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DEM analysis of railway track lateral resistance

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Abstract

In this study, a sensitivity analysis of track lateral resistance using DEM was carried out on a number of concrete sleepers on a test track and the results of the Single Tie Push Test were simulated by the discreet element method implemented in PFC^{3D}. By incremental loading of sleeper in STPT simulation, the obtained load-lateral displacement was compared with those obtained in field tests. Based on the good compatibility of the results, many sensitivity analyses were performed on ballast depth, ballast shoulder width, ballast shoulder height, inter particle friction of ballast material and ballast layer porosity (density).

Keywords: Ballasted track lateral resistance; Single Tie Push Test (STPT); Discrete Element Method (DEM); PFC^{3D}; Ballast particles

1. Introduction

The large axial forces on continuous welded rails (CWR), mostly due to daily and seasonal temperature gradients, can lead to the lateral instability of railway tracks or track buckling. Because of the maintenance and expense required for railway renovation after buckling, investigating ways to increase track lateral resistance or to prevent track buckling is of great importance. Track lateral stability, known as the prohibiting factor against buckling, is a function of different characteristics of track elements. Rail section properties, fastener lateral, longitudinal and torsional stiffness, sleeper type and geometry and ballast specifications all contribute to the track lateral resistance. Experimental studies have shown that the proportion of ballast (ballast-sleeper interaction included), rails and fasteners in the total lateral resistance is almost 65%, 25% and 10% respectively (see Zakeri, 2012), indicating that the ballast layer plays a crucial role in the provision of track lateral resistance. Furthermore, many geometrical and mechanical specifications of the ballast layer (like under sleeper ballast depth, shoulder width, shoulder height, inter particle coefficient of friction and porosity) potentially affect track lateral resistance. Based on these facts, a detailed characterization of ballast lateral resistance capable of taking all the contributing parameters into consideration could be beneficial.

The Single sleeper (Tie) Push Test (STPT) was chosen for this investigation because it is capable of measuring the lateral force-displacement response of tracks.

Many experimental and numerical STPT studies have been performed to investigate the effect of ballast depth, shoulder width and shoulder height on track lateral resistance. The effect of ballast depth on STPT result was experimentally studied by Zakeri and Bakhtiary (2013) in conjunction with the idea of innovative frictional sleeper. Based on the results of this study, presented in Table 1, a decreasing trend was observed due to the increase of ballast Depth. On the other hand, similar field STPTs performed by Esmaeili et al. (2015) obtained different results. Results of the numerical investigations reported by Zakeri et al.

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Table 1
Results of track lateral resistance for different ballast depths and shoulder width of 40 cm.

Reference	BD (mm)	Total lateral resistance (KN)	Difference (%)	Method
Zakeri and Bakhtiary (2013)	100	6.93		Experimental
	200	5.86	−15.44	
	300	5.11	−12.80	
Zakeri et al. (2014)	200	36.97		Numerical,[a] FEM
	300	31.76	−14.09	
Zakeri et al. (2014)	200	46.17		Numerical,[b] FEM
	300	39.76	−13.88	
Esmaeili et al. (2015)	300	6		Experimental
	400	13.5	125	
	500	11	−18.52	

[a] The friction angle between sleeper and ballast layer is assumed 0.1.
[b] The friction angle between sleeper and ballast layer is assumed 0.8.

(2014), using and FEM model on loaded track agrees with the findings of Zakeri and Bakhtiary (2013). Other different values found in the literature have shown the non-uniformity of track lateral resistance changes due to variation of ballast depth.

In addition, the effect of shoulder width has been considered in many studies with a relatively wide range of variations in lateral resistance reported. Zakeri and Bakhtiary reported in 2013 that adding ballast material to increase the shoulder width can increase lateral resistance, but in some cases the increase was negligible. Similar results had been obtained in an earlier study carried out by Zakeri (2012). The results of an experimental study reported by Esmaeili et al. (2015) indicate that when ballast depth is 30 cm, the increase of shoulder width from 30 to 40 cm made no change in lateral resistance. But Le Pen and Powrie (2010) reported a greater increase in the lateral resistance due to the increase of shoulder width. In the numerical studies carried out by Zakeri et al. (2014) and Kabo (2006) on the basis of FEM, extending the shoulder width resulted in a considerable increase in the lateral resistance, which was consistent with the results presented in ERRI D 202/RP 2 (1995) and ERRI D 202/RP 4 (1999). A review of the results of some case studies of the shoulder width effect on track lateral resistance is summarized in Table 2. The declining rate of lateral resistance increase due to shoulder width extension was explained by Le Pen et al. (2014) based on critical width concept of mobilized volume of passive ballast in the ultimate limit state. Based on the results presented by Le Pen et al. (2014), exceeding the critical width has no benefit for lateral resistance enhancement and increasing the shoulder height provides better results.

The effect of the gibbous shaped part over the shoulder (shoulder height) was experimentally studied by Zakeri and Bakhtiary (2013); Esmaeili et al. (2015); Le Pen and Powrie (2010) and Le Pen et al. (2014). A comparisonof the results with those for the flat shoulder condition indicated an increase of lateral resistance in the range of 0–57.73% in different experimental cases. In the FEM model of Kabo (2006), an increase in the shoulder height resulted in a reduction in lateral resistance.

In the case of the mechanical properties of the ballast layer, the friction coefficient of the sleeper-ballast interface was considered in the FEM models of Zakeri et al. (2014) and Kabo (2006), but the inter particle friction coefficient was not included based on the assumption that the ballast layer was continuum environment.

A three dimensional simulation of STPT was performed in the DEM software DEMPack, with spherical balls used as ballast particles. In addition, some parametrical studies were carried out on material properties, like the friction coefficients and other input parameters like the sleeper velocity (see González, 2015).

While the review on the literature of experimental STPT studies showed that the effect of ballast layer geometry on the track lateral resistance has been widely studied, no exclusive trends have been observed even when the track conditions were similar. Using an FEM simulation, a wide variety of track models with different geometries and loading patterns could be analyzed, but due to the ballast layer assumption as continuum region, particle related characteristics like ballast shape, inter particle friction and porosity of ballast layer could not be specified properly. Using DEM, it is possible to simulate individual ballast particles by studying the effect of ballast shape, ballast layer porosity and also inter-particle contact parameters like the friction coefficient.

The authors found no published discrete element simulation of track lateral resistance which considered realistic ballast shapes. As such, an investigation was carried out on track lateral resistance based on a realistic DEM simulation of STPT and a comprehensive sensitivity analysis on geometrical and mechanical properties of ballast layer.

A test track in the Aprin railway station in the vicinity of Tehran city was prepared and several field STPTs were performed. The degradation of local ballast and the in-situ density of the ballast layer were measured. The inter particle friction of the ballast material, elastic modulus and Poisson's ratio of ballast mother rock were measured using a set of laboratory tests. A three dimensional model of the STPT using PFC^{3D} was developed. Irregular-shaped ballast aggregates were simulated and the sleeper element was generated as a clump element. After the validation of

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