The Fifth International Conference on Railway Technology
RAILWAYS 2022
22-25 August 2022
Montpellier, France

Proceedings of the Fifth International Conference on
Railway Technology:
Research, Development and Maintenance
Edited by J. Pombo
Civil-Comp Conferences, Volume 1, Paper 3.3
Civil-Comp Press, Edinburgh, United Kingdom, 2022, doi: 10.4203/ccc.1.3.3

The behaviour of railway formation materials at increased axle loading from 20 to 26 tonnes per axle

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Abstract

The transportation of bulk and heavy freight by rail is beneficial from an economic, environmental and safety perspective, such that in South Africa, there are strategic plans to increase some of the corridors from 20 to 26 tonnes per axle. This has therefore created a need to understand the engineering behaviour and performance of each railway track component at higher axle loading in order to maintain a sustainable railway network. The purpose of this work is to analyse the behaviour and performance of railway formation materials, particularly the subballast and subgrade layer at an initial axle loading of 20 tonnes per axle, increased to 26 tonnes per axle. The methodology involved the characterisation of railway loading, experimental work using an advanced cyclic triaxial apparatus on materials representative of the subballast and subgrade material, followed by detailed processing, analysis and interpretation of the results and conclusion. Based on the test results, the behaviour of both materials when loaded at cyclic stresses equivalent to 20 tonnes per axle was in dilation and the plastic strains remained stable. At cyclic stresses equivalent to 26 tonnes per axle, both materials underwent a phase-transfer in soil behaviour from dilation to contraction and upon the phase-transfer the plastic strains became exponential. It is therefore concluded that for design and maintenance of railway foundations, geomaterials that tend to undergo a phase-transfer in soil behaviour from dilation to contraction should ideally not be used for operation in railway track foundations, as they might result in excessive plastic deformation and differential settlement.

Keywords: increased axle loading, railway foundation materials, railway cyclic loading, cyclic triaxial testing.

1 Introduction

The current maximum axle loading for general freight in the South African railway network is 20 tonnes per axle. Given the demand for transportation of bulk commodities and the benefits associated with increased axle loading, there are strategic plans for the South African freight rail network to increase some of the corridors from 20 tonnes per axle lines to 26 tonnes per axle, in line with the heavy-haul standards stipulated by the International Heavy Haul Association. The benefits include economies of scale, reduced rolling resistance, maximum payload, increased efficiency in energy consumption and therefore reduced greenhouse gas emission. However, it remains crucially important to understand the engineering behaviour and performance of each railway track component at increased axle loading, in order to maintain a sustainable railway network. The purpose of this work is to analyse the behaviour and performance of railway formation materials, particularly the subballast and subgrade layers, at increased axle loading from 20 to 26 tonnes per axle, as part of the research work by [1] and [2]. The methodology involved characterisation of railway cyclic loading using finite element analysis as recommended by [3], experimental work in the laboratory using an advanced cyclic triaxial as originally developed by [4]. Part of the substructure of a railway formation consists of the subballast and subgrade layers to evenly distribute the stresses into the underlaying weaker materials [5] as shown in Figure 1. As such, railway foundation materials which are representative of the subballast and subgrade material were used as test materials for the experimental work followed by detailed processing, analysis and interpretation of the results and conclusion.

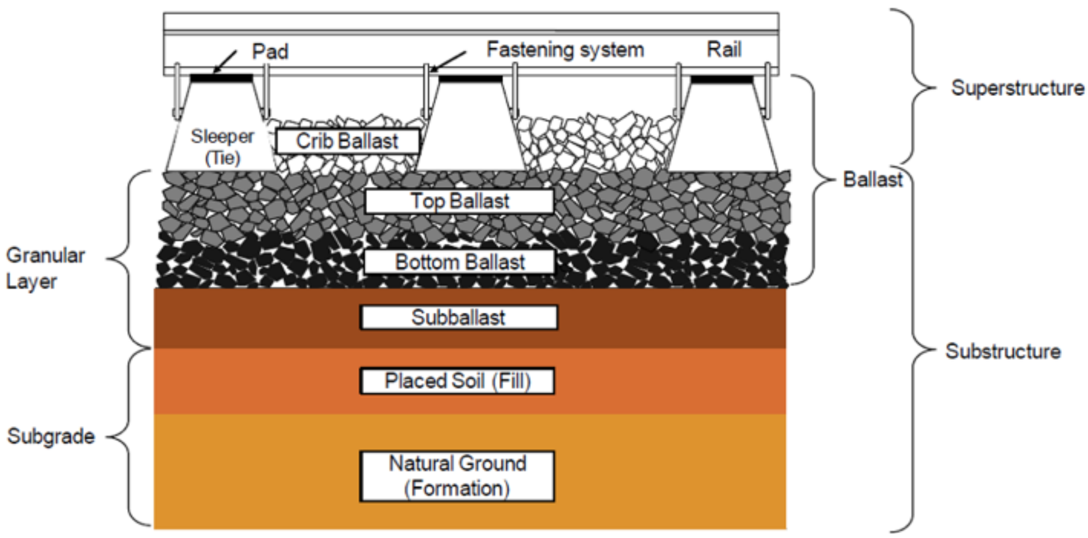

Figure 1: Conventional railway track structure from [5]

2 Methods

The initial part of the methodology involved characterisation of railway cyclic loading, which is defined by the initial deviator stress, cyclic amplitude and the frequency of the loading. Finite element analysis is used to characterise the railway cyclic loading and for a two-axle bogie, the four closest axles of the two adjacent wagons are taken as the critical case, as shown in Figure 2. A triaxial apparatus is ideal for determining the engineering properties and behaviour of soils [6]. Due to the cyclic nature of railway loading, a triaxial apparatus capable of cyclic loading was used for the experimental work, which is shown in Figure 3 with all its different components. The samples were prepared using under-compaction in order to achieve homogeneity [7]. Testing was carried out on fully saturated samples, as deemed the worst-case scenario [8].

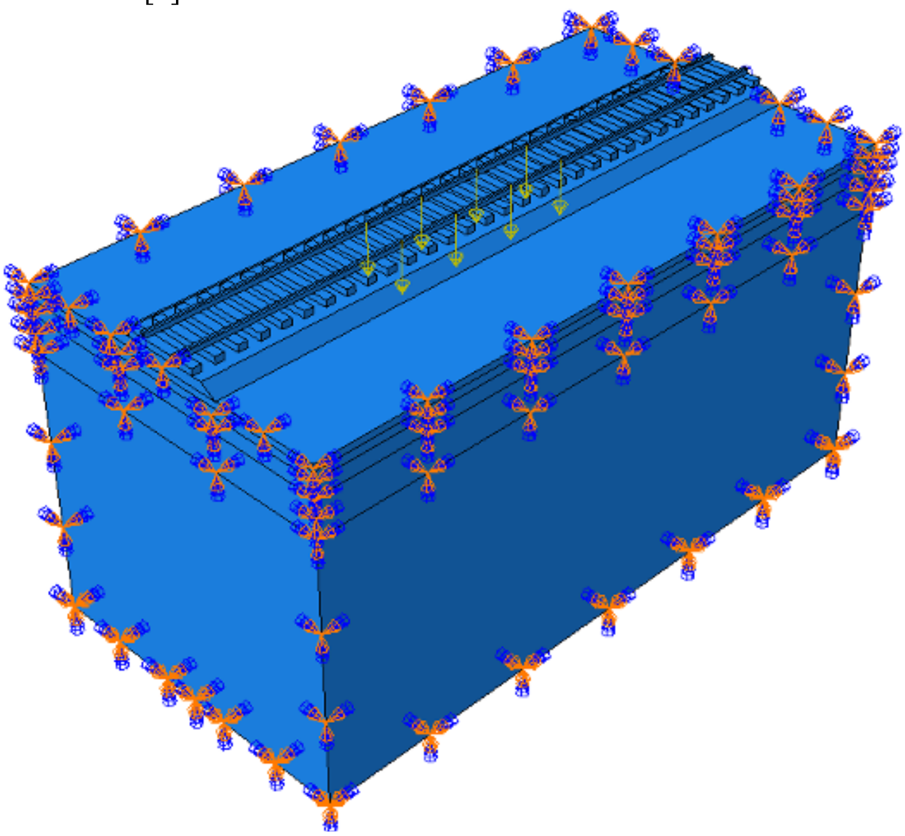

Figure 2: Finite element model from [1], [2],
(note: loading is at the tail of arrow)

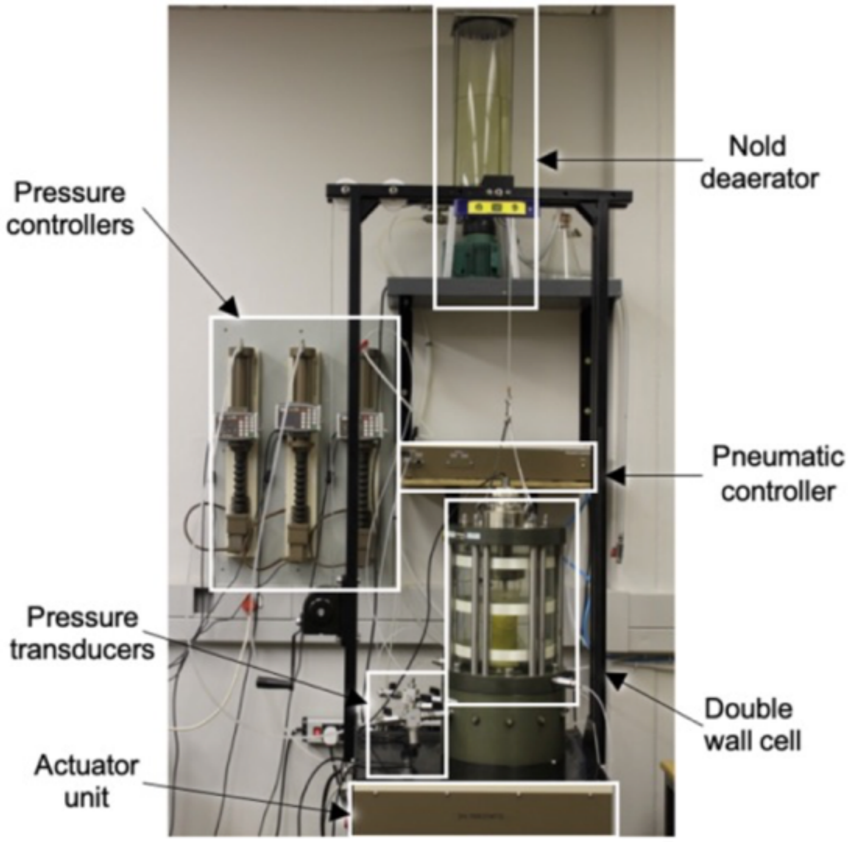

Figure 3: Cyclic triaxial apparatus

The engineering behaviour of soils during cyclic loading can be described by means of stress-paths [9], [10]. In this study, stress-paths are used to analyse the effect of increased axle loading from 20 to 26 tonnes per axle in order to investigate the behaviour of railway formation materials. The deviator stress and mean effective stress are used as stress state variables [11], as represented by Equations (1) and (2), respectively. The performance of railway foundation materials can be assessed by means of the cumulative plastic strain, which should be limited to 2 percent [12]. As such, the cumulative plastic strain was used as a parameter to assess the performance of the test material during cyclic loading at stresses equivalent to 20 and 26 tonnes per axle.

$$q = \sigma_1' - \sigma_3' \quad (1)$$

$$p' = \frac{\sigma_1' + 2\sigma_3'}{3} \quad (2)$$

Where:
q = deviator stress,
p' = mean effective stress,
σ_1' = effective major principal stress,
σ_3' = effective minor principal stress.

3 Results

The Atterberg limits of the test materials are shown in Table 1. Although both materials were classified as silty sand, the subballast consists of more sand particles as compared to the subgrade.

Table 1: Atterberg limits of test material

Material property	Material	
	Subballast	Subgrade
% gravel	2	1
% sand	75	67
% silts	18	29
% clay	5	3
Description	Silty sand	Silty sand
Liquid limit (%)	17	25
Plastic limit (%)	20	34
Plasticity index (%)	3	9
Linear shrinkage (%)	2	4
Specific gravity	2.89	2.64
Grading modulus	1.30	1.09

The results from the characterisation of the railway cyclic loading based on finite element model conducted by [1] and [2] as shown in Figure 2 are presented in Table 2. As expected, the stresses at 26 tonnes per axle are higher than those at 20 tonnes per axle. A frequency of 1.0 Hz is equivalent to a train speed 80 km/h.

Table 2: Triaxial cyclic loading for subballast and subgrade material

Axle load (tonnes)	Subballast material		Subgrade material		Frequency (Hz)
	Initial deviator stress (kPa)	Cyclic amplitude (kPa)	Initial deviator stress (kPa)	Cyclic amplitude (kPa)	
20	43.1	37.0	33.6	23.6	1.0
26	54.2	48.1	40.7	30.6	

The state of stresses in response to cyclic loading equivalent to 20 and 26 tonnes per axle is depicted in Figure 4 (a) and (b) for the subballast and subgrade material, respectively. The behaviour of both materials at cyclic loading equivalent to 20 tonnes per axle is mainly dilation throughout the test duration. At increased axle loading of 26 tonnes per axle, there is a phase-transfer from dilation to contraction in both materials. The cumulative plastic strain at cyclic loading equivalent to 20 and 26 tonnes per axle for the subballast and subgrade material are shown in Figure 5 (a) and (b), respectively. The cumulative plastic strain at 20 tonnes per tends to be linear, while at 26 tonnes per axle, it is exponential. It can be stated that linear (and stable) plastic strains are associated with dilation and exponential (and unstable) plastic strains are associated with a phase-transfer in soil behaviour from dilation to contraction.

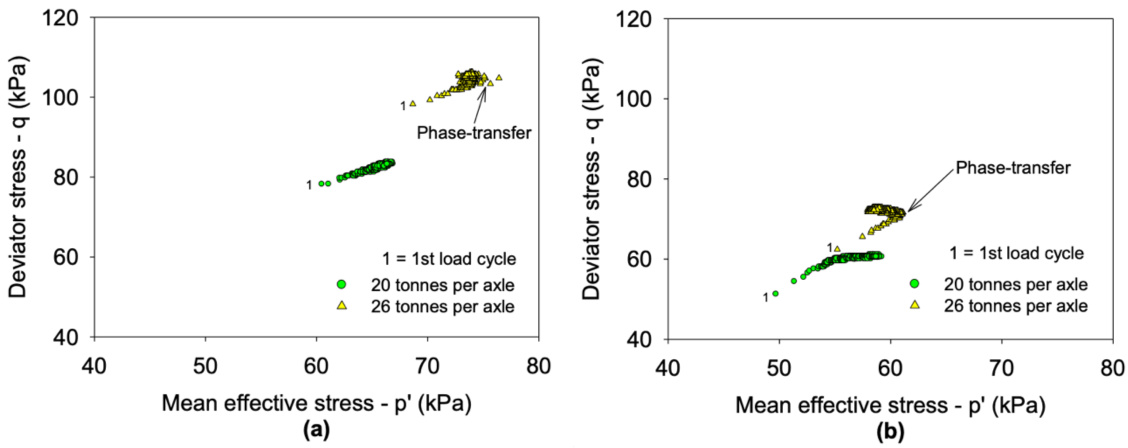

Figure 4: Stress states at 20 and 26 tonnes per axle for (a) subballast material and (b) subgrade material

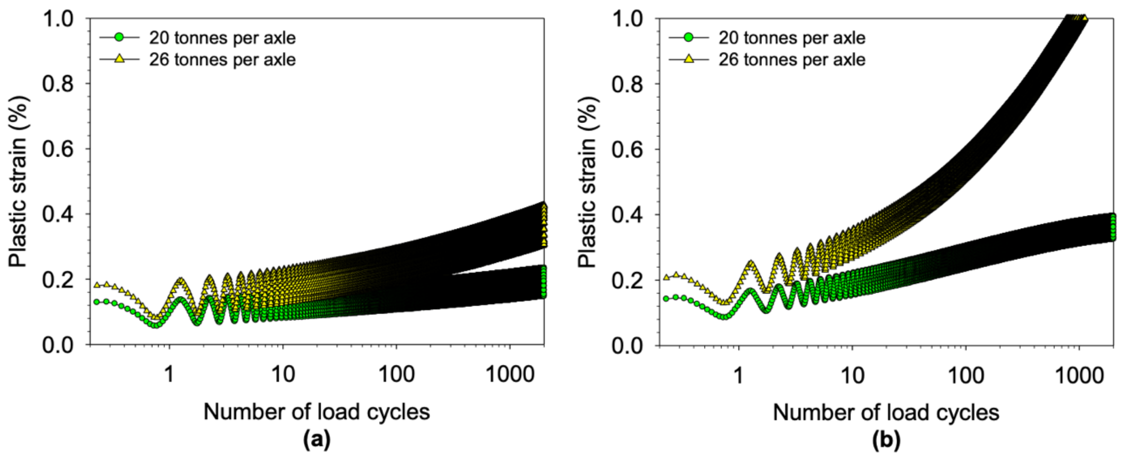

Figure 5: Cumulative plastic strains at 20 and 26 tonnes per axle for (a) subballast material and (b) subgrade material

4 Conclusions and Contributions

The purpose of this study was to analyse and compare the engineering behaviour of railway formation materials at increased axle loading from 20 to 26 tonnes per axle. Based on the test results, the resultant behaviour of the subballast and subgrade at cyclic loading equivalent to 20 tonnes per axle was found to be dilation with linear and stable increase in the cumulative plastic strain, which can be said to be safe and sustainable for railway operations. The resultant behaviour of the subballast and subgrade material at cyclic loading equivalent to 26 tonnes per axle was found to be associated with a phase-transfer in soil behaviour from dilation to contraction with an exponential and unstable increase in the cumulative plastic strain. Furthermore, the exponential cumulative plastic strain commenced upon the phase-transfer and can be associated with railway foundation failure and thus unsafe and unsustainable for railway operations. It can therefore be concluded that railway foundation materials that undergo phase-transfer from dilation to contraction during cyclic loading will accumulate plastic deformations much faster than those with dilative behaviour and no-phase transfer. Lastly, as a contribution, it therefore means that for design and maintenance purposes, foundation materials that undergo a phase-transfer from dilation to contraction should ideally not be used for operation in a railway track formation, as they might result in excessive plastic deformation and differential settlement which will ultimately lead to railway foundation failure.

Acknowledgements

The authors would like to acknowledge the University of Pretoria and Transnet Freight Rail for the support during this research.

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