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Abstract

This article reviews on current knowledge of rail track geomechanics, including several important concepts and topics related to laboratory testing and computational modelling, to study the shear stress-strain and deformation of ballast improved by geosynthetics and recycled rubber mats. The effect that impact loads have on ballast degradation and its mitigation due to resilient synthetic mats (i.e. rubber mats) between the ballast and the subballast is investigated using large-scale impact-testing apparatus. Computational modelling with finite element and discrete element methods are increasingly being used to model ballasted tracks reinforced with geosynthetics to capture the continuum media of formation soils and the discrete nature of ballast aggregates. The article focuses on reviewing previous studies by the University of Wollongong on ballasted track substructure and highlights some practical implications whereby innovation progresses from theory to practice.

Keywords

geoinclusions, evidence, dem, experimental, simulation, stabilization, substructure, track

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Stabilisation of track substructure with geo-inclusions – experimental evidence and DEM simulation

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ABSTRACT: This paper reviews on current knowledge of rail track geomechanics, including several important concepts and topics related to laboratory testing and computational modelling, to study the shear stress-strain and deformation of ballast improved by geosynthetics and recycled rubber mats. The effect that impact loads have on ballast degradation and its mitigation due to resilient synthetic mats (i.e. rubber mats) between the ballast and subballast is investigated using large-scale impact testing apparatus. Computational modelling with finite element and discrete element methods are increasingly being used to model ballasted tracks reinforced with geosynthetics to capture the continuum media of formation soils and the discrete nature of ballast aggregates. This paper focuses on reviewing previous studies by the University of Wollongong on ballasted track substructure, and highlights some practical implications whereby innovation progresses from theory to practice.

KEYWORDS: Rail transportation; ballasted tracks; geosynthetics; computational modelling

1. Introduction

Ballasted rail tracks are the major infrastructure catering for public and freight transport in Australia, with a 33,400 km long network that offers an essential supply chain for agricultural and mining industries. Traditional rail track substructures are becoming overloaded due to an increasing demand for hauling heavier freight and faster trains, both of which increase the rate of track deterioration and the maintenance costs [1, 2]. Ballast is a free-draining granular medium designed as a load-bearing layer in rail tracks; its main functions are: (i) transmitting induced train loads to the underneath layers at a reduced and acceptable level of stress, (ii) providing lateral resistance, and (iii) facilitating drainage for tracks [1, 3]. Significant degradation of ballast due to track substructures subjected to large cyclic stresses causes the ballast becomes fouled, less angular, and its shear strength decreases. These problems can be mitigated by utilising planar geosynthetics (geogrids, geotextiles, geocomposite); three-dimensional cellular reinforcement (geocells) and energy absorbing rubber mats. Budiono *et al.* [4] state that fine particles reduce the strength and stiffness of track substructure, while Tutumluer *et al.* [5] report that its shear strength decreases continually as the level of fouling increases; ballast fouling leads to excessive track settlement and instability, as well as high maintenance costs [6, 7]. There are a number of studies which highlight that ballast breakage and confining pressure are key parameters governing the behaviour of ballasted rail tracks [8, 9, 10, 11, 12], which is why railway associations resist the inroads of other modes of transportation by continuously improving rail efficiency and the cost of construction and maintenance.

The cost of track maintenance can decrease if the geotechnical engineering of the ballast aggregates is assessed properly [2, 13, 14] because inserting artificial synthetic materials into the ballast enhances the efficiency and performance of ballasted track substructures [15, 16, 17]. Reinforcing track with geogrids also helps to confine the ballast within the apertures which in turn reduces the downward propagation of stresses, reduces vertical and lateral plastic deformation, and increases the resilient long term performance of the ballast layer [18, 19]. Geocomposite such as geogrid and non-woven geotextiles simultaneously reinforce the ballast grains and provide filtration and separation functions [20, 21]. Moreover, sub-surface drainage via geosynthetic drains has also been very effective in rapidly dissipating cyclic-induced pore water pressures in the soft subgrade (e.g. clay and silts) during the passage of trains, as well as preventing soil liquefaction (mud pumping) [22].

2. Applications of geosynthetics, geocells and rubber mats in ballasted tracks

The use of planar geosynthetics to improve the performance of ballasted tracks are the subject of numerous studies carried out by Bathurst and Raymond [23]; McDowell *et al.* [12], Brown *et al.* [24]; Indraratna *et al.* [25], among others. Placing geosynthetics such as geogrids or non-woven geotextiles under the ballast layer confines the aggregates via interlock or frictional resistance between the ballast grains which then stiffens the surrounding particles [3, 7], and increases the shearing resistance. This results in a more resilient long term performance of rail track, as well as helping with drainage and reducing ballast degradation [17, 19, 26]. The ability of geogrids to provide additional confinement to track substructures is noted by Selig and Waters [1], Indraratna *et al.* [10], Rujikiatkamjorn *et al.* [27]; their studies indicate that the interaction between ballast and geogrid is one of the governing parameters controlling the performance of geogrids in ballasted rail tracks.

2.1. Laboratory testing

A series of large-scale cyclic tests for fresh and coal-fouled ballast were carried out using a unique track process simulation apparatus (TPSA) designed and built at the University of Wollongong (Figure 1). This apparatus can accommodate a ballast assembly that is 800 mm long, 600 mm wide and 600 mm high. It is large enough to accommodate a unit cell that represents the length of a typical sleeper ($l = 800$ mm) and the distance between two adjacent sleepers ($B = 600$ mm). Settlement pegs and Linear Voltage Differential Transformers (LVDTs) are installed at various locations in the TPSA to measure the vertical and horizontal deformation of ballast, while the cyclic vertical stresses are measured by pressure cells at the sleeper-ballast and ballast-subballast interfaces. Samples of ballast selected from Bombo quarry, New South Wales, Australia, are cleaned and sieved according to Australia Standard [28]. A 100mm thick layer of dry gravel and sand is compacted and used as subballast to achieve a representative field unit weight of about 18.5 kN/m^3 . A layer of geosynthetics is then placed onto the subballast (i.e. at the interface of capping (sub-ballast) and ballast layer), which is then covered with ballast and compacted to a field unit weight of 15.5 kN/m^3 . It is noted that compaction of ballast was carried out in several layers, each about 100 mm thick using a ballast compactor. By correlating the stiffness of support and its effect on the vibration frequency of vibratory rollers, the density of constructed ballast layers in the field can be controlled. The ballast is placed in multiple layers, each of which is compacted with a hand-held vibratory tamper to achieve the desired unit weight. The total thickness of ballast layer is 300 mm. Fouled ballast is made by spreading a predetermined amount of coal fines into each sub-layer of ballast,

and then an air hose is used to blow the fines through the ballast voids. This realistically mimics fines falling off wagons and infiltrating the ballast in the field. Table 1 shows the technical specifications of the geosynthetics and granular materials used in this study; the materials tested in this study are presented in Figure 2, and the particle size distribution of materials used in the laboratory are shown in Figure 3. Coal fines were used as the fouling material and the Void Contamination Index (VCI) proposed earlier by Indraratna et al. [29] was adopted used to quantify the levels of ballast fouling.

A cyclic load is applied by a servo-dynamic hydraulic actuator at a frequency of 15 Hz with a maximum cyclic stress of 420 kPa, to simulate an Australian train travelling at approximately 80-90km/h. The maximum cyclic stress is determined using the American Railway Engineering Association (AREA) method. Lateral confining pressures of 7 kPa in a transverse direction (parallel to sleeper), and 10 kPa in a longitudinal direction (perpendicular to sleeper) are applied to simulate in-situ track conditions; this confining pressure is applied through the hydraulic jacks mounted on the sides of the apparatus. Fresh and fouled ballast is then tested at different Void Contamination Indexes, VCI [6, 30] up to $N = 500,000$ number of cycles, that is enough to capture the long term performance of ballasted tracks.

The vertical settlement of ballast is determined by excluding any deformation of the sub-ballast and subgrade. Figure 4a shows variations in the settlement (S) of fresh and fouled ballast with and without geogrid against an increased number of load cycles; for a given VCI, geogrid-reinforced fouled ballast experiences less settlement than the unreinforced assembly, possibly due to the mechanical interlock at the ballast-geogrid interface that minimises displacement. As anticipated, an increasing degree of fouling leads to increased ballast settlement, in fact ballast settles rapidly as soon as the loading cycles commence, but the rate of settlement decreases once it reaches a relatively 'stable' zone after a certain number of load cycles (i.e. 300,000 cycles). This indicates that ballast aggregates undergo considerable rearrangement and densification during the initial load cycles [2, 5]. Figure 4b shows the horizontal displacement (L) of fresh and fouled ballast plotted against the number of load cycles, and illustrates how the geogrid substantially reduces the lateral displacement of ballast in comparison to the unreinforced cases. Geogrid offers internal confinement which improves the lateral stability of ballast layer [2, 31]. This reinforcement action by the geogrid commences during cyclic loading and is responsible for reducing the lateral deformation of ballast [32]. Indeed, when the ballast aggregates are compacted over the geogrid, they partially penetrate and are then locked into the apertures, which then create a strong mechanical interlock between the geogrid and now restrained grains of ballast. This interlocking effect enables geogrids to act like a non-horizontal displacement boundary which confines

and restrains the ballast from free displacement. This finding is supported by studies carried out by Tutumluer *et al.* [5] and McDowell *et al.* [12]. This result has a significant bearing on the maintenance of rail tracks due to the way geogrids curtail the deformation of ballast.

2.2. Field study at Singleton

To determine how well different types of geosynthetics would enhance the overall performance of ballasted tracks under in-situ conditions, an extensive study has been carried out on fully instrumented sections of track. Construction of this track began in July 2009 and commissioning took place in May 2010 by Indraratna *et al.* [22]. The track has several sections with different types of subgrades, including (i) relatively soft general fill and alluvial silty clay (Sections 1-5 and Section A), (ii) intermediate cut siltstone (Section C), and (iii) a stiff reinforced concrete bridge deck supported by a piled abutment (Section B), as shown in Figure 5a. The track substructure has a 300 mm thick layer of ballast over a 150 mm thick layer of subballast, and a 500 mm thick layer of structural fill with below the subballast. Three types of geosynthetics have been installed; (i) geogrid (aperture size $A1 = 65 \times 65$ mm), (ii) geogrid (aperture size, $A2 = 44 \times 44$ mm), and (iii) geogrid ($A3 = 40 \times 40$ mm). There is also a layer of geogrid at Sections 1-3 and 5 and a layer of geocomposite (aperture size $A4 = 31 \times 31$ mm combined with nonwoven geotextile) at Section 4. Further details of the physical characteristics and technical specifications of the geosynthetic grids are given elsewhere by Indraratna *et al.* [22].

Figure 5b shows the vertical deformation (S_v) of the ballast plotted against the number of load cycles (N) for soft soil foundations; these results indicate that the relationship between deformation and the number of load cycles is non-linear, regardless of how the substructure has been built. The rate of increase in S_v decreases as the number of load cycles increases. For a given section, the vertical settlements of the reinforced sections are 10-32% smaller than those without reinforcement. This pattern is similar to that observed in the laboratory [29], and is mainly due to interlocking between the ballast grains and geogrids. When the results for sections with similar geogrids are compared, it is observed that the ability of geogrid reinforcement to reduce track settlement is generally greater for softer subgrades (low track stiffness). Previous studies has shown that the geogrid with aperture size 40×40 mm is the optimum size because this size aperture (40 mm) interlocks the ballast particles best [2, 7]). This finding also agrees with the criteria for optimum size apertures for reinforcing geogrids that the optimum geogrid aperture to maximise the interface shear strength is 1.20 times D_{50} . Field data from the Singleton study

indicates that geogrid is more effective with weaker subgrade, and geogrids reduce the vertical deformation of ballast, improve track stability, and decrease the cost of maintenance.

2.3. Applications of resilient rubber mats in rail tracks

Planar geosynthetics placed beneath the ballast do not absorb the impact loads imparted by stiff foundations such as concrete bridge decks or level crossings [22], whereas synthetic rubber mats are an attractive option in these situations. Rubber mats have recently undergone trials on track substructure in Europe in an attempt to decrease the deformation and degradation of ballast and improve overall track stability [34, 35]. These mats rely on their damping properties and energy absorbing capacity to isolate track structure from the relatively softer subgrade, attenuate the transmission of vibrations, and thereby reduce track deformation while having a beneficial effect on track alignment [36]. The ability of rubber mats to minimise noise along stiff tracks over concrete bridges and in tunnels, as well as controlling vibration along open tracks has been studied by Auersch [37], and Anastasopoulos *et al.* [38]. However, there is a limited scientific basis for their use as inclusions to absorb energy from repeated passing trains. Preliminary studies by Nimbalkar *et al.* [22] showed that the performance of rubber mats depends on the type of substructure (e.g., soft soil, stiff clay, and rock etc.), the loading magnitude and frequency (i.e. axle loads and train speeds), and their energy absorbing properties.

Nimbalkar *et al.* [33] carried out large scale drop-weight impact tests (Figure 6) to study how impact loads affect the deformation of ballast. The equipment has been designed and built at the University of Wollongong (UOW) and consists of a 5.81 kN free fall hammer that can be dropped from a height of 6 m at an equivalent velocity of 10 m/s. The hammer is lifted mechanically to a designed drop height and released electronically. Ballast specimens 300mm in diameter by 300mm high are used in the laboratory (Figure 6b,c). Details of the material specifications and test program are described elsewhere by Nimbalkar *et al.* [33]. All the test assemblies are confined within a 10mm thick rubber membrane to prevent piercing by sharp edges during testing. The 10 mm thick rubber mat used is made from 1-3 mm recycled rubber granulates bound by a polyurethane elastomer compound. A circular steel plate (thickness $t = 50$ mm) is used to represent a stiff subgrade such as a bridge deck, and a thin layer of compacted sand is used to simulate relatively weak subgrade conditions. Weak subgrade was tested as soft sandy sand, having modulus of around 75 kPa. The stiff subgrade was used as concrete plate, having modulus of about 17 GPa. During testing, the transient impact forces are measured by a dynamic load cell (capacity of 1200 kN) placed on the drop-weight hammer. Piezoelectric accelerometers are

used to record the transient accelerations, and sample deformations are recorded by electronic potentiometers after each blow.

Two distinct force peaks occur during impact loading, i.e. an instantaneous sharp peak with a very high frequency known as P_1 , and a gradual peak with a smaller magnitude and slightly less frequency, known as P_2 . The force P_2 lasts longer and is attributed to the mechanical resistance of the track substructure which leads to its ultimate compression [39]. Force P_2 directly influences the degradation of ballast grains and is determined by its nominal maximum speed and nominal gross mass of the vehicle, as given by:

$$P_2 = P_0 + 2\alpha V_m \times \sqrt{\frac{M_u}{M_u + M_t}} \times \left[1 - \frac{C_t \pi}{4 \times \sqrt{K_t (M_u + M_t)}} \right] \times \sqrt{K_t M_u} \quad (1)$$

where P_0 = maximum static wheel load (kN); M_u = vehicle unsprung mass per wheel (kg), that is, the effective unsprung mass includes the rotational inertia of the traction motor armature and casing as well as the inertia force for vertical movement of the wheelset; 2α = total joint dip angle (radians), V_m = maximum normal operating velocity (m/s), M_t = equivalent track mass (kg), nominally $M_t=133\text{kg}$; K_t = equivalent track stiffness (MN/m), nominally 109MN/m; and C_t = equivalent track damping (kNs/m), nominally 52kNs/m.

The response of the impact load-time subjected to the 1st drop of the free-fall hammer is presented in Figure 7 where two distinct types of force peaks P_1 and P_2 are measured. Note that multiple P_1 type peaks followed by a distinct P_2 type peak occurs often, followed by a large increase of P_2 at the initial stages of impact loading, which then it becomes almost imperceptible. This shows that the ballast stabilises after being impacted a certain number of times to produce an almost constant P_2 . The vertical and lateral deformation of the ballast is recorded after each blow, while the shear strain (ϵ_s) and volumetric strain (ϵ_v) of ballast with and without the inclusion of rubber mats are shown in Figure 7. Note how the inclusion of rubber mats at the top and bottom of the ballast reduces the shear and volumetric strains (i.e. in the order of 40 to 50%) quite significantly, but this reduction is marginal with weak subgrade. Unlike planar geogrids where the apertures of the grids lock the aggregates together to provide a non-displacement boundary, a typical ballast mat will not provide the same degree of interlocking. However, the much greater energy absorption by these mats to reduce the effects of high impact loads would more than compensate for the less frictional interaction mobilised at the ballast-mat interface compared to geogrid with large apertures.

2.4. Applications of geocells in stabilising subballast in rail tracks

Geocells (three dimensional structures) were originally developed by the U.S. Army Corps of Engineers to improve vehicular mobility over loose sandy subgrade. The performance of geocell mattress stabilised with different types of infill soils has been carried out by Saride *et al.* [40]. It is well recognized that the improved performance using geocells is mainly due to increased confinement. Railway organisations do not usually use geocells to confine ballast because it leads to problems with track maintenance by machinery. Instead, geocells can be used to reinforce subballast because the hoop stress mobilised in the geocell provides an additional confinement which arrests the lateral spreading of infill materials. The cost of track construction or maintenance can be reduced significantly if appropriate reinforcement is used to stabilise track substructures [16, 32].

Preliminary studies carried out at the University of Wollongong to investigate the improved performance of subballast using geocells indicate that improves the load carrying capacity by increasing the rigidity of in-filled subballast, which then improves track performance [17, 18]. The large-scale TPSA (Figure 8) has also been used to investigate the improved performance of subballast using geocells. The particle size distribution of the tested subballast is within the range specified by the Australian rail industry ($D_{50} = 3.3$ mm, $D_{max} = 19$ mm, $D_{min} = 0.075$ mm, $C_u = 16.3$, $C_c = 1.3$, $\gamma_d = 19$ kN/m³). All the tests are carried out at various frequencies ($f=10-30$ Hz) under different confining pressures ($\sigma_3 = 5-30$ kPa), to represent trains travelling at approximately 75-285 km/h. Figure 9 shows the vertical strains of geocell-reinforced subballast plotted against the number of load cycles (N) at various frequencies and confining pressures; note how the increased confinement by the geocells helps to reduce the vertical strains of subballast at any given frequency and confining pressure. During the first few thousand cycles the vertical strains (i.e. settlements) increase rapidly due to initial particle rearrangement and compression, but this rate of increase decreases in cycles beyond the unstable zone such that at a very high value of N the vertical strain is almost a constant which is commonly known as ‘shakedown’ or stable densification.

Finite element analysis is also used to increase our understanding of subballast reinforced by geocell. Model tests are simulated in the finite element method (FEM) where the material properties are determined from the experimental data and model geometry that follows the TPSA (800 mm $\times$ 600 mm $\times$ 450 mm), as shown in Figure 10. A layer of subballast modelled with a depth of 450 mm is used to represent variations in its height, as measured in the field. An elasto-plastic constitutive model (i.e. the Drucker-Prager yield criterion) with a non-associative rule is used to model the subballast, and linear,

elastic-perfectly plastic material is used to simulate the geocell mattress. The elastic properties of the geocell strips are determined by tensile tests and then incorporated into the FEM model in ABAQUS. A hexagonal shape is used to simulate the actual geometry and shape of the geocell pockets. A cyclic load is applied in a stress controlled mode with a frequency of $f = 10$ Hz, where the maximum and minimum load amplitudes are 166 kPa and 41 kPa, respectively, under the same low confining pressures ($5 \text{ kPa} \leq \sigma_3 \leq 30 \text{ kPa}$) as those carried out in the laboratory.

Figures 10a-c present the deviatoric stress, vertical settlement contours in subballast, and stress contour in geocell for reinforced subballast subjected to cyclic loading (frequency of $f = 10$ Hz; confining pressure of $\sigma_3 = 10 \text{ kPa}$) at a load cycle of $N = 10,000$. The numerical results indicate that the subballast experiences the highest vertical deformation of about $S_V = 2.57 \text{ mm}$ under the footing surface, and this gradually decreases with depth, such that settlement at a depth of $h = 200\text{--}250 \text{ mm}$ is only around $S_V = 1.71 \text{ mm}$. Figure 10d shows a comparison between the vertical settlement of geocell-reinforced subballast obtained from the FEM simulations, and those measured experimentally under varying confining pressures ($\sigma_3 = 10\text{--}20 \text{ kPa}$) under a frequency of $f = 10$ Hz. Note that the settlements obtained from the FEM analysis agree well with those measured in the laboratory. Most of the deformation in reinforced subballast occurs at the early stage of loading ($N \leq 3,000$ cycles) because settlement commences immediately during the initial number of cycles (particle rearrangement). The experimental and numerical results both confirm that the rate of settlement decreases to a controlled steady state after $N \geq 5,000$ cycles.

3. Computational modelling for ballast aggregates

3.1. Angles of dilatancy and friction of ballast

The stress-dilatancy concept [41, 42] can be used to model ballast degradation under triaxial monotonic loading:

$$\frac{\sigma'_1}{\sigma'_3} = \left(1 - \frac{d\varepsilon_v^p}{d\varepsilon_1^p}\right) \tan^2 \left(45 + \frac{\phi'_f}{2}\right) + \frac{dE_B}{\sigma'_3 d\varepsilon_1^p} (1 + \sin \phi'_f) \quad (2)$$

where, ϕ'_f is the effective friction angle excluding the effect of dilation and particle breakage ($\phi'_f = 44^\circ$), and dE_B is the incremental energy consumption by particle breakage per unit volume. The dE_B can be expressed in terms of the ballast breakage index (BBI) as:

$$\left(\frac{dE_B}{d\varepsilon_1^p}\right) = \kappa \left[\left(\frac{dBBI}{d\varepsilon_1^p}\right) \right] \quad (3)$$

where, κ is the constant of proportionality ($\kappa = 175.8$). A new Ballast Breakage Index (BBI) specifically for railway ballast proposed by Indraratna et al. [2] was used to quantify the extent of degradation. The non-associated plastic flow rule incorporating the rate of particle breakage during shearing is represented by:

$$d\varepsilon_v^p = \left[1 - \left(\frac{\sigma_1'}{\sigma_3'}\right) \tan^2 \left(45 - \frac{\phi_f'}{2} \right) + \kappa \left(\frac{dBBI}{\sigma_3' d\varepsilon_1^p} \right) (1 - \sin \phi_f') \right] d\varepsilon_1^p \quad (4)$$

The mobilised dilatancy angle ψ_m during loading/reloading phase is expressed as:

$$\sin \psi_m = \frac{d\varepsilon_1^p + x d\varepsilon_3^p}{d\varepsilon_1^p - x d\varepsilon_3^p} = \frac{d\varepsilon_v^p / d\varepsilon_1^p}{2 - d\varepsilon_v^p / d\varepsilon_1^p} \quad (5)$$

where, x is a constant ($x = 1$ for plane strain, and $x = 2$ for axisymmetry). By incorporating the effect of particle breakage, ψ_m can be expressed as [10]:

$$\psi_m = \sin^{-1} \left\{ \frac{\left[1 - \left(\frac{\sigma_1'}{\sigma_3'}\right) \left(\frac{1 - \sin \phi_f'}{1 + \sin \phi_f'} \right) + \kappa \left(\frac{dBBI}{d\varepsilon_1^p} \right) \left(\frac{1}{\sigma_3'} \right) (1 - \sin \phi_f') \right]}{\left[1 + \left(\frac{\sigma_1'}{\sigma_3'}\right) \left(\frac{1 - \sin \phi_f'}{1 + \sin \phi_f'} \right) - \kappa \left(\frac{dBBI}{d\varepsilon_1^p} \right) \left(\frac{1}{\sigma_3'} \right) (1 - \sin \phi_f') \right]} \right\} \quad (6)$$

The ballast deformation during cyclic loading can be determined by incremental axial strains [2, 10]:

$$\frac{d\varepsilon_1^p}{dN} = \varepsilon_{11}^p \left(\frac{a'}{N} + \frac{b'}{N} \right) \quad (7)$$

where, ε_{11}^p represents vertical plastic strain after the first loading cycle, and a' and b' are two empirical

constants. For axi-symmetric ($\sigma_2' = \sigma_3'$; $d\varepsilon_2^p = d\varepsilon_3^p$) and plane strain ($d\varepsilon_2^p = 0$) testing conditions,

incremental volumetric strain under cyclic loading is expressed as [10]:

$$\frac{d\varepsilon_v^p}{dN} = \left[\left(\varepsilon_{11}^p \left(\frac{a'}{N} + \frac{b'}{N} \right) \right) - \left(\frac{\sigma_1'}{\sigma_3'} \right) \left(\frac{1 - \sin \phi_f'}{1 + \sin \phi_f'} \right) \left(\varepsilon_{11}^p \left(\frac{a'}{N} + \frac{b'}{N} \right) \right) + \kappa \left(\frac{dBBI}{dN} \right) \left(\frac{1}{\sigma_3'} \right) (1 - \sin \phi_f') \right] \quad (8)$$

The values of $d\varepsilon_v^p/d\varepsilon_1^p$ can be computed from Equation (8) for a corresponding friction mobilisation, progressive breakage, and evolution of the stress state during loading or reloading. These Equations provide fundamental mathematical frameworks in determining friction coefficient of ballast, considering particle breakage. It is then used in the process of parametric study to determine appropriate input parameters for DEM model presented in the following sections.

3.2. Discrete element modelling for ballasted tracks

The discrete element method (DEM) introduced by Cundall and Strack [43] has been used extensively to study the behaviour of granular materials. DEM is often used to model ballast because it captures the discrete nature of a granular assembly which consists of a collection of arbitrarily shaped discrete particles subjected to quasi-static and dynamic conditions [44, 45]. Particle motion is determined using Newton's second law and the interaction between particles is determined using Newton's second law contact laws. At a given time, the force vector $\vec{F}$ that represents the interaction between the two particles (Figure 2) is resolved into normal ($\vec{F}_N$) and shear component ($\vec{F}_T$) with respect to the contact plane:

$$\vec{F}_N = K_N U^n \quad (9)$$

$$\delta \vec{F}_T = -K_T \cdot \delta U^s \quad (10)$$

where, K_N and K_T are the normal and tangential stiffnesses at the contact; U^n is the normal penetration between two particles; δU^s is the incremental tangential displacement; and $\delta \vec{F}_T$ is the incremental tangential force. The rolling resistance moment $\vec{M}_r$ is introduced to represent the rolling restraint between the two particles A and B and is determined by:

$$\vec{M}_r = \begin{cases} K_r \vec{\omega}_r & \text{if } K_r \|\vec{\omega}_r\| < \|\vec{M}_r\|_{lim} \\ \|\vec{M}_r\|_{lim} \frac{\vec{\omega}_r}{\|\vec{\omega}_r\|} & \text{if } K_r \|\vec{\omega}_r\| \geq \|\vec{M}_r\|_{lim} \end{cases} \quad (11)$$

where, $\|\vec{M}_r\|_{lim} = \eta_r \|\vec{F}_r\| \frac{R_A + R_B}{2}$; $K_r = \gamma_r \left(\frac{R_A + R_B}{2} \right)^2$; $\vec{\omega}_r$ is a rolling angular vector representing the relative orientation change between two particles and is computed by adding the angular vectors of the incremental rolling; η_r is the dimensionless coefficient; and γ_r is the rolling resistance coefficient.

The new shear contact force is determined by summing the old shear force existing at the start of the time-step with the shear elastic force increment

$$\vec{F}_T \leftarrow \vec{F}_T + \delta \vec{F}_T \leq \mu \vec{F}_N \quad (12)$$

where, μ is the coefficient of friction.

3.3. Modelling laboratory tests for ballast in DEM

Figure 11 shows how DEM is used to model geogrid-reinforced ballast in a direct shear test and track process simulation apparatus (TPSA). The model dimensions are the same as those carried out in the laboratory. Ballast grains with different shapes and sizes are modelled by clumping many spheres together to represent actual ballast gradation (Figure 11a). This method is widely used to simulate ballast aggregates, which are then placed at random locations within the specified wall boundary and without overlapping. The micromechanical parameters used to model ballast, geogrid and coal fines are adopted from Indraratna *et al.* [44], Ngo *et al.* [7] as given in Table 2. Figures 11 b-c are describing a geogrid and a direct shear box modelled in DEM. The geogrid was secured in the middle of shear box (between the lower and upper boxes).

DEM simulations of direct shear tests are implemented at three normal stresses of $\sigma_n = 27\text{kPa}$, 51kPa , and 75kPa for fresh and fouled ballast ($VCI=40\%$) with and without the inclusion of geogrid. Figure 12 presents comparisons of shear stress-displacement responses of geogrid-reinforced ballast from the DEM analysis and those measured in the laboratory. Note that the predicted results match reasonably well with the laboratory data for a given normal stress and level of fouling. The strain softening behaviour of ballast and volumetric dilation is observed in all the simulations and show that the higher the normal stress (σ_n), the greater the shear strength and the smaller the dilation. The ability of geogrid reinforcement to increase the shear strength of fresh and fouled ballast can be seen by comparing it with an assembly with unreinforced ballast.

DEM simulations of the TPSA in a plane strain condition are shown in Figure 11d. The realistic shape and size of ballast grains and the procedures for simulating them in two dimensions are adopted from Indraratna *et al.* [46]. Clusters of bonded circular particles are used to model irregularly shaped grains of ballast, so the breakage of bonds is considered to represent particle breakage. Cyclic tests for fresh and fouled ballast at $VCI=10\%$, 20% , 40% and 70% are then simulated to a number of load cycles where $N=4000$. The loading characteristics and boundary conditions exerted onto the TPSA are identical to

those carried out in the laboratory [29]. All ballast samples had a thickness of 300 mm and there is no geogrid simulated in DEM simulations of the TPSA in a plane strain condition. The cross section in Figure 11d shows the DEM simulation of the TPSA in a plane strain condition. During loading, movement of the top and surrounding walls is measured to compute the axial and associated lateral displacements. Figure 13 shows a comparison between the predicted and measured lateral displacement, settlement, and the number of broken bonds with an increase in the load cycles. Here the DEM simulations capture the load-deformation behaviour of fresh and fouled ballast reasonably well. An increase in the level of fouling (i.e. increased *VCI*) results in an increased lateral displacement of ballast and a subsequent increase in settlement. The DEM analysis also shows that the accumulation of broken bonds decreases as the *VCI* increases (Figure 13c). This observation can be justified because fine particles that clog the voids of large aggregates could help to transfer the contact forces more uniformly through the ballast skeletons; in fact the contact forces that are transferred from the ballast grains and through the fine particles in the fouled ballast matrix mimic the “cushioning effect” of fines that effectively reduce the inter-particle contact stresses, and which in turn reduce particle breakage.

Load transfer in a ballast assembly depends on the contact force distributions developed across the aggregates through an interconnected network of force chains at contact points [43, 45]. Under a shearing load these contact forces develop and evolve so that the number of load-carrying contacts and their orientations inevitably vary to carry induced stresses. Figure 14 shows the distributions of contact force chains of fresh and fouled ballast (*VCI*=40%) with and without geogrid reinforcement under a given normal stress of 51 kPa, at a shear displacement of $\Delta h = 18$ mm. The contact forces between the aggregates are shown as lines whose thickness is proportional to the magnitude of the force. Note how fouled ballast has denser contact chains and less maximum force than those in the fresh ballast assembly. This can be attributed to fine particles clogging the pore spaces between the large grains and the partially supported and transmitted forces across the assembly; this is believed to be due to the interlocking effect that occurs between the ballast grains and geogrid.

4. Conclusions

This paper encapsulates the extent of our knowledge of rail track geomechanics resulting from tests and studies carried out at the University of Wollongong over the last two decades. The use of geosynthetics (geogrids, geocomposites, geocells) and rubber mats to enhance the performance of rail tracks has been

discussed, and we have included several important concepts/topics related to large-scale laboratory testing, field measurements, and approaches to computational modelling. A series of large-scale laboratory tests using a direct shear box, track process simulation apparatus (TPSA) and impact testing apparatus has also been carried out to study the role played by geosynthetics, geocells, and rubber mats in relation to the stress-strain and degradation response of ballast under cyclic and impact loads. Experimental data shows that geogrid increases the shear strength of ballast and decreases dilation due to interlocking between the ballast and geogrid, but fouling materials that accumulate in the ballast assemblies reduces the benefits gained from using geogrid as reinforcement because they fill the voids between the ballast particles and reduce inter-particle friction at the interface. Coal dust fouling was considered primarily as the ballast fouling case in many of the findings presented in this paper. Dynamic impact testing indicates that impact loads cause most of the damage to ballast, and substantial reduction in shear strains and particle breakage can be gained by using rubber mats. The specimens of subballast reinforced with geocell experienced much less deformation than the unreinforced cases because the confinement provided by geocell prevented the free displacement of in-fill aggregates.

DEM simulations for large-scale direct shear tests and TPSA were carried out for fresh and fouled ballast ($VCI=40\%$) to examine how geogrids improve the performance of ballast. The shear stress-strain behaviour obtained from the DEM analysis matched reasonably well with the measured data; in fact the DEM analysis showed that while the numbers of contacts increase significantly as the degree of fouling increases, the magnitude of the contact force also decreases considerably. That is thought to be due to the cushioning effect of fine grains lubricating ballast surfaces and reducing the particle contact forces, which in turns reduces particle degradation. The findings of these studies provide a better understanding of crucial aspects such as the ballast-geogrid interface mechanism, long-term deformation and degradation, as well as the benefits of using geosynthetics, geocells, and rubber mats to improve the performance of ballasted tracks

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Table 1. Properties of geosynthetics and granular materials used in this study

Material		Properties					
Geosynthetics	Nominal Area (mm ²)	Density (g/cm ³)	Cell depth (mm)	Thickness (mm)	Aperture size (mm)	Tensile strength (kN.m)	
Geocell	46 × 10 ³	0.95	150	1.3	320 × 287	9.5 (Bulk) 8 (Seam)	
Geogrid	-	-	-	-	40 × 40	10.5	
Granular layers	D_{min} (mm)	D_{max} (mm)	D_{50} (mm)	D_{10} (mm)	Uniformity Coefficient C_u	Coeff. of Curvature C_c	G_s
Ballast	19	63	32	21	1.6	1	2.7
Sub-ballast	0.075	19	3.3	0.3	16.3	1.3	2.7

Table 2. Micromechanical parameters of geogrid, ballast and coal fines adopted for DEM simulation

Parameter	Geogrid	Ballast	Coal fines
Particle density (kg/m^3)	800	2700	800
Coefficient of friction	0.5	0.8	0.2
Contact normal stiffness, k_n (N/m)	1.77×10^7	0.52×10^8	1.27×10^4
Contact shear stiffness, k_s (N/m)	0.88×10^7	0.52×10^8	1.27×10^4
Contact normal stiffness of wall-particle, k_{n-wall} (N/m)	1×10^8	1×10^8	1×10^8
Shear stiffness of wall of wall-particle, k_{s-wall} (N/m)	1×10^8	1×10^8	1×10^8
Parallel bond radius multiplier, r_p	0.5		
Parallel bond normal stiffness, k_{np} (kPa/m)	5.68×10^8		
Parallel bond shears tiffness, k_{sp} (kPa/m)	5.68×10^8		
Parallel bond normal strength, σ_{np} (MPa)	456		
Parallel bond shear strength, σ_{sp} (MPa)	456

(a)

(b)

Figure 1. Large-scale laboratory testing apparatus: (a) Track Process Simulation Apparatus (TPSA); (b) sample preparation

Figure 2. Materials tested in laboratory : (a) fresh ballast; (b) coal fines; (c) biaxial geogrid, 40 x 40 mm; and (c) rubber mat

Figure 3. Gradations of materials tested in laboratory

Figure 4. Variation of (a) settlements, S and (b) lateral displacement, L of fresh and fouled ballast assemblies with and without geogrid inclusions

(a)

(b)

Figure 5. (a) Location of track sections constructed in Singleton; (b) Vertical deformation of ballast layer measured at various locations (*modified after Indraratna et al.[22]*)

Figure 6. Impact testing system apparatus: (a) Perspective view of the equipment; (b) ballast specimen; (c) Schematic diagram of a typical test specimen

Figure 7. (a) Impact force responses measured in laboratory; (b) Measured shear strain behaviour of ballast with and without shock mat (*modified after Nimbalkar et al.[33]*)

Figure 8. Laboratory setup for testing of geocell-reinforced subballast (*modified after Indraratna et al.[18]*)

Figure 9. Variations of vertical strain against number of cycles for geocell-reinforced subballast at various frequencies and confining pressures (*modified after Indraratna et al.[18]*)

Figure 10. FEM analysis for geocell-reinforced subballast: (a) deviatoric stress contour; (b) vertical settlement contour; (c) tensile stress developed in a geocell; and (d) predicted subballast settlements versus measured data (*modified after Biabani et al.[17]*).

Figure 11. Discrete element modelling of geogrid-reinforced ballast: (a) modelled ballast grains; (b) modelled geogrid; (c) large-scale direct shear box; and (c) track process simulation apparatus

Figure 12. Comparisons of shear stress-strain behaviour of geogrid-reinforced ballast between laboratory test and DEM simulation: (a) fresh ballast; and (b) fouled ballast (*modified after Ngo et al.[44]*)

Figure 13. Comparisons of lateral and vertical deformation between laboratory data and DEM simulations: (a) lateral displacement; (b) settlement; (c) number of broken bonds (*modified after Indraratna et al.[11]*)

Figure 14. Distributions of contact forces: (a) unreinforced-fresh ballast; (b) 40% VCI-unreinforced ballast; (c) geogrid-reinforced fresh ballast; (d) geogrid reinforced fouled ballast (*modified after Ngo et al.[44]*)