Study on Settlement Characteristics of Fouled Ballast for an Effective Maintenance Method

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ABSTRACT: Understanding of settlement characteristics of ballast is essential to ensure an effective maintenance application for ballasted railway tracks. Ballast fouling makes understanding of settlement characteristics even harder as they depend on many aspects including amount of fouling materials and maintenance method. In this research, cyclic loading tests on fresh and fouled ballasts were carried out using a laboratory model test subjected to tamping application. The local deformations induced by tamping tines were evaluated by a particle image velocimetry (PIV) approach using continuous images captured during the loading process. The results from the PIV analysis revealed that tamping application affects settlement characteristics by loosening top ballast. The results also suggested that the tamping application increased residual settlement rate when ballast is fouled by 30% or more of fouling materials. Therefore, we conclude that fouled ballast should be improved before fouled ballast consists of 30% or more of fouling materials for an effective maintenance application.

1 INTRODUCTION

In ballasted railway tracks, track settlement occurs after long-term service with large number of train passes. Excessive settlement can cause poor passenger comfort, speed restriction and potential derailments. As reported in Selig and Waters (1994), ballast contributes most of the substructure settlements though the main function of ballast is to restrain track geometry. In ballasted railway tracks, ballast fouling occurs when finer materials mix with ballast due to heavy repeated train loads. Generally, finer materials come from underneath layers as well as from particle crushing (Selig and Waters 1994). Finer material intrusions alters the original particle size distribution (PSD) of ballast, from uniform gradation to less uniform gradation. The altered gradation of fouled ballast results in different settlement characteristics than fresh ballasts (Indraratna et al. 2006).

Once the railway track settlement reaches the allowable limit, a maintenance method should be applied to bring the railway track into the original position. The tamping application is practiced worldwide as the main maintenance application (Indraratna and Salim 2005). One of the problems arisen from use of tamping application is that, tamping tines can loosen top ballast and also induce particle crushing. However, effects of ballast fouling or tamping application itself on settlement characteristics have scarcely been studied in the past.

Generally, the degree of ballast fouling is described by a fouling index (Ionescu 2004; Selig and Waters 1994). The equation for fouling index proposed by Ionescu (2004) was modified to fit into the laboratory-scale materials used in this research as given in Eq. 1.

$$FI_{\mathrm{p}} = P_{0.015} + P_{2.64} \quad (1)$$

where $P_{0.015}$ and $P_{2.64}$ are percentages passing at 0.015 and 2.64 mm respectively.

In this research, settlement characteristics of fouled ballast with different fouling indexes were studied by conducting model tests on a scaled-down railway track. The tamping application was simulated on the model trackbed using a simple tool and its effects on subsequent settlement were examined using a particle image velocimetry (PIV) approach.

2 MATERIALS AND TESTING METHODS

A scaled-down (i.e., 1/5th of the field scale) model trackbed was constructed in a sand box with the interior dimensions of 800 mm length, 304 mm width and 300 mm height. The front wall of the sand box is made of glass to facilitate capturing of images during the loading process. A duralumin footing, 48 mm wide and 290 mm long, was used as the sleeper.

2.1 *Sample preparation*

Gravel, approximately 1/5th size of the field ballast, were used as ballast. The field ballast and the gravels tested in this research are produced from the same source. Particle size distribution (PSD) curves of fresh ballast, fouling material, fouled ballast (i.e., sand-gravel mixtures) along with Japanese standard ballast gradation (i.e., 1/5th of the field scale) are shown in Fig. 1.

Ballast thickness was selected as 50 mm (i.e., 1/5th of the field ballast thickness). The model trackbed was prepared with 80% of relative density, D_r to simulate the field railway track conditions. A wooden plate placed on the ballast surface was subjected to vibration by a hand vibrator to achieve the required relative density. As intrusion of fouling materials into ballast is not significant until fouling materials increase up to 10% or more (Selig 1985), we selected fouled ballast having over 15% of fouling materials. It should be noted that, coincidentally, fouling index, FI_p adopted in this research is equal to the percentage of fouling materials of the fouled ballast samples. The values of FI_p, percentage of fouling material and dry density, ρ_d of the test samples are given in Table 1. The density tests were conducted according to Japanese Industrial Standards (JIS 2009).

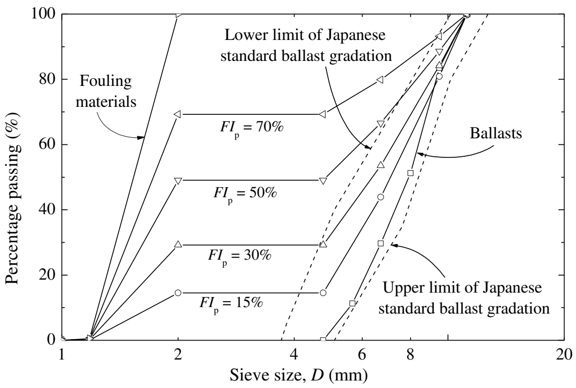

Fig. 1 Particle size distribution of fresh and fouled ballasts

2.2 *Cyclic loading*

Cyclic loading was applied to simulate train passes. 100 number of loading cycles each were applied in pre- and post-tamping application. Due to the manual process of loading control system, we limited the number of loading cycles to 100. There had been reports that initial settlement of ballasted railway track reached within a small number of loading cycles, then, residual settlement continues (Hayano et al. 2013). Therefore, 100 loading cycles should be sufficient to study settlement characteristics of ballasted railway tracks.

Table 1: Fouling index, percentage of fouling materials and dry density of the test samples

Test sample	Fouling index, FI_p (%)	Percentage of fouling materials	Dry density, ρ_d (kg/m^3)
Case 1	0	0	1519
Case 2	15	15	1698
Case 3	30	30	1829
Case 4	50	50	1929
Case 5	70	70	1788
Case 6	100	100	1684

The cyclic loading was applied to the model trackbed through the sleeper at a constant displacement rate of 0.05 mm/s. The maximum amplitude of the applied stress, σ_v was maintained at 120 kN/m^2. Since the model trackbed prepared of fouling material fails at a relatively smaller vertical stress than fresh and fouled ballasts, an equal and relatively smaller vertical stress than in field conditions was applied.

2.3 *Tamping application*

Tamping application was simulated by the tool shown in Fig. 2a. First, 100 loading cycles were applied to the model trackbed through the sleeper (Fig. 2b). Then, the sleeper was lifted to the initial position (Fig. 2c). Next, the tamping tool was inserted (e.g., about 10-12 mm) into the model trackbed by sides of the sleeper. After the tamping tool had reached the required depth, it was tilted horizontally several times to permit ballast to move laterally. This procedure was followed at several locations until the voids between the sleeper and the ground surface were completely filled by ballast. Finally, additional ballast was added to the ground surface near the sleeper to produce a flat ground surface. After tamping application, again 100 loading cycles were applied (Fig. 2d).

2.4 *Particle image velocimetry (PIV) approach*

A PIV approach was implemented to study strain distributions underneath the railway sleeper. In the method, a digital single-lens reflex (DSLR) camera was fixed on a tripod in front of the test apparatus. A number of images were captured during each loading cycles using a remote controller. The images were used to track particle movements in vertical and horizontal directions. First, the images were analysed in Flow-PIV which is a PIV based 2D software. Flow-PIV produces velocity vectors on a user-defined area on the ballast layer. The displacement vector was then generated in the software called "FEA Visualizer" by using the velocity vector produced. The displacements are measured at nodal points. Then, strains between two consecutive nodal points are calculated. Then, strains are calculated for element using the strains between nodal points. Finally, maximum shear strain, $\gamma_{\max}$ is evaluated using vertical strain, ε_v, horizontal strain, ε_h, and shear strain, γ_{vh} as given in Eq. 2. More details on the PIV analysis can be found in Kumara (2013).

$$\gamma_{\max} = \sqrt{(\varepsilon_v - \varepsilon_h) + \gamma_{vh}} \tag{2}$$

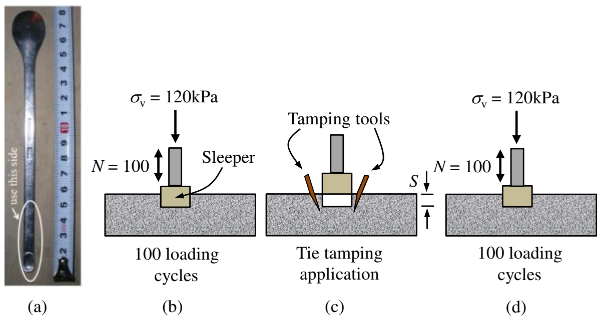

Fig. 2 (a) Photograph of the tamping tool, (b) cyclic loading in pre-tamping application (TA), (c) TA and (d) cyclic loading in post-TA

3 RESULTS AND DISCUSSIONS

3.1 Effects of PSDs on settlement characteristics

Figs. 3a and 3b show the results of settlement, S with no. of loading cycles, N for pre- and post-tamping application respectively. Due to densification process in pre-tamping application by no. of loading cycles, settlement reduced in post-tamping application. Fig. 3 clearly shows that intrusion of fouling materials into ballast alters the settlement characteristics from fresh ballast significantly, in both pre- and post-tamping application. The smallest settlement was observed when the specimens have 30 and 50% of fouling index, FI_p.

3.2 Effects of tamping application on settlement characteristics

The empirical equation proposed by Sekine et al. (2005) (i.e., Eq. 3) was selected here as it can distinguish initial and residual settlement characteristics.

$$S = c\left(1 - e^{-\alpha N}\right) + \beta N \tag{3}$$

where S is settlement after N number of loading cycles, c is initial settlement, α and β are initial and residual settlement rates respectively.

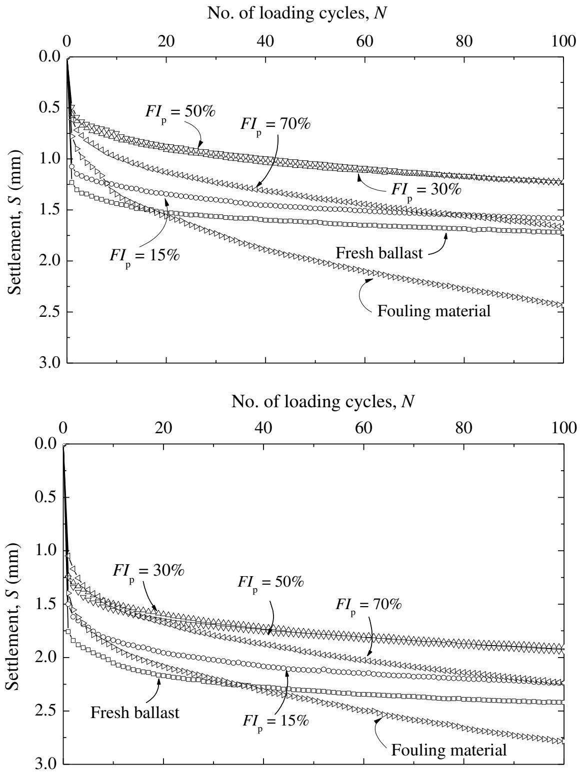

Fig. 3. Settlement vs. no. of loading cycles in (a) pre- and (b) post-tamping application

Fig. 4 shows relations of c, α and β with FI_p. As shown in Fig. 4a, c reduces with FI_p up to 30-50% and then increases. As shown in Figs. 4b and 4c, while α reduces with FI_p, β increase with FI_p both in pre-and post-maintenance applications. However, reduction of α with FI_p is larger in post-tamping application as initial settlement rate decreases significantly with FI_p in post-tamping application. The results also showed that β becomes higher in post-tamping application on the specimens having more than 30% of FI_p. That is to say, the settlement in post-maintenance application reaches the allowable settlement within a smaller number of train passes compared to pre-maintenance application when ballast is fouled by 30% or more of FI_p. Therefore, we can say that tamping application is effective for fouled ballast having maximum of 30% of FI_p.

The maximum shear strain distributions for fresh ballast is shown in Fig. 5. As shown in Fig. 5, fresh ballast shows densification process beneath the sleeper in pre-tamping application. It also shows that tamping application loosen ballast mostly at the sides of the sleeper, therein, showing strain localisation on the ballast. Fouled ballast also showed similar behaviour. The results also revealed that fouled ballast shows strain localization beneath the sleeper more than fresh ballast in post-tamping application, which could be interpreted as fouled ballast is affected more than fresh ballast by tamping application. The increase in residual settlement rate on fouled ballast having over 30% of FI_p in post-tamping application can be attributed to the damages caused by inserted tamping tools during the maintenance application.

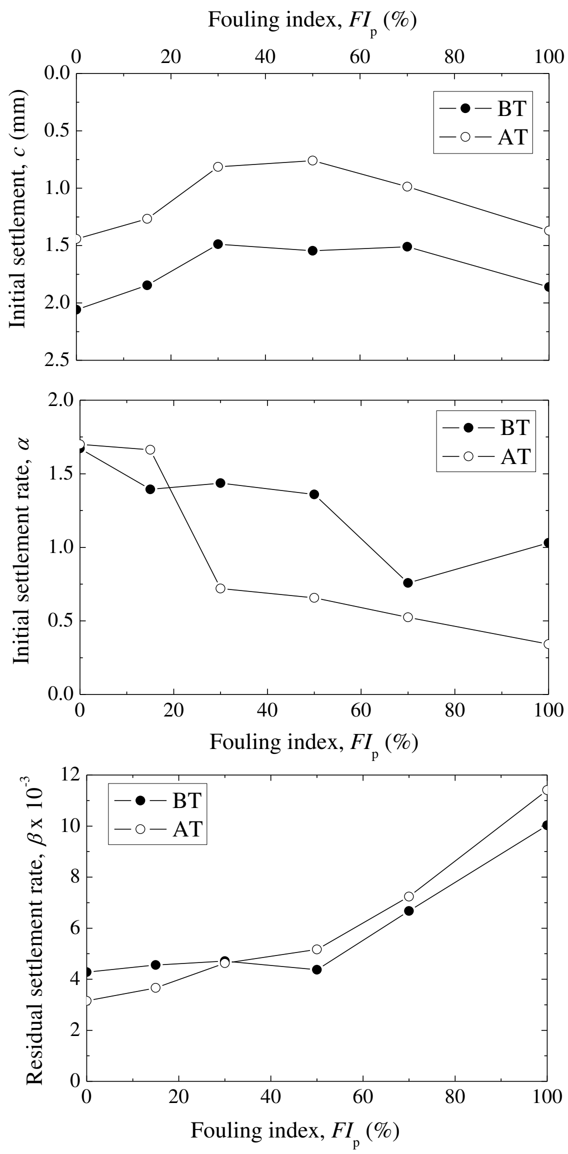

Fig. 4. (a) Initial settlement, (b) initial settlement rate and (c) residual settlement rate vs. fouling index

4 CONCLUSIONS

Uniform gradation of fresh ballast is altered into moderately uniform gradation by intruded fouling materials. Thus, the settlement characteristics of ballasted railway tracks are altered subsequently. The model test results show that the tamping application alters settlement characteristics of fouled ballast significantly, particularly the residual settlement. The magnitude and rate of initial settlement reduce in post-maintenance application than pre-maintenance application. However, residual settlement rate, which is responsible for long-term settlement, increases in post-tamping application than in pre-tamping application when fouled ballasts having over 30% of FI_p. The particle image velocimetry (PIV) results on strain distributions verified the damages by tamping tines on fouled ballast where it was found that local deformations are induced by inserted tamping tines on the sides of the sleepers. The results suggest, for practical purposes, the tamping application should be applied for fouled ballast before FI_p becomes over 30%.

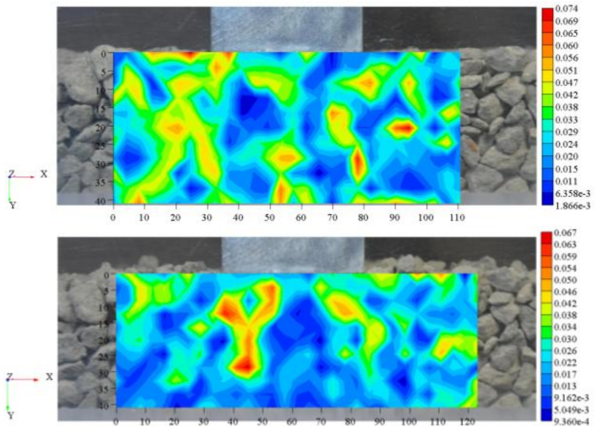

Fig. 5. Maximum shear strain distributions for fresh ballast in (a) pre- and (b) post-tamping application

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