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Closure to "Micromechanics-Based Investigation of Fouled Ballast Using Large-Scale Triaxial Tests and Discrete Element Modeling"

Abstract
The writers would like to express their appreciation for the feedback provided by the discusser, and for raising some important aspects of clay-fouled ballast used in the laboratory and as simulated using the discrete element method (DEM). Although the writers are in general agreement with the discusser's comments, some points warrant further clarification, as highlighted herein.

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Closure to Discussion of "Micromechanics-Based Investigation of Fouled Ballast Using Large-Scale Triaxial Tests and Discrete Element Modelling"

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Closure to Discussion

The authors would like to express their appreciation for the feedback provided by the Discusser, and for raising some important aspects of clay-fouled ballast used in the laboratory and as simulated using the Discrete Element Method (DEM). While the Authors are in general agreement with the Discusser's comments, some points warrant further clarification as highlighted below.

The main purpose of this study was to examine the influence of clay-fouling on the deformation and degradation of fouled ballast, by means of both laboratory investigation and Discrete Element Modeling (DEM). The complex deformation and degradation mechanism of clay-fouled ballast has not been documented earlier in view of a micro-mechanical perspective, and this reflects the uniqueness of the present work. It is noted that while significant progress has been made in advancing the understanding of granular material behavior over the past few decades (e.g. the development of critical state mechanics framework for soil mechanic), the relationship between the particle scale interactions and the overall material response is still not completely understood. DEM based on discrete particle mechanics first introduced by Cundall and Strack (1979) has progressed rapidly over the past 20 years and can now provide more insightful micro-mechanical behavior of granular materials that cannot be established purely experimentally (e.g. McDowell *et al.* 2006, Tutumluer *et al.* 2012, Ngo *et al.* 2014). In this aspect, our understanding of conventional stress-strain behavior of granular materials in relation to continuum mechanics is quite different to the micro-mechanical implications that are commonly governed by the evolutions of anisotropy, contact force distribution, strain localization, and associated principal stress relationships; these major disparities have been further elaborated by Bolton *et al.* (2008), Wang *et al.* (2007), O'Sullivan and Cui (2009), among others.

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The Authors fully agree with the Discusser that the minerology of the clay can influence the behavior of fouled ballast. In this study, the clay used for the fouling was kaolinite which is essentially a non-expansive clay mineral with low activity and a low value of coefficient of friction. It is the commonest clay in the state of NSW. When the clay coats the surfaces of ballast aggregates it would result in a decrease in the mobilized friction angle. Extensive laboratory tests conducted earlier by Indraratna *et al.* (2013a) indicated that clay fouling reduced the effective angularity of the ballast, and decreased its overall shear strength. At significantly higher levels of fouling, the ballast specimens showed an increasingly ductile behavior. Also, this behavior may be attributed to the "cushioning" effect provided by the clay seams between the angular aggregates, partially protecting them against harsh abrasion (Indraratna *et al.* 2011, 2013b). It is noted that the dilatational component of the internal angle of friction of a granular is well known to reduce logarithmically with mean effective stress, since at high stresses, crushing eliminates dilatancy of the granular assembly. A study carried out by Bolton *et al.* (2008) indicated that reduced peak strength and dilation as stress level increases is also associated with particle degradation. It is also noted that if fouling materials comprising of an expansive fines such as montmorillonite (i.e. smectite group in general), one could expect that dilation rather than compression would be observed during the loading progress. The effect of fouling can be even more pronounced during the drying and wetting cycles for actual ballasted tracks as the moisture content varies significantly due to seasonal changes. Further efforts will be needed to investigate influence of different types of fouling materials on the geotechnical behavior of fouled ballast.

The practical applications of this study in view of examining the evolution of contact orientations and fabric anisotropy obtained from the proposed DEM model provides insightful information into how the presence of clay fines in the pores of the granular mass influence the force transmission and the associated anisotropy. The fouling materials can partially carry and transmit contact forces across the assembly resulting in decreased particle degradation. The Authors agree with the Discusser's comment that further studies could be undertaken for cyclic load testing of fouled ballast resulting from different types of fouling materials, considering the influence of the changing weather (i.e. drying and wetting cycles) on the deformations and degradation of ballasted tracks. In fact, further large-scale experimentation taking into account of the water content, different ballast and fouling materials (e.g., gradation, angularity, harness, toughness and mineralogy), and ongoing extensive field investigations are currently progressing at the Centre for Geomechanics and Railway Engineering, at the University of Wollongong, Australia.

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