# Experimental and Numerical Study on the Shear-Strain Behavior of Ballast with Different Gradations

**S. Venuja, S. K. Navaratnarajah, C. S. Bandara, and J. A. S. C. Jayasinghe**

**Abstract** Rockfill materials are widely used in many infrastructure constructions including earth dams, rail tracks, retaining walls, highways, etc. The major role of these coarse granular materials is to stabilize the body of the structure and maintain the geometry. Ballast is one such material used primarily in rail track substructures. Several factors are governing the mechanical properties of the ballast layer such as particle size, shape, angularity, gradation, particle density, hardness, etc. Ballast gradations are varying from country to country based on geology, climatic condition, source of parent rock, and economics. In Sri Lanka, biotite gneiss is used as the ballast material and there is no specific gradation for ballast. Further, the shear strength behaviour of the ballast is not fully understood with different gradations. Therefore, this study was carried out to analyse the effect of gradations on the shear behaviour of ballast using experimental and numerical analysis for Sri Lanka. Shear stress increased with normal stress increase due to the improved and intensified contact between particles. About 30% increase in shear stress was obtained from the laboratory test results for gradation with a high number of larger particles. Generated numerical results showed a good acceptance of experimental results and led to carrying out a parametric study with different normal stresses. The findings of this study suggest that the presence of larger size particles causes higher friction which in turn results in an increase in shear strength.

**Keywords** Ballast · Contact · Gradation · Mechanical properties · Shear strength

## 1 Introduction

Rail transport is a popular mode of transport due to numerous benefits including safety, low cost, less time delay, and less traffic congestion. Urbanization and growing population demand faster and heavier trains on traditional ballasted tracks

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R. Dissanayake et al. (eds.), *ICSBE 2022*, Lecture Notes in Civil Engineering 362,
https://doi.org/10.1007/978-981-99-3471-3_18

[2, 5, 11]. The ballast layer is the largest component in the track system. Ballast material is obtained from crushing parent rocks namely Biotite, Basalt, Granite, Gneiss, Dolomite, etc. It is placed under and around the sleepers on rail tracks. It helps to keep sleepers in position without any larger movements in longitudinal, transverse, and vertical directions. The primary function of the ballast layer is to transfer the loads from sleepers to the underlying layers at a reduced level and provide rapid drainage. With time, due to the continuous passage of trains, ballast materials undergo breakage and become fouled. This ballast deterioration affects the overall track performance and longevity [6, 9, 10]. Therefore, it is important to understand the mechanical characteristics of the ballast.

The shear strength of the ballast provides lateral confinement and resistance to maintain the geometry of the track structure. The shear behaviour of ballast varies with different factors. Ballast gradation is one such factor that affects shear strength. Particle size distribution of ballast is not the same for all the countries. It varies considering the subgrade properties, load application, climate, the strength of the parent rock, etc. [1, 8]. Gradations are selected mainly by considering the strength and drainage properties of the ballast layer. Researchers studied the shear behaviour of the ballast by conducting large-scale direct shear tests and triaxial tests [3, 4, 7, 12, 14, 16, 19–21]. Danesh et al. [3] concluded that the effect of maximum particle size ($d_{max}$) is having more impact on the shear behaviour than the Coefficient of Uniformity ($C_u$). It is found that with increasing $d_{max}$ and $C_u$ the shear strength increases. Sun et al. [17] considered $d_{max}$, $C_u$, median particle size ($d_{50}$), and initial void ratio ($e_0$) as controlling factors and suggested $2.3 \le C_u \le 2.6$ and $36 \le d_{50} \le 41$ mm for $d_{max}$ of 53 mm.

In Sri Lanka, ballast particle sizes from 19 to 63 mm are used in rail tracks. There is no unique gradation used in Sri Lankan tracks. No studies have been conducted so far on the shear behaviour of ballast with various gradations in Sri Lanka. Therefore, this study mainly focuses on understanding the effect of different gradations on the shear behaviour of the ballast in Sri Lanka. A series of large-scale direct shear tests were conducted on the ballast with three different gradations and a numerical model was developed to represent the laboratory test. This paper discusses the outcome of both experimental and numerical studies.

## 2 Laboratory Testing Using Large-Scale Direct Shear Test Apparatus

Ballast material was collected from the Gampola stockpile. Ballast was washed, dried, and sieved using 19, 25, 37.5, 50, and 63 mm sieves to separate particles into the required size ranges. The main aim of this study is to analyse the effect of gradation on the shear behaviour of railway ballast. For that, three gradations were chosen considering Indian gradation limits as shown in Fig. 1. Indian gradation limits are considered in this study as it is adopted in the Sri Lankan rail tracks as well. Here

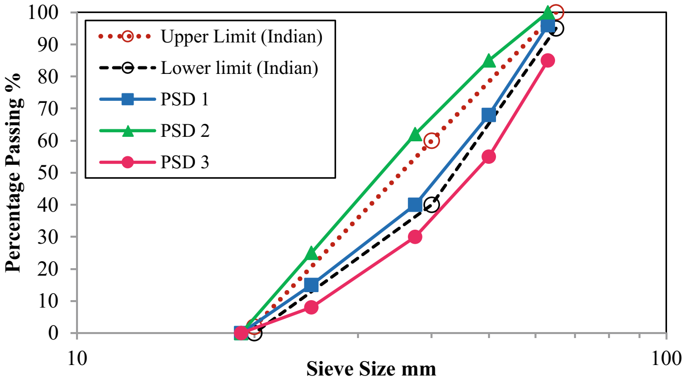


**Fig. 1** Different gradations used in this study and Indian gradation limits

PSD 1 is in between the upper and lower limits of Indian standard which is normally adopted in Sri Lankan rail tracks. PSD 2 is obtained by increasing the percentage of particles between 19 mm and 37.5 mm size ranges, beyond the upper limit. On the other hand, PSD 3 is obtained by increasing the percentage of particles between 37.5 mm and 63 mm size ranges.

Large-scale direct shear apparatus with a circular shear plane was used in this study. Details of the apparatus can be found elsewhere [13, 19]. The test specimen was prepared based on the gradation by adding the required amount of ballast and thoroughly mixing using a shovel. The material was filled into the apparatus in three layers and compacted using a rubber-padded hammer to obtain field unit weight. Three different normal stresses were selected as 30, 60, and 90 kPa. Test specimen with PSD 1 was tested for all three normal stresses. Only one test under 60 kPa normal stress was conducted for specimen with PSD 2 and PSD 3 to limit the effort and laboratory testing by making use of numerical techniques.

## 3 Numerical Modelling Using DEM

Two major approaches in numerical analysis are (1) Finite Element Method (FEM); (2) Discrete Element Method (DEM). Considering the granular angular distinct particles of the ballast material, DEM was chosen in this study. Particle shape is an important factor that affects the mechanical behaviour of the ballast assembly. Therefore, the shape of the particle for the model was obtained as a shape file by scanning with a 3D laser scanner and creating a closed surface by connecting point cloud data. Then, particles were generated using the multi-sphere clump method as illustrated in Venuja et al. [18]. Figure 2 shows the apparatus model created along with the complete test setup. The top plate was used to apply the normal stress and shearing was applied to the lower cylinder until a 15% shear strain is obtained.

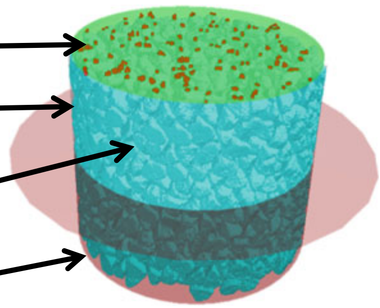


**Fig. 2** Numerical model of a complete test setup

# 4 Results and Discussion

## *4.1 Effect of Gradation Experimental Results*

Shear stress was calculated using the shear load and horizontal displacement data obtained from the data logger. Shear area correction factor was suggested by [15] for the circular shear plane. Figure 3 elaborates the shear stress and vertical strain variation of PSD 1 with shear strain under different normal stresses. As expected, with the normal stress increase, a growth in shear stress was observed owing to the higher particle interlocking. On the other hand, a reduction in dilation was observed with high normal stresses. This is as a result of restrictions in particle movements.

Figure 4a illustrates the shear stress vs shear strain of ballast with different gradations as explained in Sect. 2. A higher shear stress variation was obtained for PSD 3 where the percentage of particles between 37.5 mm and 63 mm is high. There is no significant improvement in shear behaviour when increasing the percentage of particles between 19 mm and 37.5 mm. When comparing with PSD 1, there are 29.7% increase and 16.5% increase for PSD 3 at 7.5% and 15% shear strains, respectively. This is mainly because of the higher contribution to the shear resistance from larger particles in comparison to smaller particles through the high contact area. As shown in Figure 4b, an initial compression followed by higher dilation was observed in PSD 2 and PSD 3. This slightly high dilation resulted from the increased void spaces.

## *4.2 Numerical Model Calibration and Validation*

By changing the coefficients of restitution, static friction, and rolling friction at ballast-ballast contact and ballast-steel contact, an acceptable agreement between experimental shear variation and numerical shear variation was obtained for PSD 1 under 60 kPa normal stress using the trial-and-error method. Using these calibrated

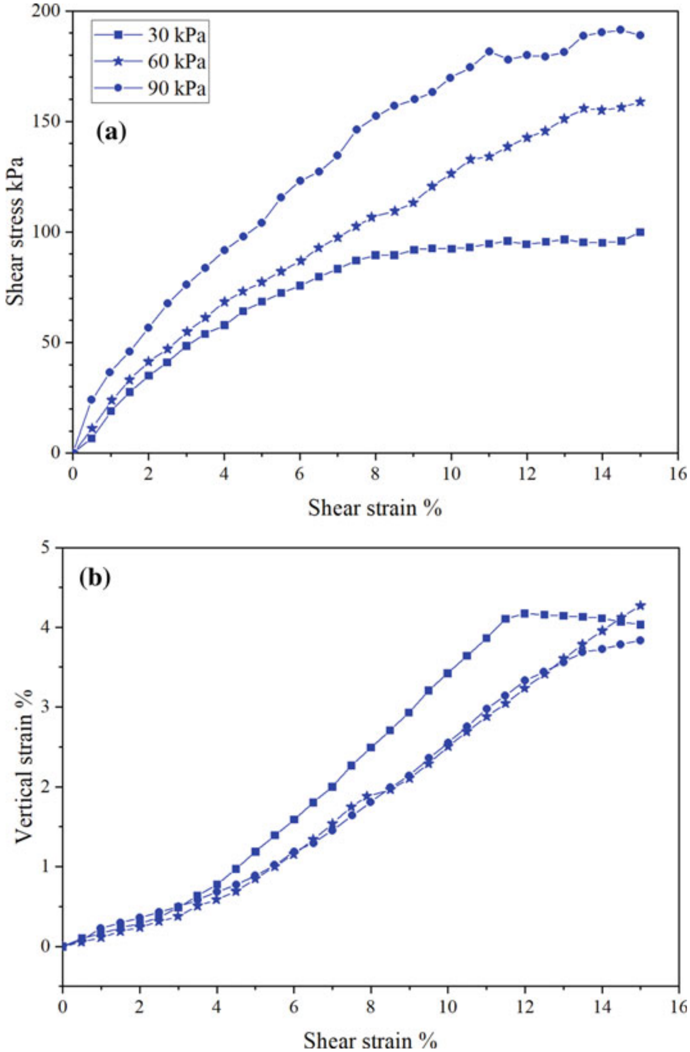


**Fig. 3** **a** Shear Stress and **b** Vertical Strain variation of Ballast with PSD1 under different normal stresses

coefficients, the same model was run for the other two normal stresses of 30 and 90 kPa. Numerical results were obtained and compared with experimental results as shown in Fig. 5. An acceptable agreement was observed in this comparison and the calibrated model is validated. After that, by changing the gradations in the numerical model, the other two models for PSD 2 and PSD 3 were run and compared with the laboratory test results as illustrated in Fig. 6.

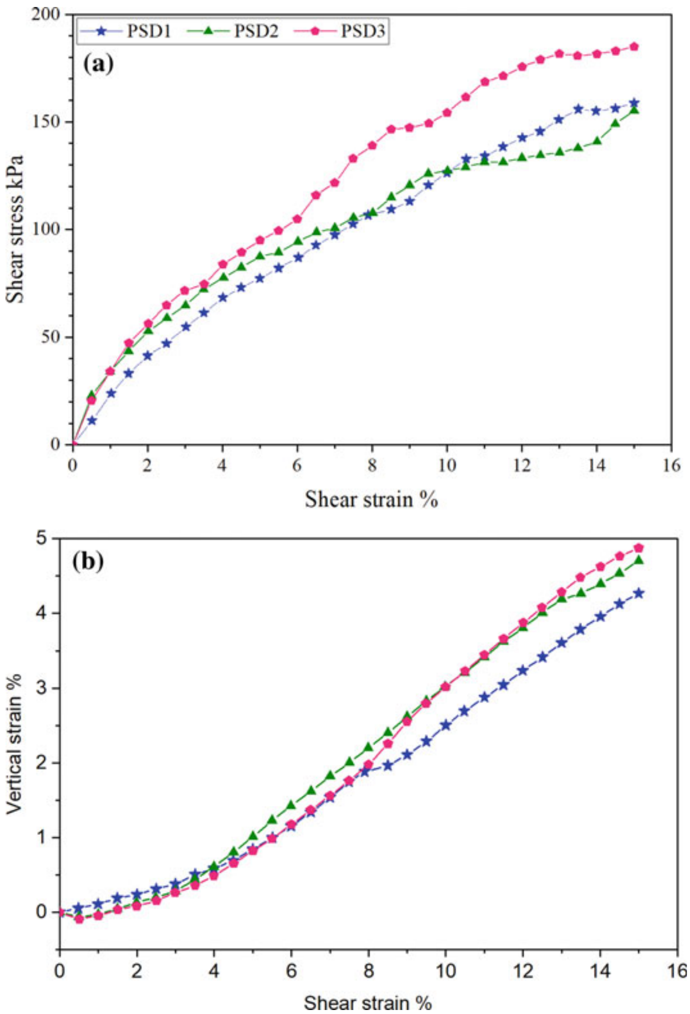


**Fig. 4** **a** Shear Stress and **b** Vertical Strain variation of Ballast with different gradations under 60 kPa normal stress

## *4.3 Parametric Study*

Using the distinct calibrated models of PSD 2 and PSD 3, models were run for 30 and 90 kPa normal stresses, and results were plotted (see Fig. 7). As observed in the laboratory test results of PSD 1, the percentage increase in shear stress is lesser for the shear stress variation from 60 to 90 kPa normal stress. In addition to this, non-linear Mohr–Coulomb failure envelopes were developed using the numerical results as shown in Fig. 8. The friction angle varied from 74° to 63° for PSD 1, from 76° to

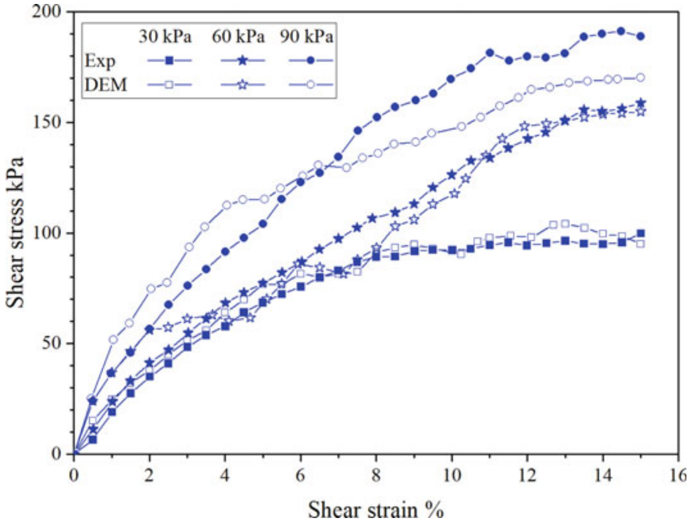


**Fig. 5** Comparison of experimental and numerical shear stress variation with shear strain (For PSD 1)

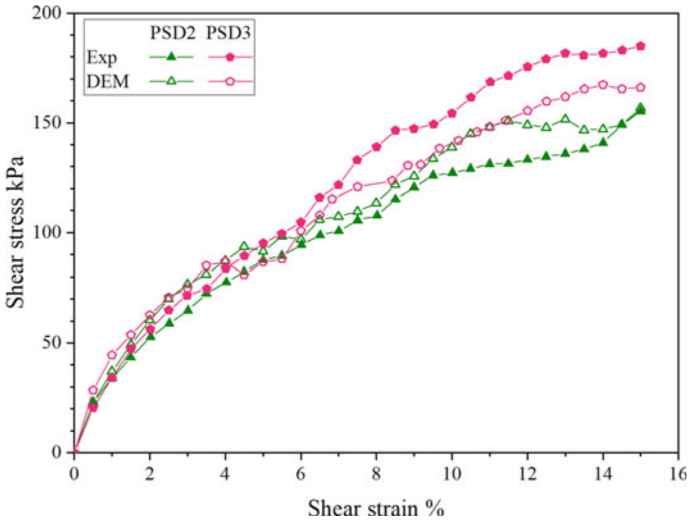


**Fig. 6** Numerical model validation using experimental results for PSD 2 and PSD 3

62° for PSD 2, and from 78° to 66° for PSD 3 within the applied normal stress range. Friction angle reduced with high normal stresses due to the high particle breakage results in lesser shear resistance.

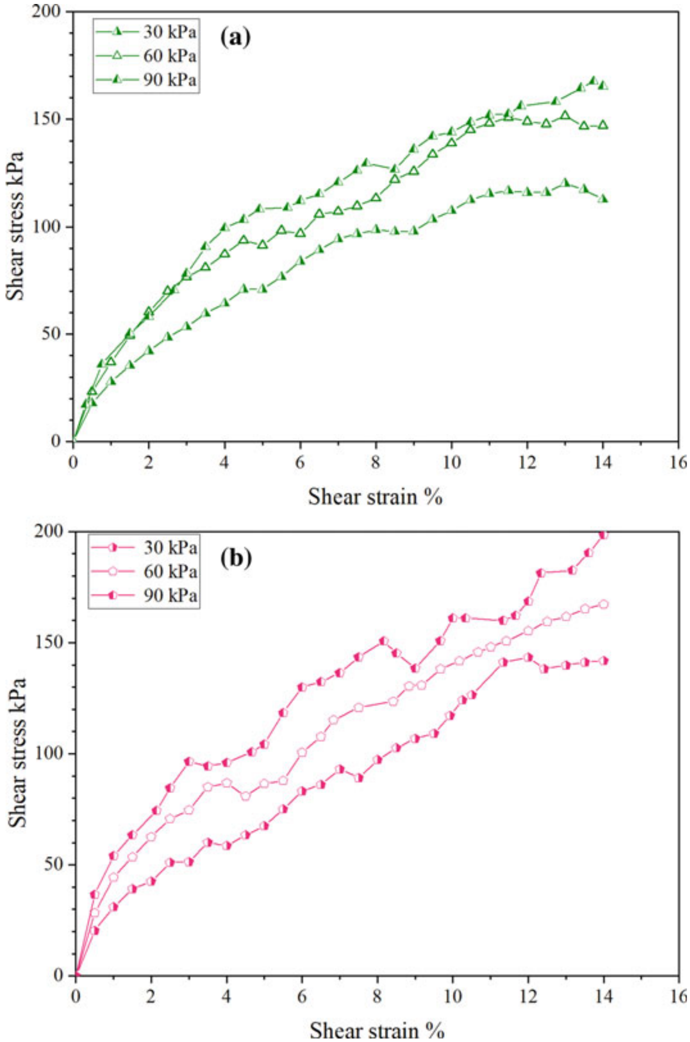


**Fig. 7** Parametric study on shear stress variation using validated DEM models; **a** PSD 2; **b** PSD 3

## 5 Conclusions

This paper elaborates the effect of particle size distribution on the shear behaviour of ballast. For that, three different gradations were chosen, and large-scale direct shear tests were conducted. In addition to this, numerical simulation using DEM was also carried out. By increasing the normal stress, the shear stress of the ballast was observed due to the higher particle interlocking. In contrast, dilation is reduced due to the high compaction of materials. The presence of a higher number of larger particles

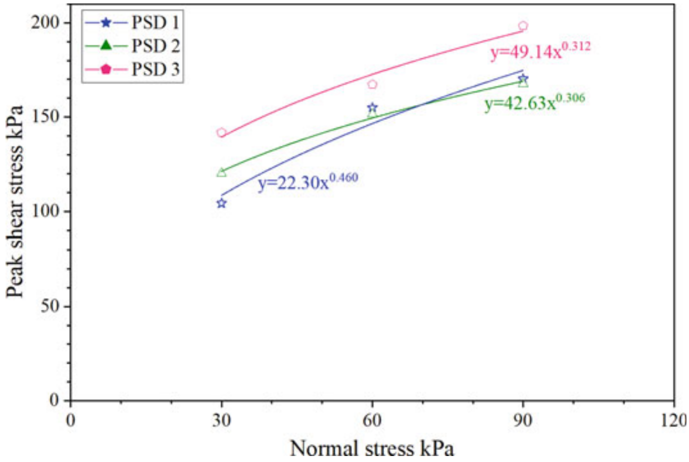


**Fig. 8** Non-linear Mohr–Coulomb envelopes developed from numerical outcomes

resulted in higher shear strength. Numerical results showed acceptable agreement with the experimental results. The DEM was further extended to predict the results for normal stresses of 30 and 90 kPa, and Mohr–Coulomb envelopes were developed. As observed from experimental results of 60 kPa normal stress for all three gradations, an increase in shear stress was observed. Approximately, a 3–4-degree increase was observed in friction angle for PSD 3 than that for PSD 1.

In conclusion, the findings show that the shear behaviour of the ballast is changing with gradation and showing high shear strength for the gradation with a higher amount of larger size particles. Moreover, the validated model can be used to conduct parametric studies under higher normal stresses to find out the friction angle variation, which is always very difficult in laboratory large-scale testing.

**Acknowledgements** Accelerating Higher Education Expansion and Development (AHEAD) Operation of the Ministry of Higher Education funded by the World Bank (Grant No: AHEAD/RA3/DOR/STEM/No.63) is acknowledged by the authors for the financial support provided throughout this research.

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