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From theory to practice in track geomechanics – Australian perspective for synthetic inclusions

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ABSTRACT

The adoption of heavier axle loads and high speed rails have posed serious geotechnical issues with ballasted railway tracks. These issues include poor drainage of soft coastal soils, ballast degradation under cyclic and impact loads, differential settlement of track and misalignment due to lateral movements, and inadequate bearing capacity of some compacted ballast. The mechanisms of ballast degradation and deformation, the need for effective track confinement, understanding of interface behaviour, determining dynamic bearing capacity and use of energy absorbing shock mats and synthetic grids require further insight to improve the existing design guidelines for future high speed commuter and heavier freight trains. In this paper, the current state-of-the-art knowledge of rail track geomechanics is discussed, with particular emphasis on the effects of geosynthetic applications on ballast degradation, and track performance. The stress–strain response and volumetric changes of ballast stabilised with geosynthetics observed in the laboratory experiments were captured through discrete element and finite element models. Installing shock mats and geosynthetics in the track substructure led to the attenuation of high cyclic and impact forces, thereby mitigating ballast degradation. Comprehensive field studies on instrumented tracks at Bulli (near Wollongong) and Singleton (near Newcastle) supported by Sydney Trains and ARTC, were carried out to measure the in situ stresses and deformation of ballast embankments. The paper focuses primarily on research conducted at University of Wollongong for enhanced track performance, highlighting some examples of innovation from theory to practice.

Introduction

Compared to other land transportation systems, railways are safe and popular, and within railroad structures, ballasted track is the most popular because of its relatively lower cost of construction. Railroad structures consist of superstructure (rails, fastening devices, and sleepers), laid on substructure (ballast, capping, structural fill, and subgrade), and within the substructure the ballast is very important because it ensures a safe and comfortable ride for the train. The ballast layer should transmit stresses to a level of allowable bearing capacity of the subgrade soils while also preventing excessive settlement and lateral spread (Selig and Waters, 1994).

The crushed rock fines (due to particle breakage) accumulate within the voids of the ballast bed and adversely affect the strength of track structures (Indraratna et al., 2011), while wheel and rail defects can cause substantial impact loads (Jenkins et al., 1974; Indraratna et al., 2012). These impact loads cause aggravated particle

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breakage and are detrimental to track stability. It is therefore imperative that ballast degradation be minimised in order to sustain its primary functions and the overall working of the substructure. The use of geosynthetics and shock mats can improve track stability and reduce the life-cycle cost. Geogrids can reduce lateral spreading as well as the degradation of ballast (Shin et al., 2002; McDowell et al., 2006; Indraratna et al., 2006, 2007; Brown et al., 2007), indeed these geocomposites can simultaneously provide reinforcement to the ballast layer filtration and separation functions (Brown et al., 2007; Indraratna and Nimbalkar, 2013; Indraratna et al., 2010a; Woodward et al., 2007, 2012). Despite these benefits our existing knowledge of the behaviour of geosynthetics-ballast interface through numerical studies (Banimahd et al., 2012; Chen et al., 2012; Ngo et al., 2014) is still limited.

Under ballast mats (UBM) and under sleeper pads (USPs) can attenuate the dynamic forces and improve overall performance. The use of USPs in reducing dynamic stresses and vibrations in high speed rail (HSR) networks (Ferreira and López-Pita, 2013) and the ability of UBMs to reduce ballast breakage (Indraratna et al., 2012; Nimbalkar et al., 2012) has been studied extensively, but not enough is known when different geosynthetics are used as reinforcing elements for ballasted tracks, and when UBMs/USPs are used for mitigating particle degradation when subjected to the stresses resulting from moving wheel loads. To fill this gap, extensive field trials on sections of instrumented rail track at Bulli and Singleton, New South Wales (NSW), Australia have been conducted. The purpose of this paper is to present the current state of the art of track geomechanics, with an emphasis on the analyses of the performance of ballast through large-scale laboratory testing, full-scale field monitoring and numerical modeling, and to demonstrate the beneficial use of geosynthetics, USPs and UBMs for rail infrastructure.

Logistics for HSR and train speed-frequency relation

A typical global railroad operation is a network with a broad mix of train services, including intercity passenger, commuter, freight and high speed. While typical speeds are about 250–400 km/h for HSR networks (France, UK, China, and Japan), most passenger trains travel below 200 km/h and are broadly mixed with relatively slower speed (below 100 km/h) freight train operations. As HSR is becoming increasingly popular around the globe, track is often subjected to cyclic loads of high magnitudes and frequencies (Priest et al., 2012; Cunha and Correia, 2012, 2009). The proposed HSR network in Australia (length > 1600 km) is anticipated to support train speeds of about 350 km/h (Engineer Australia, 2010). The transfer of moving wheel loads at higher speeds (>150 km/h) results in a significant increase in track damage because the quasi-static response at relatively low speeds transforms to a dynamic (vibratory) state at elevated speeds. Ballast degradation is clearly associated with increased cyclic loads (Indraratna et al., 2011; Lackenby et al., 2007), which in turn, adversely affects track geometry and increases the cost of maintenance. The design of a HSR network faces significant geotechnical challenges due to ballast breakage, inadequate track confinement, and the often low bearing capacity of soft clay deposits in coastal regions. These issues are further elaborated in this paper.

The load frequency of a train is expressed as $f = v/\lambda$, where v is train speed and λ is the characteristic length between axles. The determination of λ is critical. According to previous studies λ was considered to be the length of a typical freight wagon, passenger car or a bogie, which results in a lower value of frequency for a given train speed (Zhou and Gong, 2001; Liu and Xiao, 2010; Ni et al., 2013). However, a typical freight wagon often has multiple axles (e.g. four axles, see Fig. 1a) that impart individual load cycles (Fig. 1b). As the axle distance is much smaller than the bogie distance, two rear axles of a leading wagon and two front axles of a trailing wagon induce maximum frequency. Therefore, a train travelling at 93 km/h represents a cyclic load frequency (f) of 15 Hz for an axle distance of 1.72 m, but if there are significant abnormalities at the wheel-rail interface, a train would impart much higher vibrations (in-phase (f = 50–200 Hz), out-of-phase (f = 200–600 Hz), and pin-pin (f = 800–1200 Hz)). In this paper, the effects of cyclic and impact loads are also discussed. The method of computation of frequency of cyclic loading has been adopted for laboratory testing as well as to determine number of load cycles (=number of axle passes) from total traffic tonnage as illustrated in subsequent sections of this paper.

Current state of the art

Assessment of ballast breakage

Ballast is usually composed of medium to coarse sized aggregates originating from high quality igneous or metamorphic rock quarries that usually includes dolomite, rhyolite, gneiss, basalt, granite, and quartzite (Raymond, 1979). The breakage of ballast particles due to repeated (cyclic) wheel loading can occur due to: (a) particle splitting, (b) breakage of angular projections, and (c) grinding of small-scale asperities. This breakage contributes to differential track settlement and increases the vertical and lateral deformation.

Indraratna et al. (2005) introduced a ballast breakage index (*BBI*) to quantify the extent of degradation based on the particle size distribution (*PSD*) curves. The ballast breakage index (*BBI*) is calculated on the basis of changes in the fraction passing a range of sieves. The increase in extent of particle breakage causes the *PSD* curve to shift further towards the smaller particle size region on a conventional *PSD* plot. By referring to the linear particle size axis, the *BBI* is determined, i.e. $BBI = A/(A + B)$, where A is the area defined previously, and B is the potential breakage or area between the arbitrary boundary of maximum breakage and the final *PSD*. Using this method, ballast breakage is assessed under cyclic and impact loading as reported in this paper.

Effect of confining pressure

In rail track environments, the confining pressure is of major concern. Track substructure has very low lateral constraints parallel to the sleepers. Confinement in a real