Analysis of shear and degradation behaviour of fresh and fouled rail track ballast using large-scale direct shear tests

S. Venuja and S. K. Navaratnarajah

Abstract: Railway transport plays a vital role in safely carrying away commuters and freights from one place to another, both short and long distances with comparatively low cost and high efficiency. Ballasted tracks and concrete slab tracks are widely utilized as railways for many countries. Substructure foundation of ballasted track system comprises a layered system with a ballast layer, followed by a capping layer and compacted subgrade over natural formation soil. The ballast layer is the major load-bearing layer that distributes loads from superstructure (wheel, rail and sleeper) to the underlying layers at a minimal level through a wider area. However, ballast undergoes deterioration with time under recurring cyclic and impact loadings due to less confinement. Accordingly, the service life span of rail track reduces as differential settlement and fouling resulted from ballast deterioration. Besides ballast is also contaminated with external fouling which obstructs the drainage of the layered foundation system. The shear stress and degradation behaviour of ballast with various fouling materials like sand and clay were analysed by conducting large-scale direct shear tests on fresh and fouled ballast with three different normal loads. The outcomes of this experimental study indicate that the compression, dilation and breakage behaviour of ballast depend on applied static normal load, type of fouling material and fouling percentage.

Keywords: Ballasted tracks, Layered system, Load-bearing, Degradation, Fouling

1. Introduction

The traffic bottleneck is a big crisis nowadays due to increased population and superlative vehicle usage inland transit. Thus rail transport is extensively utilized by travellers to escape from unnecessary time delays. Trains carry a higher number of commuters at a time-efficient and provide an economically profitable mode of transportation for both public and freights. Ballasted rail tracks are the highly used track type all over the world due to the low initial construction cost and ease of construction [1].

Ballast is a coarse granular crushed material with high hardness, toughness and durability, obtained by blasting rocks [2]. The ballast layer is the major load-bearing layer in the track foundation system [3]. It absorbs train exerted loads from sleepers and distributes it to the underlying layer in a wider area at a minimal level [4, 5]. The ballast layer maintains the track in position by making minor adjustments and it carries off the rainwater quickly through its larger interconnected voids thus leads to minimal or no excess pore water pressure development inside the ballast layer [6, 7].

Ballast undergoes deterioration due to heavier repeated dynamic loads transferred from moving trains and severe weather conditions. Ballast particles undergo breakage and lose shear strength as well as drainage properties. It affects the overall track performance and service life [8]. Timely observation and maintenance activities help to maintain the performance of the track. Ballast tamping and artificial inclusions are the commonly adapted remedial actions [9].

This paper describes the experimental test procedure carried out on clean and fouled ballasts and their outcomes in detail. Large-scale direct shear tests were carried out on clean ballast and ballast contaminated with clay and river sand in various percentages under three different normal static loading conditions.

2. Related work

Ballast fouling is the phenomenon where the voids in the ballast layer partially or completely

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filled with finer particles such as broken ballast particles, sand, silt, clay, coal, droppings from trains, etc [10, 11]. Figure 1 shows the phases of ballast fouling [12] and how fines affect the contacts between ballast particles. Finer particles intrusion deters the rapid drainage and reduces the resiliency of the ballast layer thus leads to progressive track deformation [13-15]. The weight ratios were used in the measurement of ballast fouling in past. But specific gravities of the ballast and finer material are different. Thus, the volume ratios are used presently [16].

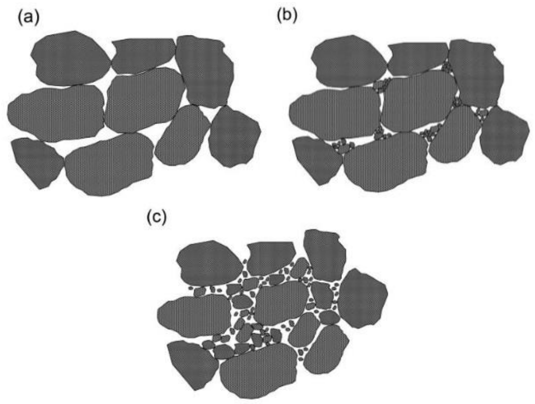


Figure 1 - (a) Clean ballast; (b) Partially filled voids; (c) Voids fully filled with fines

Proper understanding of the shear strength properties of ballast and the variations after ballast fouling is mandatory. The standard direct shear box is not capable to conduct a direct shear test on the ballast sample as the ballast particles are larger and consist of different sized particles. Therefore, some researchers had built a large-scale direct shear box to study the shear behaviour of railway ballast under static load conditions without adapting the parallel gradation technique [6, 17-20]. The parallel gradation technique will not provide the actual shear strength parameters of coarser materials.

Dissanayake et.al. [6] evaluated the friction angle values of fresh and fouled ballast (17 % fouling) at dry conditions by conducting a series of large-scale direct shear tests under four different normal loads. The schematic diagram of the test apparatus is shown in Figure 2. Shear strength and dilation were higher for fresh ballast compared to fouled ballast as the effective particle interlocking gave higher strength and the absence of finer particles led to more dilation in fresh ballast.

Huang et.al. [17] performed large-scale direct shear tests on clean and fouled ballasts under dry and wet conditions. Various types of contaminants such as coal dust, clay and mineral filler were used during the testings. The main conclusions from this study are apart from the kind of finer material, shear strength reduces with fouling and it is worse in wet conditions. Moreover, coal dust was found to be the worst fouling agent as the extreme reduction in shear strength was resulted.

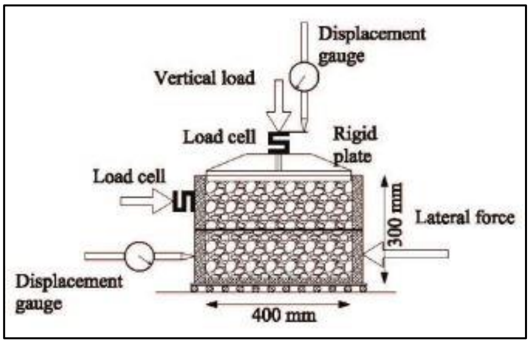


Figure 2 - Schematic diagram of large-scale direct shear apparatus

TolouKian et.al. [19] studied the effect of sand contamination on the shear behaviour of ballast under static loading conditions and found that the sand fouling reduces the shear strength and also the dilation behaviour of ballast as the sand covers the ballast particles. Further, when the ballast is fouled with a higher amount of sand, a drastic reduction in lateral strength may occur which leads to track deformations.

3. Methodology

3.1 Materials

Raw materials used in this experimental study are railway ballast, river sand and clay. Ballast consists of various sized particles from 19 mm to 63 mm. The ballast sample was selected as bounding between upper and lower standard limits defined by Indian Railways as this standard is employed by Sri Lankan Railways (Cu = 2.0, Cc = 0.91).

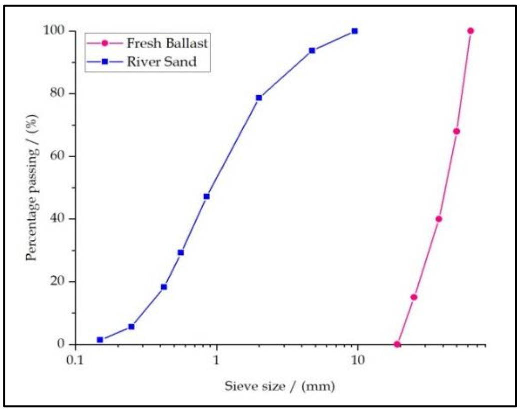
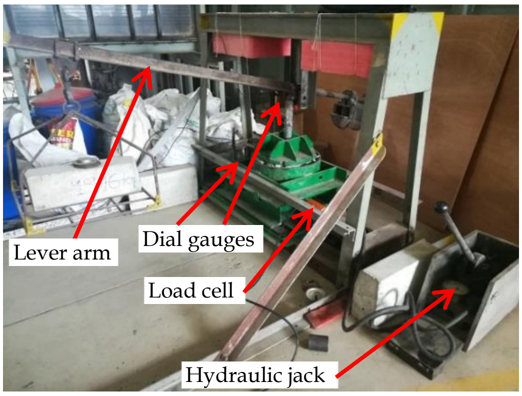


Figure 3 - Particle size distributions of ballast and river sand

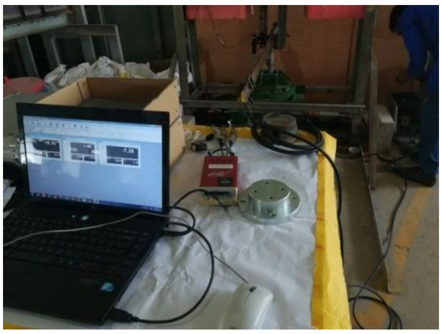
Ballast was brought from Gampola stockyard. The physical properties of ballast could be found elsewhere [6]. Sand available in Geotechnical laboratory was used (Cu = 3.67, Cc = 0.92). The particle size distributions of ballast and river sand are shown in Figure 3. Clay was collected from Digana area and it has a LL of 37 and a PI of 23.

3.2 Test apparatus and sample establishment

The large scale direct shear apparatus available at the Geotechnical laboratory of the University of Peradeniya is adequate to perform direct shear tests on full-size granular materials used in rail tracks. It comprises top and bottom cylindrical bisections with a diameter of 400 mm and a height of 150 mm each. The top part is anchored with the support frame thus it is immobile. The bottom part is movable horizontally where the constant shear displacement is applied. Normal stress is applied using the lever arm method on the top plate. Shearing is applied manually using a hydraulic jack with a shearing rate of 4 mm/min up to a maximum shear displacement of 60 mm. Vertical and horizontal displacements were measured using displacement transducers and shear load was measured using load cell connected to the bottom part.



(a)



(b)

Figure 4 - (a) Large scale direct shear test apparatus; (b) Data acquisition system

The complete test setup is illustrated in Figure 4(a). The readings were recorded digitally using a data acquisition system connected with dial gauges and load cell (See Figure 4(b)). Collected ballast material was initially sieved using ISO 3310-1 standard sieve series, washed and air dried to remove any adhered dust and fines. After that, cleaned ballast was mixed in the predetermined proportion to obtain the desired gradation as shown in Figure 3.

Ballast was filled in three layers into the test apparatus and each layer was compacted using a rubber-padded hammer to obtain the field density of 16.1 kN/m^3 (See Figure 5). Rubber padded hammer does not break the angular corners of the ballast particles and allow to give a small vibration for well packing inside the test apparatus.

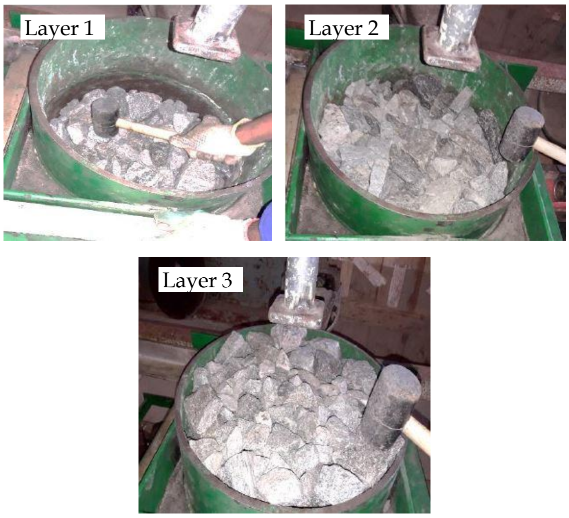


Figure 5 - Compaction of ballast into three layers

The amount of clay and sand was established using the percentage by weight of the ballast. 5 % clay fouling and, 10 and 15 % sand fouling were chosen. Clay was dried and pulverized to remove any unwanted particles. Then clay was wet-mixed with ballast and allowed to dry. Then the clay-coated ballast was filled in three layers into the apparatus. In contrast, for sand fouled ballast tests, ballast was filled and the calculated amount of sand was poured on top of the sample. After that, small vibration was applied using a shutter vibrator to settle the sand particles into the voids in the ballast sample. At the end of each test, the sample was collected carefully and sieve analysis was carried out.

4. Experimental outcomes and dissertation

4.1 Shear behaviour of ballast

Shear strength variation of ballast under different normal loads and with various fouling materials were tested and the test results are exhibited in Figure 6. For all types of samples, shear stress was increased with higher normal loads as well as with the shear displacement. In most situations, as expected, the shear stress was gradually increased up to 45 to 55 mm shear displacement, after that there was a reducing trend in shear stress was observed.

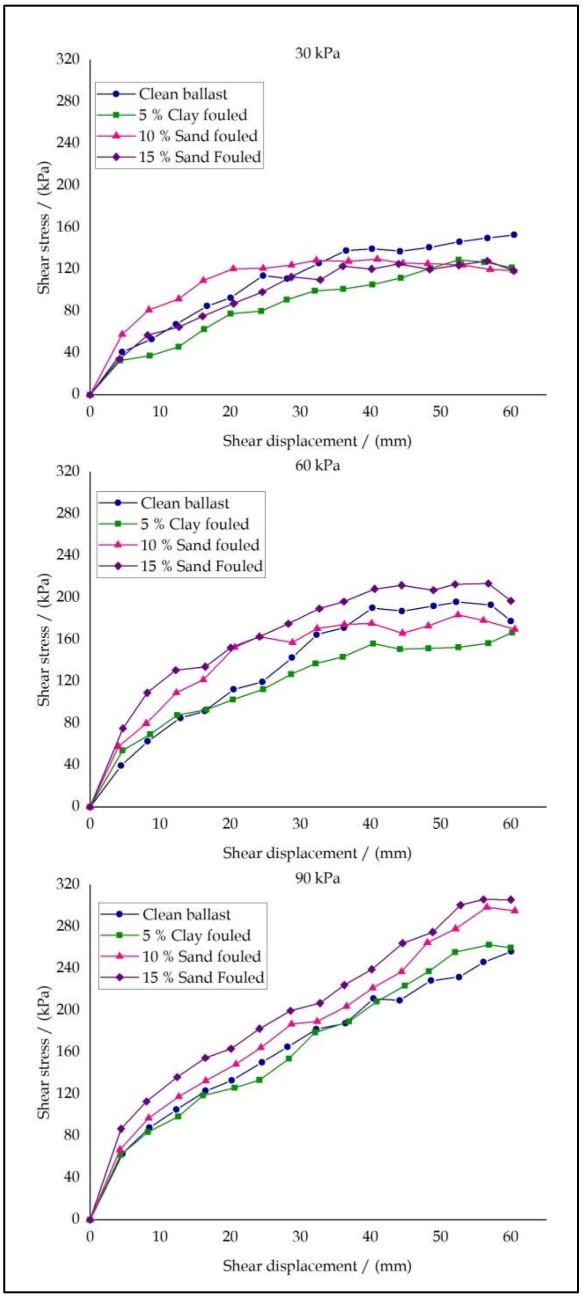


Figure 6 - Shear stress variation with shear displacement under various normal stresses

At a lower normal load of 30 kPa, peak shear stress was obtained with fresh ballast compared to fouled ballast. But with 60 and 90 kPa normal loads, 15 % sand fouled ballast gave a higher peak shear stress compared to clean ballast due to the overall increase in the density of the sand fouled ballast sample. Clay fouled sample produced lower shear stress than the clean ballast as the clay coating was acted as a lubricant and reduced the friction between ballast particles. Fluctuations in the results may be attributed to the failure of sharp angular edges of ballast as well as to the manual shearing rate application.

Using peak shear stresses corresponding to each normal stresses were obtained and Mohr-Coulomb failure envelopes were developed for all types of samples. The friction angle of clean ballast 70° increased to 71° and 73° when fouled with 10 and 15 % sand by weight. On the other hand, the friction angle was reduced to 67° for 5 % clay fouled ballast.

4.2 Dilation behaviour of ballast

Figure 7 illustrates the dilation behaviour of ballast under three different normal loads. When the normal load is applied, there is compression at the starting of the lateral displacement application, it can be observed at higher normal loads. After that, with the application of shear displacement, the coarser ballast particles started to roll over and dilated. The dilation was reduced with higher normal stresses as the vertical particle movements are restricted under high normal loads. The effect of fouling on the dilation behaviour of ballast was not significantly observed from these test results as the dilation behaviour of clean and fouled ballasts did not follow a uniform variation.

4.3 Breakage behaviour of ballast

Ballast particles breakage was observed when the sample is removed from the apparatus after conducting the test. Corner breakage, broken ballast pieces and a small amount of powdered ballast were remarked. Ballast Breakage Index (BBI) is a method proposed by Indraratna et.al. [21] to quantify the ballast breakage. It uses the particle size distribution of ballast before and after the tests. Therefore the sieve analysis was conducted at the end of each test to calculate the BBI.

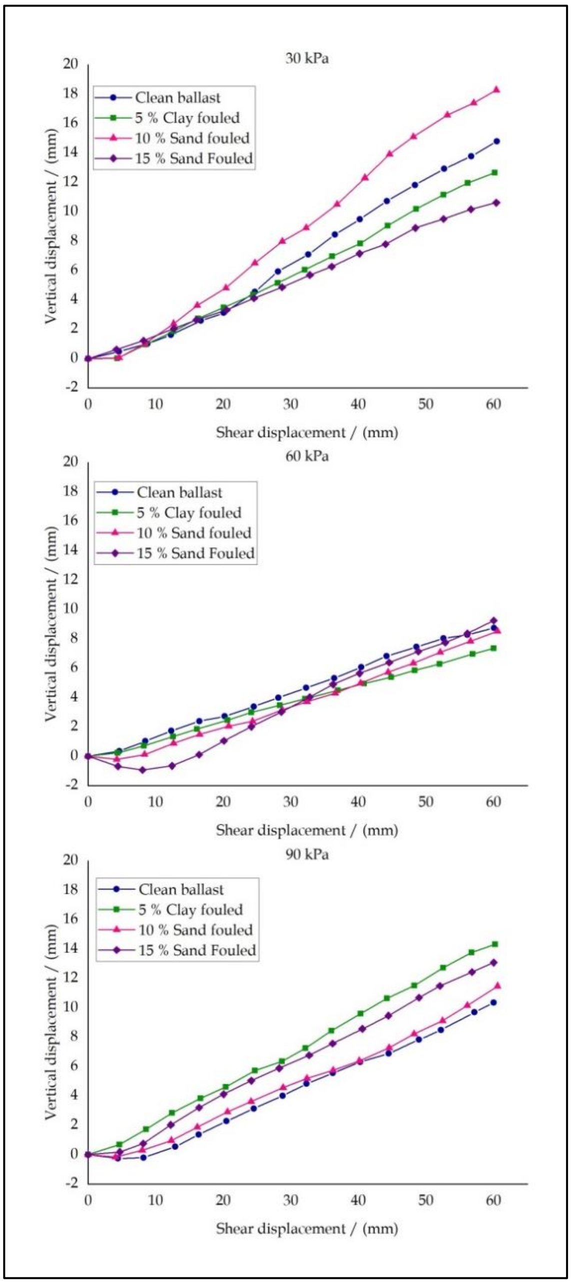


Figure 7 - Dilation behaviour of clean and fouled ballasts

Figure 8 illustrates the BBI values of four different ballast samples under three various normal stresses. As predicted, BBI for all samples was increased with the increase in the normal load. Higher normal loads induce higher breakage. When the ballast is fouled with sand or clay, a lower BBI value was observed. This is because the free movement of ballast particles are restricted as the voids are filled with fines. Lubricant behaviour of clay was clearly shown as the BBI of clay fouled ballast is lower than the sand fouled ballast, this is due to the friction between particles was reduced when there is clay coating thus lesser particle breakage.

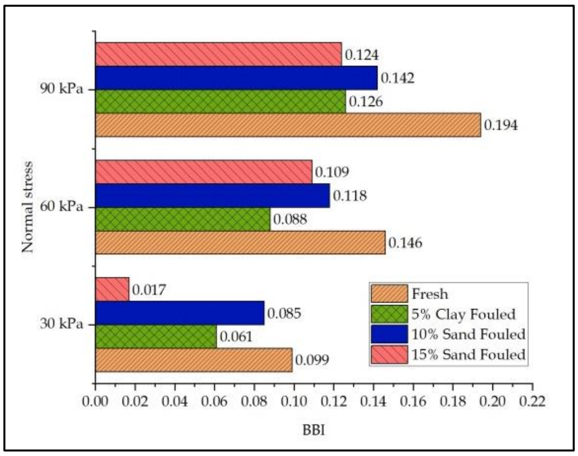


Figure 8 - Ballast Breakage Index of clean and fouled ballasts

5. Closures and suggestions

Ballast fouling reduces the mechanical properties of the clean ballast as the voids are filled with finer particles. When the ballast is fully fouled, the fine materials break the contact between the ballast particles and leads to the reduction in bearing capacity, lateral resistance and drainage property. In contrast, the shear strength of ballast increases with sand fouling as the friction angle increases. As the clay coating reduces the friction between ballast particles thus leads to a reduction in shear strength as well as in the friction angle.

In this research, there were some fluctuations in the results obtained from the tests. This may be due to the manual application of shearing displacement using a hydraulic jack. This manual hydraulic jack can be replaced with a mechanically operatable jack to get more accurate results. Even though the shear strength increases with sand fouling, the effect of fouling on the drainage capability was not analysed. Therefore, the effect of fouling in the drainage behaviour can be analysed using a large-scale constant head permeameter apparatus. Only one type of gradation of ballast was tested in this study, therefore the effect of fouling in the different gradations could be studied using numerical modelling after generating a numerical model for this large-scale direct shear test. The effect of monsoon on the fouled railway tracks may be studied by conducting the above tests in dry and wet conditions. This study only analysed ballast behaviour under static loading conditions. In the actual scenario, the ballast is subjected to cyclic and impact loading. Accordingly, large-scale tests have been planned to be conducted using a hydraulic dynamic actuator which is under construction at the University of Peradeniya to understand the realistic ballast behaviour when the tracks experiencing moving train loads.

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