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AN INVESTIGATION OF THE MICRO-MECHANICAL CONTACT BEHAVIOUR OF RAILWAY BALLAST PARTICLES

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Abstract: The micromechanical behaviour of basalt ballast particles was studied by subjecting them to normal (N) and tangential loading (T) under various loads. It is observed that the natural ballast particle pairs subjected to normal loading have a softer response than that predicted by Hertz (1882) theory. The coefficient of interparticle friction (μ), measured during monotonic shearing, is about 0.5-0.6, while during cyclic loading, μ was found to stabilise around 0.65-0.85 after about 30 cycles. The value of μ was not affected by the normal load or the loading rate. Roughness, measured before and after testing, was found to change with loading, attributed to deformation of the asperities.

1. Introduction

Incentives for reduced maintenance of railway ballast have prompted the need for more fundamental research in their behaviour. Ballast is made up of discrete particles, and researchers have often used the Discrete Element Method (DEM) in an attempt to predict their mechanical behaviour. Recent developments include implementing more realistic shapes of ballast into the simulations [1], however there is experimental evidence that the contact laws used in DEM may not represent well their behaviour [2,3], at least for one type of granitic ballast. It is generally the case that the source material for railway ballast is geographically close to its application, so that different countries tend to use very different types of ballast, e.g. granitic ballast in the UK, basalt ballast in Australia or andesite ballast some regions of Iran and China. This paper presents unique experimental data obtained on pairs of basalt ballast particles from Australia subjected to normal and tangential loading, monotonic and cyclic, that will help inform discrete element modellers and allow them to improve existing numerical models. The evolution of the particle surface roughness is also presented.

2. Methodology

The micro-mechanical behaviour of the basalt ballast was studied using the inter-particle apparatus developed at UCL (Figure 1; [2]). The apparatus was developed to investigate the contact behaviour of coarse-grained materials, with vertical and horizontal capacities of 1 and 0.5kN. Two particles can be mounted on platens and subjected to loads along three axes that are concentric with their contact. During the test, the load application is controlled via a software that allows for displacement or force control of each axis, with accuracies of 10^{-2} μm or 0.01-0.02 N respectively. The lower platen is held in place by a sled, under which is a three-point bearing system, for which friction was calibrated and found to be negligible. The particles were cut and their cut flat side attached to the platens using epoxy glue. The case of a natural angular to flat contact was used in the experiments, selecting the apex of the natural ballast as the contact point. Normal loading was load-controlled while shearing was displacement-controlled, the goal being to avoid heavy impact between the two surfaces at the first point of contact. The pairs of basalt ballast particles were subjected to normal loading followed by monotonic or cyclic tangential loading, at different stress levels.

The evolution of the roughness of the top and bottom particles was mapped by using optical microscopy (Stereo-Discovery V8 microscope by Zeiss) before and after testing (Fig. 2), where the roughness within the contact area was imaged by the use of Z-stacking, with an accuracy of 0.63 μm.

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The measurements were performed at a magnification of 80, covering a total viewing area of 1.62 mm x 1.34 mm which was kept the same for all measurements.

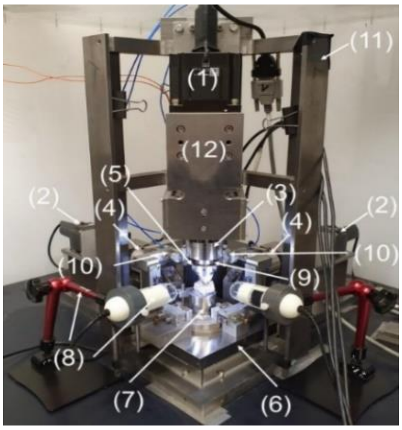

Figure 1. Interparticle loading apparatus [2]
(1) vertical and (2) horizontal linear actuator; (3) vertical and (4) horizontal load cells; (5) vertical displacement transducer; (6) sled; (7) bottom platen; (8) digital microscope camera and stand; (9) top platen; (10) horizontal displacement transducer; (11) stainless steel frame; (12) front plate

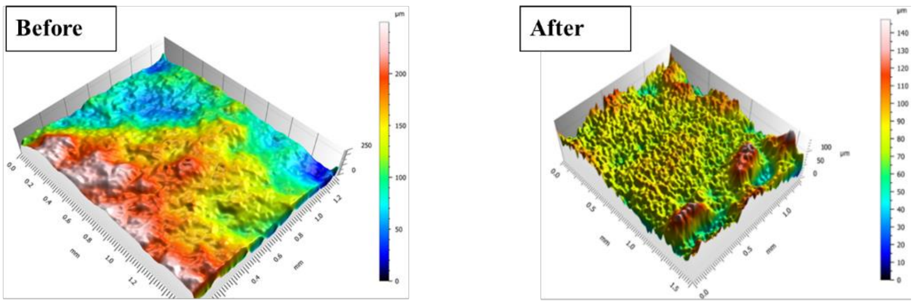

Figure 2. Surface analysis before and after normal loading (flat bottom particle, 100N)

The analysis of the surface characteristics was facilitated by the ConfoMap7 software (Mountains 7), which provides a comprehensive examination of topography, including fractal analysis and peak analysis. The fractal dimension (D_f), a parameter indicating asperity frequency, was determined using the boxing method within ConfoMap 7, while the root-mean-square value of roughness (S_q) was determined after applying filters for noise and form removal. The change in surface roughness during normal testing was evaluated by considering that the apex of the angular particle corresponded to the area of contact against the flatter surface.

3. Results and discussion

<u>Monotonic loading</u>: A typical model used in DEM follows Hertz theory (1882), which was initially developed to predict the load-displacement behaviour of two elastic contacting smooth spheres subjected to normal loading. Predictions by Hertz can be computed for an experimental setup by measuring the radii at the contact and using the elastic properties of the material, here basalt. The effect of roughness can be included by following Greenwood et al.'s model (1966), which uses S_q as a measure of roughness. Figure 3 shows that the response of the basalt ballast to normal loading is

softer than that predicted by Hertz (1882) but the model by Greenwood et al., here called RMS, agrees with the experimental data better at low load levels. Measurements of the surface roughness indicate that S_q decreases during normal compression, which was attributed to chipping or plastic flattening of the asperities, the size of which being likely to be below the comminution limit. The value of D_f however was found to increase, indicative of a more irregular surface, suggesting that the peak count might have increased while the height of the peaks decreased.

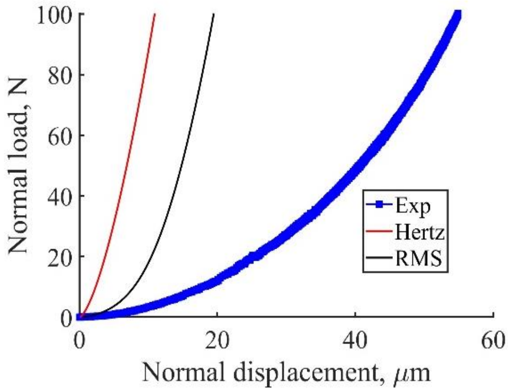

Figure 3. Comparison of experimental and predicted normal loading data

Monotonic Tangential Loading: Under monotonic tangential loading, the shear strength is slowly mobilised until the particles start sliding against each other. The tangential load, T, is plotted below (Fig. 4) divided by the normal load, N. The ratio T/N initially increases quickly, followed by mobilisation of the interparticle frictional forces with displacement. Ultimately, a stable coefficient of interparticle friction (μ) of approximately 0.5-0.6 is reached.

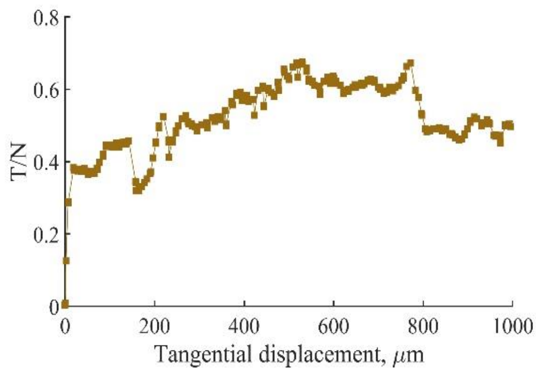

Figure 4. Mobilised interparticle friction during monotonic shearing

Cyclic Shearing: During cyclic shearing, the evolution of the coefficient of friction (μ) demonstrates a more complex response compared to monotonic loading. Initial fluctuations in μ within the first few cycles, plotted as darker colours, are likely to be due to the settling and rearrangement of asperities (roughness peaks) at the particle contact. Subsequently, the cyclic response tends to stabilise with continued cyclic loading, reaching a stable value of coefficient of friction μ around 0.65-0.80 after approximately 30 cycles (as illustrated in Figure 5). The increase in μ with cyclic loading suggests a potential work-hardening effect, where repeated shearing strengthens the contact interface, although vertical displacements at the contact point, not shown here, indicate that abrasive wear may also be occurring at the asperities and affect the contact area. One explanation for the higher value of μ could be interlocking between asperities. Measurements of the surface roughness were less conclusive than for normal loading.

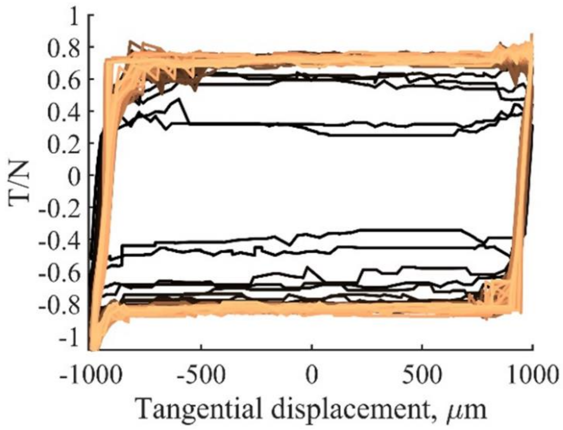

Figure 5. Evolution of load-displacement response with cycle number under a normal load of 100 N (low cycle numbers in dark colour, high cycle number in light colour)

4. Conclusion

Basalt ballast particles subjected to normal loading shows a much softer behaviour than that predicted by Hertz, as was found in previous work on granitic ballast. During monotonic tangential loading, the ratio of tangential to normal load increases then stabilises at a coefficient of interparticle friction of about 0.5-0.6. During cyclic shearing, the value of μ changed in the first few cycles, then tended to stabilise while the vertical displacements at the contact kept increasing as the cycles continued, indicating abrasion. The coefficient of sliding resistance, μ, typically increased with the cycle number, then tended to stabilise around 0.65-0.80 after about 30 cycles. Measurements of roughness before and after cyclic test show that plastic deformation has occurred, mostly at the asperities. Notable features distinct from previous results on granitic ballast are the increase in surface roughness irregularity with loading and the smaller cycle numbers to stabilisation of μ.

Acknowledgement

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