but the geotechnical problems associated with poor ground conditions and  
75 soft coastal terrain (Budiono *et al.* 2004, Powrie *et al.* 2007, Sayeed and Shahin 2016, Indraratna and  
76 Ngo 2018).

77 The geotechnical challenges surrounding the performance of heavy hauls and high-speed trains on  
78 ballasted railway tracks are numerous, particularly when a track profile is built along the coastal areas  
79 of Australia (Indraratna *et al.* 2018a, Cai *et al.* 2020). Typical problems that arise in track substructure  
80 include: (i) ballast breakage; (ii) mud pumping in railway tracks constructed on clays and other soft  
81 soils (Indraratna *et al.* 2020b), consisting of the upward migration of subgrade clays and fine silts  
82 (slurry) under heavy traffic loading, which promotes settlement by “lubrication” and increases the risk  
83 of train derailment (Wang *et al.* 2020); (iii) ballast fouling due to voids in aggregates filled with  
84 relatively finer materials or fouling agents that reduce the shear strength and lead to poor drainage  
85 (Huang *et al.* 2009, Li *et al.* 2015, Touqan *et al.* 2020); and (iv) differential settlement and shear failure  
86 that may occur on tracks built on highly compressible soft clays residing in low lying terrain, and with  
87 very low undrained shear strength.

88 With this increasing demand for freight trains in Australia, it would be inappropriate to operate heavy  
89 hauls on ballasted tracks built on formation soils without testing on large-scale sections of prototype  
90 model track. Since existing Australian railway design practices are mainly based on static loading  
91 conditions, they are only suited to shorter trains with low axle loads travelling at speeds of less than  
92 80 km/h. In some parts of Australia, freight trains can be almost 4 km long, so the ballast degradation  
93 (breakage), mud pumping of certain formation soils, and differential settlements must be studied and  
94 quantified to achieve a resilient track design and avoid hefty maintenance costs after construction  
95 (Raymond and Bathurst 1994, Brown *et al.* 2007, Biabani *et al.* 2016, Ferreira and Indraratna 2018,  
96 Indraratna *et al.* 2018b, 2019, Powrie *et al.* 2019).

97 Conventional triaxial testing is a popular approach of evaluating the strength and breakage of ballast

98 aggregates in the laboratory (Raymond and Davies 1978, McDowell *et al.* 2005, Brown *et al.* 2007,  
99 Aursudkij *et al.* 2009, Sevi *et al.* 2009, Zhang *et al.* 2017, Harkness *et al.* 2016, among others).  
100 However, the discrepancy between the actual shape and size of particles in the field and the much  
101 smaller particle sizes adopted in conventional laboratory equipment contributes to inaccurate load and  
102 deformation responses measured in the laboratory. Moreover, since the bottom boundary is rigid and  
103 is typically less than 600mm deep, this boundary condition cannot simulate the actual field track  
104 substructure. This means that testing coarse aggregates in conventional apparatus can yield misleading  
105 results due to the disparity in size between particle and equipment and the limited depth of subgrade  
106 (Lim *et al.* 2005, Peijun and Xubin 2007, Indraratna *et al.* 2018a). Previous large-scale triaxial tests  
107 carried out by many researchers have shown that the ratio between the size of the testing chamber and  
108 the particle size must be greater than 7-8 to reduce boundary effects (Marachi *et al.* 1972, Marsal 1973,  
109 Lade *et al.* 1996).

110 To alleviate these size dependent issues, examine a range of Australian ground conditions and  
111 integrated track components, the National Facility for Heavy-haul Railroad Testing (NFHRT) was the  
112 first to be designed and built in-house at Russell Vale, NSW, Australia. The NFHRT allows for a full  
113 size instrumented railway track section to be tested so that the effects of track substructure can be  
114 captured. Such a facility could not be established through purely commercial means; rather, it was  
115 designed and built in close cooperation with the Australian rail industry, a consortium of transport  
116 research centres in several Australian Universities and the Australian Research Council, c/o Ministry  
117 of Education, under the leadership of the first author.

118 In fact, the Australian rail industry has strongly promoted the state-of-the-art test facilities for heavy  
119 haul track modelling, and this was the main driver for constructing the first NFHRT under  
120 Commonwealth government funding channelled through the Australian Research Council. In  
121 particular, the NFHRT was designed and built in close cooperation with Australian Rail Track  
122 Corporation (ARTC) and Sydney Trains, whereby an array of typical ground conditions and integrated  
123 track components were considered in relation to the national flagship project Melbourne to Brisbane  
124 Inland Rail (MBIR), one of the longest heavy haul tracks to be completed soon.

125 Although similar test facilities have also been built in other countries (Brown *et al.* 2007, Bian *et al.*  
126 2014, Abadi *et al.* 2016, Li *et al.* 2018, Bian *et al.* 2020, Hasnayn *et al.* 2020), these were built mainly  
127 for high-speed passenger trains capturing more favourable foundation characteristics in cold regions

128 (e.g., stiff boulder clays and glacial tills) or for concrete slab tracks used for short high speed commuter  
129 trains (Zhang *et al.* 2019a, 2019b, Zhai *et al.* 2020, Li *et al.* 2020). Conversely, the Australian soft soil  
130 terrains for very long heavy axle freight trains are considerably different, including highly compressible  
131 black soils and deposits of upper Holocene soft clays. In this regard, the overall objective of the NFHRT  
132 is to contribute to innovative and more cost-effective designs for heavy haul tracks built on an array of  
133 problematic ground conditions.

134 It is noteworthy that the true moving load effect cannot be properly modelled using the NFHRT, as the  
135 cyclic loading is applied by four dynamic actuators in synchronized operation. This facility is mainly  
136 for simulating heavy haul ballast tracks for high axle freight trains that operate at low speeds. At high  
137 speeds exceeding say 130 km/h, there is significant principal stress rotation under moving loads, which  
138 cannot be simulated accurately by this facility as it only has two pairs of actuators. For simulating a  
139 true moving load at high speeds (exceeding say 130 km/h), one needs more than two pairs of actuators  
140 acting along a greater number of sleepers (Bian *et al.* 2014). In addition, the dynamic and impact effects  
141 due to track irregularities could not be captured in these model tests, and this is a limitation of the  
142 current study.

143 The main objective of this research is to introduce Australia's NFHRT that has recently been  
144 constructed and is now fully operational, as well as to validate the observed results against past field  
145 measurements available from heavy haul tracks located in the towns of Bulli and Singleton (NSW,  
146 Australia). The results of the first test are presented in this paper and compared with the available field  
147 monitoring data. These results will also serve as a benchmark for future tests considering varying track  
148 substructure conditions (e.g., excessive settlement of compressible soft soils and instability of saturated  
149 subgrade including mud-pumping), the effectiveness of artificial inclusions such as geosynthetics for  
150 improved track stability and the vibration mitigation of carriage-track-foundation interactions using  
151 damping elements made of recycled rubber. Details of the NFHRT, test set up, instrumentation, and  
152 the results of the first test are presented in the following sections.

153

## 154 **2. National Facility for Heavy-haul Railroad Testing**

### 155 ***2.1. Design and construction of the NFHRT***

156 The NFHRT consists of a large-scale laboratory test facility that allows the testing of a fully

157 instrumented ballasted track section at 1:1 prototype scale. It includes a test pit, loading frames, a  
158 hydraulic servo-controlled system with four dynamic actuators and a high capacity hydraulic power  
159 unit, an electrical system, an instrumentation and data acquisition system, and a 5-tonne overhead  
160 crane. A schematic of the NFHRT is shown in Figure 1a.

161 A 6.0m-long  $\times$  6.0m-wide  $\times$  2.3m-deep test pit was excavated, and four 900mm-thick reinforced  
162 concrete walls and a 600mm-thick reinforced concrete floor were then constructed (Fig. 1b). The  
163 hydraulic actuators and power unit of the NFHRT were designed, fabricated and then assembled (Fig.  
164 1c). A trench for the hydraulic pipework (9.13m long  $\times$  1.35m wide  $\times$  0.5m high) was built with  
165 reinforced concrete walls (Fig. 1d).

166 Track materials such as ballast, capping, structural fills, subgrade, and a drainage layer are installed  
167 beneath a rail-sleeper assembly to accurately estimate their actual response when subjected to realistic  
168 loading conditions. A hybrid hydro-electrical substation with heavy duty hose connections from the  
169 hydraulic pipework to the four dynamic actuators provide the cyclic loading capable of simulating up  
170 to 40-tonne axle trains operating at speeds up to 200km/h. The actuators apply the designed cyclic  
171 loading directly onto the rails and are fully controlled through the computerised operating system also  
172 linked to an automated data acquisition system.

## 173 **2.2. Materials and test procedures**

174 In this first test, a 75mm thick drainage layer consisting of coarse grained gravel was placed at the  
175 bottom of the test pit (Fig. 2a) overlain by a geotextile filter to avoid clogging. A 795mm-thick layer  
176 of fine-grained subgrade soil (classified as CL according to the Unified Soil Classification System)  
177 was then installed and spread by a mini excavator. The subgrade was compacted in four sub-layers to  
178 a dry unit weight of 16.5 kN/m<sup>3</sup> (moisture content,  $w=20\%$ ) using a lightweight compaction plate.  
179 Pressure cells, soil moisture sensors and pore water pressure gauges were installed within the subgrade  
180 to measure the respective parameters during testing (Fig. 2b and 2d). An irrigation system consisting  
181 of a series of perforated pipes wrapped with a geotextile filter was installed in the subgrade layer to  
182 control the water content and the degree of saturation of the track foundation (Fig. 2c).

183 A 650mm-thick structural fill layer (moisture content,  $w=11.5\%$ ) was placed on top of the subgrade  
184 and compacted in sub-layers of 150 mm thick to achieve a dry unit weight of 18.5 kN/m<sup>3</sup>, using similar  
185 procedures to those described earlier for the subgrade layer. A 180mm thick capping layer (sub-ballast)



186 consisting of a sand and gravel mixture was then placed over the structural fill (Fig. 3a) and compacted  
187 in two sub-layers (90mm thick) to a dry unit weight of  $19.5 \text{ kN/m}^3$ , corresponding to about 90% of  
188  $\gamma_{dmax}$  based on the standard Proctor compaction method in accordance with AS 1289.5.1.1 (2017). A  
189 heavier compaction plate was used to compact the sub-ballast material, giving the higher compaction  
190 requirements of this layer. To ensure all the materials from the bottom subgrade layer to the capping  
191 layer had been compacted to the desired unit weight, sand cone tests were conducted following the  
192 ASTM D1556 (2007) (Fig. 3b). Pressure cells and horizontal displacement transducers were then  
193 placed over the capping layer, as shown in Figure 3c.

194 Ballast (latite basalt aggregates) was obtained from the Bombo quarry, about 100km South of Sydney,  
195 then cleaned and sieved following the Australian Standards (AS 2758.7, 2015). The ballast was  
196 compacted in three sub-layers (100mm-thick) to achieve a density of nearly  $16 \text{ kN/m}^3$  and the total  
197 thickness of the load-bearing ballast was 300mm, as typically used in actual Australian heavy-haul  
198 tracks (Fig. 3d). The selected densities for the track substructure layers are comparable with other  
199 studies reported earlier by Suiker *et al.* (2005), Aursudkij *et al.* (2009), Biabani *et al.* (2016) and  
200 Anderson and Fair (2008).

201 A system of rails and sleepers provided by the Australian Rail Track Corporation (ARTC) was laid  
202 onto the ballast layer (Fig. 3e) and additional ballast aggregates were then placed to simulate the crib  
203 and shoulder ballast. The loading frames were bolted in position and the four dynamic actuators were  
204 installed to apply a dynamic train loading (Fig. 3f). The particle size distribution (PSD) of the ballast,  
205 capping, structural fill and subgrade materials used for this test are shown in Figure 4.

### 206 **2.3 Instrumentations**

207 Figure 5a presents a plan view of the instrumentation installed into the track substructure such as  
208 settlement pegs (1-16), horizontal displacement transducers ( $E_{1T}$ ,  $E_{1B}$ ,  $E_{2T}$  and  $E_{2B}$ ), pressure cells and  
209 the positions of the rail and sleeper system. Figure 5b is a cross section (North-South section) of the  
210 testing pit showing the locations of the sensors. Twenty rapid response hydraulic pressure cells were  
211 installed at different locations and depths to measure the transient vertical and horizontal stresses;  
212 sixteen settlement pegs were installed at varying depths in the structural fill, capping and ballast layers  
213 to measure the permanent vertical deformations. Four horizontal displacement transducers were placed  
214 bellow the loaded sleepers at two different depths (i.e., two of which were installed underneath the  
215 sleepers and the other two were installed at the bottom of the ballast layer). Two triaxial accelerometers

216 were installed on the rail and sleeper to measure acceleration (vibration) during the tests (Fig. 6a). In  
217 addition, eight pore water pressure transducers, four moisture sensors and four water potential sensors  
218 were placed in the subgrade to monitor the excess pore pressure and/or the changes of water content  
219 and water potential, depending on the moisture conditions of the subgrade layer in each test. These  
220 sensors were installed in the subgrade layer for future tests considering the submergence of subgrade  
221 through the irrigation system to study track problems associated with flooded track conditions in low-  
222 lying coastal areas as well as the saturated subgrade instability, e.g., mud-pumping. Measurements  
223 from these sensors will be available for the future tests when the track substructure is made to be  
224 saturated. All the sensors and instruments were calibrated before testing. A data acquisition system  
225 controlled by a host computer automatically recorded all the data collected during the test (Fig. 6b).  
226 The selected sample rate (data logging frequency) for all the signals was 1200 Hz.

#### 227 **2.4 Cyclic loading characteristics**

228 In this test, the load was selected based on a typical Australian freight train having an equivalent 25-  
229 tonne axle load. Therefore, a maximum load of 12.5 tonnes (125 kN) was applied by each dynamic  
230 actuator, simulating a realistic wheel load. The applied loading characteristics are schematically shown  
231 in Figure 7 corresponding to a vertical load of  $P_{max}=125$  kN,  $P_{min}=15$  kN and  $P_{mean}=70$  kN,  
232 corroborating to a freight train of 25-tonne axle load. The minimum load of 15kN ensured continual  
233 contact between the dynamic actuators and the rails during the test.

234 The applied frequency of  $f=15$  Hz in the experimental program is assumed to cover a realistic range of  
235 heavy haul train speeds of 60-80km/h on standard gauge tracks, based on Indraratna et al. (2011), Sun  
236 et al. (2016) and Navaratnarajah et al. (2018). In reality, the frequency is not only dependent on the  
237 train speed but also on track geometry, bogey spacing, rest periods, variations in cyclic and impact  
238 loading among other variables. For typical Australian freight train, the loading frequency was estimated  
239 by considering the distance between the last wheel of the front bogie and the first wheel of the next  
240 bogie on a standard gauge track in Australia. As the axle distance is much smaller than the length  
241 between bogie centers ( $L_b$ ) or vehicle length, the two rear axles of a leading wagon and two front axles  
242 of a trailing wagon would represent the highest generated frequency (Indraratna *et al.* 2011). Heavy  
243 haul trains in Australia are often 4-5 km long and they travel on standard gauge tracks at relatively low  
244 speed (@ 40-60 km/h in most cases and rarely exceed 70k/h), and the applied frequency in the  
245 laboratory is indeed corroborated with the track geometry and train speed (e.g. Indraratna et al. 2011,

246 Sun et al. 2016, Navaratnarajah et al. 2018). It is also noticed that there can be several variables  
247 including the sleeper spacing, speed of train, track irregularities, occasional impact loading, influence  
248 of rest periods, variation in cyclic loading due to non-uniform axle spacing etc. that can contribute to  
249 the real-life frequency in contrast to the simplified (constant) experimental magnitude of frequency.

250 The actuators worked in synchronised pattern up to  $N=500,000$  load cycles to simulate the realistic  
251 repeated loading on the rails, but given the limitation of having only two pairs of actuators, the ideal  
252 simulation of moving loads from the bogies of a long train was not possible. As mentioned earlier, the  
253 design of this equipment is reasonable for slow moving heavy haul trains in Australia, but not for  
254 representing high speed passenger trains where significant principal stress rotation occurs under fast  
255 moving loads. In addition, it is noted that the loading sequence capturing rest periods is not considered  
256 in this study. This is because the worst conditions occur when very long heavy haul trains apply  
257 continual loading over a substantial period of time, and busy freight tracks in the mining hubs have  
258 relatively small rest periods. For example in Western Australia, different mineral ore trains can travel  
259 over very long distances at slow speeds (40-60 km/h) from source to port (sometimes up to 300 km)  
260 regularly most of the day, and the ballast relaxation during relatively short rest periods between these  
261 slow-moving trains can be ignored. For instance, for iron ore trains that can be up to 6 km long moving  
262 at only 40 km/h, the worst-case scenario simulated in the laboratory is without any rest period, so that  
263 the fatigue of ballast is maximised during testing to determine the maximum deformation, i.e.  
264 settlement and lateral movement. Both the axle load and loading frequency influence the resulting  
265 settlement, but the axle load magnitude is more dominant than the frequency. Nevertheless, the load  
266 frequency must still be highlighted, because that is the only loading parameter in cyclic laboratory  
267 testing that is related to the train speed (Esveld, 2014; Indraratna et al. 2011). In other words, the  
268 number of axle loads passing through a specific in situ reference point (worksite) over a given period  
269 of time is related to the frequency.

270

### 271 **3. Results and discussion**

#### 272 ***3.1. Measured vertical settlement***

273 Figure 8 shows the accumulated track settlement after being subjected to a 25-tonne axle load at a  
274 frequency of  $f=15$  Hz, as recorded by the settlement pegs installed below the sleepers ( $S_1$ ,  $S_5$ ,  $S_{10}$  and  
275  $S_{16}$  – Fig. 5a). It can be concluded that the vertical displacement ( $S_v$ ) of ballast increased rapidly up to

276 about  $N=50,000$  cycles due to its initial densification and subsequent packing as the corners of the  
277 sharp angular ballast aggregates began to break ( $S_v = 6.2$  mm to 8.7 mm). However, once the aggregates  
278 began to stabilise the rate of vertical displacement gradually decreased and remained relatively constant  
279 after  $N=200,000$  cycles ( $S_v = 8.7$  mm to 12.1 mm). This shows the aggregate density has reached  
280 threshold compression and would resist further rearrangement and densification with additional cycles.  
281 The measured final track settlement, taking the average of the four settlement pegs, was about  $S_v=14.2$   
282 mm. These observations are in agreement with the data obtained in the laboratory (Indraratna *et al.*  
283 2013) and the field measurements taken at the Bulli and Singleton tracks (Indraratna *et al.* 2010, 2014).  
284 It is noted that while the track settlement measured at the Bulli track matched those measured at the  
285 NFHRT facility, field data from the Singleton track showed higher vertical settlement, especially after  
286  $N=200,000$  cycles. This could be due to the track section at Singleton being built on a flood plain with  
287 a 7-10 m thick layer of alluvial silty clay, which could lead to greater vertical deformation of the track.

### 288 **3.2. Measured lateral displacement**

289 Figure 9 presents the lateral displacement ( $S_h$ ) of the ballast layer as recorded by the four horizontal  
290 displacement transducers, two of which ( $E_{1T}$ ,  $E_{2T}$ ) were placed underneath the sleepers and the other  
291 two ( $E_{1B}$ ,  $E_{2B}$ ) were installed at the boundary between the ballast and capping layers at the bottom of  
292 the ballast layer (Fig. 5). The lateral displacement of ballast measured at the Bulli track and from  
293 laboratory tests performed earlier (Indraratna *et al.* 2010, 2013) are also shown in Figure 9 for  
294 comparison purposes. The measurements from all the displacement transducers show consistent  
295 increases in lateral displacement with increased  $N$ . The ballast aggregates showed a significant  
296 horizontal spread ( $S_h=5.8$  mm - 6.2 mm) within the initial  $N=100,000$  cycles, followed by a gradual  
297 increase in  $S_h$  up to  $N=300,000$  cycles, after which  $S_h$  remained nearly constant towards the end of the  
298 test. The final horizontal displacement of the track varied from  $S_h=6.8$  mm - 9.1mm, depending on the  
299 location of each measurement. This trend is similar to those observed earlier in actual rail tracks and  
300 in the laboratory by Indraratna *et al.* (2013). However, the data from the field trial at Bulli track show  
301 higher lateral displacements than those measured at the NFHRT. This is possibly because moving  
302 freight trains generate greater impact forces due to wheel or rail irregularities such as flat wheels,  
303 dipped rails, expansion gaps and rail corrugations, which could accelerate the degradation and lateral  
304 spreading of ballast (Auersch 2015, Ferreira and Indraratna 2018, Indraratna *et al.* 2020a).  
305 Furthermore, in the NFHRT two aluminium panels (200mm-high) were placed on both sides of the  
306 shoulder ballast to maintain track geometry during the commissioning process, which may have

307 provided some additional confinement to the ballast layer leading to slightly lower lateral deformations  
308 when compared to the field measurements at Bulli track.

### 309 **3.3. The vertical and lateral stresses**

310 Figure 10a shows the typical vertical stresses recorded over time at different depths of the track  
311 substructure (from the top surface of the ballast to the drainage layer) during the test. Pressure cells  
312 were placed between the sleepers and ballast, beneath the ballast layer, between the capping and  
313 structural fill, and on top of the subgrade and drainage layers to measure the stresses at different depths  
314 (Fig. 5b). Under a 25-tonne axle load the maximum vertical stress at the sleeper-ballast interface is  
315 about  $\sigma_v = 225$  kPa, and the  $\sigma_v$  attenuates with depth. The maximum vertical stresses at the top surface  
316 of the capping layer, the structural fill, the subgrade and drainage layers are measured as  $\sigma_v = 151, 132,$   
317  $98,$  and  $54$  kPa, respectively. The vertical stresses at different depths plotted on the frequency domain  
318 are shown in Figure 10b. Here, the cyclic response of the stresses recorded in the ballast layer peaks at  
319  $f=15\text{Hz}$ , but these peaks decrease slightly in the underlying layers showing how the loading frequency  
320 attenuates with depth.

321 Figure 11 illustrates the vertical stress ( $\sigma_v$ ) measured at different layers of the track substructure and its  
322 variation with the number of load cycles. It is evident that the dynamically induced stress in the ballast  
323 layer increases with  $N$  (e.g., at the first  $N=500$  cycles,  $\sigma_v = 175$  kPa, and then  $\sigma_v$  continues to increase  
324 to  $\sigma_v = 225$  kPa at the end of the test,  $N=500,000$  cycles). On the other hand, the vertical stress  $\sigma_v$   
325 decreases with the depth of the test pit where the  $\sigma_v$  recorded in the subgrade and drainage layers is  
326 approximately  $95$  kPa and  $48$  kPa, respectively. The vertical stresses obtained in a previous laboratory  
327 study and on the field tracks (Singleton and Bulli tracks) are also plotted in Figure 11 for comparison  
328 purposes (Indraratna *et al.* 2010, 2014, Navaratnarajah *et al.* 2018). Given that the laboratory  
329 equipment used in the previous study has a limited boundary, only the stresses up to a depth of  $500$  mm  
330 below the surface of ballast are presented. The  $\sigma_v$  reported in previous studies shows some fluctuations  
331 where  $\sigma_v$  between the sleeper and ballast varies from  $172$  kPa to  $300$  kPa, and then decreases to about  
332  $38$  kPa (Bulli track) and  $87$  kPa (laboratory test) when measured at the top surface of the capping layer.

333 Figure 12 shows the horizontal stresses ( $\sigma_h$ ) in the ballast layer obtained in the longitudinal direction  
334 parallel to the rails and in the transverse direction parallel to the sleepers. Data were monitored by two  
335 pressure cells placed at the northern and southern sides of the track (lateral confinement in the  
336 transverse direction -  $\sigma_3$ ) and two pressure cells placed on the eastern and western walls to measure the

337 longitudinal stresses ( $\sigma_2$ ). It is seen that the horizontal stress ( $\sigma_h$ ) remains almost unchanged during the  
 338 test. Lateral confinement in the transverse direction, commonly known as the confining pressure ( $\sigma_3$ ),  
 339 is around  $\sigma_3=22$  kPa to 25 kPa during the test, whereas the longitudinal stress (the intermediate stress,  
 340  $\sigma_2$ ) varies from  $\sigma_2=15$  kPa to 20 kPa. The lateral stresses in the transverse direction exceeded those in  
 341 the longitudinal direction possibly because the latter were measured by pressure cells fixed to the  
 342 vertical steel walls, which were further away from the locations of load application (actuators). The  
 343 confining pressures measured in this study are generally consistent with those recorded during previous  
 344 field monitoring programmes carried out in Australian heavy-haul tracks.

### 345 **3.4. Measured resilient modulus**

346 The resilient modulus ( $M_R$ ) of ballast can be calculated as the ratio between the deviatoric stress ( $\Delta q_{cyc}$ )  
 347 and the resilient (recoverable) axial strain ( $\varepsilon_{a,rec}$ ) during loading-unloading stage, as given by:

$$348 \quad M_R = \frac{\Delta q_{cyc}}{\varepsilon_{a,rec}} = \frac{q_{cyc,max} - q_{cyc,min}}{\varepsilon_{a,rec}} \quad (1)$$

349 The resilient (recoverable) axial strain ( $\varepsilon_{a,rec}$ ) was obtained at a given number of loading–unloading  
 350 cycles ( $N$ ) using the data bursting approach to determine the resilient modulus ( $M_R$ ) of ballast. During  
 351 the test, the relevant sets of data bursting were initiated at  $N= 1, 50, 100, 500, 1000, 5000, 10,000,$   
 352  $50,000, 100,000, 200,000, 300,000, 400,000,$  and 500,000; and the recoverable axial strains ( $\varepsilon_{a,rec}$ )  
 353 during unloading were determined by subtracting the measured axial strains of the corresponding  
 354 loading-unloading cycle. Figure 13a shows the typical stress-strain hysteresis loops plotted for a given  
 355 load cycle. It can be observed that the areas of the hysteresis loops are reduced as the number of load  
 356 cycles ( $N$ ) increases, which indicates that ballast aggregates become more compacted and respond more  
 357 elastically with increased  $N$ . The variation of resilient modulus  $M_R$  with  $N$  presented in Figure 13b  
 358 shows a rapid increase of  $M_R$  within the first  $N = 200,000$  cycles ( $M_R=462$  MPa), after which the rate  
 359 at which  $M_R$  increased becomes marginal. The rapid compression and densification of ballast during  
 360 the initial load cycles increases track stiffness, leading to a rapid increase in  $M_R$  at the beginning of the  
 361 test. After  $N=200,000$  loading cycles the ballast aggregates may move to the shakedown stage, which  
 362 causes the  $M_r$  to remain relatively unchanged (Le Pen *et al.* 2016, Sun *et al.* 2019).

### 363 **3.5. Rail and sleeper acceleration**

364 As mentioned, two triaxial accelerometers ( $A_R$  and  $A_S$ ) were installed on the rail and sleeper to measure

365 acceleration (vibration) during the tests. The acceleration of the rail and sleeper plotted in time and  
366 frequency domains are shown in Figure 14. Here, the accelerations measured at the sleeper ( $A_S$ ) are  
367 greater than those recorded at the rail ( $A_R$ ), with a maximum value of  $A_S = 27.2 \text{ m/s}^2$  compared to the  
368 highest value of  $A_R = 5.6 \text{ m/s}^2$ . It is noteworthy that the rails were connected to six concrete sleepers  
369 creating a stronger system that could prevent from excessive vertical vibration, while the edge of  
370 sleeper was more prone to vertical displacement due to sitting on the discrete ballast aggregates. The  
371 accelerations were measured at the end of the test where the ballast shoulder has significantly displaced  
372 laterally and could cause the condition of hanging sleeper. As a result, there was a reduction in lateral  
373 confinement applied to the sleepers that resulted in increased sleeper displacement and associated  
374 acceleration.

375 The acceleration (vibration) in the time domain is converted into the frequency domain by the fast  
376 Fourier transform (FFT), as shown in Figure 14. It is observed that the responses reach their maximum  
377 peak values at an approximate frequency of  $f_1 = 15 \text{ Hz}$ , while some smaller peaks are reached at higher  
378 frequencies (Kouroussis *et al.* 2009). The  $f_1$  frequency is identical to the cyclic loading applied by the  
379 dynamic actuators, which indicates that the response of the track substructure to acceleration is in the  
380 same phase as the applied loading frequency.

### 381 **3.6. Measured ballast breakage**

382 After the test, ballast aggregates at four different locations (underneath two actuators, between the two  
383 rails, and at the shoulder ballast) were recovered separately for quantifying ballast breakage. This  
384 ballast was then passed through standard sieves to obtain the particle size distribution (PSD), as shown  
385 in Figure 15. Indraratna *et al.* (2005) introduced a new method to quantify ballast degradation under  
386 cyclic loading, which leads the PSD curve of ballast to shift towards the smaller size particles due to  
387 breakage. By recognising this shift as the degradation indicator, the ballast breakage index ( $BBI$ ) can  
388 be calculated using Equation 2

$$389 \quad BBI = \frac{A}{A+B} \quad (2)$$

390 where,  $A$  is the shift in PSD due to ballast breakage under cyclic loading, and  $B$  is the potential breakage  
391 or the area between the arbitrary boundary of maximum breakage and the final particle size distribution.  
392 It is noted the upper and lower limits of  $BBI$  are 0 (no breakage) and 1, respectively. A summary of the  
393 sieve analysis performed before and after the test for quantifying ballast breakage ( $BBI$ ) is presented

394 in Table 1. Measured breakage denotes that ballast aggregates collected directly underneath the  
395 actuators had the highest amount of breakage, estimated as  $BBI_{1,2} = 0.143$  and  $0.115$ , whereas the ballast  
396 collected from between two rails (crib ballast) and the edge of a sleeper (shoulder ballast) have  $BBI_{3,4}$   
397  $= 0.085$  and  $0.075$ , respectively. The ballast underneath the actuators experiences more breakage  
398 because these aggregates carry the cyclic loads directly from the dynamic actuators and also deal with  
399 the vibration transferred from the sleepers. As a consequence, these aggregates are more prone to  
400 breakage. The results also show that the average  $BBI$  for ballast samples collected underneath the  
401 actuators ( $BBI = 0.129$ ) was slightly higher than that obtained for ballast aggregates recovered from  
402 beneath the sleeper and rail seat in the actual heavy-haul track at Singleton after the same number of  
403 load cycles (Nimbalkar and Indraratna 2016). In fact, in the NFHRT the load is continually applied  
404 over the same sleepers for 500,000 cycles, which results in a slightly higher amount of ballast crushing  
405 when compared to actual field measurements.

406

#### 407 **4. Conclusions**

408 This paper described the construction and testing process of the new Australia's National Facility for  
409 Heavy-haul Railroad Testing (NFHRT), a prototype test facility that allowed investigating the  
410 performance of a real-size instrumented track section when subjected to continuous cyclic loading  
411 applied via two pairs of dynamic actuators. The first test was carried out under a 25-tonne axle load  
412 applied at a frequency of 15 Hz to cover a realistic range of heavy haul train speeds of 60-80km/h on  
413 standard gauge tracks. The results from this first test, including the measured track settlement and  
414 lateral deformation, transient vertical and lateral stresses, rail and sleeper accelerations, resilient  
415 modulus and breakage of ballast were presented and compared with actual field measurements obtained  
416 in heavy-haul tracks located in the towns of Bulli and Singleton (New South Wales, Australia).

417 The obtained results were generally consistent with real-life measurements undertaken during the  
418 aforementioned field monitoring programmes. An average track settlement of about 14 mm and lateral  
419 deformations up to 9 mm were recorded after 500,000 load cycles. Any small discrepancies between  
420 the test results and the actual field measurements may be associated with boundary conditions and  
421 loading simulations. For instance, the lateral deformation of the ballast layer recorded in the field trial  
422 conducted at Bulli exceeded that measured in the NFHRT. This is partially because moving freight  
423 trains generate greater impact forces due to wheel or rail irregularities, which could accelerate the



424 lateral spreading of ballast. On the other hand, the breakage of the load-bearing ballast estimated at the  
425 end of the test ( $BBI = 0.129$ ) was found to be slightly higher than that measured in the actual rail track  
426 at Singleton, which can be related to the fact that in the NFHRT the load was continually applied over  
427 the same sleepers for 500,000 cycles, thus resulting in a higher extent of ballast degradation.

428 It is noteworthy that the true moving load effect was not properly modelled in the test reported herein,  
429 as the cyclic loading was applied by four dynamic actuators in synchronized operation. In spite of this  
430 limitation, the obtained results for these relatively low speeds ( $\approx 60$ -80 km/h) were acceptable as the  
431 facility mimicked the cyclic loading appropriately. However, at very high speeds the results may  
432 deviate from accuracy when fast moving loads must be simulated correctly with more than two pairs  
433 of actuators acting along a greater number of sleepers (Bian *et al.* 2014).

434 When compared to smaller-scale or conventional laboratory test facilities, the NFHRT enabled to  
435 mitigate boundary effects and more realistically simulate Australian track conditions (often involving  
436 problematic subsoils) in a controlled laboratory environment. The test reported in this paper was aimed  
437 at simulating the conditions prevailing in typical Australian heavy-haul tracks. Additional tests will be  
438 carried out in the future to examine the benefits of artificial inclusions, such as geosynthetics and  
439 recycled rubber products, as well as the influence of different substructure materials (including  
440 recycled waste materials) on track performance, which will facilitate innovative and more sustainable  
441 designs for enhanced stability and resiliency of heavy haul tracks.

442

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453

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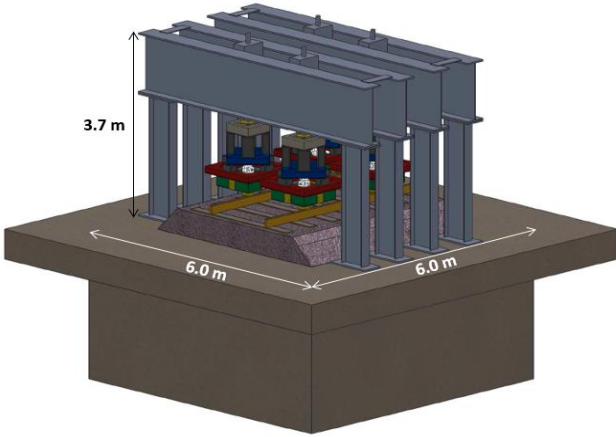
634 Table 1. Quantification of ballast breakage (*BBI*) recovered at different places after the test

Sieve size (mm)	Passing (%)				
	Initial gradation of tested ballast	Collected ballast underneath the South-East actuator	Collected ballast underneath the North-West actuator	Collected ballast between two rails	Collected ballast at the end of sleeper (shoulder ballast)
63	100	100	100	100	100
53	93.75	94.2	94.50	94.2	93.9
37.5	51.70	63.5	61.20	56.2	55.7
26.5	21.38	31.4	31.20	27.9	27.2
19	5.92	10.9	10.53	10.36	9.8
13.2	2.68	8.5	7.47	6.98	6.52
9.5	2.15	6.12	5.67	4.78	4.25
4.75	1.83	3.12	3.73	3.14	2.04
2.36	0	0	0	0	0
	<b>Measured <i>BBI</i></b>	<b>0.143</b>	<b>0.115</b>	<b>0.085</b>	<b>0.074</b>

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(a) Design concept



(b) Reinforced concrete of the test pit



(c) Hydraulic power unit



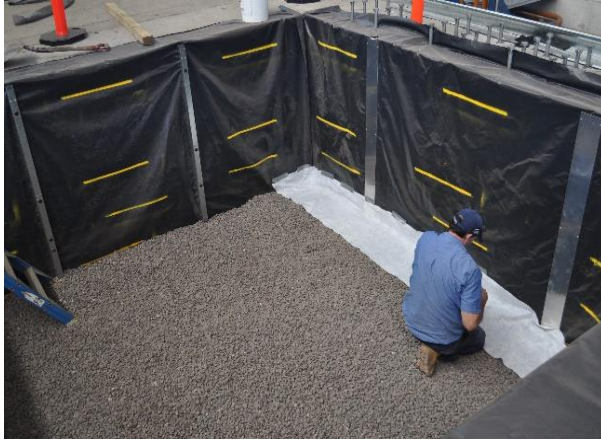
(d) Hydraulic pipe system

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638

639

Figure 1. Design and construction of the NFHRT



(a) Drainage layer



(b) Moisture sensors and pore pressure gauges



(c) Irrigation system



(d) Pressure cells on top of subgrade

640

641

Figure 2. Installation of the drainage and subgrade layers





(a) Capping layer



(b) Sand-cone test for compacted capping



(c) Placement of ballast



(d) Compaction of ballast layer



(e) Rails and sleepers

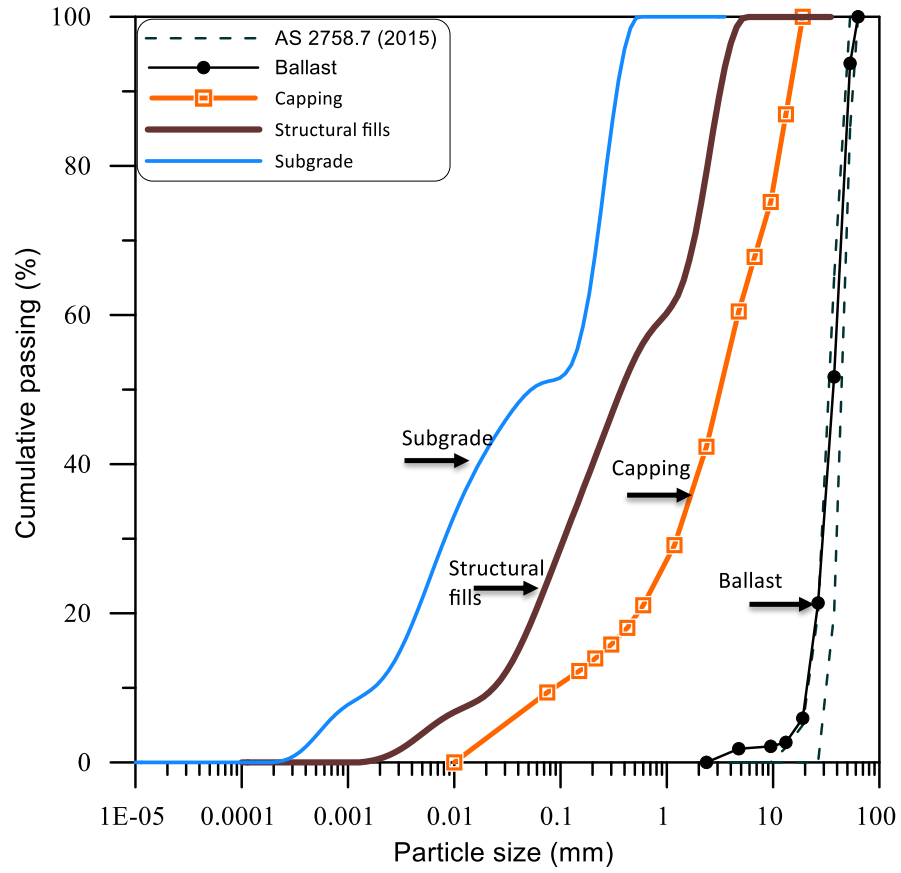


(f) Loading frames and hydraulic actuators

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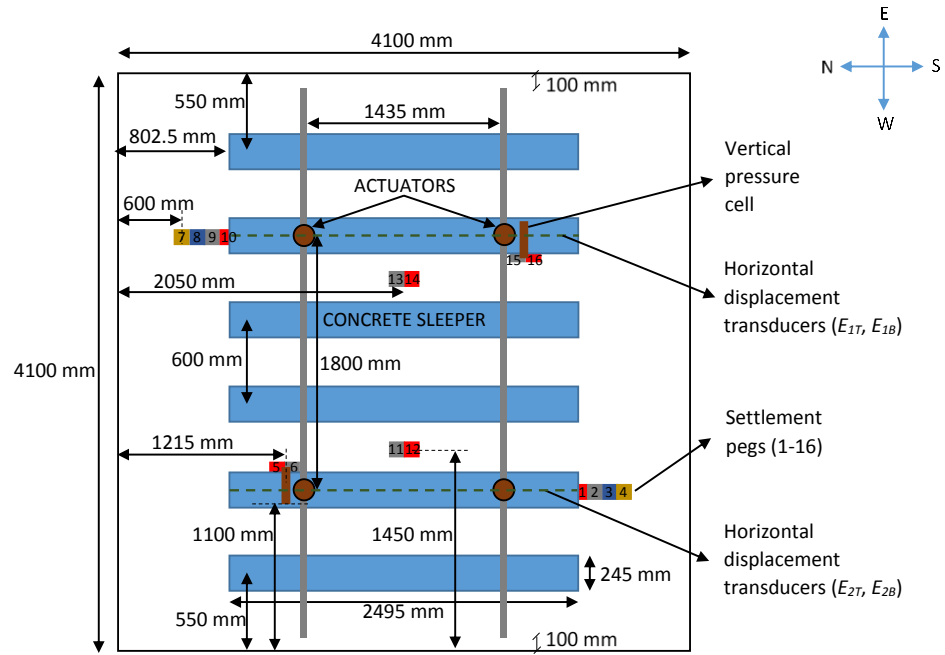
Figure 3. Installation of the capping, ballast, rail-sleeper assembly and dynamic actuators



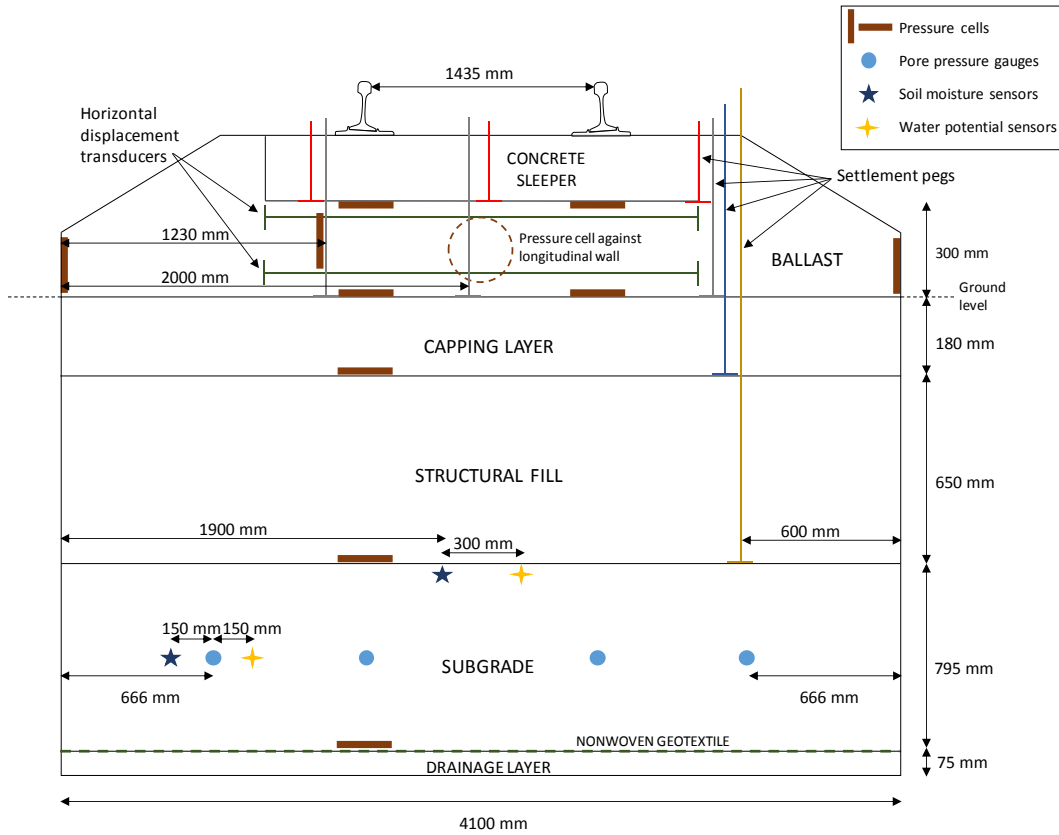
644

645

Figure 4. Particle size distribution curves of the track substructure materials



(a) Plan view of locations of instrumentations



(b) A cross-section of the test pit with detailed instrumentations

646

647

Figure 5. A plan view and cross-section of the NFHRT with detailed instrumentations

648



(a)

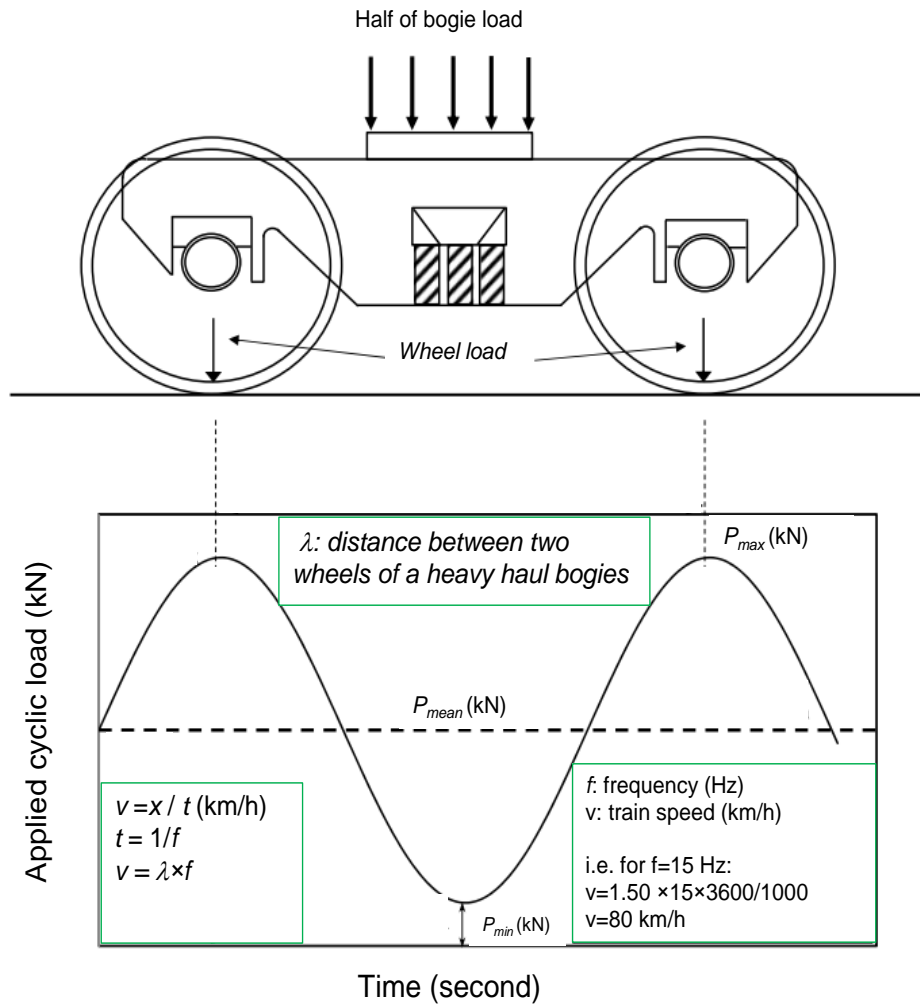


(b)

649

650 Figure 6. (a) Installation of triaxial accelerometers on the rail and sleeper; (b) data acquisition system

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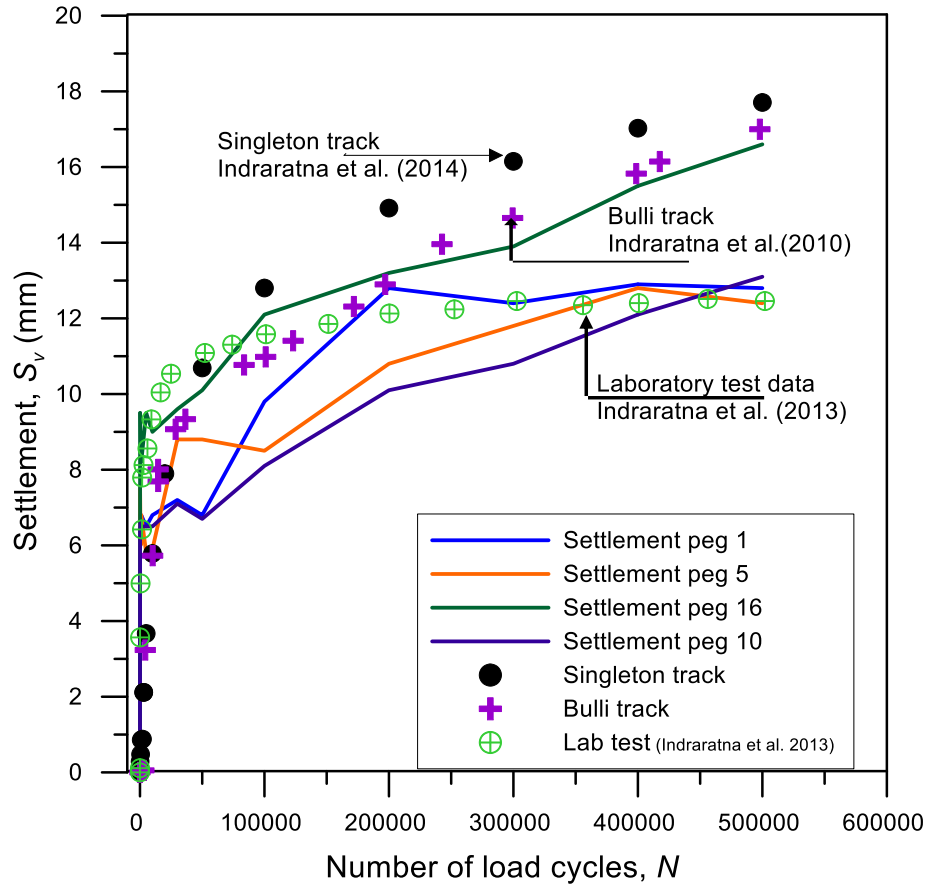
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Figure 7. Typical schematic of axle load and applied cyclic load during the test

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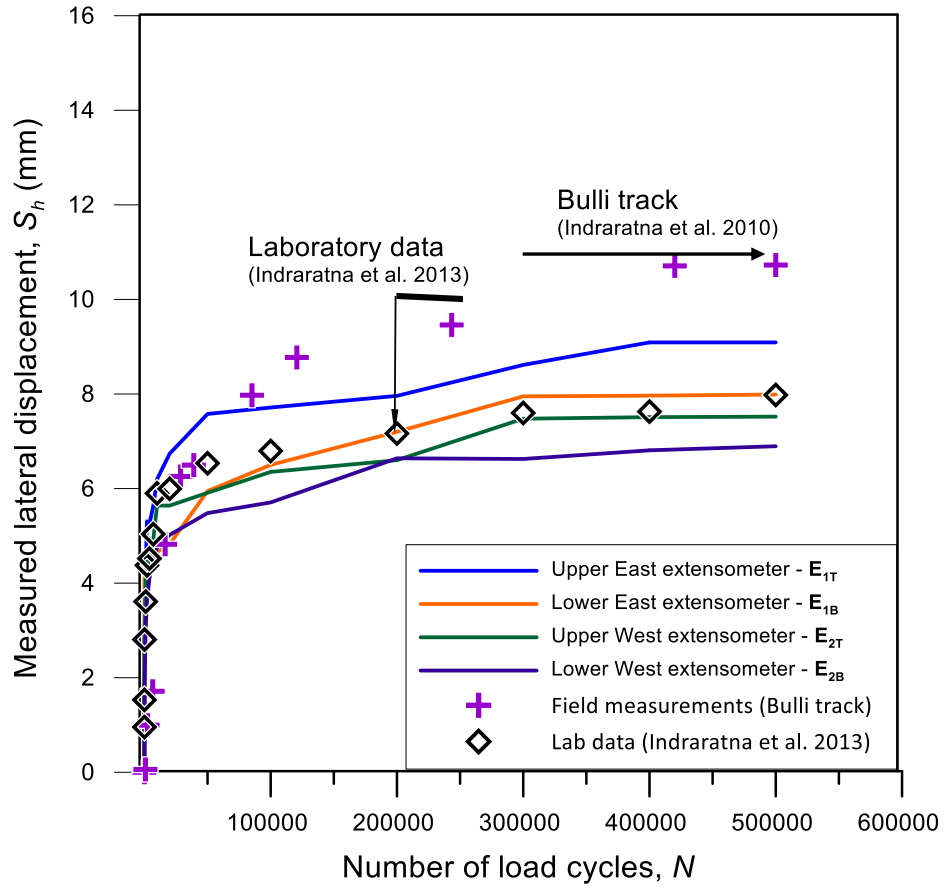
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658 Figure 8. Measured settlements of the track at different locations in comparison with laboratory and  
 659 field measurement data

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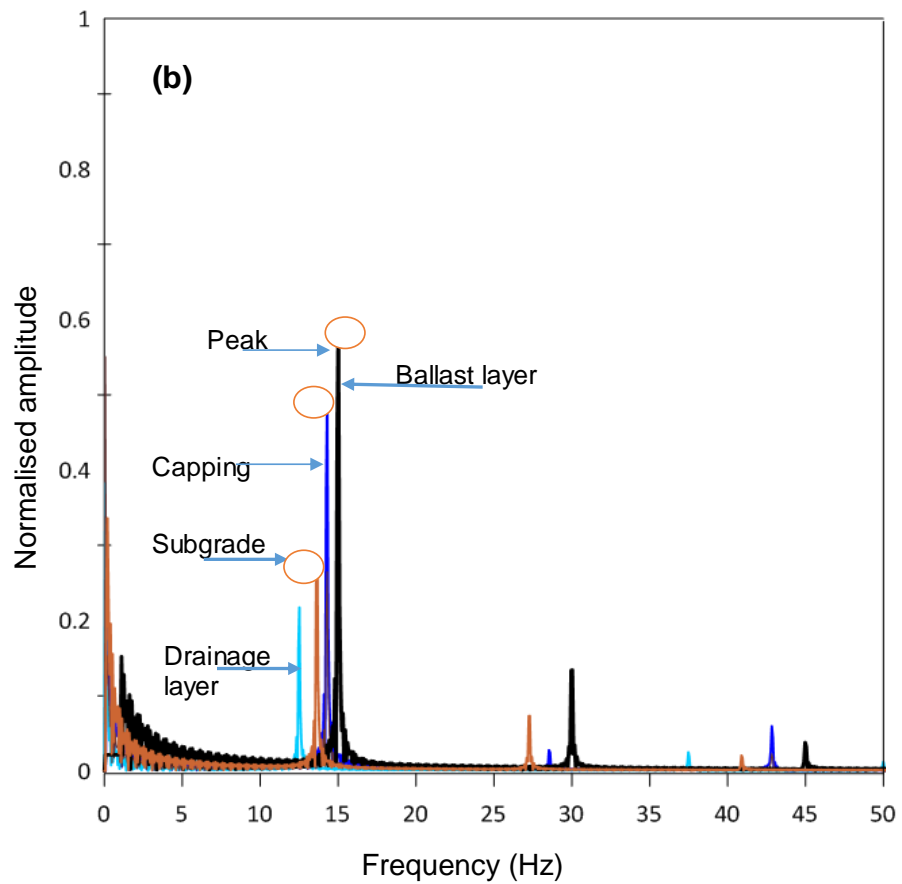
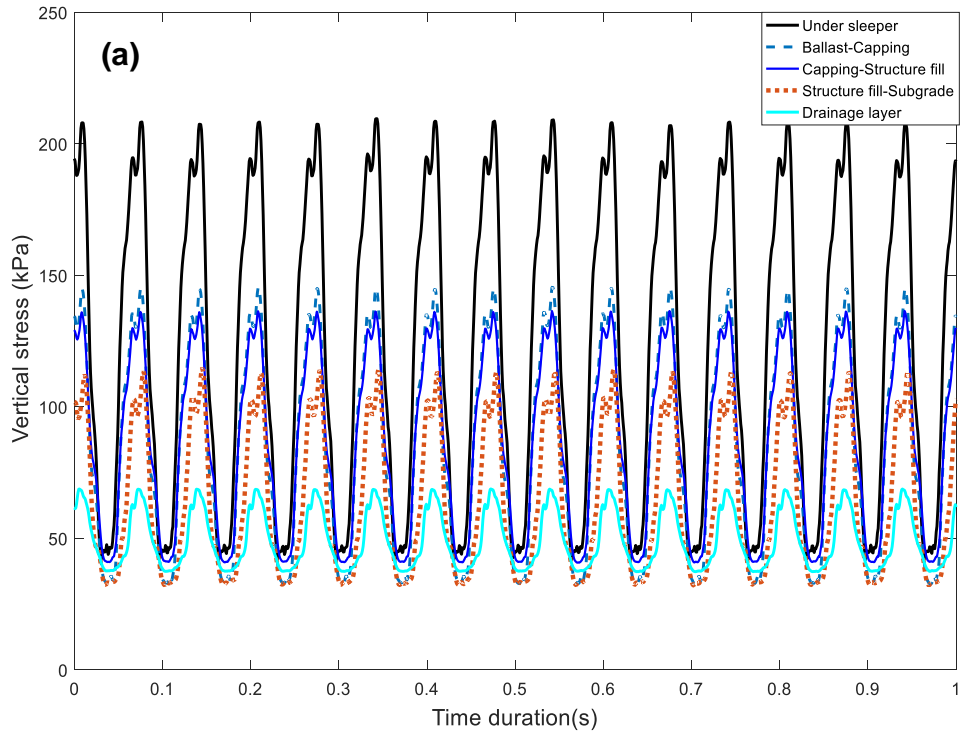




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663 Figure 9. Measured lateral displacements at varying locations in comparison with laboratory and field  
 664 measurement data

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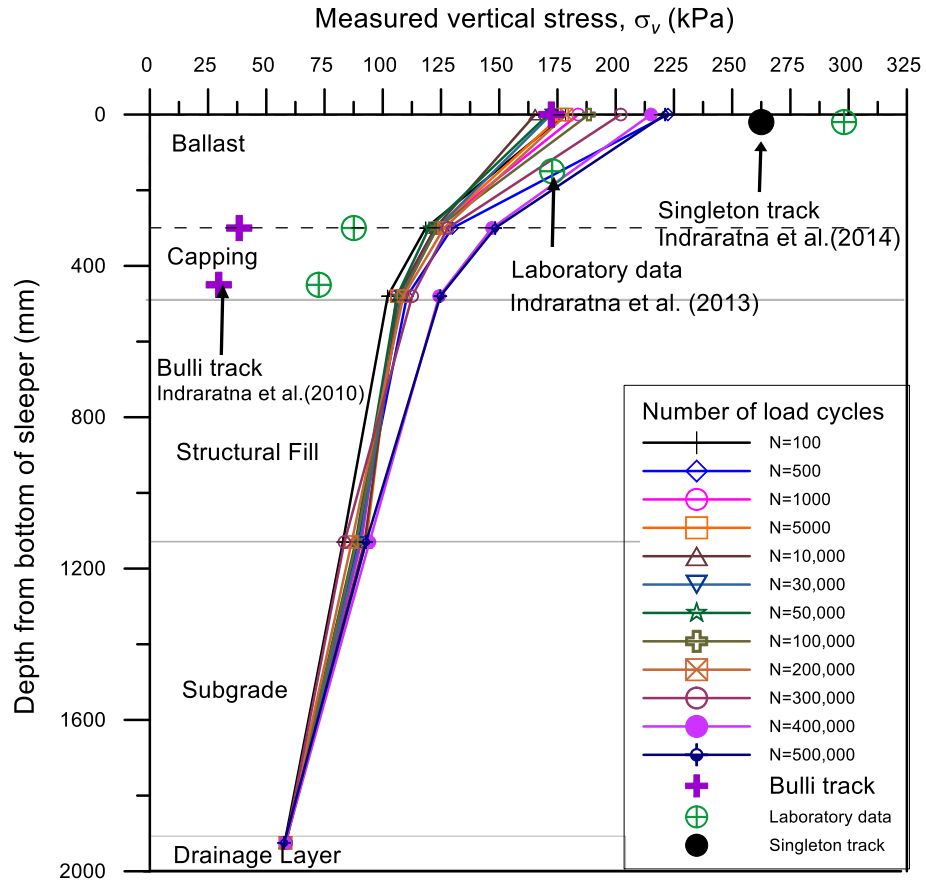


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667 Figure 10. Typical cyclic vertical stress ( $\sigma$ ) responses at varying depths measured by pressure plates:

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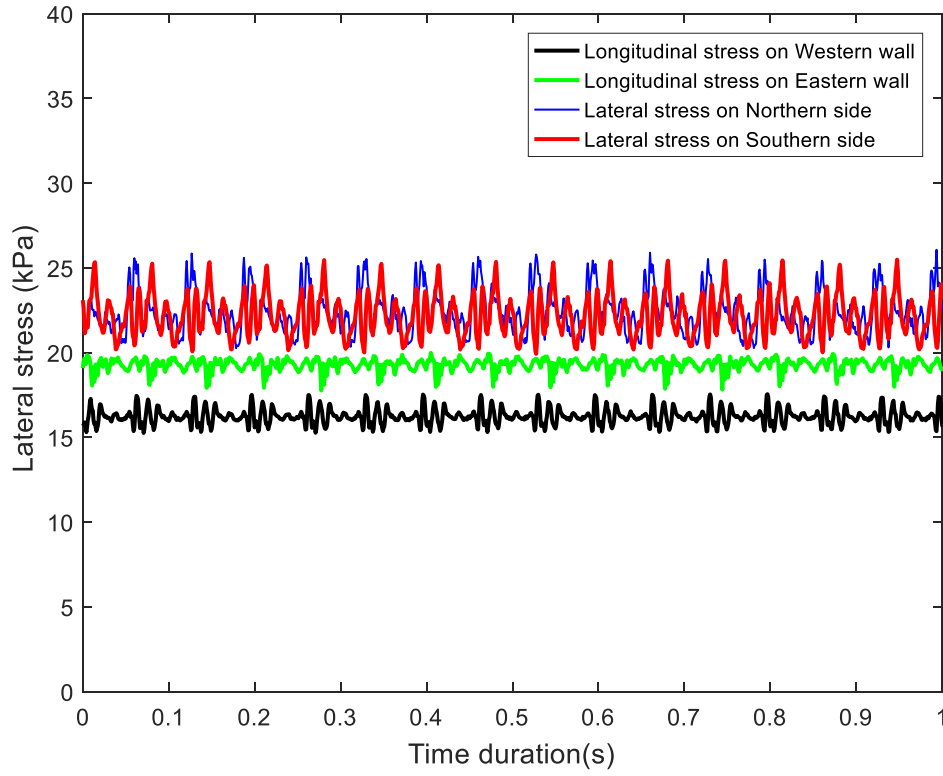
(a) time domain; (b) frequency domain



669

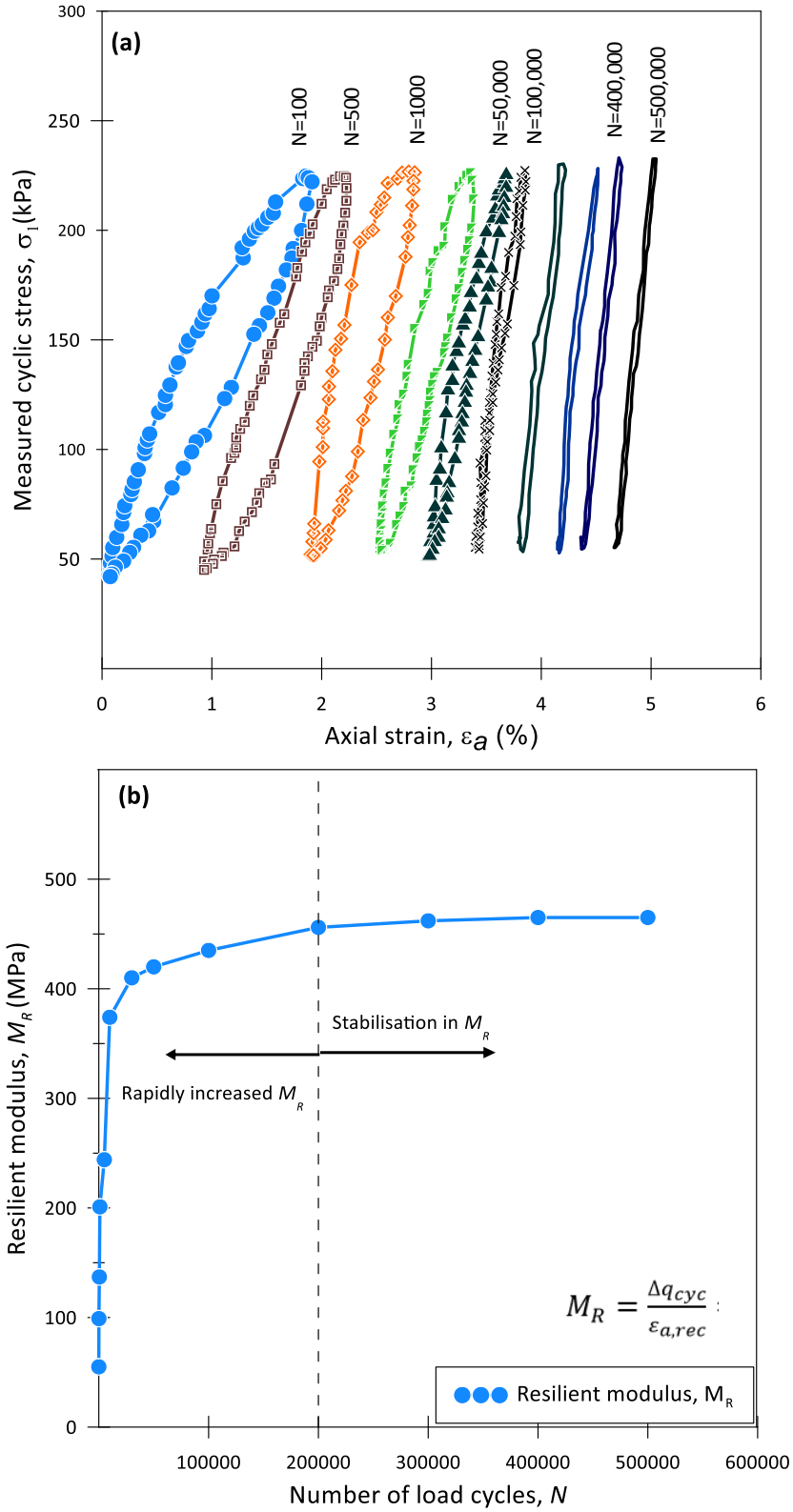
670 Figure 11. Variations of measured vertical stress ( $\sigma_v$ ) with the depth of track substructure at varying  
 671 load cycles ( $N$ )

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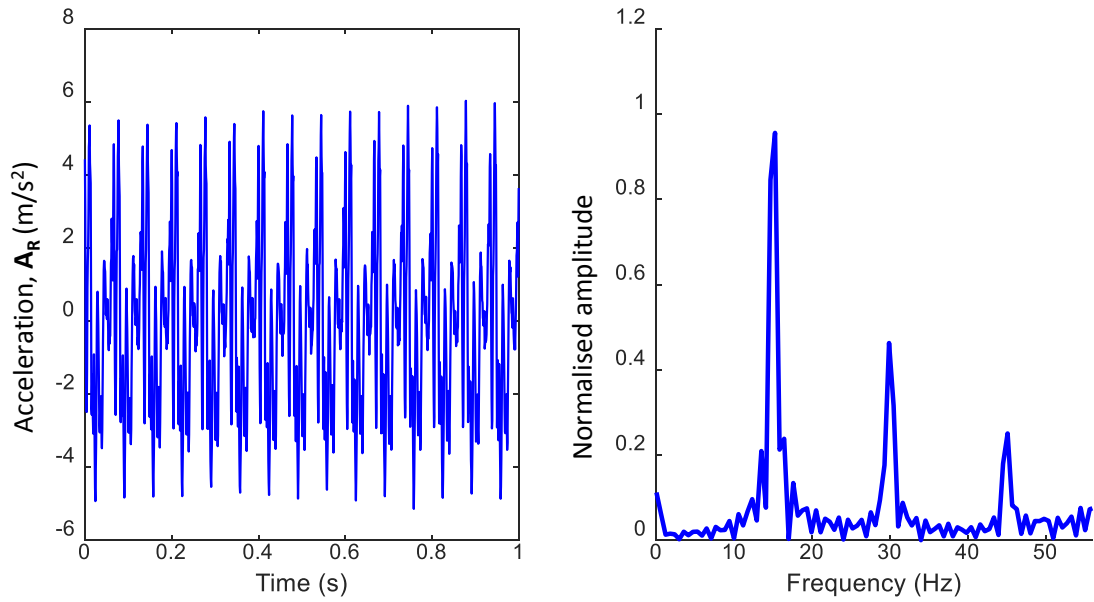
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674 Figure 12. Typical responses of horizontal stresses ( $\sigma_2$ ,  $\sigma_3$ ) in ballast measured in longitudinal and  
 675 transverse directions during the test

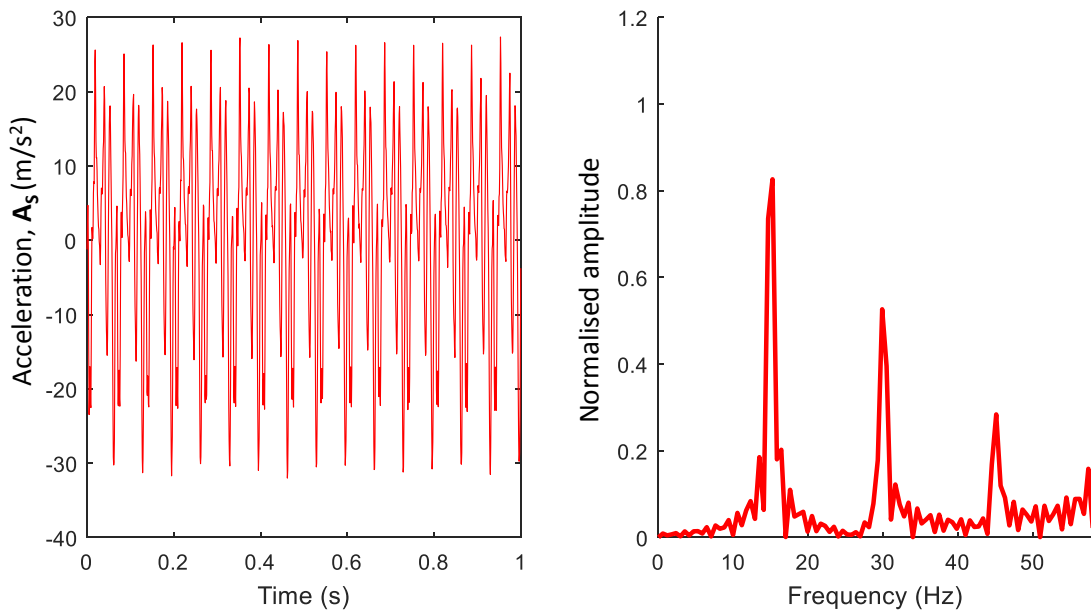


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677 Figure 13. (a) Hysteresis cyclic stress– strain responses; and (b) measured resilient modulus ( $M_R$ )



**(a)** Measured accelerations on rail



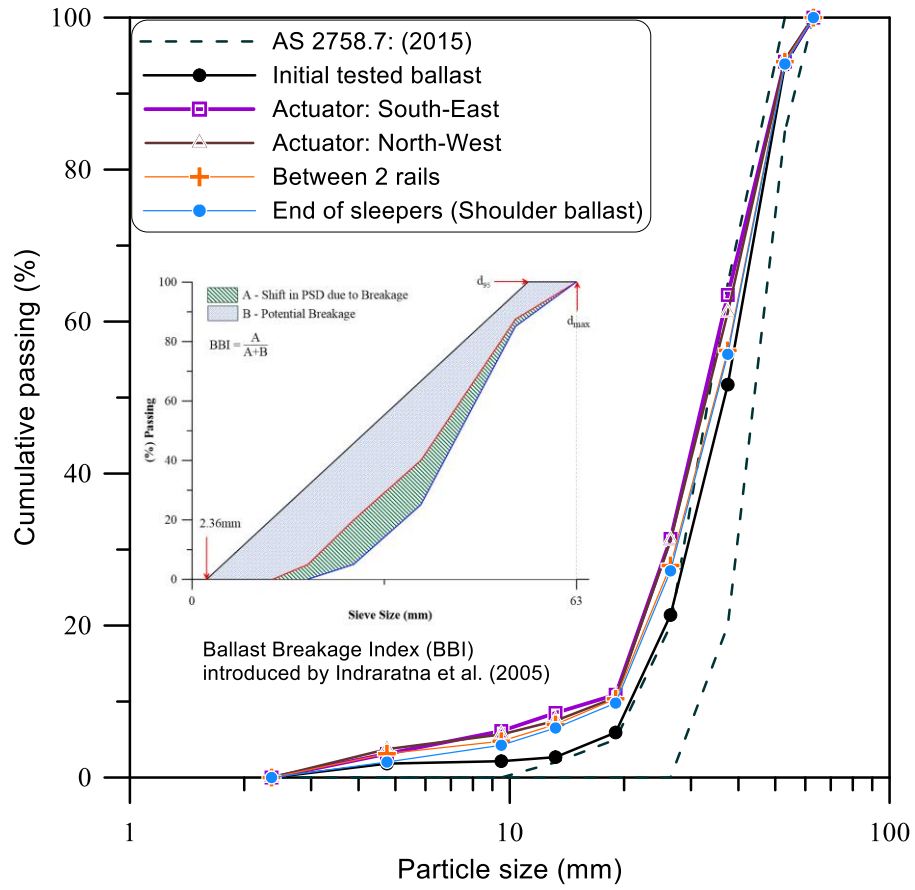
**(b)** Measured accelerations on sleeper

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Figure 14. Measured accelerations of rail and sleeper during the test

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682 Figure 15. Measured changes in particle size distributions of ballast for quantifying ballast breakage  
 683 index (*BBI*)

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# Large-scale Testing Facility for Heavy Haul Track

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**Abstract:** Given the substantially increased demand for increased axle loads of heavy haul trains, there is an imperative need to develop sustainable track infrastructure. When subjected to heavy axle loading, ballast aggregates rapidly break down, compromising the particle friction and associated load bearing capacity. Therefore, understanding the deformation and degradation (breakage) of ballast subjected to various boundary and loading conditions is crucial for improved track design and performance monitoring. Ideally, field testing should be carried out in real-life tracks to avoid laboratory scale and boundary effects, but field tests are often expensive, time-consuming and may disrupt rail traffic, hence not always feasible. A prototype test facility that can simulate appropriate axle loading and boundary conditions for standard gauge heavy haul tracks is presented in this paper. In collaboration with more than a dozen Universities and Industry organisations, Australia's first and only National Facility for Heavy-haul Railroad Testing (NFHRT) has recently been constructed and is now fully operational. This new facility enables a real-size (1:1 scale) instrumented track section to be subjected to continuous cyclic loading simulated via two pairs of dynamic actuators in synchronized operation. The results of a typical test are presented in this paper including the measured track settlement and lateral deformation, transient vertical and lateral stresses, rail and sleeper accelerations, resilient modulus and breakage of ballast. The test results show that an average track settlement of about 14 mm and lateral



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4 39 displacements up to 9 mm are recorded after 500,000 load cycles. Subjected to a 25-tonne axle load,  
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6 40 the maximum vertical stress measured at the sleeper-ballast interface is about 225 kPa and this  
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8 41 attenuates with depth. The test results of this iconic facility are generally consistent with actual field  
9  
10 42 measurements obtained in heavy-haul tracks located in the towns of Singleton and Bulli in the state of  
11  
12 43 New South Wales, Australia.

13  
14 44 *Keywords: Ballast, Rail geotechnics, Heavy hauls, Breakage, Prototype test*  
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20 46 **1. Introduction**  
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22

23 47 The current track infrastructure in various parts of Australia cannot sustain the increasing demand to  
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25 48 transport freight to and from ports in regional and rural areas. This growth in demand for faster and  
26  
27 49 heavier trains leads to an increase in the frequency and load intensity on track substructure. As a result,  
28  
29 50 ballasted tracks settle differentially, particularly on weak subgrades with poor drainage, they become  
30  
31 51 fouled due to clay pumping and ballast breakage, and the rail tracks buckle due to insufficient confining  
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33 52 pressures from the shoulder ballast aggregates (Suiker and Borst 2003, Zhai *et al.* 2004, Indraratna *et*  
34 53 *al.* 2016, 2020a, Sayeed and Shahin 2017, Sol-Sánchez *et al.* 2020, Powrie *et al.* 2019, Guo *et al.* 2020).

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36  
37 54 Upon repeated train loading, fouling of tracks occurs along with ballast degradation. Fouling agents  
38  
39 55 could decrease the shear strength of ballast and reduce the drainage capacity of ballasted track  
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41 56 (Indraratna *et al.* 2011, Touqan *et al.* 2020). Huang *et al.* (2009) studied track problems associated with  
42  
43 57 fouling issues in Wyoming, US and found that coal dust was the worst fouling agent for its impact on  
44  
45 58 track substructure and roadbed. When the coal dust fouling percentage increased, the ballast shear  
46  
47 59 strength steadily decreased. In particular, wet fouling was found to exacerbate this trend. Bian *et al.*  
48 60 (2017) investigated track problems related to the hanging of sleepers and showed that a hanging tie  
49  
50 61 would lead to an increase in dynamic impact loading on the ballast and therefore further deteriorate the  
51  
52 62 track substructure. Another track problem receiving increasing attention worldwide is associated with  
53  
54 63 the transition zones between a ballasted track and a concrete bridge deck leading to enhanced dynamic  
55  
56 64 load, differential settlement and accelerated track degradation (Hu *et al.* 2019, Mishra *et al.* 2014,  
57 65 Paixão *et al.* 2016).

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60 66 Previous research carried out worldwide over the past decades has shown that ballast breaks down and  
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62 67 progressively deteriorates under freight train loading. Over the years, heavy trains and faster passenger  
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4 68 services have caused progressive deterioration of ballast which in turn results in loss of track geometry;  
5  
6 69 this compromises safety and leads to more frequent maintenance (Selig and Waters 1994, Priest *et al.*  
7  
8 70 2010, Esveld 2014, Bian *et al.* 2020). In response, Australian railway companies are now emphasising  
9  
10 71 on high-speed train corridors (5 routes across NSW) and heavier freight operations (Brisbane-  
11  
12 72 Melbourne Inland rail) to achieve more efficient and cost effective services, particularly in the mining  
13  
14 73 and agricultural sectors. One of the major challenges in delivering heavier and faster trains in Australia  
15  
16 74 is not the immediate cost, but the geotechnical problems associated with poor ground conditions and  
17  
18 75 soft coastal terrain (Budiono *et al.* 2004, Powrie *et al.* 2007, Sayeed and Shahin 2016, Indraratna and  
19  
20 76 Ngo 2018).

21  
22 77 The geotechnical challenges surrounding the performance of heavy hauls and high-speed trains on  
23  
24 78 ballasted railway tracks are numerous, particularly when a track profile is built along the coastal areas  
25  
26 79 of Australia (Indraratna *et al.* 2018a, Cai *et al.* 2020). Typical problems that arise in track substructure  
27  
28 80 include: (i) ballast breakage; (ii) mud pumping in railway tracks constructed on clays and other soft  
29  
30 81 soils (Indraratna *et al.* 2020b), consisting of the upward migration of subgrade clays and fine silts  
31  
32 82 (slurry) under heavy traffic loading, which promotes settlement by “lubrication” and increases the risk  
33  
34 83 of train derailment (Wang *et al.* 2020); (iii) ballast fouling due to voids in aggregates filled with  
35  
36 84 relatively finer materials or fouling agents that reduce the shear strength and lead to poor drainage  
37  
38 85 (Huang *et al.* 2009, Li *et al.* 2015, Touqan *et al.* 2020); and (iv) differential settlement and shear failure  
39  
40 86 that may occur on tracks built on highly compressible soft clays residing in low lying terrain, and with  
41  
42 87 very low undrained shear strength.

43 88 With this increasing demand for freight trains in Australia, it would be inappropriate to operate heavy  
44  
45 89 hauls on ballasted tracks built on formation soils without testing on large-scale sections of prototype  
46  
47 90 model track. Since existing Australian railway design practices are mainly based on static loading  
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49 91 conditions, they are only suited to shorter trains with low axle loads travelling at speeds of less than  
50  
51 92 80 km/h. In some parts of Australia, freight trains can be almost 4 km long, so the ballast degradation  
52  
53 93 (breakage), mud pumping of certain formation soils, and differential settlements must be studied and  
54  
55 94 quantified to achieve a resilient track design and avoid hefty maintenance costs after construction  
56  
57 95 (Raymond and Bathurst 1994, Brown *et al.* 2007, Biabani *et al.* 2016, Ferreira and Indraratna 2018,  
58  
59 96 Indraratna *et al.* 2018b, 2019, Powrie *et al.* 2019).

60 97 Conventional triaxial testing is a popular approach of evaluating the strength and breakage of ballast  
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4 98 aggregates in the laboratory (Raymond and Davies 1978, McDowell *et al.* 2005, Brown *et al.* 2007,  
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6 99 Aursudkij *et al.* 2009, Sevi *et al.* 2009, Zhang *et al.* 2017, Harkness *et al.* 2016, among others).  
7  
8 100 However, the discrepancy between the actual shape and size of particles in the field and the much  
9  
10 101 smaller particle sizes adopted in conventional laboratory equipment contributes to inaccurate load and  
11  
12 102 deformation responses measured in the laboratory. Moreover, since the bottom boundary is rigid and  
13  
14 103 is typically less than 600mm deep, this boundary condition cannot simulate the actual field track  
15  
16 104 substructure. This means that testing coarse aggregates in conventional apparatus can yield misleading  
17  
18 105 results due to the disparity in size between particle and equipment and the limited depth of subgrade  
19  
20 106 (Lim *et al.* 2005, Peijun and Xubin 2007, Indraratna *et al.* 2018a). Previous large-scale triaxial tests  
21  
22 107 carried out by many researchers have shown that the ratio between the size of the testing chamber and  
23  
24 108 the particle size must be greater than 7-8 to reduce boundary effects (Marachi *et al.* 1972, Marsal 1973,  
25  
26 109 Lade *et al.* 1996).

27 110 To alleviate these size dependent issues, examine a range of Australian ground conditions and  
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29 111 integrated track components, the National Facility for Heavy-haul Railroad Testing (NFHRT) was the  
30  
31 112 first to be designed and built in-house at Russell Vale, NSW, Australia. The NFHRT allows for a full  
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33 113 size instrumented railway track section to be tested so that the effects of track substructure can be  
34  
35 114 captured. Such a facility could not be established through purely commercial means; rather, it was  
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37 115 designed and built in close cooperation with the Australian rail industry, a consortium of transport  
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39 116 research centres in several Australian Universities and the Australian Research Council, c/o Ministry  
40  
41 117 of Education, under the leadership of the first author.

42  
43 118 In fact, the Australian rail industry has strongly promoted the state-of-the-art test facilities for heavy  
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45 119 haul track modelling, and this was the main driver for constructing the first NFHRT under  
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47 120 Commonwealth government funding channelled through the Australian Research Council. In  
48  
49 121 particular, the NFHRT was designed and built in close cooperation with Australian Rail Track  
50  
51 122 Corporation (ARTC) and Sydney Trains, whereby an array of typical ground conditions and integrated  
52  
53 123 track components were considered in relation to the national flagship project Melbourne to Brisbane  
54  
55 124 Inland Rail (MBIR), one of the longest heavy haul tracks to be completed soon.

56  
57 125 Although similar test facilities have also been built in other countries (Brown *et al.* 2007, Bian *et al.*  
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59 126 2014, Abadi *et al.* 2016, Li *et al.* 2018, Bian *et al.* 2020, Hasnayn *et al.* 2020), these were built mainly  
60  
61 127 for high-speed passenger trains capturing more favourable foundation characteristics in cold regions  
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4 128 (e.g., stiff boulder clays and glacial tills) or for concrete slab tracks used for short high speed commuter  
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6 129 trains (Zhang *et al.* 2019a, 2019b, Zhai *et al.* 2020, Li *et al.* 2020). Conversely, the Australian soft soil  
7  
8 130 terrains for very long heavy axle freight trains are considerably different, including highly compressible  
9  
10 131 black soils and deposits of upper Holocene soft clays. In this regard, the overall objective of the NFHRT  
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12 132 is to contribute to innovative and more cost-effective designs for heavy haul tracks built on an array of  
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14 133 problematic ground conditions.

15  
16 134 It is noteworthy that the true moving load effect cannot be properly modelled using the NFHRT, as the  
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18 135 cyclic loading is applied by four dynamic actuators in synchronized operation. This facility is mainly  
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20 136 for simulating heavy haul ballast tracks for high axle freight trains that operate at low speeds. At high  
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22 137 speeds exceeding say 130 km/h, there is significant principal stress rotation under moving loads, which  
23  
24 138 cannot be simulated accurately by this facility as it only has two pairs of actuators. For simulating a  
25  
26 139 true moving load at high speeds (exceeding say 130 km/h), one needs more than two pairs of actuators  
27  
28 140 acting along a greater number of sleepers (Bian *et al.* 2014). [In addition, the dynamic and impact effects](#)  
29  
30 141 [due to track irregularities could not be captured in these model tests, and this is a limitation of the](#)  
31  
32 142 [current study.](#)

33  
34 143 The main objective of this research is to introduce Australia's NFHRT that has recently been  
35  
36 144 constructed and is now fully operational, as well as to validate the observed results against past field  
37  
38 145 measurements available from heavy haul tracks located in the towns of Bulli and Singleton (NSW,  
39  
40 146 Australia). The results of the first test are presented in this paper and compared with the available field  
41  
42 147 monitoring data. These results will also serve as a benchmark for future tests considering varying track  
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44 148 substructure conditions (e.g., excessive settlement of compressible soft soils and instability of saturated  
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46 149 subgrade including mud-pumping), the effectiveness of artificial inclusions such as geosynthetics for  
47  
48 150 improved track stability and the vibration mitigation of carriage-track-foundation interactions using  
49  
50 151 damping elements made of recycled rubber. Details of the NFHRT, test set up, instrumentation, and  
51  
52 152 the results of the first test are presented in the following sections.

## 53 153

## 54 154 **2. National Facility for Heavy-haul Railroad Testing**

### 55 155 ***2.1. Design and construction of the NFHRT***

56 156 The NFHRT consists of a large-scale laboratory test facility that allows the testing of a fully

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4 157 instrumented ballasted track section at 1:1 prototype scale. It includes a test pit, loading frames, a  
5  
6 158 hydraulic servo-controlled system with four dynamic actuators and a high capacity hydraulic power  
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8 159 unit, an electrical system, an instrumentation and data acquisition system, and a 5-tonne overhead  
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10 160 crane. A schematic of the NFHRT is shown in Figure 1a.

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12  
13 161 A 6.0m-long  $\times$  6.0m-wide  $\times$  2.3m-deep test pit was excavated, and four 900mm-thick reinforced  
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15 162 concrete walls and a 600mm-thick reinforced concrete floor were then constructed (Fig. 1b). The  
16  
17 163 hydraulic actuators and power unit of the NFHRT were designed, fabricated and then assembled (Fig.  
18  
19 164 1c). A trench for the hydraulic pipework (9.13m long  $\times$  1.35m wide  $\times$  0.5m high) was built with  
20 165 reinforced concrete walls (Fig. 1d).

21  
22  
23 166 Track materials such as ballast, capping, structural fills, subgrade, and a drainage layer are installed  
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25 167 beneath a rail-sleeper assembly to accurately estimate their actual response when subjected to realistic  
26  
27 168 loading conditions. A hybrid hydro-electrical substation with heavy duty hose connections from the  
28  
29 169 hydraulic pipework to the four dynamic actuators provide the cyclic loading capable of simulating up  
30 170 to 40-tonne axle trains operating at speeds up to 200km/h. The actuators apply the designed cyclic  
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32 171 loading directly onto the rails and are fully controlled through the computerised operating system also  
33  
34 172 linked to an automated data acquisition system.

## 35 36 37 173 **2.2. Materials and test procedures**

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39 174 In this first test, a 75mm thick drainage layer consisting of coarse grained gravel was placed at the  
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41 175 bottom of the test pit (Fig. 2a) overlain by a geotextile filter to avoid clogging. A 795mm-thick layer  
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43 176 of fine-grained subgrade soil (classified as CL according to the Unified Soil Classification System)  
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45 177 was then installed and spread by a mini excavator. The subgrade was compacted in four sub-layers to  
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47 178 a dry unit weight of 16.5 kN/m<sup>3</sup> (moisture content,  $w=20\%$ ) using a lightweight compaction plate.  
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49 179 Pressure cells, soil moisture sensors and pore water pressure gauges were installed within the subgrade  
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51 180 to measure the respective parameters during testing (Fig. 2b and 2d). An irrigation system consisting  
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53 181 of a series of perforated pipes wrapped with a geotextile filter was installed in the subgrade layer to  
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55 182 control the water content and the degree of saturation of the track foundation (Fig. 2c).

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57 183 A 650mm-thick structural fill layer (moisture content,  $w=11.5\%$ ) was placed on top of the subgrade  
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59 184 and compacted in sub-layers of 150 mm thick to achieve a dry unit weight of 18.5 kN/m<sup>3</sup>, using similar  
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61 185 procedures to those described earlier for the subgrade layer. A 180mm thick capping layer (sub-ballast)

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4 186 consisting of a sand and gravel mixture was then placed over the structural fill (Fig. 3a) and compacted  
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6 187 in two sub-layers (90mm thick) to a dry unit weight of  $19.5 \text{ kN/m}^3$ , corresponding to about 90% of  
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8 188  $\gamma_{dmax}$  based on the standard Proctor compaction method in accordance with AS 1289.5.1.1 (2017). A  
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10 189 heavier compaction plate was used to compact the sub-ballast material, giving the higher compaction  
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12 190 requirements of this layer. To ensure all the materials from the bottom subgrade layer to the capping  
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14 191 layer had been compacted to the desired unit weight, sand cone tests were conducted following the  
15 192 ASTM D1556 (2007) (Fig. 3b). Pressure cells and horizontal displacement transducers were then  
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17 193 placed over the capping layer, as shown in Figure 3c.  
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20 194 Ballast (latite basalt aggregates) was obtained from the Bombo quarry, about 100km South of Sydney,  
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22 195 then cleaned and sieved following the Australian Standards (AS 2758.7, 2015). The ballast was  
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24 196 compacted in three sub-layers (100mm-thick) to achieve a density of nearly  $16 \text{ kN/m}^3$  and the total  
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26 197 thickness of the load-bearing ballast was 300mm, as typically used in actual Australian heavy-haul  
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28 198 tracks (Fig. 3d). The selected densities for the track substructure layers are comparable with other  
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30 199 studies reported earlier by Suiker *et al.* (2005), Aursudkij *et al.* (2009), Biabani *et al.* (2016) and  
31 200 Anderson and Fair (2008).  
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34 201 A system of rails and sleepers provided by the Australian Rail Track Corporation (ARTC) was laid  
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36 202 onto the ballast layer (Fig. 3e) and additional ballast aggregates were then placed to simulate the crib  
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38 203 and shoulder ballast. The loading frames were bolted in position and the four dynamic actuators were  
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40 204 installed to apply a dynamic train loading (Fig. 3f). The particle size distribution (PSD) of the ballast,  
41 205 capping, structural fill and subgrade materials used for this test are shown in Figure 4.  
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### 44 206 **2.3 Instrumentations**

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47 207 Figure 5a presents a plan view of the instrumentation installed into the track substructure such as  
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49 208 settlement pegs (1-16), horizontal displacement transducers ( $E_{1T}$ ,  $E_{1B}$ ,  $E_{2T}$  and  $E_{2B}$ ), pressure cells and  
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51 209 the positions of the rail and sleeper system. Figure 5b is a cross section (North-South section) of the  
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53 210 testing pit showing the locations of the sensors. Twenty rapid response hydraulic pressure cells were  
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55 211 installed at different locations and depths to measure the transient vertical and horizontal stresses;  
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57 212 sixteen settlement pegs were installed at varying depths in the structural fill, capping and ballast layers  
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59 213 to measure the permanent vertical deformations. Four horizontal displacement transducers were placed  
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61 214 bellow the loaded sleepers at two different depths (i.e., two of which were installed underneath the  
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4 216 were installed on the rail and sleeper to measure acceleration (vibration) during the tests (Fig. 6a). In  
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6 217 addition, eight pore water pressure transducers, four moisture sensors and four water potential sensors  
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8 218 were placed in the subgrade to monitor the excess pore pressure and/or the changes of water content  
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10 219 and water potential, depending on the moisture conditions of the subgrade layer in each test. These  
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12 220 sensors were installed in the subgrade layer for future tests considering the submergence of subgrade  
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14 221 through the irrigation system to study track problems associated with flooded track conditions in low-  
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16 222 lying coastal areas as well as the saturated subgrade instability, e.g., mud-pumping. Measurements  
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18 223 from these sensors will be available for the future tests when the track substructure is made to be  
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20 224 saturated.

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22 225 All the sensors and instruments were calibrated before testing. A data acquisition system controlled by  
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24 226 a host computer automatically recorded all the data collected during the test (Fig. 6b). The selected  
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26 227 sample rate (data logging frequency) for all the signals was 1200 Hz.

#### 28 228 ***2.4 Cyclic loading characteristics***

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31 229 In this test, the load was selected based on a typical Australian freight train having an equivalent 25-  
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33 230 tonne axle load. Therefore, a maximum load of 12.5 tonnes (125 kN) was applied by each dynamic  
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35 231 actuator, simulating a realistic wheel load. The applied loading characteristics are schematically shown  
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37 232 in Figure 7 corresponding to a vertical load of  $P_{max}=125$  kN,  $P_{min}=15$  kN and  $P_{mean}=70$  kN,  
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39 233 corroborating to a freight train of 25-tonne axle load. The minimum load of 15kN ensured continual  
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41 234 contact between the dynamic actuators and the rails during the test.

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43 235 The applied frequency of  $f=15$  Hz in the experimental program is assumed to cover a realistic range of  
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45 236 heavy haul train speeds of 60-80km/h on standard gauge tracks, based on Indraratna et al. (2011), Sun  
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47 237 et al. (2016) and Navaratnarajah et al. (2018). In reality, the frequency is not only dependent on the  
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49 238 train speed but also on track geometry, bogey spacing, rest periods, variations in cyclic and impact  
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51 239 loading among other variables~~The cyclic load was applied at a frequency of  $f=15$  Hz that simulated an~~  
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53 240 ~~operational speed of less than 80 km/h, mimicking the upper bound of heavy haul trains in Australia.~~  
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55 241 For typical Australian freight train speeds (50–60 km/h in most cases, with a maximum of 80km/h for  
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57 242 ~~very long straight sections~~), the loading frequency was estimated by considering the distance between  
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59 243 the last wheel of the front bogie and the first wheel of the next bogie on a standard gauge track in  
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61 244 Australia. As the axle distance is much smaller than the length between bogie centers ( $L_b$ ) or vehicle  
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63 245 length, the two rear axles of a leading wagon and two front axles of a trailing wagon would represent  
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4 246 the highest generated frequency (Indraratna *et al.* 2011). Heavy haul trains in Australia are often 4-5  
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6 247 km long and they travel on standard gauge tracks at relatively low speed (@ 40-60 km/h in most cases  
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8 248 and rarely exceed 70k/h), and the applied frequency in the laboratory is indeed corroborated with the  
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10 249 track geometry and train speed (e.g. Indraratna et al. 2011, Sun et al. 2016, Navaratnarajah et al. 2018).  
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12 250 It is also noticed that there can be several variables including the sleeper spacing, speed of train, track  
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14 251 irregularities, occasional impact loading, influence of rest periods, variation in cyclic loading due to  
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16 252 non-uniform axle spacing etc. that can contribute to the real-life frequency in contrast to the simplified  
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18 253 (constant) experimental magnitude of frequency.  
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20 254 The actuators worked in synchronised pattern up to  $N=500,000$  load cycles to simulate the realistic  
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22 255 repeated loading on the rails, but given the limitation of having only two pairs of actuators, the ideal  
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24 256 simulation of moving loads from the bogies of a long train was not possible. As mentioned earlier, the  
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26 257 design of this equipment is reasonable for slow moving heavy haul trains in Australia, but not for  
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28 258 representing high speed passenger trains where significant principal stress rotation occurs under fast  
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30 259 moving loads. In addition, it is noted that the loading sequence capturing rest periods is not considered  
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32 260 in this study. This is because the worst conditions occur when very long heavy haul trains apply  
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34 261 continual loading over a substantial period of time, and busy freight tracks in the mining hubs have  
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36 262 relatively small rest periods. For example in Western Australia different mineral ore trains can travel  
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38 263 over very long distances at slow speeds (40-60 km/h) from source to port (sometimes up to 300 km)  
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40 264 regularly most of the day, and the ballast relaxation during relatively short rest periods between these  
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42 265 slow-moving trains can be ignored. For instance for iron ore trains that can be up to 6 km long moving  
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44 266 at only 40 km/h, the worst-case scenario simulated in the laboratory is without any rest period, so that  
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46 267 the fatigue of ballast is maximised during testing to determine the maximum deformation, i.e.  
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48 268 settlement and lateral movement. Both the axle load and loading frequency influence the resulting  
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50 269 settlement, but the axle load magnitude is more dominant than the frequency. Nevertheless, the load  
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52 270 frequency must still be highlighted, because that is the only loading parameter in cyclic laboratory  
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54 271 testing that is related to the train speed (Esveld, 2014; Indraratna et al. 2011). In other words, the  
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56 272 number of axle loads passing through a specific in situ reference point (worksite) over a given period  
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58 273 of time is related to the frequency.  
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### 3. Results and discussion

#### 3.1. Measured vertical settlement

Figure 8 shows the accumulated track settlement after being subjected to a 25-tonne axle load at a frequency of  $f=15$  Hz, as recorded by the settlement pegs installed below the sleepers ( $S_1, S_5, S_{10}$  and  $S_{16}$  – Fig. 5a). It can be concluded that the vertical displacement ( $S_v$ ) of ballast increased rapidly up to about  $N=50,000$  cycles due to its initial densification and subsequent packing as the corners of the sharp angular ballast aggregates began to break ( $S_v = 6.2$  mm to 8.7 mm). However, once the aggregates began to stabilise the rate of vertical displacement gradually decreased and remained relatively constant after  $N=200,000$  cycles ( $S_v = 8.7$  mm to 12.1 mm). This shows the aggregate density has reached threshold compression and would resist further rearrangement and densification with additional cycles. The measured final track settlement, taking the average of the four settlement pegs, was about  $S_v=14.2$  mm. These observations are in agreement with the data obtained in the laboratory (Indraratna *et al.* 2013) and the field measurements taken at the Bulli and Singleton tracks (Indraratna *et al.* 2010, 2014). It is noted that while the track settlement measured at the Bulli track matched those measured at the NFHRT facility, field data from the Singleton track showed higher vertical settlement, especially after  $N=200,000$  cycles. This could be due to the track section at Singleton being built on a flood plain with a 7-10 m thick layer of alluvial silty clay, which could lead to greater vertical deformation of the track.

#### 3.2. Measured lateral displacement

Figure 9 presents the lateral displacement ( $S_h$ ) of the ballast layer as recorded by the four horizontal displacement transducers, two of which ( $E_{1T}, E_{2T}$ ) were placed underneath the sleepers and the other two ( $E_{1B}, E_{2B}$ ) were installed at the boundary between the ballast and capping layers at the bottom of the ballast layer (Fig. 5). The lateral displacement of ballast measured at the Bulli track and from laboratory tests performed earlier (Indraratna *et al.* 2010, 2013) are also shown in Figure 9 for comparison purposes. The measurements from all the displacement transducers show consistent increases in lateral displacement with increased  $N$ . The ballast aggregates showed a significant horizontal spread ( $S_h=5.8$  mm - 6.2 mm) within the initial  $N=100,000$  cycles, followed by a gradual increase in  $S_h$  up to  $N=300,000$  cycles, after which  $S_h$  remained nearly constant towards the end of the test. The final horizontal displacement of the track varied from  $S_h=6.8$  mm - 9.1mm, depending on the location of each measurement. This trend is similar to those observed earlier in actual rail tracks and in the laboratory by Indraratna *et al.* (2013). However, the data from the field trial at Bulli track show

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4 305 higher lateral displacements than those measured at the NFHRT. This is possibly because moving  
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6 306 freight trains generate greater impact forces due to wheel or rail irregularities such as flat wheels,  
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8 307 dipped rails, expansion gaps and rail corrugations, which could accelerate the degradation and lateral  
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10 308 spreading of ballast (Auersch 2015, Ferreira and Indraratna 2018, Indraratna *et al.* 2020a).  
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12 309 Furthermore, in the NFHRT two aluminium panels (200mm-high) were placed on both sides of the  
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14 310 shoulder ballast to maintain track geometry during the commissioning process, which may have  
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16 311 provided some additional confinement to the ballast layer leading to slightly lower lateral deformations  
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18 312 when compared to the field measurements at Bulli track.  
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### 20 313 **3.3. The vertical and lateral stresses**

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23 314 Figure 10a shows the typical vertical stresses recorded over time at different depths of the track  
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25 315 substructure (from the top surface of the ballast to the drainage layer) during the test. Pressure cells  
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27 316 were placed between the sleepers and ballast, beneath the ballast layer, between the capping and  
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29 317 structural fill, and on top of the subgrade and drainage layers to measure the stresses at different depths  
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31 318 (Fig. 5b). Under a 25-tonne axle load the maximum vertical stress at the sleeper-ballast interface is  
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33 319 about  $\sigma_v = 225$  kPa, and the  $\sigma_v$  attenuates with depth. The maximum vertical stresses at the top surface  
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35 320 of the capping layer, the structural fill, the subgrade and drainage layers are measured as  $\sigma_v = 151, 132,$   
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37 321  $98,$  and  $54$  kPa, respectively. The vertical stresses at different depths plotted on the frequency domain  
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39 322 are shown in Figure 10b. Here, the cyclic response of the stresses recorded in the ballast layer peaks at  
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41 323  $f=15$ Hz, but these peaks decrease slightly in the underlying layers showing how the loading frequency  
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43 324 attenuates with depth.

44 325 Figure 11 illustrates the vertical stress ( $\sigma_v$ ) measured at different layers of the track substructure and its  
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46 326 variation with the number of load cycles. It is evident that the dynamically induced stress in the ballast  
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48 327 layer increases with  $N$  (e.g., at the first  $N=500$  cycles,  $\sigma_v = 175$  kPa, and then  $\sigma_v$  continues to increase  
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50 328 to  $\sigma_v = 225$  kPa at the end of the test,  $N=500,000$  cycles). On the other hand, the vertical stress  $\sigma_v$   
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52 329 decreases with the depth of the test pit where the  $\sigma_v$  recorded in the subgrade and drainage layers is  
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54 330 approximately  $95$  kPa and  $48$  kPa, respectively. The vertical stresses obtained in a previous laboratory  
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56 331 study and on the field tracks (Singleton and Bulli tracks) are also plotted in Figure 11 for comparison  
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58 332 purposes (Indraratna *et al.* 2010, 2014, Navaratnarajah *et al.* 2018). Given that the laboratory  
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60 333 equipment used in the previous study has a limited boundary, only the stresses up to a depth of  $500$  mm  
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62 334 below the surface of ballast are presented. The  $\sigma_v$  reported in previous studies shows some fluctuations  
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where  $\sigma_v$  between the sleeper and ballast varies from 172 kPa to 300 kPa, and then decreases to about 38 kPa (Bulli track) and 87 kPa (laboratory test) when measured at the top surface of the capping layer.

Figure 12 shows the horizontal stresses ( $\sigma_h$ ) in the ballast layer obtained in the longitudinal direction parallel to the rails and in the transverse direction parallel to the sleepers. Data were monitored by two pressure cells placed at the northern and southern sides of the track (lateral confinement in the transverse direction -  $\sigma_3$ ) and two pressure cells placed on the eastern and western walls to measure the longitudinal stresses ( $\sigma_2$ ). It is seen that the horizontal stress ( $\sigma_h$ ) remains almost unchanged during the test. Lateral confinement in the transverse direction, commonly known as the confining pressure ( $\sigma_3$ ), is around  $\sigma_3=22$  kPa to 25 kPa during the test, whereas the longitudinal stress (the intermediate stress,  $\sigma_2$ ) varies from  $\sigma_2=15$  kPa to 20 kPa. The lateral stresses in the transverse direction exceeded those in the longitudinal direction possibly because the latter were measured by pressure cells fixed to the vertical steel walls, which were further away from the locations of load application (actuators). The confining pressures measured in this study are generally consistent with those recorded during previous field monitoring programmes carried out in Australian heavy-haul tracks.

### 3.4. Measured resilient modulus

The resilient modulus ( $M_R$ ) of ballast can be calculated as the ratio between the deviatoric stress ( $\Delta q_{cyc}$ ) and the resilient (recoverable) axial strain ( $\varepsilon_{a,rec}$ ) during loading-unloading stage, as given by:

$$M_R = \frac{\Delta q_{cyc}}{\varepsilon_{a,rec}} = \frac{q_{cyc,max} - q_{cyc,min}}{\varepsilon_{a,rec}} \quad (1)$$

The resilient (recoverable) axial strain ( $\varepsilon_{a,rec}$ ) was obtained at a given number of loading-unloading cycles ( $N$ ) using the data bursting approach to determine the resilient modulus ( $M_R$ ) of ballast. During the test, the relevant sets of data bursting were initiated at  $N= 1, 50, 100, 500, 1000, 5000, 10,000, 50,000, 100,000, 200,000, 300,000, 400,000, \text{ and } 500,000$ ; and the recoverable axial strains ( $\varepsilon_{a,rec}$ ) during unloading were determined by subtracting the measured axial strains of the corresponding loading-unloading cycle. Figure 13a shows the typical stress-strain hysteresis loops plotted for a given load cycle. It can be observed that the areas of the hysteresis loops are reduced as the number of load cycles ( $N$ ) increases, which indicates that ballast aggregates become more compacted and respond more elastically with increased  $N$ . The variation of resilient modulus  $M_R$  with  $N$  presented in Figure 13b shows a rapid increase of  $M_R$  within the first  $N = 200,000$  cycles ( $M_R=462$  MPa), after which the rate at which  $M_R$  increased becomes marginal. The rapid compression and densification of ballast during

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4 364 the initial load cycles increases track stiffness, leading to a rapid increase in  $M_R$  at the beginning of the  
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6 365 test. After  $N=200,000$  loading cycles the ballast aggregates may move to the shakedown stage, which  
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8 366 causes the  $M_r$  to remain relatively unchanged (Le Pen *et al.* 2016, Sun *et al.* 2019).  
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### 10 367 **3.5. Rail and sleeper acceleration**

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14 368 As mentioned, two triaxial accelerometers ( $A_R$  and  $A_S$ ) were installed on the rail and sleeper to measure  
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16 369 acceleration (vibration) during the tests. The acceleration of the rail and sleeper plotted in time and  
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18 370 frequency domains are shown in Figure 14. Here, the accelerations measured at the sleeper ( $A_S$ ) are  
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20 371 greater than those recorded at the rail ( $A_R$ ), with a maximum value of  $A_s = 27.2 \text{ m/s}^2$  compared to the  
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22 372 highest value of  $A_R = 5.6 \text{ m/s}^2$ . It is noteworthy that the rails were connected to six concrete sleepers  
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24 373 creating a stronger system that could prevent from excessive vertical vibration, while the edge of  
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26 374 sleeper was more prone to vertical displacement due to sitting on the discrete ballast aggregates. The  
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28 375 accelerations were measured at the end of the test where the ballast shoulder has significantly displaced  
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30 376 laterally and could cause the condition of hanging sleeper. As a result, there was a reduction in lateral  
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32 377 confinement applied to the sleepers that resulted in increased sleeper displacement and associated  
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34 378 acceleration.

35 379 The acceleration (vibration) in the time domain is converted into the frequency domain by the fast  
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37 380 Fourier transform (FFT), as shown in Figure 14. It is observed that the responses reach their maximum  
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39 381 peak values at an approximate frequency of  $f_1 = 15 \text{ Hz}$ , while some smaller peaks are reached at higher  
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41 382 frequencies (Kouroussis *et al.* 2009). The  $f_1$  frequency is identical to the cyclic loading applied by the  
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43 383 dynamic actuators, which indicates that the response of the track substructure to acceleration is in the  
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45 384 same phase as the applied loading frequency.  
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### 47 385 **3.6. Measured ballast breakage**

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50 386 After the test, ballast aggregates at four different locations (underneath two actuators, between the two  
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52 387 rails, and at the shoulder ballast) were recovered separately for quantifying ballast breakage. This  
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54 388 ballast was then passed through standard sieves to obtain the particle size distribution (PSD), as shown  
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56 389 in Figure 15. Indraratna *et al.* (2005) introduced a new method to quantify ballast degradation under  
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58 390 cyclic loading, which leads the PSD curve of ballast to shift towards the smaller size particles due to  
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60 391 breakage. By recognising this shift as the degradation indicator, the ballast breakage index ( $BBI$ ) can  
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62 392 be calculated using Equation 2  
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$$393 \quad BBI = \frac{A}{A+B} \quad (2)$$

394 where,  $A$  is the shift in PSD due to ballast breakage under cyclic loading, and  $B$  is the potential breakage  
395 or the area between the arbitrary boundary of maximum breakage and the final particle size distribution.  
396 It is noted the upper and lower limits of  $BBI$  are 0 (no breakage) and 1, respectively. A summary of the  
397 sieve analysis performed before and after the test for quantifying ballast breakage ( $BBI$ ) is presented  
398 in Table 1. Measured breakage denotes that ballast aggregates collected directly underneath the  
399 actuators had the highest amount of breakage, estimated as  $BBI_{1,2} = 0.143$  and  $0.115$ , whereas the ballast  
400 collected from between two rails (crib ballast) and the edge of a sleeper (shoulder ballast) have  $BBI_{3,4}$   
401  $= 0.085$  and  $0.075$ , respectively. The ballast underneath the actuators experiences more breakage  
402 because these aggregates carry the cyclic loads directly from the dynamic actuators and also deal with  
403 the vibration transferred from the sleepers. As a consequence, these aggregates are more prone to  
404 breakage. The results also show that the average  $BBI$  for ballast samples collected underneath the  
405 actuators ( $BBI = 0.129$ ) was slightly higher than that obtained for ballast aggregates recovered from  
406 beneath the sleeper and rail seat in the actual heavy-haul track at Singleton after the same number of  
407 load cycles (Nimbalkar and Indraratna 2016). In fact, in the NFHRT the load is continually applied  
408 over the same sleepers for 500,000 cycles, which results in a slightly higher amount of ballast crushing  
409 when compared to actual field measurements.

#### 411 4. Conclusions

412 This paper described the construction and testing process of the new Australia's National Facility for  
413 Heavy-haul Railroad Testing (NFHRT), a prototype test facility that allowed investigating the  
414 performance of a real-size instrumented track section when subjected to continuous cyclic loading  
415 applied via two pairs of dynamic actuators. The first test was carried out under a 25-tonne axle load  
416 applied at a frequency of 15 Hz to [cover a realistic range of heavy haul train speeds of 60-80km/h on](#)  
417 [standard gauge trackssimulate a freight train travelling at a speed of approximately 80 km/h](#). The results  
418 from this first test, including the measured track settlement and lateral deformation, transient vertical  
419 and lateral stresses, rail and sleeper accelerations, resilient modulus and breakage of ballast were  
420 presented and compared with actual field measurements obtained in heavy-haul tracks located in the  
421 towns of Bulli and Singleton (New South Wales, Australia).

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4 422 The obtained results were generally consistent with real-life measurements undertaken during the  
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6 423 aforementioned field monitoring programmes. An average track settlement of about 14 mm and lateral  
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8 424 deformations up to 9 mm were recorded after 500,000 load cycles. Any small discrepancies between  
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10 425 the test results and the actual field measurements may be associated with boundary conditions and  
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12 426 loading simulations. For instance, the lateral deformation of the ballast layer recorded in the field trial  
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14 427 conducted at Bulli exceeded that measured in the NFHRT. This is partially because moving freight  
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16 428 trains generate greater impact forces due to wheel or rail irregularities, which could accelerate the  
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18 429 lateral spreading of ballast. On the other hand, the breakage of the load-bearing ballast estimated at the  
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20 430 end of the test ( $BBI = 0.129$ ) was found to be slightly higher than that measured in the actual rail track  
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22 431 at Singleton, which can be related to the fact that in the NFHRT the load was continually applied over  
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24 432 the same sleepers for 500,000 cycles, thus resulting in a higher extent of ballast degradation.

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26 433 It is noteworthy that the true moving load effect was not properly modelled in the test reported herein,  
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28 434 as the cyclic loading was applied by four dynamic actuators in synchronized operation. In spite of this  
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30 435 limitation, the obtained results for these relatively low speeds ( $\approx 80$  km/h) were acceptable as the  
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32 436 facility mimicked the cyclic loading appropriately. However, at very high speeds the results may  
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34 437 deviate from accuracy when fast moving loads must be simulated correctly with more than two pairs  
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36 438 of actuators acting along a greater number of sleepers (Bian *et al.* 2014).

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38 439 When compared to smaller-scale or conventional laboratory test facilities, the NFHRT enabled to  
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40 440 mitigate boundary effects and more realistically simulate Australian track conditions (often involving  
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42 441 problematic subsoils) in a controlled laboratory environment. The test reported in this paper was aimed  
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44 442 at simulating the conditions prevailing in typical Australian heavy-haul tracks. Additional tests will be  
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46 443 carried out in the future to examine the benefits of artificial inclusions, such as geosynthetics and  
47  
48 444 recycled rubber products, as well as the influence of different substructure materials (including  
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50 445 recycled waste materials) on track performance, which will facilitate innovative and more sustainable  
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52 446 designs for enhanced stability and resiliency of heavy haul tracks.

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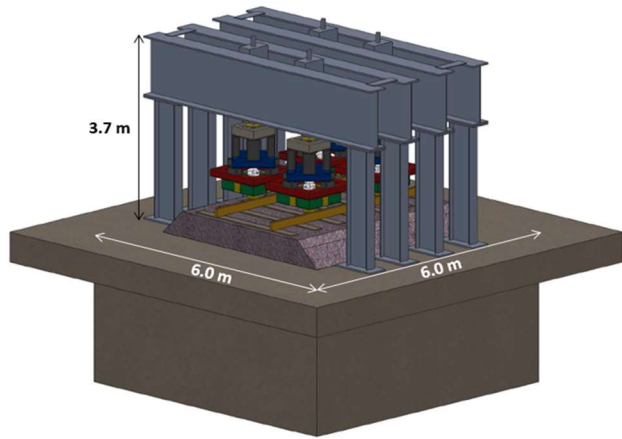
639 Table 1. Quantification of ballast breakage (*BBI*) recovered at different places after the test

Sieve size (mm)	Passing (%)				
	Initial gradation of tested ballast	Collected ballast underneath the South-East actuator	Collected ballast underneath the North-West actuator	Collected ballast between two rails	Collected ballast at the end of sleeper (shoulder ballast)
63	100	100	100	100	100
53	93.75	94.2	94.50	94.2	93.9
37.5	51.70	63.5	61.20	56.2	55.7
26.5	21.38	31.4	31.20	27.9	27.2
19	5.92	10.9	10.53	10.36	9.8
13.2	2.68	8.5	7.47	6.98	6.52
9.5	2.15	6.12	5.67	4.78	4.25
4.75	1.83	3.12	3.73	3.14	2.04
2.36	0	0	0	0	0
	<b>Measured <i>BBI</i></b>	<b>0.143</b>	<b>0.115</b>	<b>0.085</b>	<b>0.074</b>

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(a) Design concept



(b) Reinforced concrete of the test pit



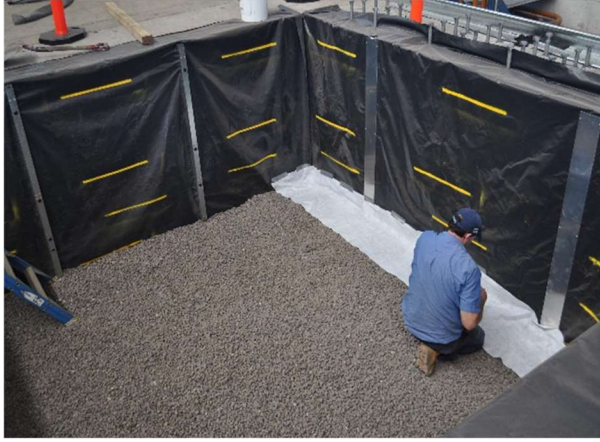
(c) Hydraulic power unit



(d) Hydraulic pipe system

Figure 1. Design and construction of the NFHRT

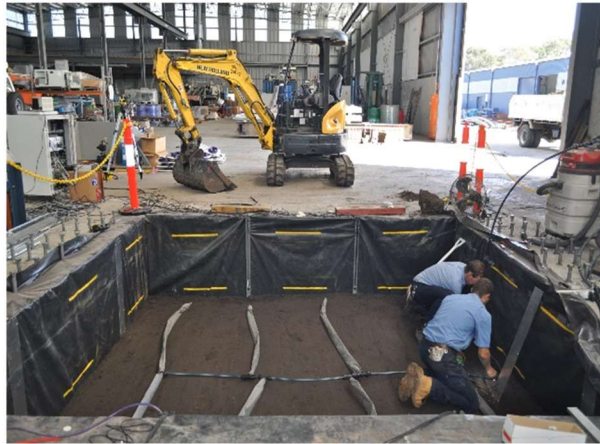




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20 (a) Drainage layer



21 (b) Moisture sensors and pore pressure gauges



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39 (c) Irrigation system



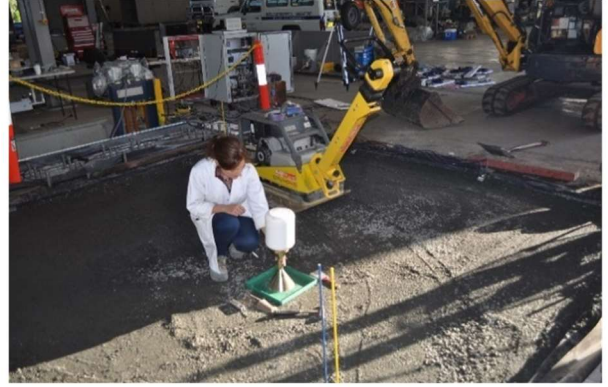
40 (d) Pressure cells on top of subgrade

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Figure 2. Installation of the drainage and subgrade layers



(a) Capping layer



(b) Sand-cone test for compacted capping



(c) Placement of ballast



(d) Compaction of ballast layer



(e) Rails and sleepers



(f) Loading frames and hydraulic actuators

Figure 3. Installation of the capping, ballast, rail-sleeper assembly and dynamic actuators



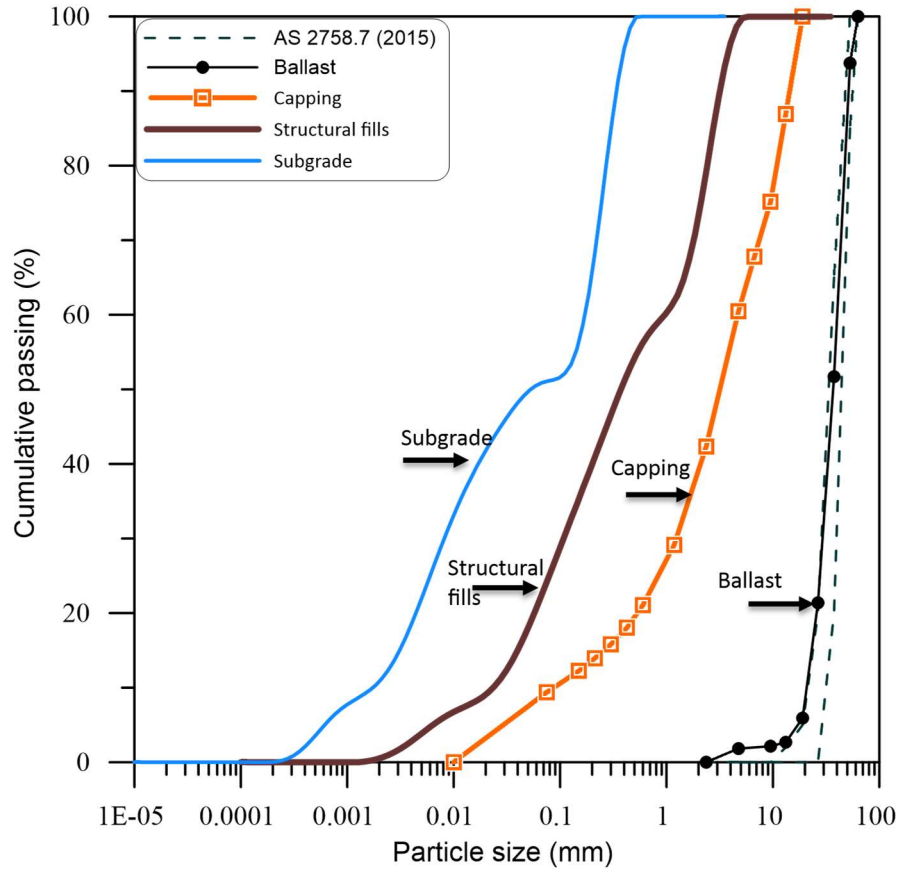
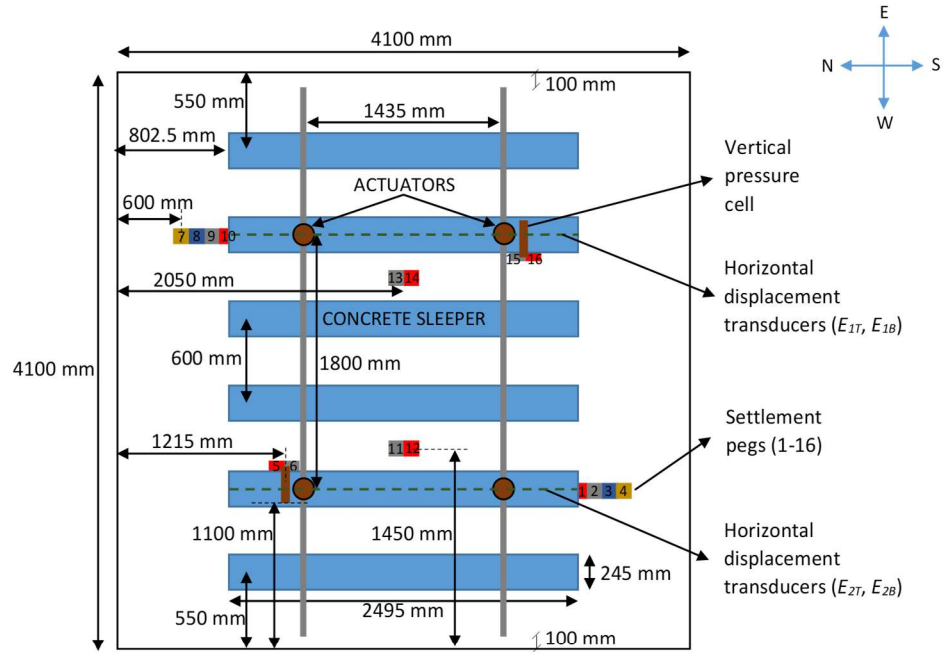
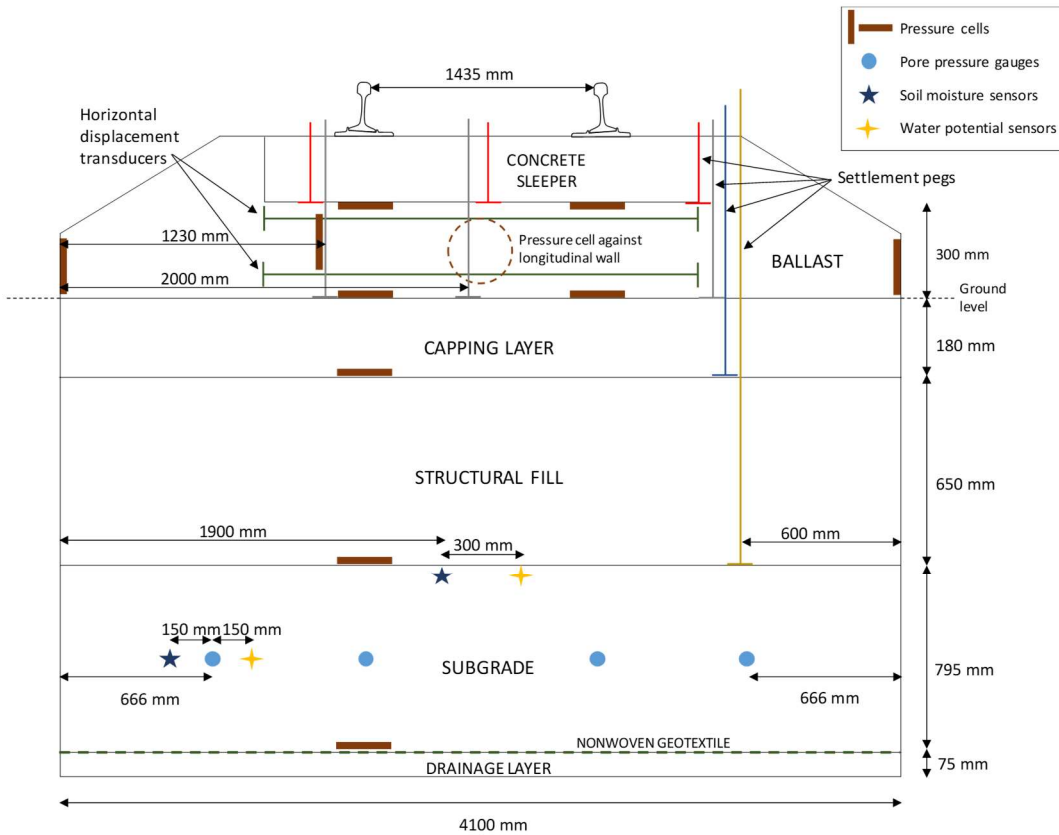


Figure 4. Particle size distribution curves of the track substructure materials

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(a) Plan view of locations of instrumentations

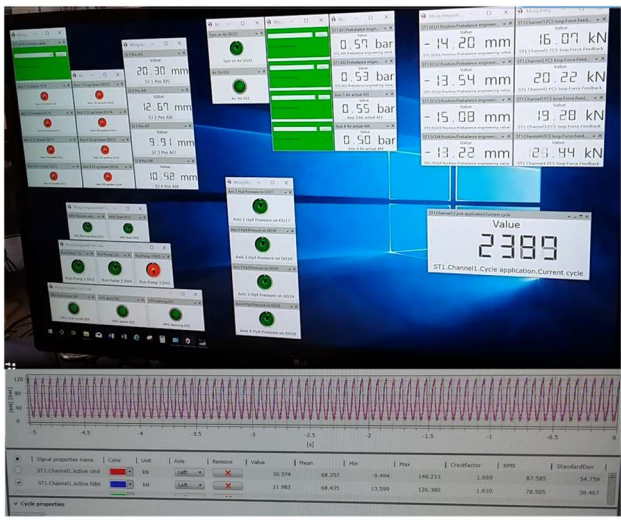
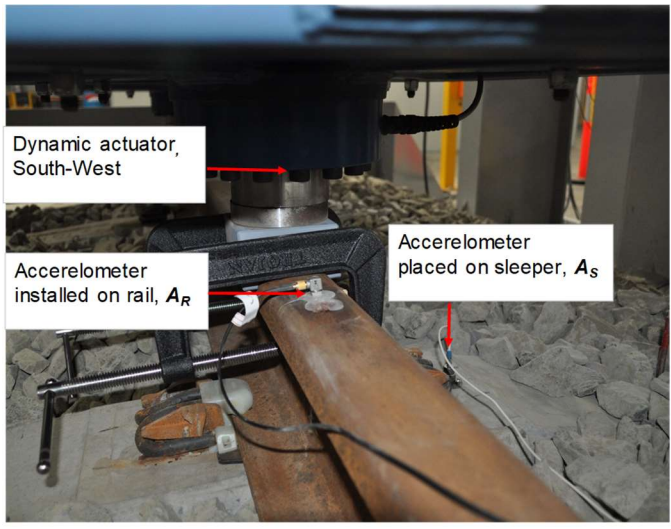


(b) A cross-section of the test pit with detailed instrumentations

Figure 5. A plan view and cross-section of the NFHRT with detailed instrumentations

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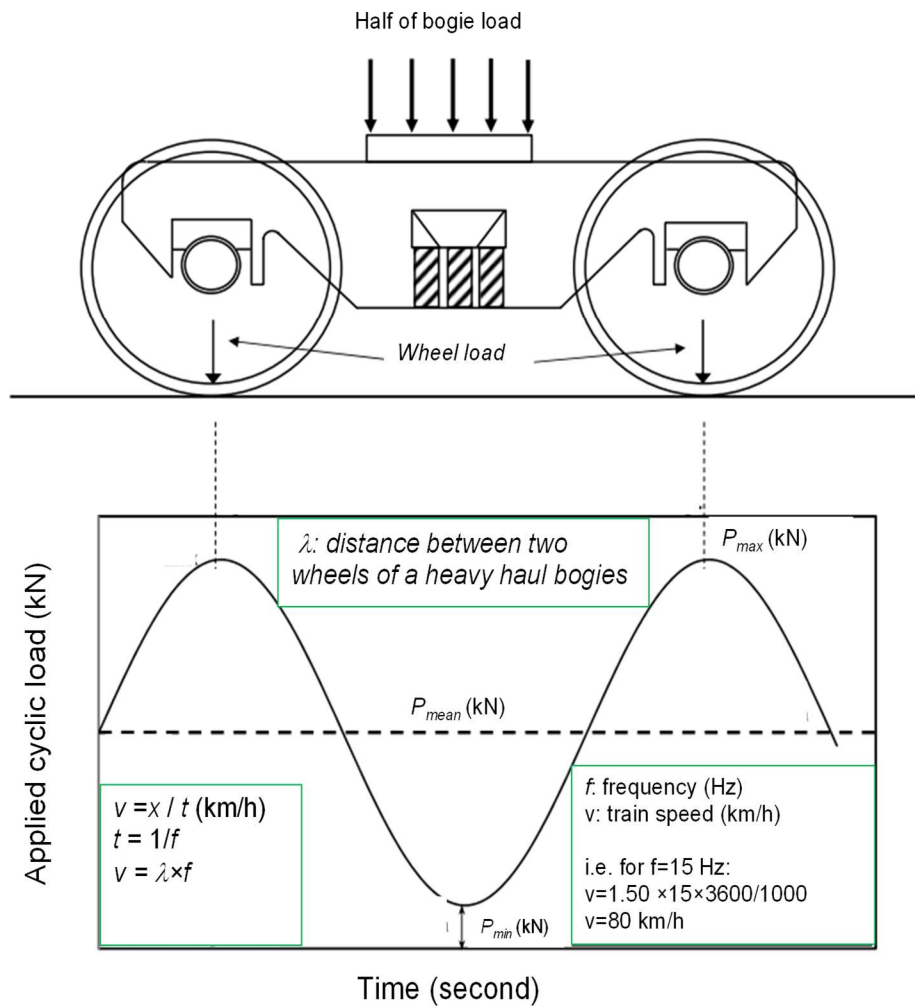
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Figure 6. (a) Installation of triaxial accelerometers on the rail and sleeper; (b) data acquisition system

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657  
658 Figure 7. Typical schematic of axle load and applied cyclic load during the test

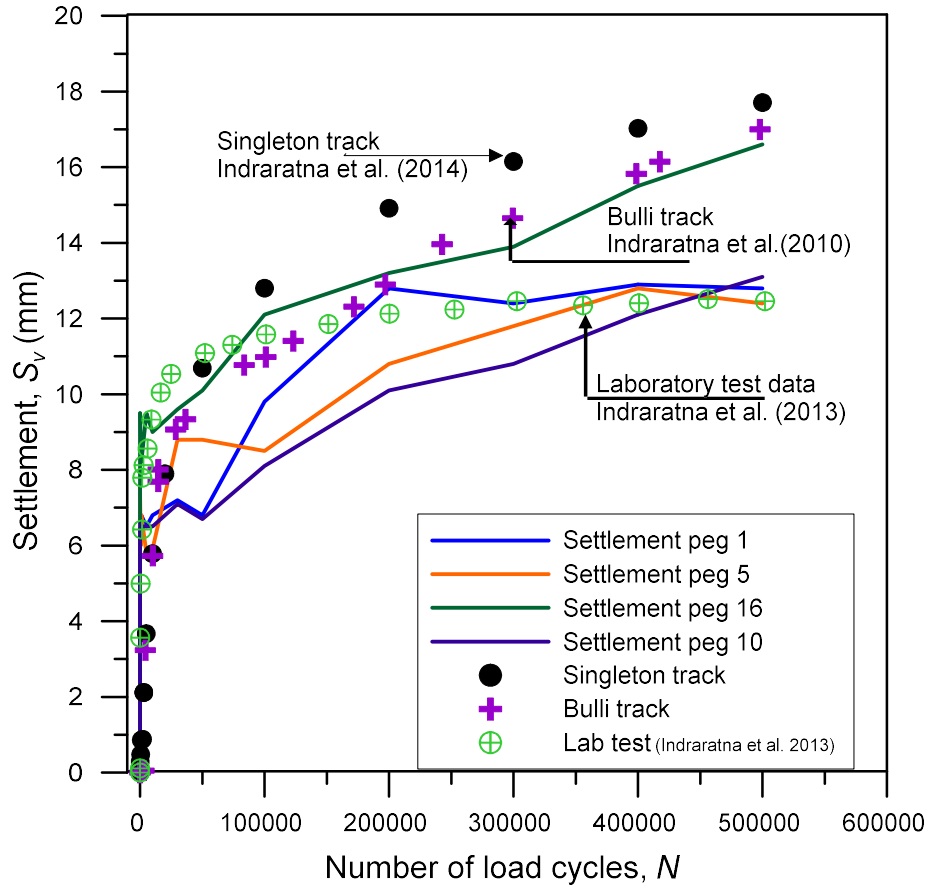
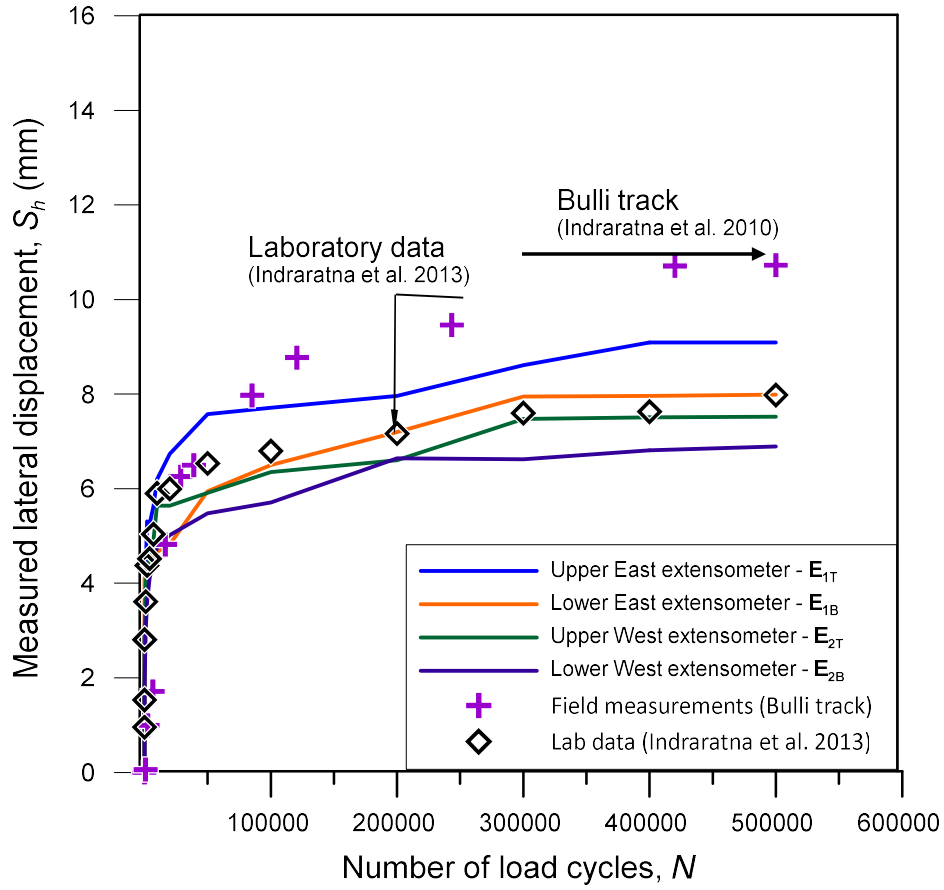
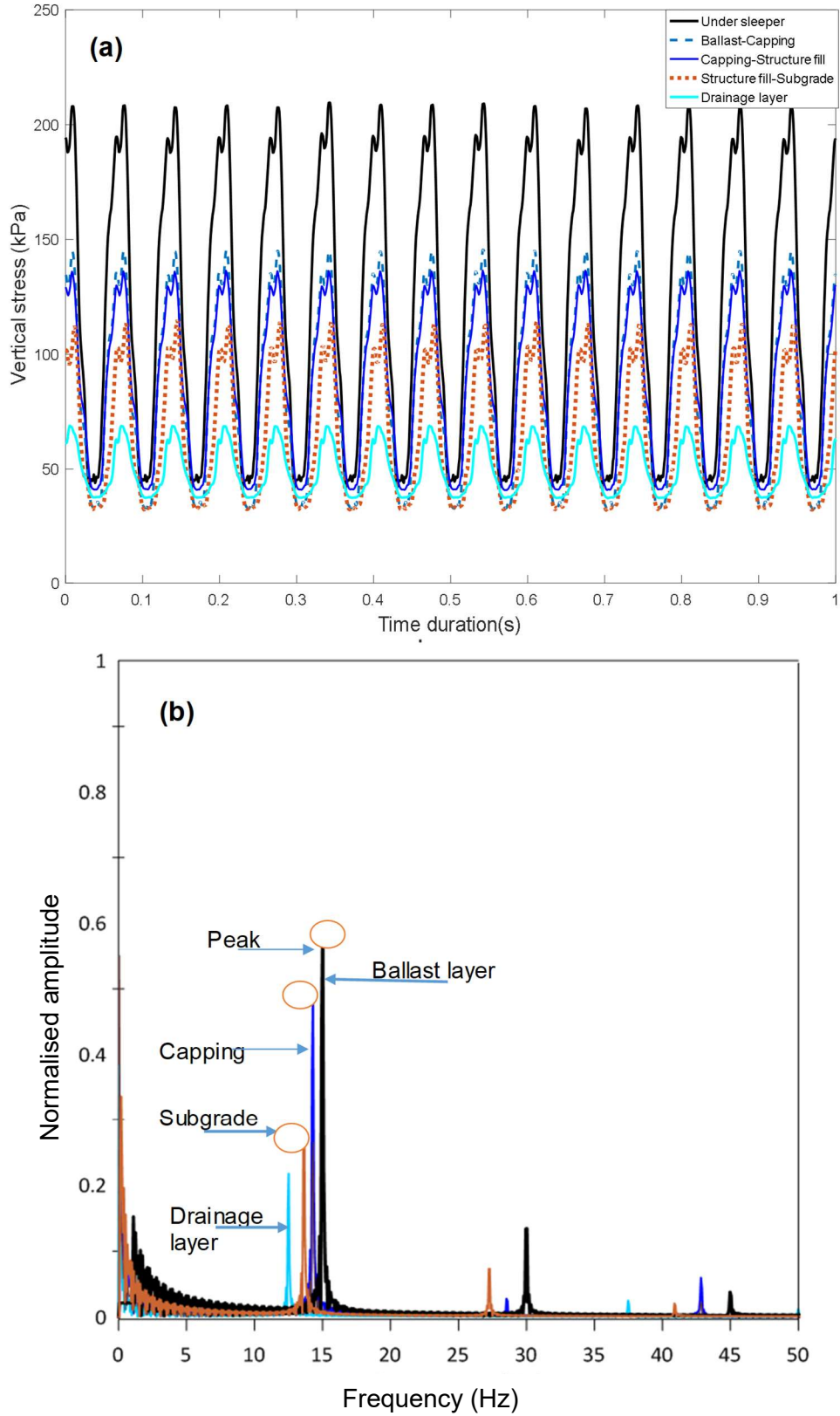


Figure 8. Measured settlements of the track at different locations in comparison with laboratory and field measurement data



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 668 Figure 9. Measured lateral displacements at varying locations in comparison with laboratory and field  
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671  
672 Figure 10. Typical cyclic vertical stress ( $\sigma_v$ ) responses at varying depths measured by pressure plates:  
673 (a) time domain; (b) frequency domain

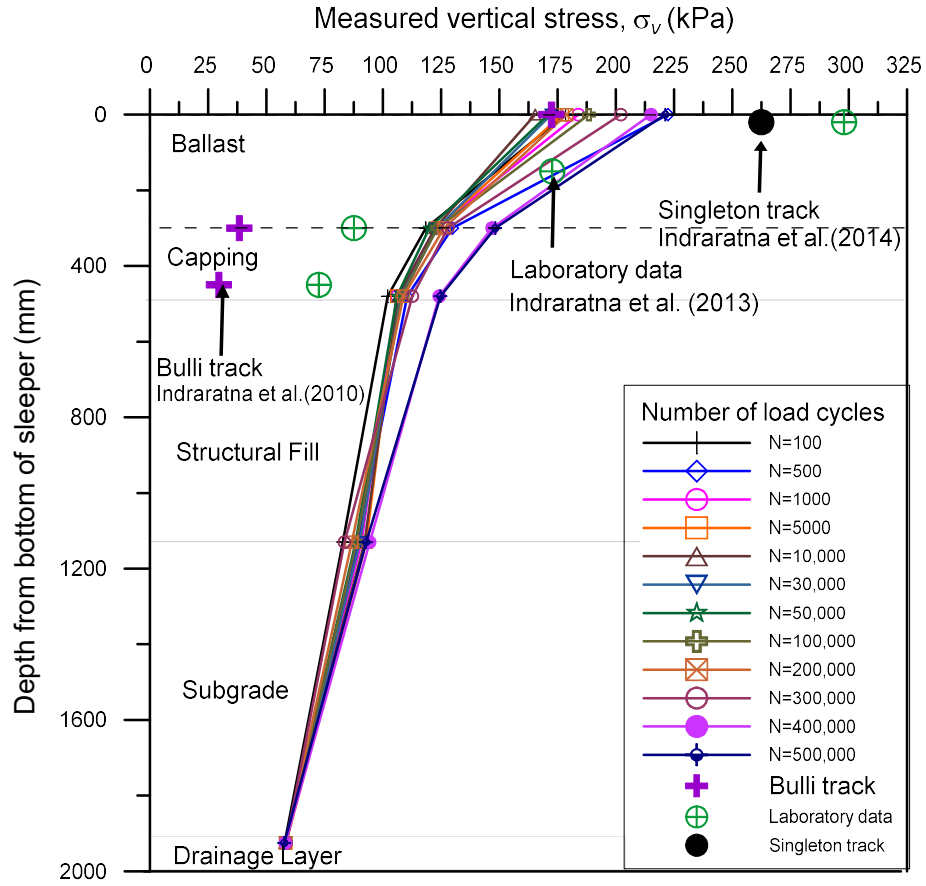
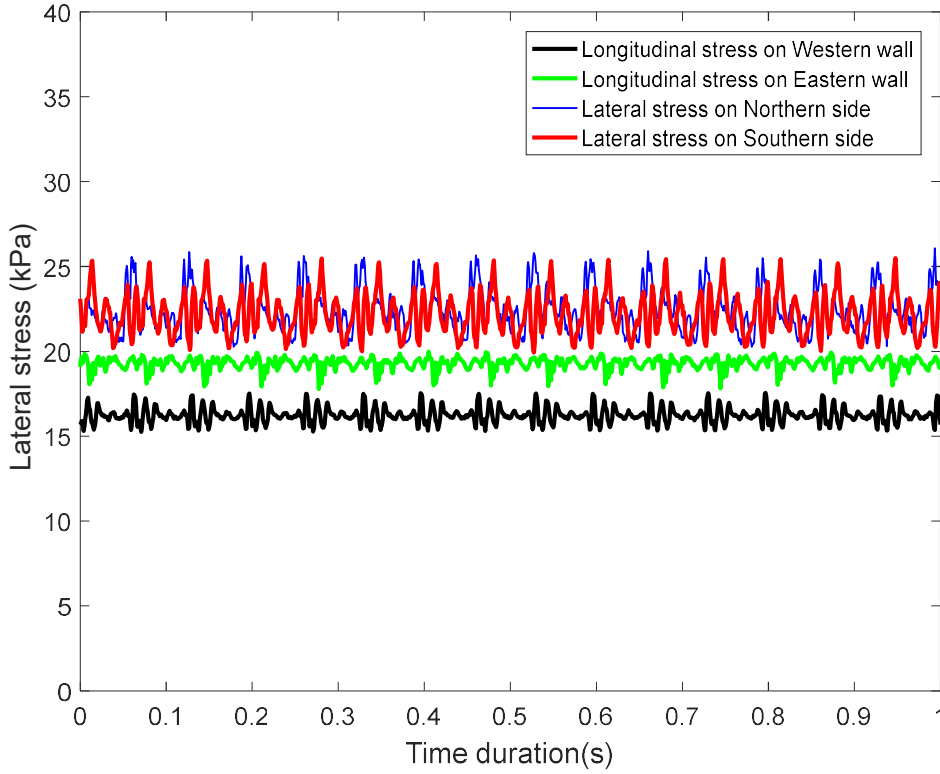


Figure 11. Variations of measured vertical stress ( $\sigma_v$ ) with the depth of track substructure at varying load cycles ( $N$ )





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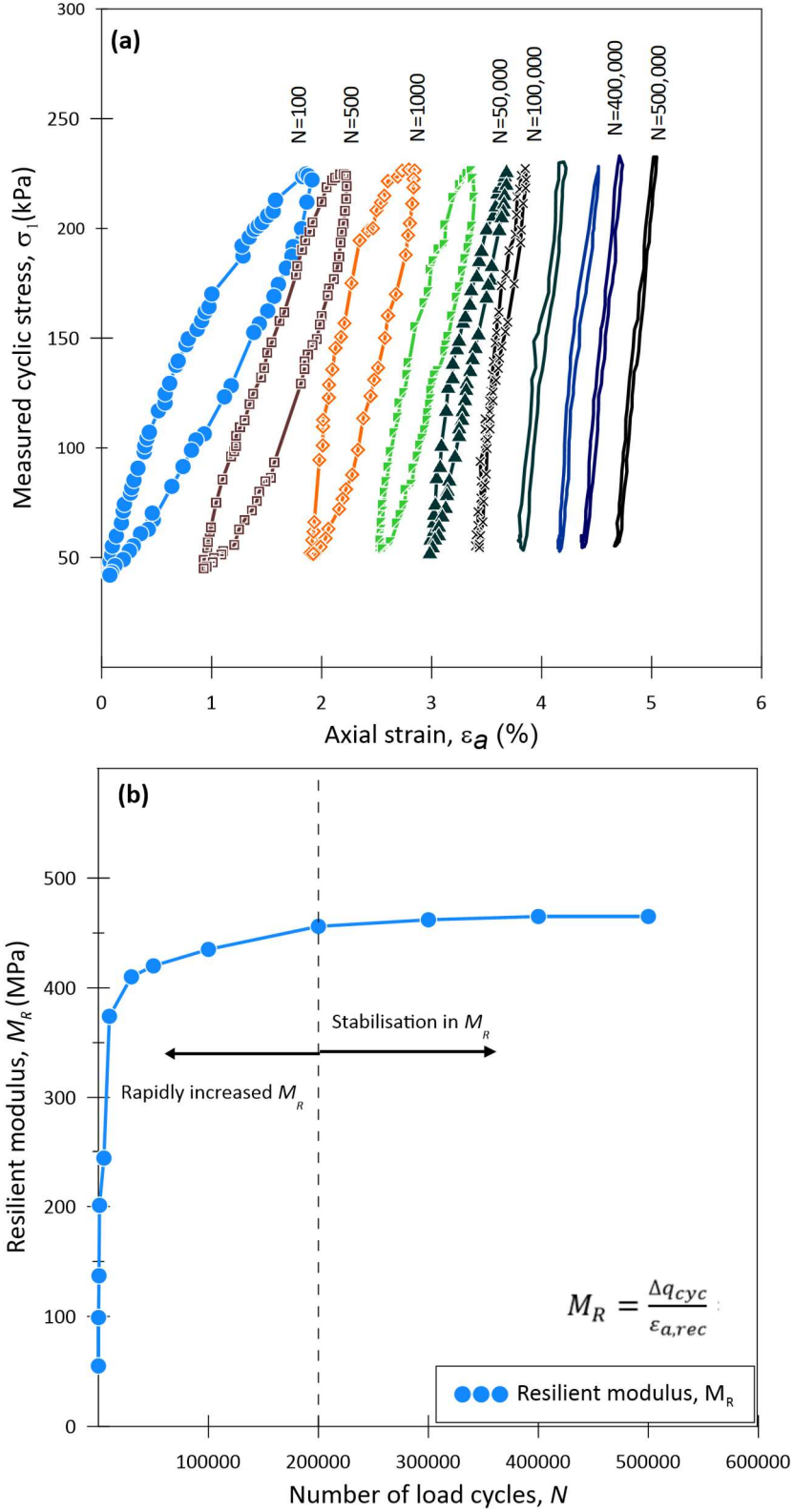
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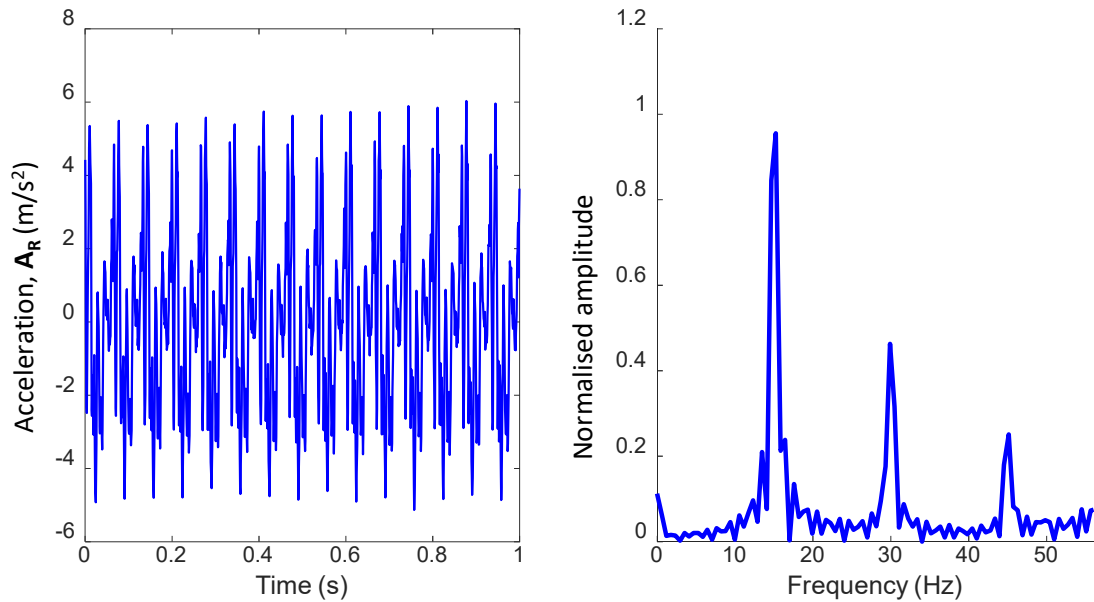
Figure 12. Typical responses of horizontal stresses ( $\sigma_2, \sigma_3$ ) in ballast measured in longitudinal and transverse directions during the test

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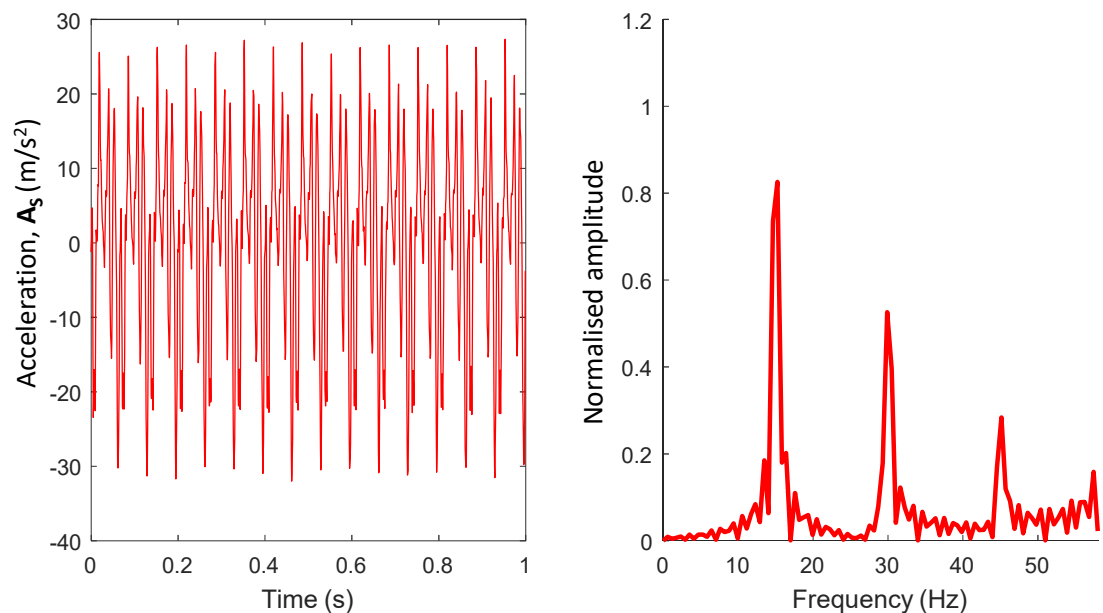
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682 Figure 13. (a) Hysteresis cyclic stress– strain responses; and (b) measured resilient modulus ( $M_R$ )



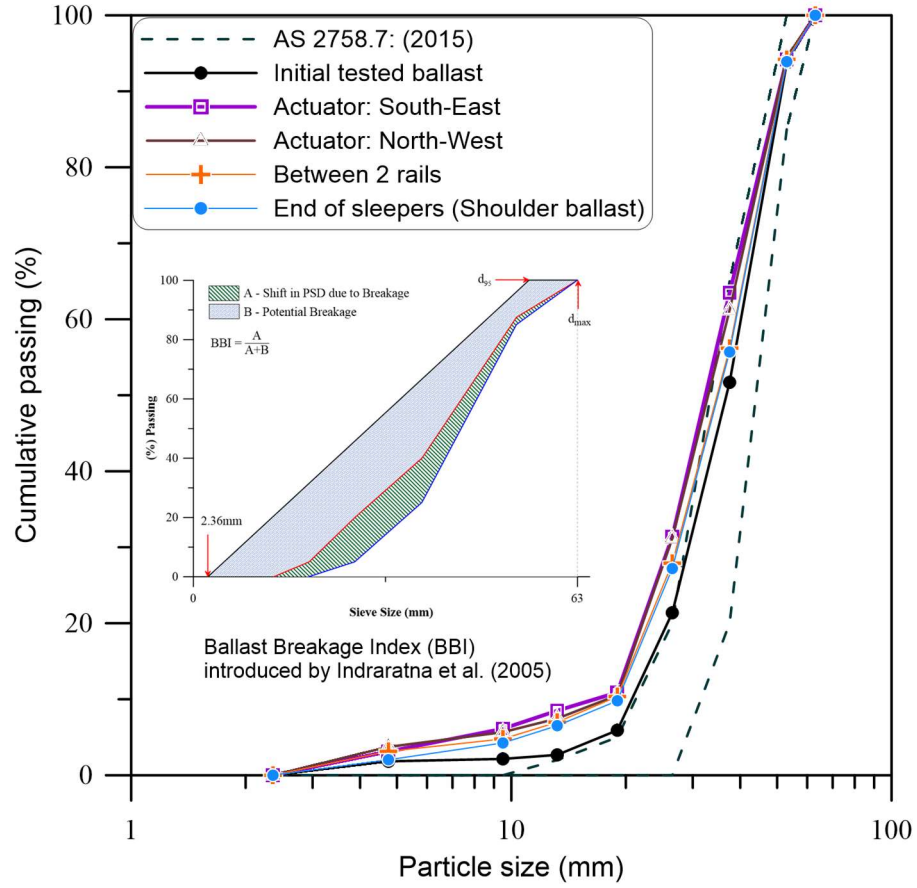
(a) Measured accelerations on rail



(b) Measured accelerations on sleeper

Figure 14. Measured accelerations of rail and sleeper during the test

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687 Figure 15. Measured changes in particle size distributions of ballast for quantifying ballast breakage  
688 index (*BBI*)  
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## Transportation Geotechnics

### Authors Responses to Review Comments to Manuscript ID: TRGEO-D-20-00552R1

*Paper title:* Large-scale Testing Facility for Heavy Haul Track

*Authors:* Buddhima Indraratna, Trung Ngo, Fernanda Ferreira, Cholachat Rujikiatkamjorn, and Ameyu Tucho

**Reviewer #3:** *The manuscript has been well revised according to reviewer's recommendations.*

*I still don't agree the statement that cyclic loads with the frequency of 15 Hz are equivalent to train loads with a speed of 80km/h, because it is not verified by the authors. There are several constant spacing distances for a certain train, the highest passing frequency (corresponding to the 1.5m wheel base) cannot represent the actual frequency characteristics, and a load sequence with the rest times should be more appropriate. Additionally, for the heavy haul railway (<120km/h), many previous researches showed that the axle load and the number of axes passing through the worksite is important to track settlement, not the running speed of train. A numerical simulation showed that if the frequency of periodic harmonic loads is considerable high, the settlement trend of track model is quite different. In terms of the laboratory model experiment, using high frequency cyclic loads still cannot obtain accurately track dynamic response, because dynamic effect due to the track irregularities can not be considered reasonably in the actuators. Thus, I think the load frequency should not be discussed too much in this manuscript.*

**Response:** The authors appreciate the Review comments that help to significantly improve the quality and flow of the re-revised final manuscript.

Regarding the loading frequency, the authors wish to clarify that heavy haul trains in Australia are often 4-5 km long and they travel on standard gauge tracks at relatively low speed (@ 40-60 km/h in most cases and rarely exceed 70km/h), and the applied frequency in the laboratory is indeed corroborated with the track geometry and train speed (e.g. Indraratna et al. 2011, Sun et al. 2016, Navaratnarajah et al. 2018). The authors agree that there can be several variables including the sleeper spacing, speed of train, track irregularities, occasional impact loading, influence of rest periods, variation in cyclic loading due to non-uniform axle spacing etc. that can contribute to the real-life frequency in contrast to the simplified (constant) experimental magnitude of frequency. To avoid confusion, the statement “a frequency of 15 Hz to simulate to simulate a freight train travelling at approximately  $v = 80 \text{ km/h}$ ” has now been amended. Instead, it is mentioned that: “The applied frequency of 15 Hz in the experimental program is assumed to cover a realistic range of heavy haul train speeds of 60-80km/h on standard gauge tracks, based on Indraratna et al. (2011), Sun et al. (2016) and Navaratnarajah et al. (2018) In reality, the frequency is not only dependent on the train speed but also on track geometry, bogey spacing, rest periods, variations in cyclic and impact loading among other variables. (Page 9, Para 1).

In addition, it is noted that the loading sequence capturing rest periods is not considered in this study. This is because the worst conditions occur when very long heavy haul trains apply continual loading over a substantial period of time, and busy freight tracks in the mining hubs have relatively small rest periods. For example in Western Australia different mineral ore trains can travel over very long distances at slow speeds (40-60 km/h) from source to port (sometimes up to 300 km) regularly most of the day, and the ballast relaxation during relatively short rest periods between these slow-moving trains can be ignored. For instance for iron ore trains that can be up to 6 km long moving at only 40 km/h, the worst-case scenario simulated in the laboratory is without any rest period, so that the fatigue of ballast is maximised during testing to determine the maximum deformation, i.e. settlement and lateral movement.

The above statement has now included in the Loading Section of the revised manuscript (**Page 9, Para 2**).

The dynamic and impact effects due to track irregularities could not be captured in these model tests, and the authors have included this as a limitation of the current study (**Page 5, Para 2**)

The Authors agree with the Reviwer that both the axle load and loading frequency influence the resulting settlement, but the axle load magnitude is more dominant than the frequency. Nevertheless, the load frequency must still be highlighted, because that is the only loading parameter in cyclic laboratory testing that is related to the train speed (Esveld, 2014; Indraratna et al. 2011). In other words, the number of axle loads passing through a specific in situ reference point (worksite) over a given period of time is related to the frequency. This is clarified on **Page 9, Paragraph 2**.

#### **References:**

Esveld, C. (2014). Modern railway track: MRT Press, The Netherlands.

Indraratna, B., W. Salim and C. Rujikiatkamjorn (2011). Advanced Rail Geotechnology - Ballasted Track, CRC Press, Taylor & Francis Group, London, UK.

Navaratnarajah, S. K., B. Indraratna and N. T. Ngo (2018). Influence of Under Sleeper Pads on Ballast Behavior Under Cyclic Loading: Experimental and Numerical Studies. *Journal of Geotechnical and Geoenvironmental Engineering*, 144(9): 04018068.

Sun, Q. D., B. Indraratna and S. Nimbalkar (2016). Deformation and Degradation Mechanisms of Railway Ballast under High Frequency Cyclic Loading. *Journal of Geotechnical and Geoenvironmental Engineering*, 142(1): 04015056.