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Experimental investigation of the characteristics of a granular ballast bed under cyclic longitudinal loading

Hao Liu [a,b], Jieling Xiao [a,b,*], Ping Wang [a,b], Ganzhong Liu [a,b], Mingyuan Gao [a,b], Shaozheng Li [a,b]

[a] MOE Key Laboratory of High-speed Railway Engineering, Southwest Jiaotong University, Chengdu 610031, China
[b] School of Civil Engineering, Southwest Jiaotong University, Chengdu 610031, China

HIGHLIGHTS

- Dynamic behavior of ballast bed under cyclic longitudinal loading are investigated.
- Resistance-displacement hysteretic curve of ballast bed is obtainted and analyzed.
- Longitudinal bearing performances of ballast bed are described.
- Images of ballast movement at different points of hysteresis curve are obtainted.

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ABSTRACT

In this study, tests are performed for studying the characteristics of a ballast bed under cyclic longitudinal loading at different loading rates and a displacement amplitude based on a full-scale test model. The deformation and resistance characteristics of the granular ballast bed are investigated under cyclic loading. The results show that the resistance of a track panel with different number of sleepers to the longitudinal displacement is obviously lower than the sum of the resistances per sleeper. In addition, monotonic and repeated loading can cause plastic deformations to accumulate continuously on the ballast bed, whereas cyclic densification occurs without much additional breakage owing to the rearrangement of the ballast particles, causing the resistance amplitude of the ballast bed to increase. Moreover, the loading and unloading curves of the granular ballast bed do not coincide with each other under cyclic loading, forming a closed hysteretic curve, and the ballast bed is subject to cyclic softening with the increase in the number of cycles. Furthermore, the response degree of the granular ballast bed is related to the displacement amplitude, and the cyclic softening behaviour of the granular ballast bed is dependent on the exerted displacement amplitude. Thus, a higher exerted displacement amplitude implies a more severe cyclic softening.

1. Introduction

Granular ballast beds, characterized by a structural dependence and discreteness, are solid and uneven structures constructed with crushed stones of different sizes based on the gradation. At the mesoscale, they are formed by numerous interlocking incompressible solid particles, and therefore, exhibit the above-mentioned characteristics. The mechanical properties of such beds are different from those of common solids or liquids because of the strong nonlinear bearing and shear resistance abilities, and generally, they cannot directly withstand tension [1,2]. Railway ballast bed structures have been adopted worldwide in view of their good elasticity, excellent damping capacity, strong water permeability, and easy maintenance [3,4]. Continuously welded rail (CWR) tracks have become standard modern track structures [5,6]. The longitudinal/lateral resistance of ballast beds, which is closely related to the line stability and rail creeping, is still a relevant research topic. The longitudinal resistance values that directly affect the longitudinal line stability, rail bar design plans, rail creeping, and safe service of CWR tracks are of particular importance [7–9]. The longitudinal load-bearing and force-transference mechanisms of ballast beds are highly complex because of the discreteness of the ballast track structures and repeatability of loads. The stress performance of ballast beds is related to the loading history; however, the stacked state of granular ballast exhibits a high degree of randomness and its structure changes randomly. Because of the periodicity of the

* Corresponding author at: MOE Key Laboratory of High-speed Railway Engineering, Southwest Jiaotong University, Chengdu 610031, China.
E-mail address: xjling@home.swjtu.edu.cn (J. Xiao).

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temperature load, ballast beds are always subject to dynamic changes yielding different displacement results, and the distribution of ballast resistance is characterized by discrete elements, randomness, and strong nonlinearity [10]. Hence, the study of the resistance performance and variation trend of granular ballast beds under cyclic longitudinal loading can be considered as a foundation for a deeper understanding of the service performance and stress deformation mechanism of CWR tracks under cyclic loading.

In recent years, ballast resistance has been studied based on experimental data and in accordance with statistics. Kerokoski performed field tests to measure the track resistance at a rail yard [11]. Le Pen and Powrie conducted a full-scale model test to quantify the relative contributions to the total sliding resistance of the sleeper base, crib, and shoulder [12,13]. Single-railroad and track panel pull-out tests were conducted on 1/5-scale models to evaluate the lateral resistance of railroad ties [14]. Jabbar Ali Zakeri compared the lateral resistance with frictional sleepers (with a ribbed underside) and conventional sleepers (with a flat underside) by using a track panel displacement test method [15]. In addition, the numerical simulation of the ballast track bed mechanical performance based on the granular grains method has also progressed [16]. Indraratna et al. presented the results of the effect of frequency on the permanent deformation and degradation behaviour of a ballast during cyclic loading [10]. Hollow cylinder tests were conducted to investigate the role of drainage conditions on the response of railway track foundation materials during cyclic loading [17]. A five-parameter ballast vibration modelling and full-scale field experiment were performed for analysing and testing the vibration of a granular ballast [18]. Tutumuler constructed ballast layers to investigate the ballast compaction, strength, and stability conditions before and after tamping [19]. Kabo established a sleeper-track bed spatial model using the finite element method, and analysed the effect of the ballast shoulder stacker and wheel load on the lateral resistance [20]. Hossain studied the permanent deformation and degradation of a ballast [21]. The published research works to date mainly focus on the vertical or transversal stability and do not cover all the aspects pertaining to the ballast response. Moreover, the ballast longitudinal resistance under cyclic longitudinal changes is still unknown, which play an important role in the thermal buckling and stress deformation mechanism of a ballasted railway track. Consequently, it is necessary to further analyse the hysteretic behaviours and variation trend of the ballast longitudinal resistance under cyclic loading for quantitatively predicting the ballast behaviour in different scenarios.

Based on the above-mentioned discussion, this research activity aims at developing a deeper understanding of the longitudinal resistance performance of ballast tracks and identifying the stress deformation mechanism of CWR tracks used under a cyclic loading. A specific testing program is necessary to characterise the behaviour of a ballast subjected to cyclic reciprocated changes in the track configurations because it allows to reproduce the testing conditions of the tracks in service, with high accuracy. Using a full-scale test model and distinct loading system, the following aspects are reported and critically discussed: longitudinal resistance characteristics of a granular ballast bed under cyclic loading, ballast longitudinal resistance–displacement hysteresis curves, variation trends of the hysteresis curve, and ballast longitudinal bearing and force transmission performances.

2. Test model and conditions

The *meso*-structure of granular ballast beds is complex, and their mechanical properties can be significantly affected by the scale effects and gradation [1,4] Simulations relating to the gradation characteristics, contact relationships, and load-caused deformation of ballast grains performed using reduced models are limited to dimensional analysis and scale effects. Full-scale models are more applicable for simulating *on-site* ballast bed structures. Therefore, a track panel with six sleepers was selected as the test model, and experimental studies of the ballast resistance under cyclic longitudinal loading were conducted.

2.1. Ballast, sleeper, and dimensions of model

The ballast bed was paved with China Railway Class I materials. Before paving, the ballast particle sizes were classified with a standard square plug gauge to ensure the gradation of the formed ballast satisfied the code requirements (Railway Ballast, TB/T 2140-2008) [22]. The ballast materials were crushed basalt stone, and the gradation of the ballast particle sizes is shown in Fig. 1. The Los Angeles abrasion (LAA) rate of the ballast particles was 23%. The standard aggregate impact toughness (IP) was 97%, marked aggregate crushing value (CA) was 8%, and ballast aggregate crushing value (CB) was 20%. The compressive strength of the stone powder specimen was 0.3 MPa. The above tests are the material parameters of the ballast and provide the basis for grading the ballast material [23].

A conventional ballasted track substructure is divided into ballast layers, subballast layers, and subgrade layers. Subballast materials are used in a railway track to reduce the cyclic stress being transmitted to the subgrade layer and prevent the migration of the fine subgrade soil into the top ballast layer [24]. The top width and thickness of the model ballast bed were 3.60 m and 0.35 m, respectively. The top of the ballast bed was 40 mm lower than the rail support surface of the sleeper, and the slope of the ballast shoulder was 1:1.75. In addition, the piled ballast shoulder was 0.15 m. The section size of the ballast bed satisfied the requirements for a single line of ballast beds of a high-speed railway ballast track in China [25], as shown in Fig. 2. The model track had six type-III concrete sleepers, and the space between the sleepers was 0.6 m. The length of a sleeper was 2.6 m, width of the sleeper bottom was 320 mm, and thickness under the rail seat was 220 mm. Moreover, the model of the rail was CHN60, and the fasteners were involved in a type-II fastener system with the longitudinal resistance no less than 15 kN/m per rail.

2.2. Model test apparatus for ballast longitudinal resistance

The model was equipped with a distinct loading apparatus consisting of an actuator unit, a sensor unit, and a data collection unit, as depicted in Fig. 3. The CF-300kN precision power servo actuator, provided with a force or displacement control function, was used

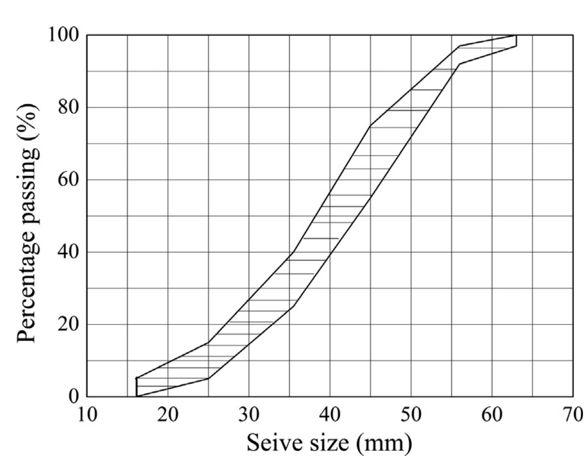

Fig. 1. Gradation of ballast particle sizes.