The influence of height of ballast crib on the longitudinal resistance of sleepers in ballasted railway tracks

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Abstract— **The longitudinal resistance of ballasted railway tracks is directly associated with track buckling due to the temperature fluctuation of induced loading by trains. In this regard, crib ballast is the main component of the ballast layer to provide adequate resistance against sleeper movement. However, in order to prevent ballast flight from the ballast top surface for high-speed tracks (> 350 km/h), the height of the crib ballast could not be the same level as the sleeper top surface. Hence, the impact of crib ballast height reduction on the longitudinal resistance is examined for a ballast layer with a density of 1450 kg/m3. The experimental outcomes showed that the crib ballast height of 0.72 H (sleeper middle height) caused a 36 % decrease in terms of sleeper longitudinal resistance. Furthermore, the effect of the crib ballast height variations on the longitudinal resistance was studied by numerical modeling. In conclusion, the existence of crib ballast plays an important role in the longitudinal resistance of the sleepers.**

Keywords— Longitudinal resistance, Crib ballast, Shoulder width, Shoulder height, DEM.

I. Introduction

The continuous welded rail (CWR) is widely used in railway tracks due to higher stability and lower maintenance cost. The longitudinal resistance of the track plays a crucial role in track buckling owing to the braking/accelerating of trains and thermal loads, particularly in sharp curves and steep areas [1-3]. As can be seen in Fig. 1, the movement of vehicles on the track causes the downward sliding of ballast aggregates. In terms of track gradient, Rail Safety and Standards Board Limited (RSSB) [4] reported that the maximum should be less than 2.5 mm/m, and the following requirements are recommended for tracks with the maximum gradients of tracks through passenger platforms of new lines gradient of 35 mm/m:

a) The gradient of the moving average length over 10 km must be lower than 25 mm/m.

b) The maximum length of a track with a continuous gradient of 35 mm/m should be lower than 6 km.

However, It has been confirmed that the loads caused by acceleration and braking of trains were less than those attributed to temperature variations [5]. In this regard, track buckling takes place when the axial force is higher than the longitudinal resistance of the track owing to the growth of temperature up to buckling temperature.

As revealed in Fig. 2, the compressive force is uniformly distributed along the rail track before buckling. As reported by Samavedam et al. [6], lower buckling temperature increases with the increase of longitudinal resistance, while upper buckling temperature (TB) remains almost constant, which is calculated according to Eq. (1):

$$f = k_f \cdot u \tag{3}$$

Where f, k_f, and u are longitudinal resistance, longitudinal stiffness, and axial rail displacement, respectively.

In this matter, the interaction of rail/fastening system, fastening system/sleeper, and sleeper/ballast provide the longitudinal resistance of the ballast in a ballasted railway track. In terms of the ballast/sleeper interaction, the presence of crib ballast between sleepers, the depth of ballast bed, shoulder ballast height and width, and sleeper type are important parameters from the perspective of the longitudinal sleeper resistance. Particularly, crib ballast has a high proportion (about 60 %) to the longitudinal resistance of the ballast layer due to the passive pressure between sleeper sides and crib ballast [7, 8].

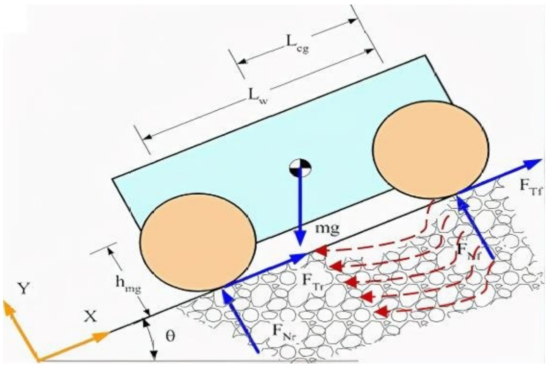

Fig. 1. Ballast sliding in steep gradient lines due to the movement of the vehicle

In another research, Queiroz, R. C [9] examined the impact of the sleeper type on the longitudinal resistance. The results confirmed that the longitudinal resistance of the mono-block concrete sleeper is higher than wooden and steel sleepers.

In order to increase the longitudinal stability of the ballast layer or sleepers, different methods could be applied. The application of geogrid, bitumen emulsion, polyurethane, and hot mix asphalt [11-15] are new approaches to reinforce the ballast layer. The use of the different shapes of concrete sleepers is another solution for resistance increments, such as frame sleeper, ladder track, winged sleeper, and anchor-reinforced sleeper [16, 17]. So far, investigations on the lateral resistance of different types of sleepers were collected by Jing et al. [18]. In this regard, the longitudinal resistance of the above-mentioned sleepers could be evaluated in further studies.

To estimate track longitudinal resistance, two of the most common methods are laboratory track panel tests and field tests on a railway track. Mohammadzadeh et al. [19] conducted field tests on 70 m track to determine track longitudinal resistance under loading and unloading conditions. Results indicated that the longitudinal resistance of the unloaded track is 42 % of the loaded track. In another research, due to the disturbance of ballast particles interlocking, the longitudinal resistance decreased by 30 % in the case of cyclic loading conditions [20, 21]. On the other hand, tests on a large number of sleepers led to an increase in the longitudinal resistance of the ballast in comparison with short panel tests. Therefore, the longitudinal resistance is mainly the function of vertical loading as well as the length of the track panel.

The discrete element method (DEM) is a proposed method for the simulation of granular material [22, 23]. This method was mainly used for the assessment of ballast behavior in terms of lateral and vertical deformation, as well as shear strength in previous studies [24-26]. The obtained results show that the DEM can accurately simulate the bulk behavior of ballast. However, there is no specific DEM modeling of the longitudinal resistance of the ballast layer, which is considered in the present study by simulation of a single sleeper on a section of the ballast layer.

As already mentioned, the crib ballast has a higher impact on the longitudinal resistance in comparison with shoulder ballast and ballast bed [7, 8]. However, the height of the crib ballast should be lower than the sleeper top surface owing to the ballast flight phenomenon caused by

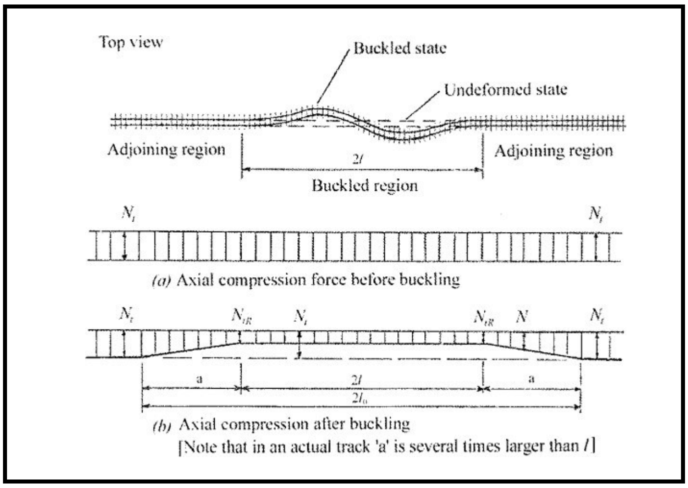

Fig. 2 Distribution of axial compression force before, and after buckling [10]

passing trains in high-speed railway tracks. Previous studies have reported that the height of crib ballast should be 50 mm lower than the sleeper top surface for railway tracks with a speed of over 350 km/h [27, 28]. So far, no previous study has investigated the influence of the variation of the crib ballast height on the longitudinal resistance. Of particular concern is ballast flight in case the crib ballast height is up to the top surface of the sleeper. In this paper, a series of numerical modeling and experiments have been conducted in order to assess the effect of crib ballast height on the longitudinal resistance of the ballasted track. In this way, modeling of mono-block sleepers on a ballast layer was performed with Particle Flow Code (PFC).

I. DESCRIPTION OF EXPERIMENTAL TESTS PROCESS

A test panel with three concrete sleepers was constructed in order to evaluate the influence of track geometry on the longitudinal resistance of the ballasted track. In all tests, the depth of the ballast bed and sleeper spacing were 400 mm, and 600 mm, respectively. The ballast gradation was compatible with China National Standard TBT 2140, illustrated in Fig. 3. As already mentioned, the density of ballast is an important parameter that influences ballast resistance. In line with that, the ballast layer was compacted by a vibration compactor so that each layer of ballast was compacted five times to provide a consolidated ballast layer with a density of 1450 kg/m^3.

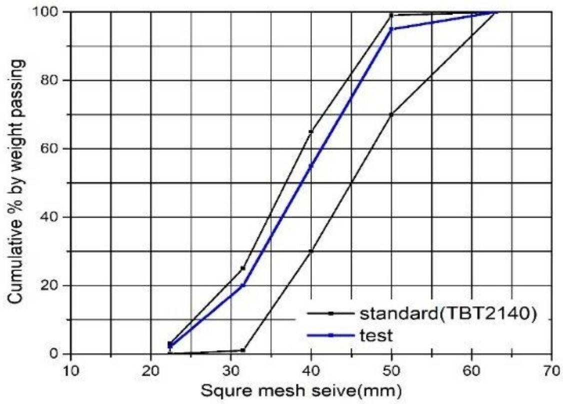

Fig. 3. Ballast particle size distribution

To examine the longitudinal resistance of the single sleeper, the axial force was applied by a hydraulic jack with the maximum value of 10 tons applying force at each 30s time step. It is noteworthy that steel rods were used as supports to fix the adjacent sleeper for applying the load to the middle sleeper. A force sensor was attached to the middle of a measured sleeper, and displacement indicators were installed on both sides of the sleeper, and measurement was continued up to 4 mm displacement. The recorded axial force at the displacement of 2 mm was defined as the longitudinal resistance of the sleeper. To prepare the various condition of shoulder ballast, the height and width of the shoulder were varied from 0 mm to 150 mm, and 300 mm to 400 mm, respectively. In order to analyze the impact of crib ballast on longitudinal resistance, experiments were conducted on panels with the crib height of 0, 0.56 H, 0.72 H, and H with respect to the sleeper middle height. The test setup is revealed in Fig. 4.

Fig. 4. Test set up and ballast layer conditions.

II. RESULTS AND DISCUSSIONS

A. Effect of crib ballast height

The influence of crib ballast height on the longitudinal resistance of a single sleeper was evaluated by experimental tests on a track panel with various crib ballast heights of 0, 0.56 H, 0.72 H, and H with respect to the sleeper middle height (Fig. 5). Accordingly, the obtained longitudinal resistance was 1.7, 4.9, 8.9, and 12.1 kN/m for a single sleeper, respectively, which are close to those stated by Wang [29]. In other words, due to the passive pressure of crib ballast against sleeper movement, the longitudinal resistance increased by 188%, 423%, and 612% for panels with 10, 5, and 0 mm crib ballast height from sleeper top surface in comparison to the track without crib ballast, respectively. On the other hand, a 50 mm reduction in crib ballast height led to a 36 % decrease in the longitudinal resistance. As already mentioned, the height of the crib ballast should be reduced by 50 mm due to the ballast flight in high-speed railway tracks. Therefore, other methods described in the introduction could be implemented in order to overcome the reduction of longitudinal resistance. It is noteworthy that the resistance of the ballast bed and shoulder ballast was steady during the sleeper movement, according to the result of NS_C18.5. It could be attributed to the frictional force between ballast and sleeper bottom as well as sleeper ends.

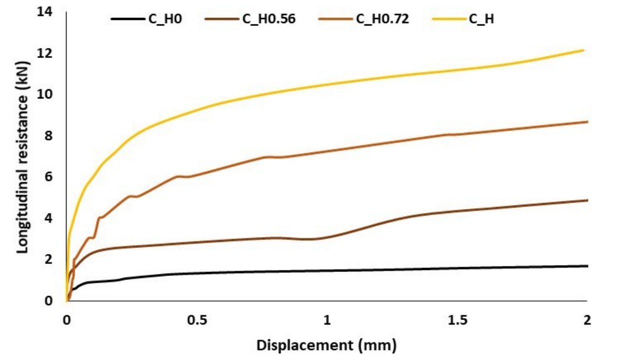

Fig. 5. Longitudinal resistance of ballast panels with different crib ballast height

III. NUMERICAL MODELING OFLONGITUDINAL RESISTANCE TESTS

In experiments, the influence of crib and shoulder ballast on the longitudinal resistance was evaluated. However, what not yet clear is the contribution of ballast components to the longitudinal resistance in the case of various crib ballast heights. In this regard, the numerical modeling of experiments was performed by the discrete element method to calculate the portion of ballast components to the longitudinal resistance when crib ballast height is 0, 0.56 H, 0.72 H, and H. Table 1 shows the mechanical properties of simulated ballast particles and sleepers.

To prepare the ballast panel, the generation of particles was continued by gravity to fill a closed box to reach the mean porosity of 0.35 (Fig. 6a). To evaluate the effect of crib ballast height on longitudinal resistance, ballast particles were deleted to achieve the desired level of crib ballast between sleepers (Fig. 6b-6e)). The final stage was running the model and measuring sleeper displacement until the layer reached the desired porosity of the ballast layer in the initial equilibrium state. Finally, longitudinal loading with the rate of 1e-5 mm/step was applied to the middle sleeper, and the displacement of the sleeper was measured as well as contact force between ballast and sleeper facets.

TABLE I MECHANICAL PARAMETERS FOR DEM SIMULATION.

Parameters	***Clump***	***Sleeper***
Normal stiffness, k_n (N/m)	1.5e8	1e8
Shear stiffness, k_s (N/m)	0.77e8	1e8
Density (kg/m^3)	2700	_
Friction	0.8	0.8

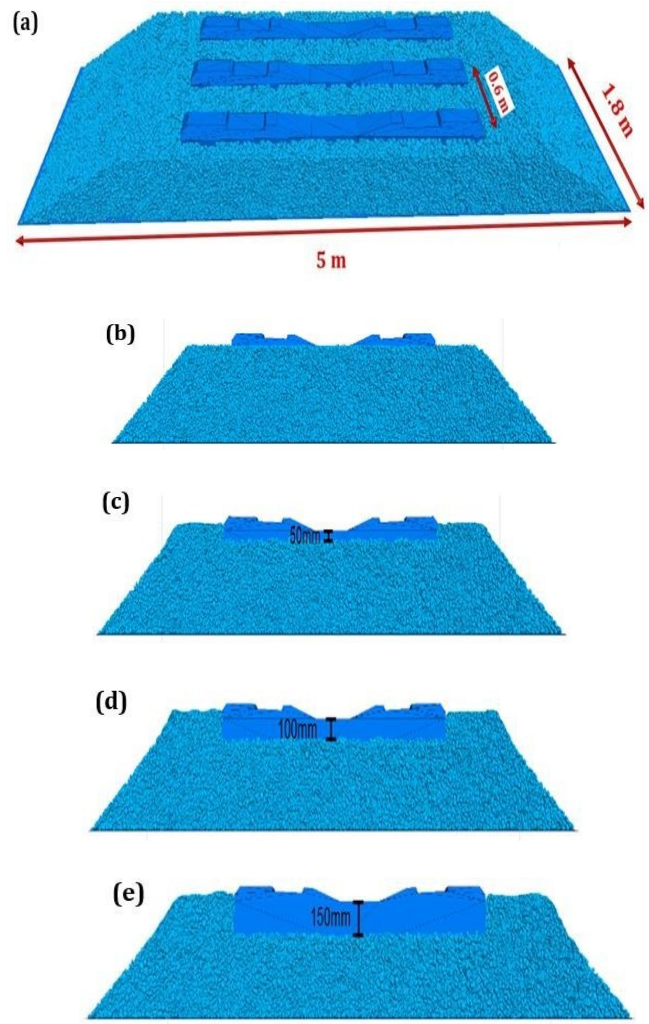

Fig. 6. (a) Simulated ballast panel, Panels with crib height of (b) 0 mm, (c) 50 mm, (d) 100 mm, and (e) 185 mm

B. Contribution of ballast components to longitudinal resistance

The influence of crib height variations on increasing lateral resistance is shown in Fig. 7. The presence of crib ballast up to the sleeper top surface resulted in the uniform distribution of contact force through the aggregates. In addition, reduction of crib ballast height led to a decrease in the dense of force chain in the shoulder section. As shown in Fig. 8, the resistance of crib ballast reduced by 6 % in case there was a 50 mm decrease in the crib height. This reduction could be compensated by reinforcement of crib ballast, such as adding polyurethane or bitumen emulsion. For a panel without crib ballast, the ballast bed has the major contribution (99.5%), which indicates the supplementary role of the ballast bed when the crib ballast is removed. This contribution was 25.6 %, 11.6 %, and 5.2 % when the crib height was 100 mm, 50 mm, and 0 mm lower than the sleeper top surface. Thus, the presence of the crib ballast is vital in terms of ballast longitudinal resistance. On the other hand, due to the frictional force and low contact area between sleeper ends and shoulder ballast, the contribution of shoulder ballast is ignorable in comparison with the other two components. For instance, the shoulder ballast has a 0.44 % contribution for a panel without the crib ballast. Therefore, the ballast bed is the second component with a high contribution to longitudinal resistance.

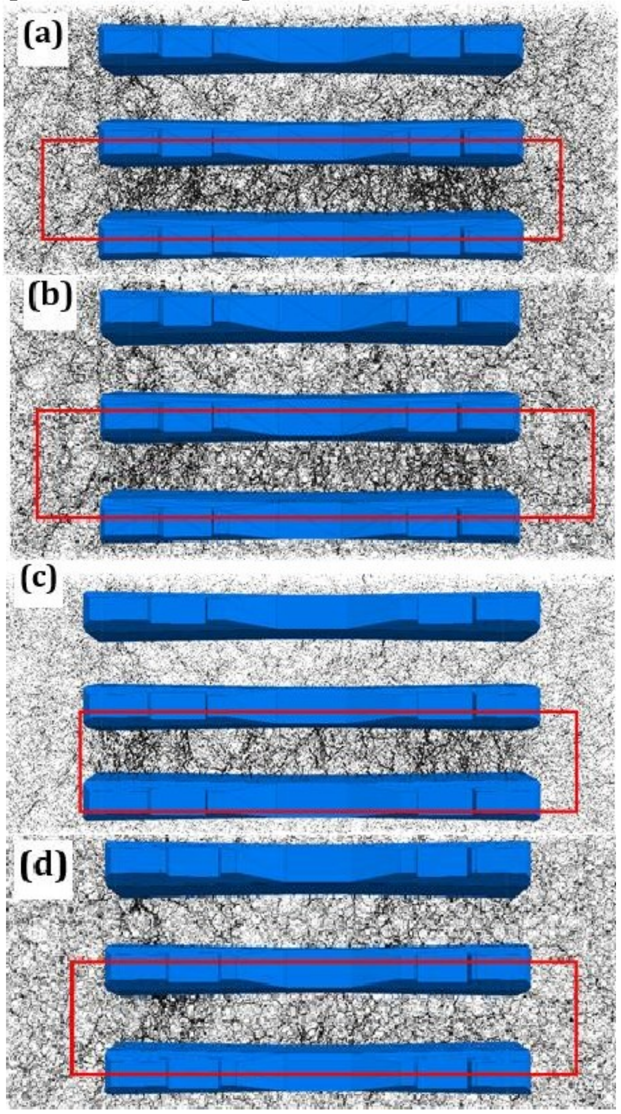

Fig. 7. Contact force distribution for panels with the crib height of (a) H, (b) 0.72 H, (c) 0.56 H, and (d) 0 H

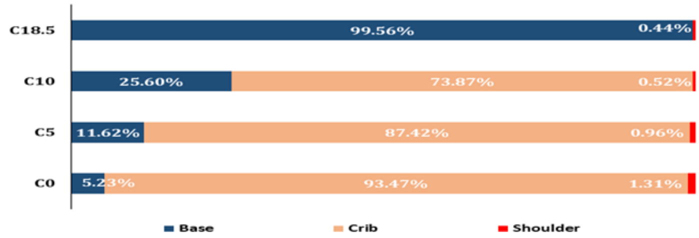

Fig. 8. The portion of the ballast component to the longitudinal resistance

IV. CONCLUSION

The longitudinal resistance of the ballasted railway tracks is connected to the tracks buckling in CWR tracks. The crib ballast has a remarkable contribution to the longitudinal resistance, owing to the passive pressure against the sleeper movement. On the other hand, a reduction in the height of crib ballast height down to 50 mm is unavoidable due to the ballast flight phenomenon. In this paper, the variation of crib ballast height was evaluated by experiments as well as numerical modeling. Major findings are highlighted as follow:

1) Based on experimental tests' results, there is a direct correlation between crib height increment and track longitudinal resistance so that increasing the crib height up to the sleeper top surface resulted in a 612% increase in the sleeper longitudinal resistance. On the contrary, the longitudinal resistance was reduced by 36 % where the crib ballast height was 0.72 H.

2) Increasing width of the ballast shoulder from 300 mm to 500 mm led to a 10 % rise in the track longitudinal resistance. Since the width of 500 mm was already defined as the suitable shoulder width from the lateral resistance's view, this size could be applied in the construction of shoulder ballast width.

3) Numerical modelling results confirmed that the sleeper longitudinal resistance considerably depends on the height of crib ballast. Based on the obtained outcomes, crib ballast has significantly affected the strength increment of the sleeper (about 94 %) in ballasted railway track which is related to the confinement of each sleeper by ballast aggregates.

For future works it is strongly suggested to investigate the effect of operation conditions, especially human factors, on deterioration and strength of ballast materials and connect it to cognitive infocommunications according to given information and ideas by Barani et al. [30, 31].

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