The Role of Recycled Rubber Inclusions on Increased Confinement in Track Substructure

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Abstract: Large cyclic and impact loads exerted by heavy haul trains can cause significant deformation and degradation of ballast, leading to poor track geometry and track instability. The application of recycled rubber elements in track substructure to increase confinement of both sub-ballast and shoulder ballast is an innovative solution. In Australia, there is a lack of adequate recycling that leads to large stockpiles of waste tyres. In addition, the reusability of giant off-the-road tyres discarded from mining industry is seriously limited due to their size and weight (over 3.0 meters in diameter weighing about 3 tonnes). This study presents a real-size prototype test using the Australia's first and only National Facility for Cyclic Testing of High-speed Rail to investigate the performance of a hybrid track where tyre-infilled granular waste materials were placed below the ballast layer to replace the traditional capping layer, and arc segments cut from the giant off-the-road tyres were used to confine shoulder ballast. The performance of this hybrid track is compared with an unreinforced track conducted earlier at the same loading conditions. Test results demonstrate that the use of this hybrid system with recycled rubber elements significantly decreases vertical and lateral displacements of ballast and effectively controls the distribution of vertical stress with depth, while reducing vibration and ballast breakage. The outcomes of this study provide a unique solution in a circular economy perspective to strengthen railways to cater for heavier and faster freight trains.

Keywords: Ballast, rubber tyres, confining pressure, displacement, particle breakage

1. Introduction

Heavier and faster rail corridors are of prime importance in transportation infrastructure development and require insightful studies to improve the future design of railways under increasing axle loads and speeds [1-3]. However, increasing speed, tonnage, and heavier axle load can present various challenges related to track stability and maintenance [4-6]. Upon repeated train loading, ballast aggregates become degraded and subsequently fouled by finer particles, leading to undesirable performance such as increased settlements, decreased shear strength, and lower porosity that can impede the drainage of the ballast layer [7-9]. Previous studies have shown that the degradation of ballast seriously hampers the safety and efficiency of railways, which leads to enforced speed restrictions and more frequent maintenance [6, 10, 11]. Efforts have been made lately to introduce novel materials and methodologies to prevent ballast degradation and for enhanced longevity of tracks with polymeric reinforcements, including geogrids to curtail lateral movement of particles and geocells to provide increased confinement [12-16]. However, owing to the proximity to the sleepers and the challenges during track maintenance, it is often difficult to stabilise the ballast layer with conventional methods. Several researchers have studied the effect of confining pressure on granular materials [17-19], and they have verified that the in-situ confining pressure plays a vital role in reducing ballast breakage. As typical confinement in a ballast track is usually between 10-20 kPa as measured during field studies carried out earlier by Indraratna et al. [6], there is a need for innovative ways to increase the in-situ lateral confinement in tracks towards an optimum value (40-60 kPa) based on extensive large-scale laboratory testing by Lackenby et al. [20].

With the increasing number of road vehicles, 1.4 billion tyres are sold around the world each year [21]. Most of these tyres are not recycled in large quantities, hence they often end up in stockpiles [22]. In some countries, waste tyres are burnt for the convenience of disposal causing severe environmental pollution or they pose a potential source of spreading diseases through breeding of mosquitoes during wet periods [23, 24]. Giant off-the-road (GOTR) tyres (about 3m in diameter and weighing over 3 tonnes) discarded mainly from mining industry are more challenging to handle and transform into rubber crumbs or mats. This study introduces the combination of two concepts of: (i) placing infilled tyre assembly beneath the bottom ballast and (ii) installing GOTR tyre (arc segments) in shoulder ballast to stabilise the track substructure.

In recent times, Indraratna et al. [25] conducted plate load tests on a single infilled tyre cell, and the experimental results showed that the infilled tyre underlying the ballast layer significantly increased the modulus and ultimate bearing capacity of the overall granular substructure. Other studies (e.g., Indraratna et al. [26]; Sun et al. [27] have evaluated the effects of tyre reinforcement on the ballast degradation and deformation subjected to cyclic loading. These studies confirm that the inclusion of recycled tyres as a capping stratum can provide substantial lateral confinement, thus enhancing the lateral track stability while reducing ballast degradation.

To the knowledge of the authors so far, there are no other studies on the use of recycled rubber to increase the confining pressure within the main load-bearing substructure of the track, including its shoulders. Indeed, this is the key reason that had motivated this study at the outset. The research objectives are to quantify the performance of a hybrid track. In this respect, tyre-infilled granular waste materials were placed as a capping layer below the load-bearing ballast, and the arc segments cut from large off-the-road tyres were used to confine the shoulder ballast. In addition, as typical confinement in a ballast track is usually very low (10-20 kPa), there is a need for innovative ways to increase the in-situ lateral confinement in tracks to reduce ballast breakage and control lateral displacement (dilation).

2. Effect of confining pressure on the performance of railway track

In order to provide adequate lateral stability, the ballast layer can be extended laterally to a desired width beyond the edge of sleepers [1]. However, the in-situ increase in confining pressure at the track shoulders is still relatively small [20]. Under repeated cyclic loading, this low confining pressure is not sufficient to effectively control excessive lateral spreading of aggregates. Indraratna et al. [6] have shown that optimising the track confinement can contribute to substantial savings on track maintenance. The role of confining pressure on shear strength and deformation behaviour of rockfill has been extensively studied earlier. For instance, Marsal [28] reported that the shear strength of basaltic and granitic aggregates could be modelled by a non-linear function of the normal stress. However, the confining pressure in these tests has been in the high range of 0.5 to 2.5 (MPa), which is most unlikely to be encountered in a ballast track. Indraratna et al. [29] presented more realistic results by varying the confining pressure in a much lower range (1 kPa to 240 kPa) to conclude that the internal friction angle and dilation of the granular mass are significantly governed by the confining pressure, as also supported by others (e.g., [19, 30]). In real-life field situations, the track confining pressure is often very low and typically less than 30 kPa [31] and highly angular ballast aggregates experience significant dilation and associated breakage under cyclic loading. Lackenby et al. [20] found that under higher confining pressure, dilation of ballast is suppressed, and the degradation mechanism also changes from the breakage of angular corners to splitting across the body of particles. In this context, Indraratna et al. [17] proposed three different zones of particle degradation in relation to confining pressure, namely, (a) dilatant, unstable degradation zone (DUDZ, $\sigma_3 < 30$ kPa), (b) optimum degradation zone (ODZ, $30 < \sigma_3 < 75$ kPa) and (c) compressive, stable degradation zone (CSDZ, $\sigma_3 > 75$ kPa).

3. Application of Recycled Rubber Elements to Construct a Hybrid Track

Although theories and conceptual developments of internal confinement attributed to frictional forces and hoop stress for confined granular materials [32, 33], and energy absorption mechanisms of rubber inclusions [34] are still evolving, there is limited scientific evidence and field verification on the use of recycled tyres in rail tracks. In addition, the concept of employing rubber tyres for improved track performance considering a 3D cylindrical geometry has not yet been examined in practice. Several recent attempts were based on static loading [25] or cyclic loading with constrained boundary conditions replicating a unit cell conceptual model [26].

To mitigate problems related to the lack of ballast confinement, one solution offered by the authors is to use arc segments of the giant off-the-road (GOTR) tyres to provide additional support to the shoulder ballast, where each cut tyre arc segment may have a central subtended angle between 40° and 60°, having a weight of around 170 to 260 kg. The entire tyre assembly placed in the track substructure is shown in Fig. 1. In addition to this self-weight of the arc segments, the weight of aggregates confined by the tyre segments also acts as a passive stabilising force against the lateral displacement of the crib and bottom ballast. This resulted in two GOTR tyre segments around 1800 mm in length to be placed in the longitudinal direction of the track on each side of the track, and the tyre segments were instrumented with strain gauges. Subsequently, the shoulder ballast was placed and compacted within these arc segment boundaries to increase the overall track confinement (Fig. 1a). The confining arc segments were placed next to each other without any rigid connection so that they can independently displace in the horizontal direction (simulating lateral displacement of tracks). A schematic cross-section of the test pit is constructed with layers of different materials and depths as shown in Fig. 1b. These rubber tyres are produced to take high heat and abrasion and to resist degradation under continual wet conditions. Tyre supplies companies have done much research to prove that any breakdown of this heavy-duty rubber when not exposed to UV light will take over 150 years before any significant degradation to occur (Goryunov et al. [38]; Bridgestone [39]). It is also noted that in the very long term (> 100 years), rubber tyres may very gradually degrade and leach out into the environment.

4. National Facility for Heavy-haul Railroad Testing

National Facility for Cyclic Testing of High-speed Rail (FCTHSR) is the first of its kind in Australia to be conceptually designed by the 1st author to accommodate a wide array of track conditions. It is expected to provide a national and international hub for high-quality collaborative research with the main objective of contributing to better and more cost-effective track design solutions catering for faster freight trains carrying heavier loads. More elaborate details of the conceptual design, construction process and technical specifications for testing are discussed elsewhere by Indraratna et al. [35]. The first benchmark test without any rubber tyre segments (unreinforced standard track) was carried out under a 25-tonne axle load and a frequency of 15 Hz subjected to a maximum of 500,000 load cycles. Results of settlement and lateral deformation, induced stresses, rail and sleeper accelerations, and ballast breakage were reported and compared with actual field data obtained for heavy haul tracks in the town of Bulli in the state of NSW and, with the large-scale physical model tests conducted in a process simulation apparatus. The relevant test results from these earlier studies are adopted here to compare with the performance of the tyre stabilised (hybrid) track.

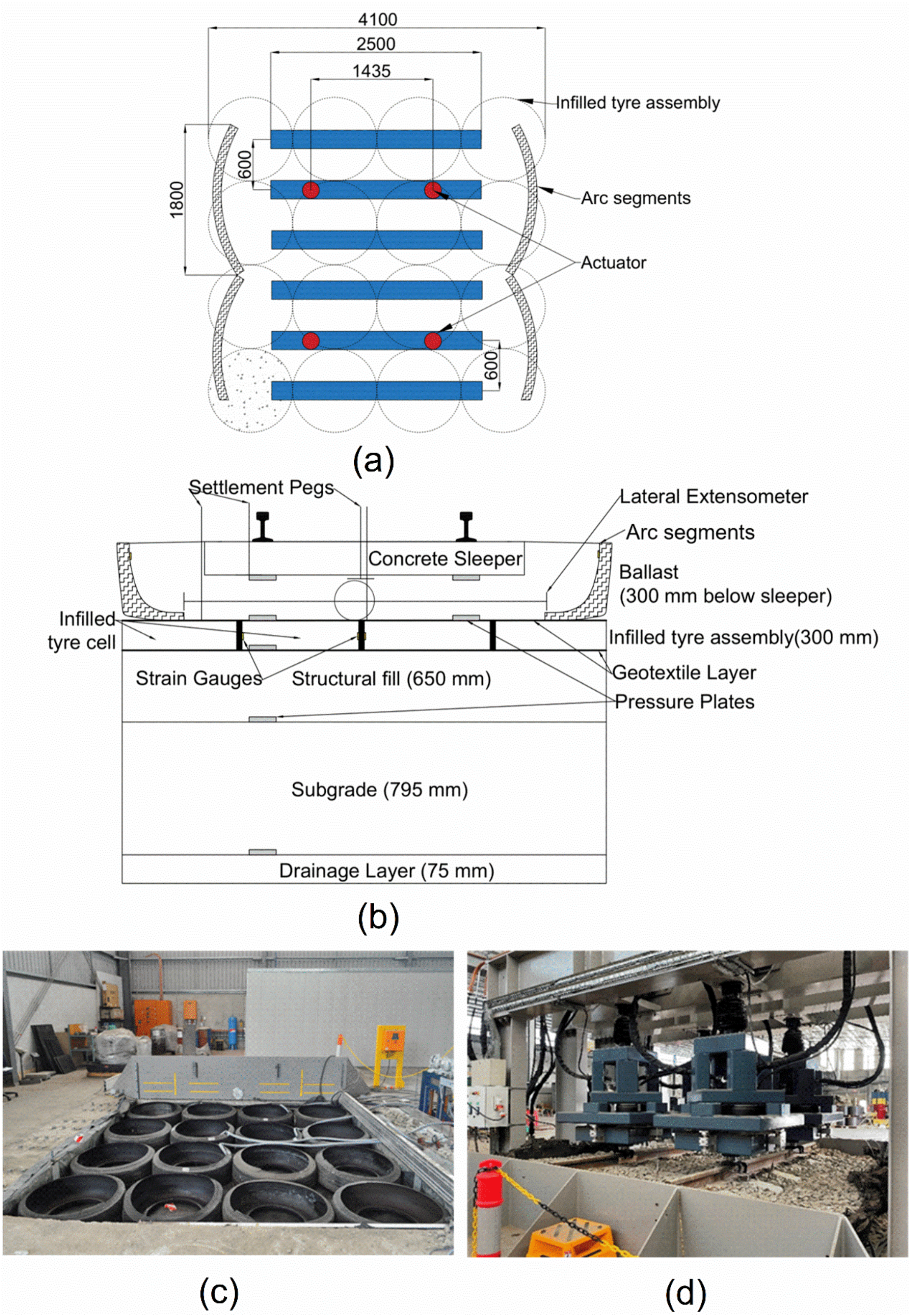


Fig. 1. The test rig and test sample assembly: (a) Top view of the test tracks; (b) cross-section of the test track; (c) a photo of recycled tyre assembly; (d) photo of a complete track with GOTR arc segments

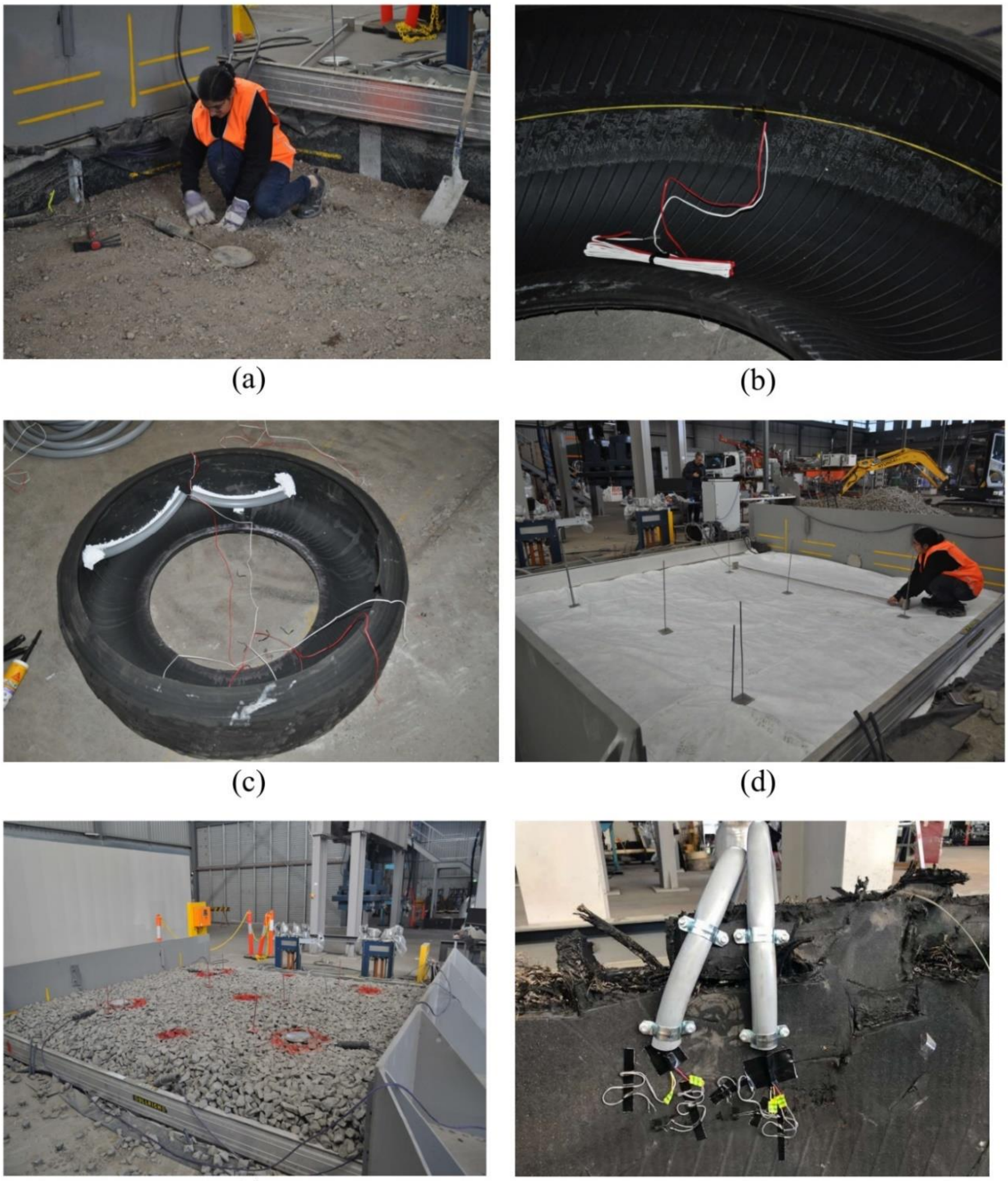
4.1. Test setup for the hybrid track with the recycled rubber elements

The FCTHSR facility was used to investigate the performance of the hybrid track reinforced with: (i) recycled rubber tyre cells as capping (tyre cell assembly, Fig. 1c); and (ii) GOTR arc segments installed in the shoulder ballast (Fig. 1d). A drainage layer (75mm thick) consisting of coarse-grained gravel was placed at the bottom of the test pit, overlain by a 795 mm-thick layer of fine-grained soil (subgrade) compacted to a unit weight of 16.5 kN/m^3, corresponding to 95% degree of compaction based on Standard Proctor recommendations. In the conventional track test, a layer of geotextile was placed on top of a 75mm thick drainage layer to prevent pore pressure build-up, and this condition was kept the same for the hybrid track test. A 650mm-thick structural fill layer was then placed on the subgrade and compacted to a unit weight of 18.5 kN/m^3. Instead of the traditional capping layer, the layer of recycled-rubber tyre cells was assembled and infilled with granular waste and compacted with a vibratory plate to a unit weight of 19.5 kN/m^3. In addition, a hand-held rod vibrator was used to compact around the tyres to eliminate any gaps. In total, 16 truck tyre cells (1m in diameter and 275~300 mm in height) were used. It is noteworthy that this assembly of tyre-infilled granular waste not only provide significant lateral confinement while increasing the track stiffness, but also possess energy absorbing properties to alleviate undue noise and vibrations. The tyre cell assembly was then overlain by fresh angular ballast (i.e., latile basalt of volcanic origin) of 300 mm thickness, conforming to Australian Standards [36]. The ballast stratum was compacted in three sub-layers (each 100mm-thick) to achieve a unit weight of approaching 16.0 kN/m^3 as usually expected in Australian heavy haul tracks. The particle size distribution (PSD) curves for ballast, subgrade, and structural fill layers have been described in detail by the authors in a previous study [35]. It is noted that different gradation curves of the ballast layer would affect the measured vibration and ballast breakage in hybrid tracks. For instance, the coarser ballast fractions would result in higher breakage and increased vibration. However, a study of the effect of different gradation curves of ballast is beyond the scope of this study.

The thickness of ballast layer carried out in the tests was 300 mm, followed by a 300mm-thick waste granular infill compacted within the tyre cell assembly sandwiched between the overlying standard ballast and the underlying structural fill and subgrade media. The infill material within the 300mm thick rubber tyre cells is a granular medium which can be taken from most waste piles in railway yards. Mixtures of capping material, drainage material and spent/broken ballast often constitute these waste granulates. There is no apparent shakedown condition that we can comfortably establish based on the observed data, and the continual settlement is also was influenced by the deformation of the infilled material within the tyre cell assembly, which now substitutes the traditional capping layer that is usually composed of quarried materials (albeit much smaller in particle sizes compared to standard load-bearing ballast). The idea of a rubber tyre cell assembly is to provide much better confinement plus energy absorbing (damping) capability to this substituted capping layer to alleviate impact damage from track irregularities. In practice, a drainage layer and a geotextile layer are commonly placed underneath the infilled-granular tyres (e.g., Chullora field testing site) so that water can be drained out and related issues with water trapping within the tyres can then be eliminated.

4.2. Instrumentation and loading program

The hybrid track consisting of the central tyre cell assembly plus the shoulder tyre arc segments was instrumented with various sensors to monitor the track response during the application of cyclic loading. An array of instrumentation (pressure cells, Linear Variable Differential Transformers, moisture sensors, pore pressure transducers, accelerometers and strain gauges) were placed in specified strategic locations. All these measuring devices have been individually tested and calibrated prior to installation in the FCTHSR. Stresses at different interfaces were recorded by pressure cells, as shown in Fig. 2a. Pressure cells placed at the bottom layer of tyre-infilled granular waste material that had replaced the traditional capping layer in the sub-ballast. Four biaxial strain gauges (Fig. 2b) were installed inside the tyre cell wall and protected by Permatex medium-strength glue (Fig. 2c) to measure the vertical and circumferential lateral strains. Four lateral extensometers were placed in the ballast layer to measure the lateral displacement. Sixteen settlement pegs were installed at different depths (infilled tyre assembly, ballast and underneath sleepers) to measure the settlements of this hybrid track (Fig. 2d). Pressure cells were also placed at the top and bottom of ballast layer to measure the vertical and lateral stresses at various locations (Fig. 2e). Four biaxial strain gauges (Fig. 2f) were also installed in the GOTR arc segments to measure the relevant strains during testing. The accelerometers were used to determine the accelerations of rail and sleepers.



(a) (b) (c) (d) (e) (f)

Fig. 2. Instrumentation arrangement in the test rig: (a) pressure cells placed at the bottom layer of tyre-infilled granular waste material; (b)&(c) strain gauges installed in tyres; (d) installation of settlement pegs and lateral extensometers in ballast; (e) pressure cells in ballast; (f) closed-view of strain gauges installed in a GOTR arc segment

The test was carried out under sinusoidal cyclic loading characteristics with maximum load (P_{max})=125 kN, minimum load (P_{min})=15 kN and mean load (P_{mean})=70 kN, simulating an equivalent 25-tonne axle freight train. The applied frequency of f=15 Hz represents a realistic range of heavy haul train speeds of 50-60km/h based on Australian standard gauge tracks. The selected sample rate (data logging frequency) for all the signals was 1200 Hz. According to USACE [40] railroad design manual assumes that the wheel point load is distributed between five sleepers, with the maximum load directly beneath the wheel (40% of the total load). The system of concrete sleepers and steel rails are connected to each other via rail join fastening, including clips and rail pads provided by the Australian Rail Track Corporation (ARTC) that are commonly used in NSW, Australia. It is the same as the components used in benchmark testing [35]. Steel rails (typed: AS60) were used in the test (density 7850 kg/m^3, elastic modulus: 210,000 MPa). Hyperelastic materials were used as the rail pads having an equivalent vertical stiffness of 200 kN/mm. It is also noted that the initial conditions of ballast, subgrade and structural fills are the same as those carried out in benchmark testing [35] for the results to be compared. The test was completed after 500,000 loading cycles, and during the application of the cyclic load, the settlements, lateral displacements, stress distribution with depth, acceleration of rail and sleepers were recorded by an automatic data acquisition system. Ballast aggregates were sieved before and after the test to measure the ballast breakage index (BBI).

5. Results and discussion

5.1. Effect of recycled rubber elements on settlement and lateral displacements

The measured vertical settlement results from the hybrid track were analysed and compared with those measured results reported earlier for the unreinforced FCTHSR testing (Indraratna et al. [35], large-scale process simulation triaxial testing [37] and selected field data taken from Bulli heavy haul track [6], as shown in Fig. 3. It is noted that the ballast depth at Bulli was also 300 mm (same as conventional tracks in NSW and also as used in our hybrid track tests). A structural fill layer (engineered fill layer with adequate permeability and shear strength) was also used in the Bulli field testing [6]. All results show a similar initial rapid settlement up to N=100,000 cycles, followed by gradually increasing settlement within N=300,000, and then remaining relatively stable to the end (N=500,000). When the number of load cycles is smaller than 300,000, the vertical settlement of hybrid track is larger than that of a conventional track. This is mainly due to ballast in the hybrid track experiencing a pronounced re-arrangement and subsequent compression during the initial N=300,000 cycles to attain a more stable track. However, over a large number of loading cycles (N=500,000), the overall accumulated settlement of the hybrid track is smaller than that of a conventional track. As the confining arc segments were placed away 300mm from the edge of sleepers, the increased confining pressure in hybrid track is found to be more effective in reducing ballast breakage [20], apart from its additional role of controlling ballast deformation. The hybrid track achieves notable stability around N=100,000, which certainly seems quicker than the unreinforced track. From a practical perspective, this suggests that a newly constructed hybrid track is able to attain operational stability earlier than a traditional ballast track, and thus, tamping would be recommended fairly early in actual practice.

Fig. 3 also compares the measured lateral displacement recorded by lateral extensometers placed in the ballast layer between the conventional and hybrid tracks. Typical data obtained from the Bulli field site and from large-scale laboratory testing conducted under similar cyclic loading conditions are also plotted for comparison. Lateral displacements were measured at underneath the sleepers and at the bottom of the ballast layer. It is seen that the lateral displacement of the hybrid track ranges from 3~6 mm with an average displacement of 4 mm, while the lateral displacement of the conventional track is significantly higher at about 9 mm. There is no doubt that the shoulder confinement by rubber arc segments effectively curtails the lateral movement of ballast. The system of recycled rubber elements can provide more than double the lateral confining pressure of the hybrid track (σ_3 = 55kPa) as measured by a pressure cell placed vertically within the shoulder ballast (Fig. 2e), compared to (σ_3 = 23kPa) the conventional track as reported earlier by Indraratna et al. [35]. These results are in sound agreement with Lackenby et al. [20] who have earlier shown using large-scale process simulation triaxial testing that rail ballast tested at low confining pressures experience excessive lateral displacements hence dilation, while increased confining pressure reduces dilation by controlling the lateral strain.

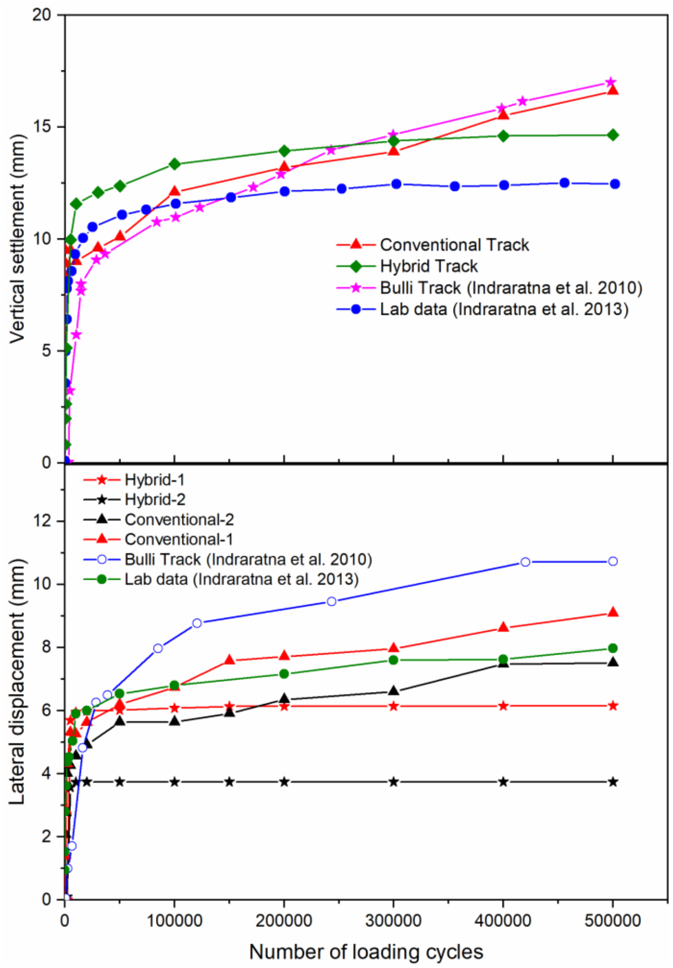


Fig. 3. Measured vertical settlements (at the top of the ballast layer) and lateral displacements of the hybrid track during the test

5.2. Measured stress distribution with depth

Fig. 4 presents the vertical stress (σ_v) recorded by pressure cells which were placed under the vertical alignment of the sleepers and actuators, as shown in Figure 1b. At the beginning of the loading stage (N<2000 cycles), the vertical stresses measured in the hybrid track are higher than those for the conventional track. However, over a large number of loading cycles (N>2,000), the vertical stresses measured in the hybrid tracks are smaller than those of a conventional track. It is seen that the stress levels at different depths reduce with an increasing number of loading cycles until N=100,000 beyond which the stresses remain relatively unchanged. This agrees with the measured vertical settlements after N=100,000 cycles shown earlier in Fig. 3. It is noted with interest that both the primary ballast layer and the underlying infilled tyre assembly take a large proportion of the substructure stresses, thus effectively controlling the propagation of any excessive stress to the underlying softer layer including the subgrade soil, which is indeed the key purpose of a sound capping stratum beneath the load-bearing primary ballast layer.

Compared to the conventional track [35], the hybrid track (reinforced by recycled rubber elements) shows significantly decreased vertical stresses on the ballast layer, infilled tyre cell assembly (capping) and the subgrade layer. For instance, at N=100,000 cycle, the vertical stresses measured at the layers of ballast, tyre cell assembly and subgrade were σ_v = 164, 76 and 52 kPa, compared to σ_v = 191, 126 and 91kPa for the conventional track. In essence, the proposed system of recycled rubber elements has contributed to about 40% and 43% reduction in the vertical stress at the sub-ballast and subgrade layers, respectively. It is noted that the loading distribution between the sleepers depends on the rail type, rail pad stiffness, and properties of the foundation, among others. So, these parameters were kept almost the same for the current tyre assembly track testing and the previous benchmark track testing [35] to ensure a proper comparison between results. Fig. 4 also compares the stress distribution with the field trial conducted at Bulli, NSW, with similar axle-loading [6]. It can be observed that the vertical stress measured at the bottom of the ballast layer in the field trial is less compared to the values obtained during the test. This difference can be attributed to having a rigid boundary (reinforced concrete) at a depth of about 2m in the testing facility. In addition to that, the presence of infilled tyre assembly below the ballast layer increases the average stiffness of the foundation, which can lead to higher stress at that depth. It can also be noted that the values obtained from the current test agree quite well with the large-scale process simulation testing conducted in the laboratory which also has a rigid boundary condition [37]. The high strain energy capacity and increased damping properties attributed to rubber elements within the infilled-tyre assembly are clearly contributory factors in reducing the stress magnitude transferred to other substructure layers. This concept is explained elsewhere [34] and not elaborated within the scope of this paper.

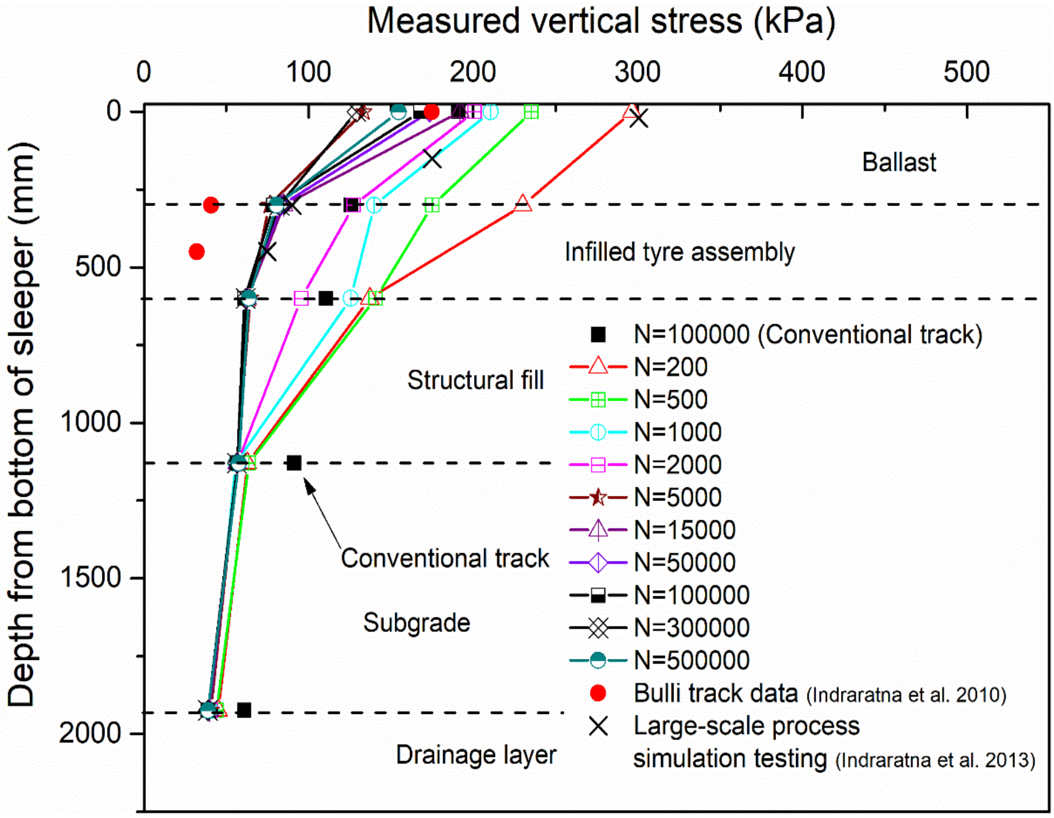


Fig. 4. Vertical stress distribution along the depth in the hybrid track compared with the conventional track, field and laboratory data

5.3. Measured vibration of rail and sleeper

Track vibrations were recorded during the test by two accelerometers that were rigidly bonded on the rail and sleeper assembly to measure acceleration (vibration). Fig. 5a compares accelerations measured on the rail in the hybrid track with those of the conventional/unreinforced track reported by Indraratna et al. [35] at N=200,000 cycles. It is seen that the accelerations in the hybrid track are less than half of the conventional track. In fact, the maximum accelerations measured on the rail of the hybrid track (A_{R_hybrid}) and the conventional track (A_{R_con}) are 2.47 m/s^2 and 5.60 m/s^2, respectively. It is noted that the dynamic response of track is influenced by the test setup and loading and boundary conditions. The measured accelerations reveal that for the given test setup and testing conditions carried out in this study, the inclusion of recycled rubber elements in the track substructure can significantly reduce vibration.

Fig. 5b shows a comparison of the measured accelerations on a sleeper of the hybrid track with those on the conventional track at N=200,000 cycles. While the acceleration measured for the hybrid track (A_{S_hybrid}) is only about 2.07 m/s^2, the recorded acceleration for the conventional track (A_{S_con}) was more than ten times greater at 27.5 m/s^2. There is no doubt that from a practical perspective, the hybrid track can experience much less vibration based on these data. It can also be observed that the degree of vibration reduction is much more in the sleeper than in the rail because of the proximity to the infilled tyre assembly which acts as an energy-absorbing stratum. The acceleration signals on the rail and sleepers from the benchmark and hybrid tests do closely resemble the sinusoidal wave of the cyclic loading, as clearly denoted by 15 loading cycles per second, as expected.

It is noteworthy that accelerometers used by the authors to measure accelerations in both cases of track testing (i.e., conventional and hybrid) are indeed the same. The type of glue, position of measuring points, the applied axle load frequency (15 Hz), the measurement systems and the corresponding data logging frequency are the same for both cases for the purpose of direct comparison. During testing of the conventional track, Indraratna et al. [35] observed undue vibration on a hanging sleeper attributed to excessive lateral displacement of ballast within the close proximity to the sleeper. The resulting gap between the sleeper and the ballast layer had contributed to significantly increased acceleration measured on this hanging sleeper. Given that the sleeper-rail assembly was firmly installed within the well-compacted ballast layer, any re-adjustment of the ballast in the sleeper vicinity to seal the gap was not practical without disturbing the surrounding track substructure. In addition, the authors wish to clarify that the conventional test [35] was subjected to the same loading frequency of 15 Hz as the hybrid test presented in the current study. The measurements were taken exactly at the same positions in the substructure. Also, the same signal processing was applied (low pass filtering), adequate sampling frequency was considered, and the results corresponded to equivalent loading cycles, i.e. N=200,000.

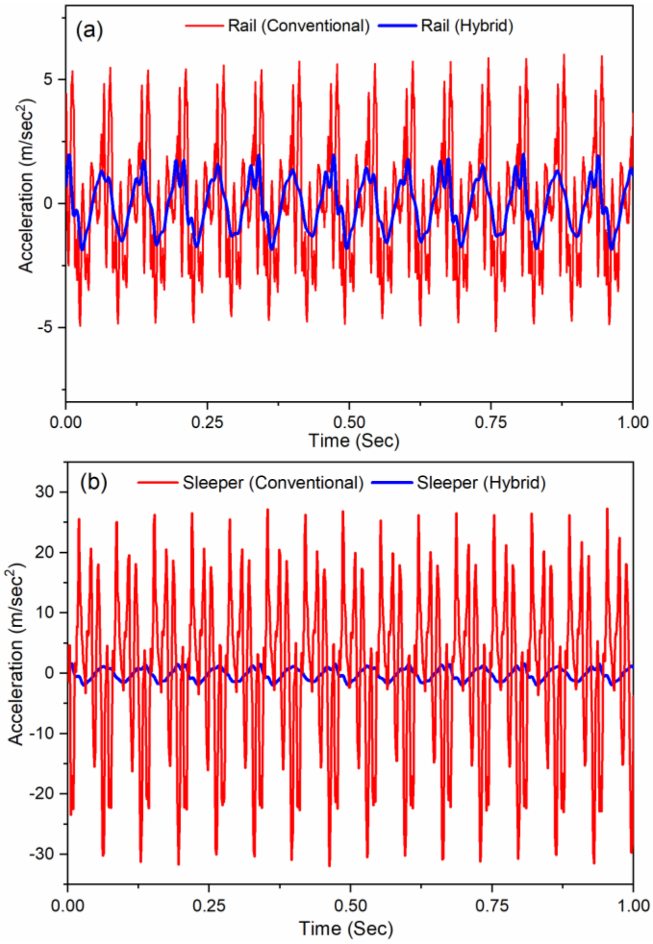


Fig. 5. Measured accelerations on top of (a) rail & (b) sleeper compared with the conventional track

5.4. Confinement by rubber elements and reduction in ballast breakage

Subjected to cyclic loading, the infilled tyre assembly was duly activated by sufficient vertical compression (axial strains in the proximity of 5%) and corresponding inducement of lateral circumferential strains albeit much smaller (< 2%). It is noteworthy that these truck tyres along their circumference are heavily reinforced by steel wires to provide very high stiffness, hence the relatively small circumferential strains even under significant hoop stress generated during loading. In contrast, at the track shoulder the tyre arc segments (1.5m away from the track centreline) were not subjected to any vertical loading, and also their shape and sheer weight (each weighing 250 kg) imposed an ideal non-displacement boundary as a gravity wall (i.e., negligible sliding) that effectively restrains the lateral movement of shoulder ballast. During cyclic loading, the measurement of insignificant circumferential tensile strains (< 0.03%) in these arc segments further implied insignificant lateral stress applied by any notable movement of shoulder ballast.

The compression of infilled granular mass upon loading will always induce some lateral (radial) push by the displacing aggregates against the tyre cell periphery thus effecting tensile (hoop) stress. This hoop stress is accompanied by an additional confinement for the infill materials, the magnitude of which depends on the circumferential stiffness (k_c) of the tyre cell. The study conducted by Indraratna et al. [32] on a system of geocell-reinforced sub-ballast subjected to cyclic loading, presented a plane strain model to determine the hoop stress and the corresponding additional confining stress, by assuming an equivalent circular area for the geocell pocket. For a tyre cell, Eq. 1 can be used to calculate the additional confinement based on the circumferential stiffness of the rubber tyre as follows [32]:

$$\sigma_c = \frac{k_c}{(1+\mu)\times(1-2\mu)} \times [(1-\mu)\varepsilon_c + \mu\varepsilon_3] \tag{1}$$

where, σ_c = circumferential stress, k_c =circumferential stiffness of tyre cell, μ =Poisson's ratio of rubber tyre, ε_c & ε_3 = circumferential and radial strains developed in the tyre.

Based on tensile testing, the circumferential stiffness of tyre cells varied in the range: 2500-3000 kN/m, and the calculated hoop stress was 108.3-111.5 kPa, with an associated additional confinement of 21.6-22.3 kPa. In fact, this calculated confining stress was comparable to the pressure cell measurements in the range of 16-23 kPa at locations just above and within the tyre cell stratum. For latite basalt aggregates with an internal friction angle of 48°-50° determined from large-scale triaxial and direct shear testing [31], the resulting lateral earth pressure coefficient is in the range of 0.13-0.15. Considering the normal stress of 225 kPa measured from an embedded pressure cell the apparent internal confining pressure within the ballast layer could be estimated to be in the proximity of 32 kPa, which is in agreement with past field data obtained from standard tracks [31]. Together with the additional confinement generated by the activated tyre cell assembly, one can reasonably anticipate the equivalent total confining pressure of this hybrid track to exceed 50 kPa. Indeed, Lackenby et al. [20] and Indraratna et al. [31] have shown with much laboratory and field evidence that the minimum ballast breakage is observed when the equivalent track confining pressure approaches at least 40 kPa, and in this regard, the tyre cell assembly has provided the desired effect, as further elaborated below.

After completion of 500,000 cycles of loading, ballast aggregates were collected from the track at different locations (e.g., below the sleeper & from the shoulder) in order to quantify the breakage of particles. The method proposed to quantify breakage [17] is adopted, whereby the Ballast Breakage Index (BBI) considers the area subtended by the shift in the particle size distribution (PSD) curve (before and after testing), in relation to the area between the original PSD and an arbitrary line representing a crushed ballast with the smallest grain size assumed to be in the range of coarse sand starting from 2.36mm. The measured ballast breakage values are shown in Table 1.

Table 1. Quantification of ballast breakage after testing for the hybrid track

Sieve Size (mm)	Percentage passing		
	Initial gradation of ballast	Collected ballast underneath South-West Actuator	Collected ballast at the end of the sleeper (shoulder ballast)
63	100	100	100
53	67.55	71.73	69.46
37.5	17.22	19.42	18.54
26.5	4.08	4.41	4.29
19	2.12	2.45	2.32
13.2	1.56	1.65	1.59
9.5	0	0.54	0.39
4.75	0	0	0
2.36	0	0	0
	Measured BBI	**0.087**	**0.043**

For the hybrid track, it can be observed that the BBI values obtained below the actuator and at the shoulder are 0.087 and 0.043, respectively. When compared to the corresponding BBI values of 0.129 and 0.074 determined earlier for the standard track [35], not surprisingly, the current hybrid counterpart indicates a substantial reduction in breakage of 33% below the actuator (BBI = 0.086) and 42% at the shoulder (BBI=0.043). This trend is further supported by the large-scale experimental data reported by Indraratna et al. [17] and Lackenby et al. [20] epitomising the reduction in ballast breakage when the confining pressure is increased from relatively low values often measured in the field (< 25 kPa) to the minimal particle degradation zone within the approximate range of 40-65 kPa. There is no doubt that the additional confinement created by the rubber-tyre stabilised substructure had significantly contributed to reducing ballast breakage. In a practical perspective this favourable outcome could be translated to longer service life of quarried ballast and reduced track maintenance cost.

Conclusions

This paper presents novel outcomes of including recycled rubber to increase the confining pressure at the main load-bearing part of track as well as its shoulders, based on 1:1 scale testing using the

Facility for Cyclic Testing of High-speed Rail (FCTHSR). Cyclic loading of prototype ballasted tracks was carried out under a 25-tonne axle load applied at a frequency of 15 Hz up to 500,000 loading cycles. In contrast to a standard ballast track, the performance of this hybrid track consisting of (i) rubber tyre assembly within the load-bearing substructure and (ii) tyre arc segments placed at the track shoulders was assessed in terms of settlement and lateral displacement of granular strata, vertical stress distribution with depth, ballast breakage and vibrations. Based on this study, the following salient conclusions could be drawn:

- The overall accumulated settlement of the hybrid track over a large number of loading cycles (N = 500,000) was smaller than the conventional track, albeit the initial rate of settlement of the hybrid track that was slightly greater, clearly attributed to the increased compressibility of the rubber tyre assembly. As expected, as a result of increase track confinement, the maximum lateral displacement of the hybrid track was measured to be less than 6 mm (average of 5 mm), while that of the conventional track was nearly 1.5 times (> 9 mm).
- Compared to a standard ballast track, the hybrid track significantly reduced the vertical stress distribution, i.e., about 40% and 43% reduction in the stresses at the location of infilled tyre assembly and subgrade layers, respectively. For instance, at N=100,000 cycle, the vertical stresses of the hybrid track at the ballast, sub-ballast and subgrade layers were measured to be: σ_v = 164, 76 and 52 kPa, respectively, in contrast to σ_v = 191, 126 and 91 kPa, for the same strata of the standard track without any rubber inclusions.
- Measured accelerations on the rail and sleeper of the hybrid track indicated that the accompanying vibrations in the hybrid track were much less than those of the standard track. For instance, the maximum acceleration measured on the hybrid track rail (A_{R_hybrid} =2.47 m/s^2) was less than half of that of the standard track (A_R =5.60 m/s^2). Moreover, the acceleration measured at a hybrid track sleeper (A_{S_hybrid} =2.07 m/s^2) was less than 10 times that of the standard track (A_S =27.5 m/s^2). These observations confirm without a doubt the damping effect (i.e., energy absorbing capacity) offered by the assembly of tyre cells.
- In the hybrid track, the infilled tyre assembly in tandem with the tyre arc segments at the shoulder provided the optimum confining pressure to significantly reduce ballast breakage. Ballast collected beneath selected sleepers and at the shoulders of the hybrid track indicated reduced breakage indices of: BBI=0.087 and 0.043, respectively. These ballast breakage reductions of 33 % and 42 % below the actuator and shoulder locations imply immense benefits in relation to track maintenance costs and extended longevity of the hybrid track.

In essence, the outcomes of this study prove without a doubt that the use of recycled rubber elements not only offer an attractive environmental solution for reduced quarrying and carbon emissions, but also a technologically superior and sustainable track stabilisation option for extended life cycle and reduced annual costs of maintenance of ballast tracks.

CRediT authorship contribution statement

Buddhima Indraratna: Conceptualisation, Methodology, Supervision, Formal analysis, Investigation, Writing – original draft, Writing – review and editing. **Fatima Mehmood:** Formal analysis, Methodology, Investigation, Writing - review and editing. **Soumyaranjan Mishra**: Formal analysis, Investigation Writing –review and editing **Trung Ngo**: Supervision, Writing – review and editing. **Cholachat Rujikiatkamjorn**: Supervision, Writing – review & editing

Declaration of Competing Interest

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.

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