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Advancements in track technology: Use of artificial inclusions for stabilising transport infrastructure

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ABSTRACT: Australian railways offer an efficient and economic mode of transporting freight and passengers across all States. Rail tracks are normally positioned on ballast because it is economical (availability and abundance), and because drainage is rapid and the tracks have a high load bearing capacity. However, repeated train loading fouls the ballast as small fines from the surface or subgrade intrude and then impair drainage that can potentially lead to track instability. In addition, the recent increases in axle loads, speed and traffic volume, coupled with the need to improve passenger comfort and reduce the cost of track life cycles, means that track designs must be optimised. Moreover, given that current ballasted tracks in many parts of Australia cannot support increasingly heavier and faster trains, the need to develop innovative and sustainable ballasted tracks is crucial for transport infrastructure.

This paper aims to demonstrate and discuss some major aspects related to stabilizing ballasted rail tracks overlying soft soils using artificial inclusions such as geosynthetics, recycled rubber mats, and end-of-life tyres. The use of geocomposites (i.e., bonded geogrid-geotextile layers) to enhance the performance of ballast is described with the aim of reducing track settlement, increasing the resilient modulus, and decreasing ballast degradation. The effects of increasing the confining pressure on rail track behaviour, particularly with regard to particle breakage has been studied using large-scale laboratory tests. We are therefore presenting a novel solution of confining the upper sub-ballast layer (capping) with energy-absorbing recycled rubber tyres to increase the stability and resiliency of track substructure. This study confirms that a sub-ballast layer confined by recycled rubber tyres can actively reduce ballast breakage within the track substructure. This study also carried out numerical simulations using finite element method (FEM) to examine how end-of-life tyres to improves track performance. The outcomes of this study will lead to a better understanding of how artificial inclusions-reinforced ballasted tracks perform, and then to a cost-effective track design with improved safety and passenger comfort.

1 INTRODUCTION

Ballast is the key foundation material placed underneath sleepers to provide structural support against the high cyclic and impact stresses from fast moving trains (Indraratna et al. 2011a; Selig and Waters 1994). Ballast is a natural or crushed granular material with a typical thickness of 250-350 mm that is placed beneath the track superstructure and above the sub-ballast (capping) or subgrade. The deterioration of ballast is one of the major contributing factors which affect the stability and longevity of railway foundations (Indraratna et al. 2011b; Tutumluer et al. 2012; Sun et al. 2017; Le Pen 2011; Ngo et al. 2014). The adoption of various forms of synthetic inclusions such as geogrids and Energy Absorbing Rubber Sheets (EARS) to reduce the plastic deformation and degradation of ballast has become more popular in recent years (Navaratnarajah et al. 2018; Indraratna et al. 2016). These synthetic inclusions eliminate the hard interface between ballast and sleeper or the underlying formations, and allow the aggregates to bed into the relatively softer pad and thus increase the contact surface area of the ballast and reduce ballast stresses. However, studies which analyse how well these synthetic inclusions can improve the performance of ballasted tracks are limited, so this paper reviews current research work carried out at the University of Wollongong, Australia using the large-scale testing apparatus, field investigations and computational modelling to evaluate the ability of artificial inclusions to reduce ballast deformation and degradation.

2 LABORATORY TESTING

2.1 *Ballast fouling*

During track operations, fine particles can accumulate within the ballast voids due to: (i) the breakage of sharp angular projections (corners), (ii) fines infiltrating from the surface, and (iii) pumping of soft saturated subgrade under excessive cyclic loads (Indraratna et al. 2011a). As the fouling material occupies the free voids of ballast it slowly impedes the drainage capacity of the track (Danesh et al. 2018). In Australia, the intrusion of coal fines and ballast breakage are the major sources of ballast fouling because they contribute about 70-95% and 5-30%, respectively (Indraratna and Ngo 2018). In low-lying coastal areas where the subgrade is usually saturated, the finer silt and clay particles are pumped up into the ballast layer as 'slurry' under train loading, but this problem could be eliminated if a properly graded filtration layer or artificial inclusions (i.e. geosynthetics, rubber mats) are placed underneath the ballast layer (Biabani et al. 2016; Tennakoon et al. 2012, Raymond, et al. 1994; Rujikiatkamjorn et al. 2012).

2.2 *Responses of ballast under monotonic and cyclic loading*

Past studies have been carried out on the effect that the loading characteristics (i.e. monotonic or cyclic loads) has on the shear stress-strain responses of railway ballast (Lackenby et al. 2007; Sun et al. 2016; McDowell and Li 2016, Qi et al. 2018). Based on extensive laboratory tests, the volumetric strains measured at different confining pressures are presented in Figure 1. Note that dilation (volume increase) occurs in the ballast samples for most confining pressures under monotonic loads, and despite similar ballast materials being tested in the same large-scale triaxial testing apparatus, they all showed different volumetric strains under different loading conditions. However, the ballast specimens subjected to cyclic loading under a confining pressure higher than 30 kPa underwent significant compression due to the re-orientation and re-arrangement of particles that occurs during cyclic loading, which creates a denser (compressing) or looser (dilating) packing assembly. Those ballast assemblies subject to a low confining pressure show a mainly dilative response, whereas the reverse happens for ballast specimens under higher confining pressures subject to monotonic loading.

2.3 *Geosynthetics-ballast interface*

The influence that the geometry and opening aperture size of geogrids has on the interface of a geogrid-reinforced ballast composite assembly has been examined by Indraratna et al. (2012). In this study, seven types of geosynthetics (G1 to G7) with square, rectangular, and triangular opening geometries and various size apertures (i.e. 36 mm to 70 mm) are tested using the large-scale direct shear test under normal stresses of 26.3 kPa to 61 kPa. The actual improvement in the behaviour of ballast-geogrid interfaces can be determined in terms of the interface efficiency factor that is defined as the ratio of the shear strength of the interface to the internal shear strength of the ballast:

$$\alpha = \tan(\delta)/\tan(\varphi) \qquad (1)$$

where, δ is the apparent friction angle of the interface and φ is the friction angle of the ballast. Note that the cohesion intercept for ballast materials is omitted.

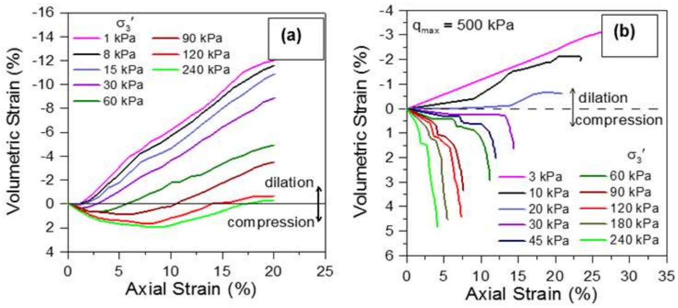

Figure 1. Volumetric strains of ballast tested under: (a) monotonic load; and (b) cyclic load (after Indraratna et al. 1998)

The influence that the size of geogrid aperture has on the shear strength of the ballast-geogrid interface (α) is evaluated as a function of the A/D_{50} ratio (i.e. D_{50}: mean ballast particle size). The measured data shows that α increases with A/D_{50} until it attains a maximum value of 1.16 at A/D_{50} of 1.21, and then it decreases towards unity as A/D_{50} approaches to 2.5. The value of α <1 shows an ineffective interlocking with ballast particles, whereas α >1 implies acceptable interlocking that may actually help to increase the shear strength. In other words, the A/D_{50} value where α =1 is the minimum condition needed to generate the beneficial effect of geogrid reinforcement. Based on the variations of α, an optimum interlock zone can be formed where the interface efficiency factor is α = 0.95 to 1.2. This study indicates that the minimum and maximum size apertures of geogrid to optimise the shear strength are $0.95D_{50}$ and $2.50D_{50}$, and the optimum size aperture of geogrid is approximately 1.2-1.3 D_{50}.

2.4 *Use of geogrids and rubber mats for improving the ballast response under impact loading*

Defects in the rails or wheels such as wheel flats, dipped rails, rail corrugations and defective rail welds may impart large impact forces onto the tracks, but impact loads can also be generated at transitions zones where the track stiffness differs (e.g., bridges, tunnels and road crossings); these impact loads exacerbate the deterioration of the track elements and also imply that more frequent maintenance operations are needed (Ferreira and Indraratna 2017; Nimbalka et al. 2012).

The large drop-weight impact test equipment (Figure 2a) developed in-house at the UOW (Kaewunruen and Remennikov 2010) is used to study the improved performance of ballast reinforced by geogrids (Figure 2b) and resilient rubber mats (Figure 2c) subject to repeated impact loading. This apparatus can accommodate test specimens within a working area of 1800 × 1500 mm. The transient impact forces are monitored by a dynamic load cell (capacity of 1200 kN) attached to the hammer connected to an automatic data acquisition system. A free-fall hammer place at the required drop height (h=150 mm) is released through an electronic quick release system. The drop height is chosen to produce dynamic stresses that are similar to those generated by wheel-flats and dipped rail joints measured in the field (Ngo et al. 2018). For data recording purposes, automatic triggering is enabled using the signal obtained as the hammer free falls, so the acquisition frequency is set to 5000 Hz. The permanent settlement and radial deformation of the test samples after each impact are estimated by manual measurements at pre-determined locations. These tests are completed after twelve blows due to the attenuation of ballast strains.

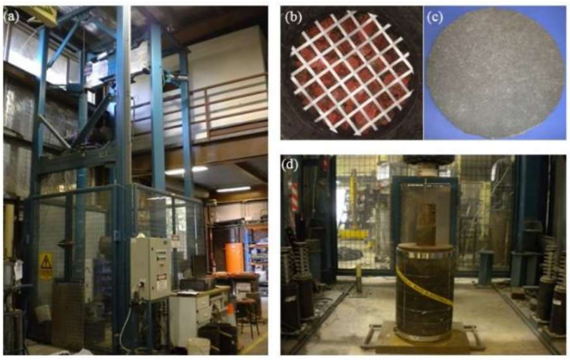

Figure 2. a) Drop-weight impact facility; b) geogrid sample; c) rubber mat sample; d) sample ready for testing

The permanent axial and radial strains of ballast over the number of blows for the aforementioned test conditions are plotted in Figures 3a-b, respectively. As expected, the ballast progressively deforms due the repeated hammer blows, although the strain increments are more pronounced during the initial impacts due to the rearrangement and corner breakage of aggregates, but this gradually decreases after a certain stage. Moreover, ballast deformation is also mitigated when rubber mats are placed below or above the ballast layer. Placing a rubber mat below the ballast and a geogrid at 100 mm height from the base further reduce the ballast deformations, which is related to the interlocking of ballast particles within the geogrid apertures. This action confines the ballast aggregates even more and also reduces the lateral displacements.

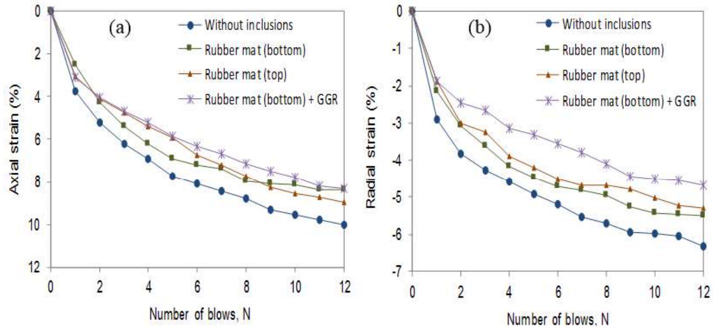

Figure 3. Influence of the location of the rubber mat and geogrid inclusion on ballast deformation: a) axial strain; b) radial strain

2.5 *Use of rubber mats to improve the performance of ballast under cyclic loading*

An innovative solution for minimising track deterioration is placing rubber mats made from waste tyres under the ballast. This study uses a large-scale process simulation prismoidal apparatus (PSPTA) to investigate the performance of ballast improved by rubber mats (Figure 4). Cyclic loads from fast and heavy-haul trains (35 ton axle load) are simulated on a stiff track foundation (concrete bridge deck). Details of the test set-up, loading conditions, data measurements and the materials used for the tests can be found in Navaratnarajah and Indraratna (2017).

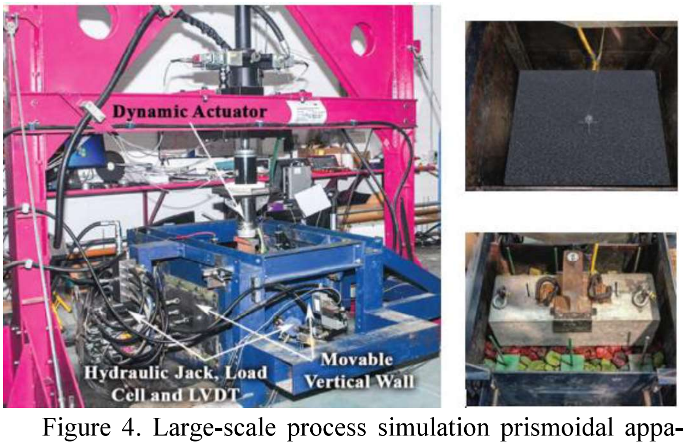

Figure 4. Large-scale process simulation prismoidal apparatus (PSPTA) for testing ballast reinforced by rubber mats

Figure 5 shows the vertical and lateral deformation (i.e. strains) of ballast that accumulates with and without rubber mats under axle loads of 35 tons. All the tests are under frequencies of f=10-20 Hz. These tests indicate that plastic deformation of ballast increases quickly up to approximately 10,000 load cycles, the rate of deformation progressively decreases up to about 100,000 cycles, and then remains relatively unchanged. When rubber mats are utilised the vertical and lateral permanent strains of ballast decrease by approximately 10-20% and 5-10%, respectively. This study confirms that rubber mats have enough damping property to absorb a certain amount of kinetic energy transmitted to the track and can therefore prevent excessive ballast deformation and degradation.

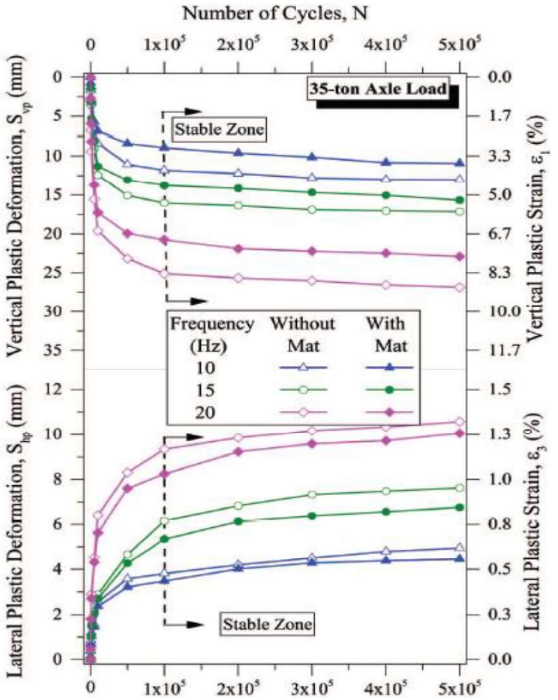

Figure 5. Variations in vertical and lateral deformation (data source: Navaratnarajah and Indraratna (2017)-with permission from ASCE)

3 APPLICATION OF GEOSYNTHETICS AND RUBBER MATS IN FIELD TRACKS

Experimental sections of tracks built at Bulli and Singleton, NSW are used to study the improvements in track performance and deformation from train-induced stresses due to the use of geosynthetics and rubber mats. The technical specifications of various materials used during construction are reported in Indraratna et al. (2010). The experimental sections are monitored such that: (i) vertical and lateral stresses are measured by pressure plates; (ii) the vertical and horizontal deformation is obtained by settlement plates and digital displacement transducers installed at the sleeper-ballast and ballast-sub-ballast interfaces, respectively. Field measurement data shows that the peak cyclic vertical (σ_v) stress decreases by 73 % and 82 % at depths of 300 mm and 450 mm, respectively. The lateral stress (σ_l) only decreases marginally with depth, which implies that artificial inclusions are needed for additional restraints, and while most of the peak cyclic vertical stresses (σ_v) are almost 230 kPa, one value of σ_v reached 415 kPa; this was later found to be associated with a wheel flat, thus proving that much larger stresses and large impact forces are exerted by wheel imperfections. The resulting particle breakage could be mitigated by a shock mat, as presented by Indraratna et al. (2014) in the Singleton study.

The vertical and horizontal deformation of ballast are measured in the field at given time intervals. A relationship between the annual rail traffic in million gross tons (MGT) and axle load (A_t) is needed to determine the number of load cycles N, as proposed by Selig and Waters (1994). This relationship is expressed as: $N_t = 106/(A_t \times N_c)$, where N_t, A_t and N_c are the numbers of load cycles per MGT, the axle load in tonnes, and the number of axles per load cycle (Powrie et al. 2007). When this relationship is used for a traffic tonnage of 60 MGT per year and four axles per load cycle, an axle load of 25 tonnes gives 600,000 load cycles per MGT. A simple survey technique is then used to record changes in the reduced level of tip of the settlement pegs. The average ballast settlements against the number of load cycles (N) are shown in Figure 6. Unlike fresh ballast, recycled ballast has less vertical and lateral deformation, possibly due to its moderately graded particle size distribution - PSD (C_u = 1.8) compared to the very uniform PSD (C_u = 1.5) of fresh ballast. These results also indicate that geocomposite reinforcement reduces the vertical (S_v) and lateral (S_l) deformation of fresh ballast by around 33 % and 49 %, as well as reducing the vertical (S_v) and lateral (S_l) deformation of recycled ballast by about 9 % and 11 %, respectively. This result enables the ballast layer to distribute the load and substantially reduce settlement under high repeated loads.

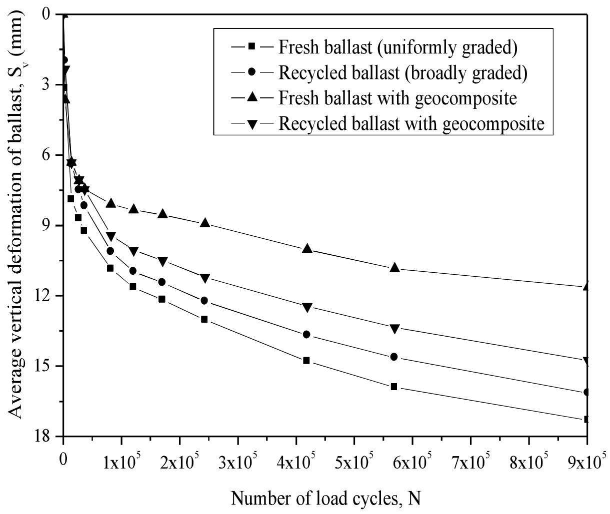

Figure 6. Average vertical deformations of the ballast (data source: Indraratna et al. (2010)-with permission from ASCE).

4 COMPUTATIONAL MODELLING OF TYRE-REINFORCED SUBBALLAST

Waste tyres are one of many major environmental concerns because every year Australia produces more than 40 million waste tyres. Recent research work carried out at the University of Wollongong has shown that when waste tyres are placed under track foundation they improve the performance of ballasted tracks by increasing the bearing capacity and reducing the lateral displacement of tracks. A 3D finite element analysis (Figure 7) is implimented in this study to examine the load-deformation responses of a capping layer of infilled rubber tyres.

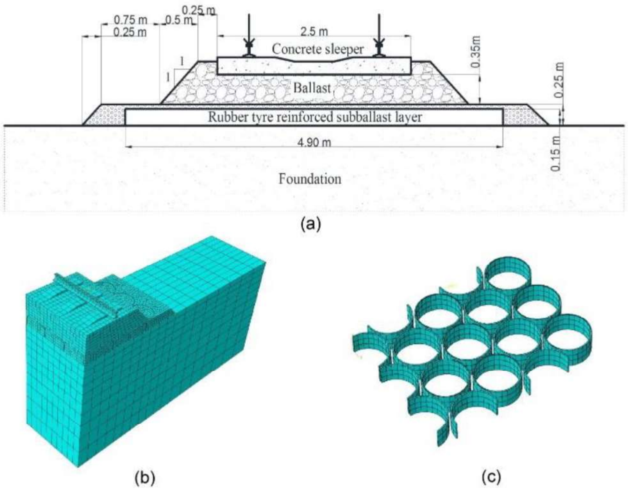

Figure 7: (a) Track geometry with rubber tyres reinforced capping layer; (b) FEM mesh; (c) FEM mesh of rubber tyres (modified after Indraratna et al. 2017)

Figure 8a shows how rubber tyres helped to reduce the deviator stresses on the subgrade. Note that the highest deviator stress occurs at the end of the sleeper and decreases towards to the middle. The FEM simulations shows an almost 12% reduction due to tyre reinforcement compared to an unreinforced section (i.e. a train with a 25 ton axle load running at a speed of 100 km/h) experiences a maximum deviator stress of 46.2 kPa. This is due to the additional confining effect by the tyres which leads to the gravel infill composite becoming stiffer, which then allows the then decreased and more uniform stresses to be transferred to the subgrade underneath. Figure 8b shows how tyres affect the distribution of deviator stresses along the depth of a track foundation. Observe how the inclusion of rubber tyres reduces the deviator stress in the subgrade, a result that could prevent excessive track deformation.

5 CONCLUSIONS

This paper presents studies on the use of artificial inclusions for minimising track deterioration induced by fast moving heavy-haul trains based on extensive laboratory testing, numerical modelling and full-scale field monitoring carried out at the University of Wollongong, Australia. It describes the key research findings of the stress-strain responses of ballast subject to static and cyclic loading, as well as the degradation of ballast and its implications on the design and performance of tracks. The influence of confining pressure and train speed (frequency) on the degradation and deformation of railroad ballast under cyclic loading was investigated by large-scale ballast testing apparatus. It was noted that the normalised aperture ratio, (A/D50) had a profound influence on the interface factor (α). The geogrid aperture which best optimised the interface shear strength was around 1.20D50. The maximum and minimum size apertures needed to attain the beneficial effects of geogrids are 0.95D50 and 2.50D50, respectively. The field performance of ballasted rail tracks with geosynthetic reinforcement was also discussed in this paper. The results of the Bulli field study indicated that the use of geocomposites as reinforcing elements for tracks with recycled ballast proved to be a feasible and affective alternative.

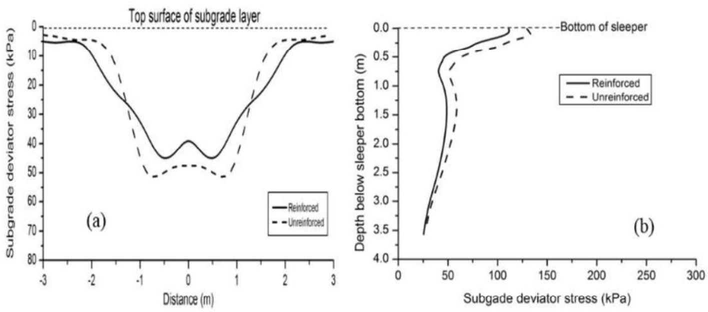

Figure 8: (a) stress distribution below reinforced and unreinforced track; (b) distribution of subgrade deviator stress with depth (data source: Indraratna et al. 2017)

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