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Performance Evaluation of Single and Double Track Configurations Through 3D Numerical Simulations

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Abstract

This paper presents the results of three-dimensional finite difference numerical models developed to evaluate the behaviour of the materials constituting the track support, considering single and double track configurations. The parameters of strength and deformability of the sub-ballast, subgrade, and embankment layers were varied in the models. Findings indicate that the double-track configuration is the most unfavourable for the analysed scenarios. The minimum and average safety factors obtained for the sub-ballast and subgrade layers are relatively low, implying an overstress and significant long-term deformations. The developed models were able to simulate satisfactorily the real stress distribution and clearly showed that the permanent deformation due to loading acting on the track is influenced by the stiffness of the support system.

Keywords: numerical modelling, safety factors, track support performance, finite difference models, double track configurations, ballasted track.

1 Introduction

The superstructure of an urban train track is generally made up of rails, fasteners, and sleepers, while the ballast, sub-ballast, and subgrade layers constitute the support of the track (i.e., substructure).

The substructure (i.e. track support) is consisted of three different materials: ballast, sub-ballast and subgrade, which have the function of transmitting stresses to a level of permissible bearing capacity to the soil, preventing excessive lateral displacement settlements [1]. The track support is subject to several factors that affect its behavior, mainly due to the effects of cyclic loading. Also, acceleration/braking of trains can increase shear deformations and horizontal ground displacements and thus the need for track maintenance at locations where trains routinely brake [2]. Liu and Zou [3] mention that the wear of granular materials such as ballast generated by cyclic loading significantly influences its strength and deformation. Due to these problems, various types of improvement of the layers that make up the track support have been employed employing geocells, geogrids, geotextile and shredded rubber [4,5,6].

Over the years, several empirical, theoretical, and numerical methods for track design have been developed. However, conventional methods for its design are based on static stress analysis and do not consider cyclic loading, or different stiffness of track support layers (i.e., ballast, sub-ballast, subgrade) and, therefore, the employment of these methods provides rough estimates and can lead to poor design [7] In particular, the stresses to which the ballast is subjected are estimated using methods based on semi-empirical equations. Two of the most frequently used methods are presented by AREMA [8] and Hay [9]. Although the methodology presented by AREMA [8] has been updated to consider the separation between sleepers (i.e., distribution factor), the velocity and diameter of the wheel (i.e., impact factor), these updates were implemented around fifty years ago, and when computing the mean pressure under the sleeper, both methods use the equation developed by Talbot [10] for the estimation of the pressure distribution with depth at the center of the sleeper. Likewise, both methodologies do not consider the calculation of deformations (elastic and plastic), so they are not able to evaluate the realistic long performance of the system.

This paper presents the results of numerical simulations carried out with three-dimensional finite difference models, where the behavior of typical materials that constitute the track support evaluate, with the aim of ensuring satisfactory performance under different track configurations (i.e., single track and double track) and various loading conditions (i.e., passengers and freight) anticipated.

2 Methods

2.1 Analytical models

The methodology presented by AREMA [8] use the equation developed by Talbot [9] in 1920, for the estimation of the pressure distribution with the depth to the center of the sleeper. To consider the dynamic component, the static load can be multiplied by an influence coefficient generally known as the impact factor.

The impact factor proposed by AREMA is calculated using Equation 1.

$$IF = \frac{33V}{100D} \tag{1}$$

Where:
V is the velocity, in mph.
D is the wheel diameter, in inches.

Sadeghi [11] proposed a series of equations from multiple measurements with pressure cells placed under the track. According to this methodology proposed the design load P is multiplied by a factor, ϕ, to account for the dynamic effect of the train passage. This dynamic factor is obtained with the following Equation 2.

$$\phi = 1 + 4.73\frac{V}{D} \tag{2}$$

Where:
V is the train speed, in km/h
D is the wheel diameter, in mm

2.2 Numerical Model

To study the expected behavior of the track support under sustained loading during the project's lifespan, a series of three-dimensional finite difference numerical models were developed using the FLAC^{3D} program [12]. The obtained results are compared with those estimated using the expressions provided by AREMA [8] and Sadeghi [11].

The elements included in the numerical model consist of the rail tracks, sleepers, layers of ballast, sub-ballast, subgrade, embankment, and natural terrain. According to the provided information, the structural section of the rail corresponds to a 115 RE profile (American Standard).

The layers of ballast, sub-ballast, subgrade, and embankment were simulated using solid elements governed by a Mohr-Coulomb constitutive law. The parameters needed to characterize these materials are: the internal friction angle, φ; Young's modulus, E; Poisson's ratio, ν; and cohesion, c.

Group	***E* [Mpa]**	**ν**	**γ [kN/m³]**	***c* [Mpa]**	**ϕ [°]**
Ballast	130	0.2	14.7	0	45
Sub-ballast	120	0.3	18.6	0	35
Subgrade	80	0.4	18.1	0.015	10
Embankment	45	0.4	17.6	0.015	10

Table 1: Properties of the ballast, sub-ballast, subgrade, and embankment layers.

To increase the safety factor of the subgrade, an increase of 0.30 m in the thickness of the ballast was evaluated, without modifying the rest of the layers that make up the track support (Case IV). Improving the properties of the materials to comply with the specifications outlined in the IMT (Mexican Institute of Transportation) [12] standards was considered (Case V).

The natural terrain, which consists of limestone rock, was simulated using the same criteria as the layers. Following the methodology proposed by Hoek et al. [13], the strength envelope for the rock strata was defined according to the Hoek & Brown Generalized constitutive model, and subsequently, the equivalent properties of the Mohr-Coulomb constitutive model.

The track performance was evaluated considering: 1) the mean minus one standard deviation, and 2) the minimum value of the quality test results (CBR), in the embankment and subgrade layers where the desired quality was not met.

Case	**Material**			
	Ballast	**Sub-ballast**	**Subgrade**	**Embankment**
I	E=130 [Mpa] ϕ=45°	E=120 [Mpa] ϕ=35°	E=80 [Mpa] ϕ=10° c=0.015 [Mpa]	E=45 [Mpa] ϕ=10° c=0.015 [Mpa]
II	E=130 [Mpa] ϕ=45°	E=62 [Mpa] ϕ=5° c=0.03 [Mpa]	E=62 [Mpa] ϕ=5° c=0.03 [Mpa]	E=40 [Mpa] ϕ=5° c=0.03 [Mpa]
III	E=130 [Mpa] ϕ=45°	E=55 [Mpa] ϕ=5° c=0.03 [Mpa]	E=55 [Mpa] ϕ=5° c=0.03 [Mpa]	E=35 [Mpa] ϕ=5° c=0.03 [Mpa]
IV	E=130 [Mpa] ϕ=45°	E=55 [Mpa] ϕ=5° c=0.03 [Mpa]	E=55 [Mpa] ϕ=5° c=0.03 [Mpa]	E=35 [Mpa] ϕ=5° c=0.03 [Mpa]
V	E=130 [Mpa] ϕ=45°	E=120 [Mpa] ϕ=35°	E=100 [Mpa] ϕ=30° c=0.02 [Mpa]	E=70 [Mpa] ϕ=25° c=0.03 [Mpa]

Table 2: Summary of considered cases.

Regarding the dimensions of the sleepers, a width of 0.30 m and a spacing of 0.60 m between centers (center to center) were considered. Figure 1 show the three-dimensional finite difference models that were developed.

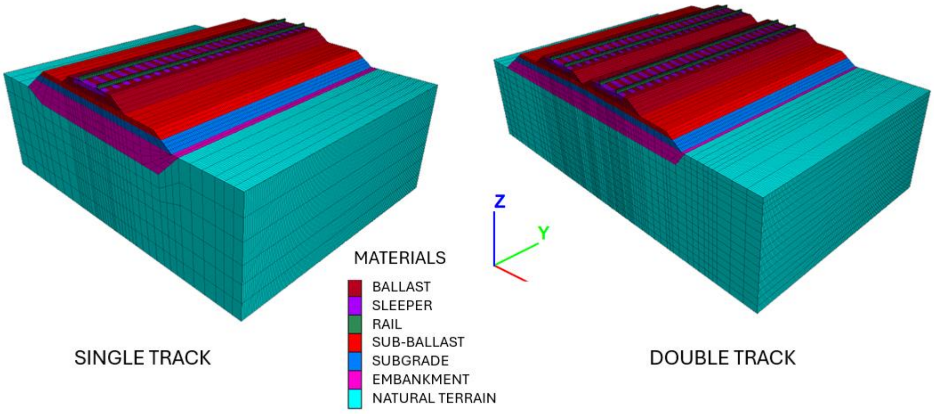

Figure 1: Three-dimensional finite difference models.

Considering a design speed of 100 km/h (62.14 mph) and a wheel diameter of 1.0 m (39.37 in), an impact factor of 0.52 was obtained. All analyzed cases considered the same load per wheel (Table 3).

Load per wheel	**Impact factor,**	**Load per wheel considering IF**
[kN]	**IF**	**[kN]**
159.4	0.52	242.2

Table 3: Load per wheel considered in the numerical models.

For each analysis case, vertical stresses and the safety factor were obtained using Equation 3 for the ballast, sub-ballast, subgrade, and embankment.

$$FS = \frac{\tau_{res}}{\tau_{oct}} \qquad (3)$$

Where:

$\tau_{res} = c + p' \tan\varphi$

$\tau_{oct} = \frac{\sqrt{(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_1 - \sigma_3)^2}}{3}$

$p' = \frac{\sigma_1 + \sigma_2 + \sigma_3}{3}$

$\sigma_1, \sigma_2, \sigma_3$ are the principal stresses.

3 Results

The results of each case are presented below. These include the vertical stresses in the control sections A-A' (Figure 2). Both single and double track configurations were considered for each case.

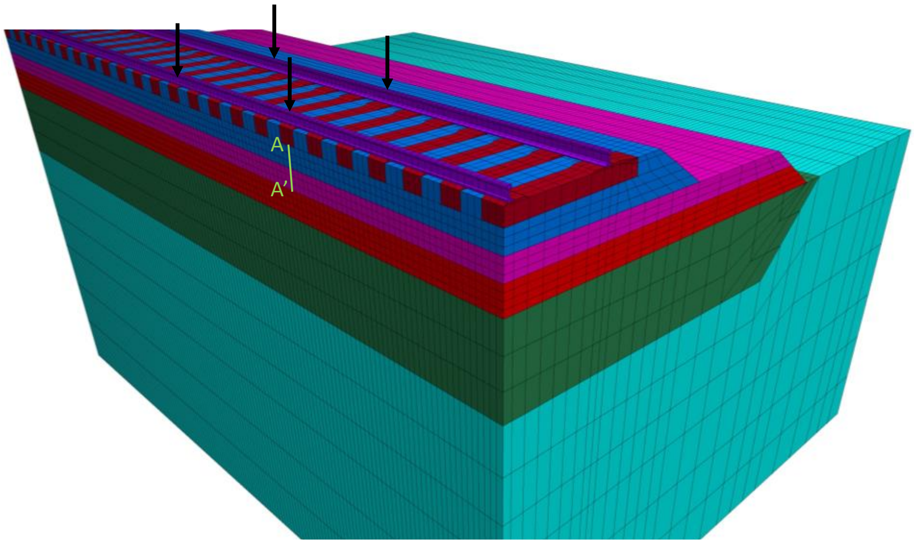

Figure 2: Control section A-A'.

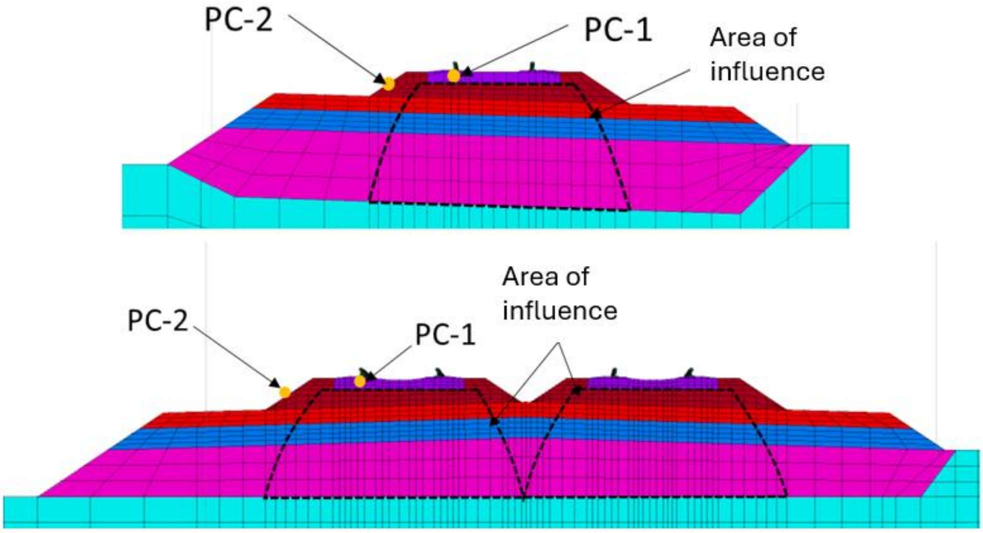

Figure 3: Control points and areas of influence where the increase in stresses due to the train load occurs (a) in single track, and (b) in double track.

Figure 4 presents the vertical stress distribution; it can be observed that the distributions calculated with AREMA [8] and with Sadeghi [11] are larger than those obtained with the models. However, the stress profile is very similar to the one calculated with Sadeghi [11] methodology for the single track.

In the case of double track, the load application was performed for both tracks, considering the same magnitude. As can be seen in Figure 5, the vertical forces have a superposition effect at depths of one meter, due to the loading of both tracks. However, this same effect was not observed for the vertical displacements (Figure 6).

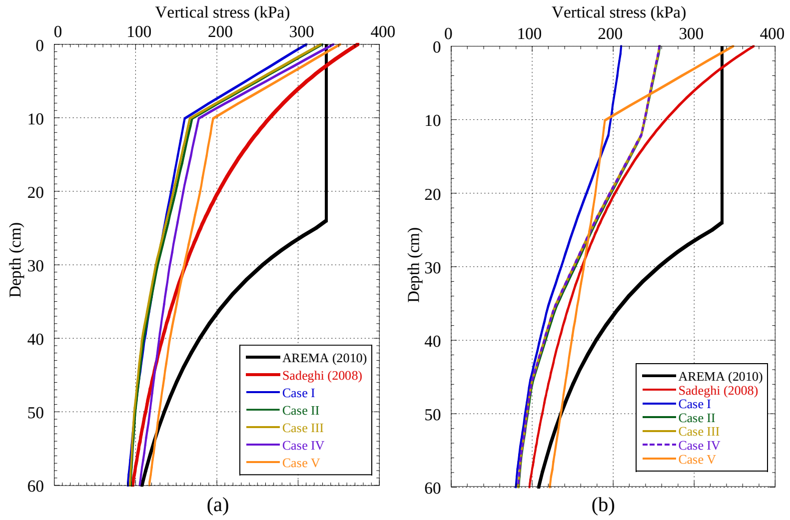

Figure 4: Distribution of vertical stress with depth a) Single track and b) Double track.

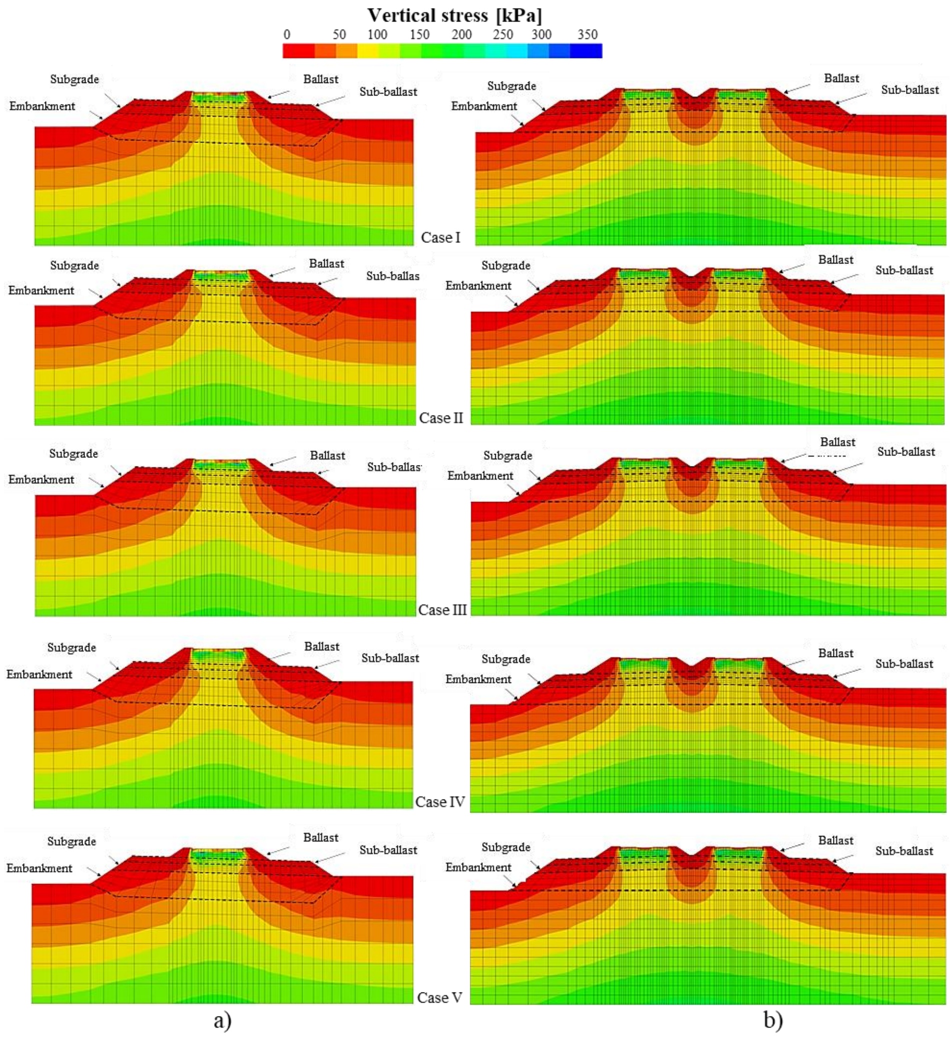

Figure 5: Vertical stress contour a) Single track and b) Double track.

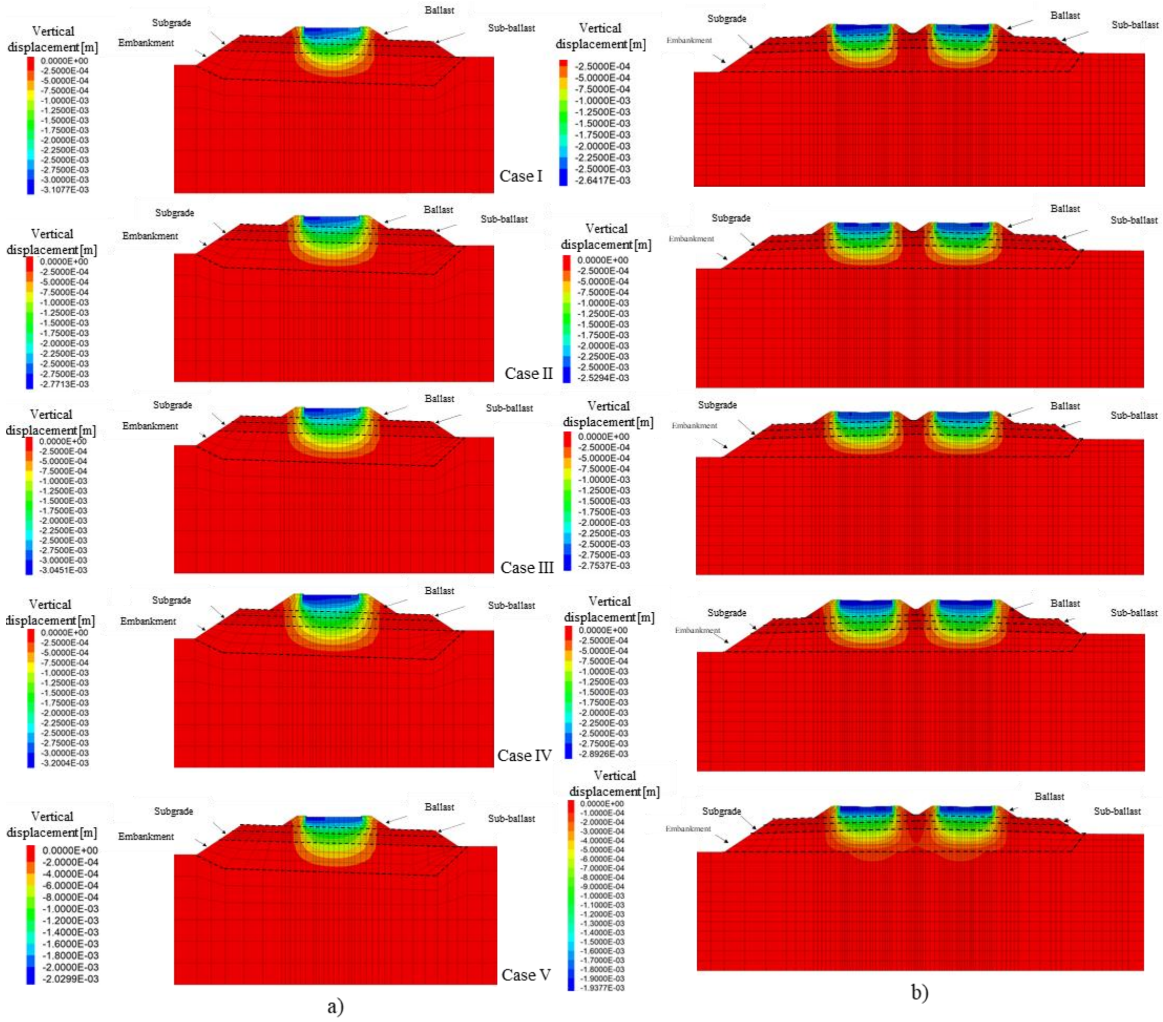

Figure 6: Vertical displacement contour a) single track and b) double track.

Table 4 presents the comparison of the vertical forces obtained in the different cases analyzed, with those obtained using AREMA [8] and Sadeghi [11] methodologies for the ballast/sub-ballast and sub-ballast/subgrade interfaces.

Track type	**Interface**	**AREMA [8] [kPa]**	**Sadeghi [11] [kPa]**	**Case I [kPa]**	**Case II [kPa]**	**Case III [kPa]**	**Case IV [kPa]**	**Case V [kPa]**
Single	Ballast-suballast	256.5	161.6	124.4	125.5	122.7	141.8	159.5
	Suballast-subgrade	107.9	96.5	90	93.5	92.7	104.4	116.3
Double	Ballast-suballast	256.5	161.6	135.3	151.8	149.9	149.9	163.4
	Suballast-subgrade	107.9	96.5	79	82.7	82.3	82.3	120.7

Table 4: Vertical stresses of the analysed cases.

Figure 6 presents the vertical displacement contours. The maximum deformation estimated by three-dimensional numerical models is of the order of 3.2 mm. However, the analyses were performed considering a Mohr-Coulomb elastoplastic model and under static conditions, so it is not possible to capture the accumulation of plastic deformations due to the cyclic loading of the train. To simulate this condition, tests with several load-unload cycles are required in order to characterize the nonlinear behavior of the materials.

Figure 7 shows the safety factor contours where it can be observed that for cases I, II and III, the minimum FS in the track support is 1.08 for all its elements with the exception of the ballast, for which it is 1.15, while the average FS are 1.18 and 1.30, respectively. It should be noted that these values are relatively low for the design of the railway and represent an overstress for the subgrade and embankment layers, which leads to poor performance with significant deformations in the long term. For Case IV, minimum FSs of 1.14 were obtained for the sub-ballast and subgrade layers, while the average FSs were 1.23 and 1.30. With respect to the results of Case V, the factors of safety close to one are concentrated only in the sub-ballast in a minimum area, with average values of 1.18, and with values of 1.50 and 2.64 for the subgrade and embankment, respectively. Due to the above, it is considered that the improvement of the material properties (Case V) is a more optimal solution than the one presented in Case IV, where the ballast thickness is increased.

It is important to mention that the models do not depict a failure mechanism, and that low factors of safety are associated with unfavorable conditions expected during the life of the project, such as significant deformations, as well as ballast embedment in the sub-ballast layer.

Table 5. presents a summary of the minimum safety factors for each track support element and the average safety factors that occur in the area of influence under the track where the stress increase occurs, according to the scheme shown in Figure 7.

Track type	**Case**	**Safety factor minimum / average**			
		Ballast	**Sub-ballast**	**Subgrade**	**Embankment**
Single	I	1.15 / 1.34	1.08 / 1.18	1.08 / 1.18	1.08 / 1.30
	II	1.21 / 1.36	1.15 / 1.20	1.15 / 1.24	1.23 / 1.87
	III	1.22 / 1.38	1.15 / 1.21	1.15 / 1.25	1.23 / 1.87
	IV	1.23 / 1.34	1.15 / 1.23	1.15 / 1.30	1.24 / 1.89
	V	1.15 / 1.34	1.12 / 1.18	1.20 / 1.50	1.79 / 2.64
Double	I	1.13 / 1.33	1.09 / 1.18	1.08 / 1.16	1.08 / 1.41
	II	1.17 / 1.36	1.14 / 1.22	1.14 / 1.30	1.27 / 1.97
	III	1.18 / 1.36	1.19 / 1.22	1.14 / 1.30	1.27 / 1.97
	IV	1.20 / 1.34	1.13 / 1.33	1.14 / 1.47	1.31 / 2.10
	V	1.13 / 1.31	1.09 / 1.18	1.20 / 1.55	1.88 / 2.69

Table 5: Safety Factors of the analysed cases.

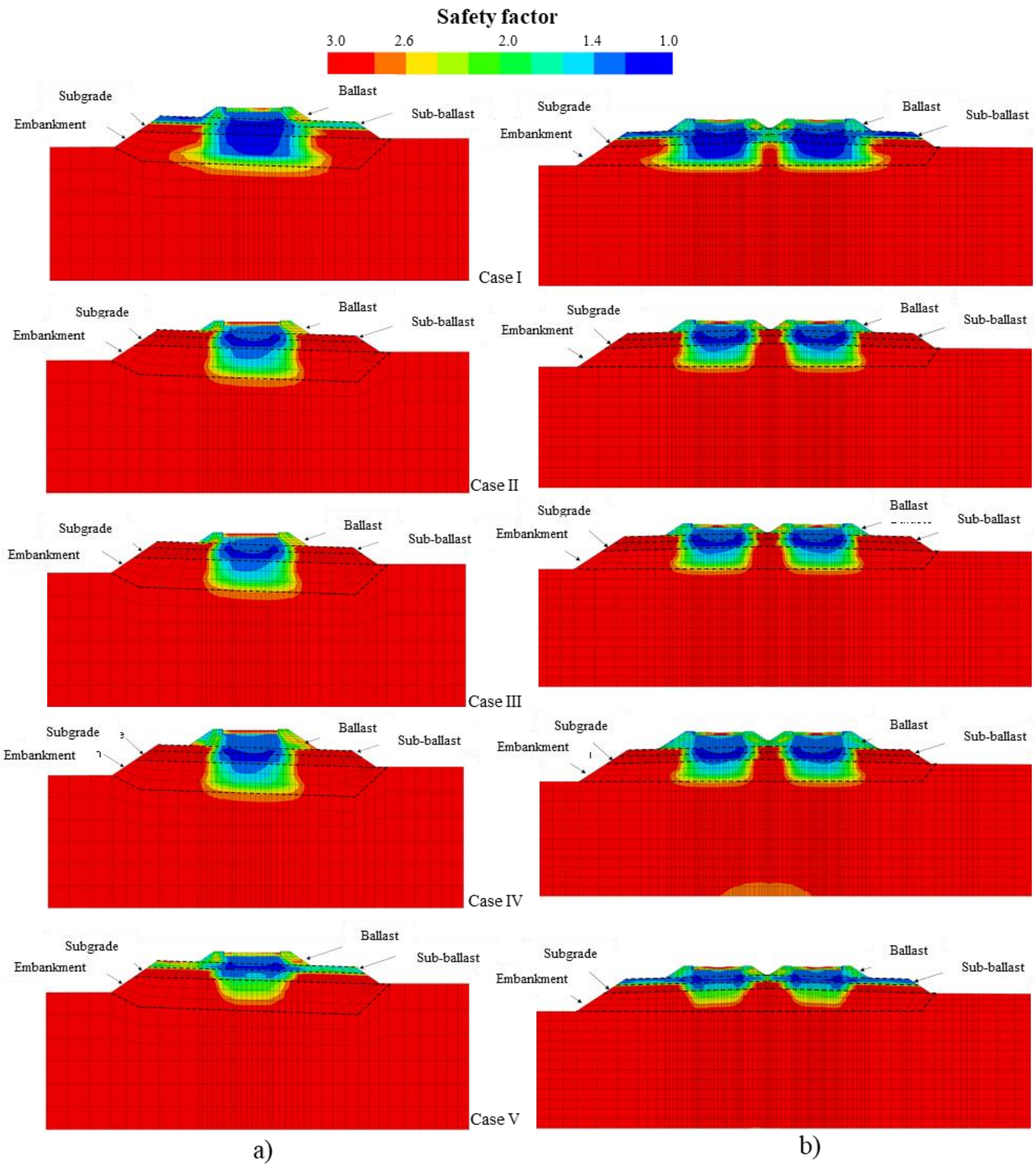

Figure 7: Safety factors contour a) Single track and b) Double track.

Due to the cyclic nature of the load, it can generate significant plastic deformations when stresses exceed the range in which their behavior is linear, near failure. Therefore, it is recommended that the maximum acting stress have a minimum safety factor of 1.2 for non-plastic materials and 1.5 for plastic materials. Figure 4 presents a schematic of the average stress level to which the ballast and the base (subgrade) are subjected. As can be observed, it is necessary to increase the Safety Factor to reduce plastic deformations.

4 Conclusions and Contributions

The numerical results of the analyses shows that the double track configuration will have low performance for critical loads such as the Cooper E80 freight train. The minimum safety factors (FS) for the track support represent an overstressed, which may lead to significant long-term deformations. Numerical analyses suggest that the FS for the sub-ballast and subgrade layers should be higher to ensure adequate performance, maintaining minimum values of 1.2 for non-plastic materials and 1.5 for plastic materials at least.

It is emphasized that improving the properties of the materials is a more efficient solution than simply increasing the thickness of the ballast. It is crucial to verify that the subgrade meets the design specifications and minimum resistance, suggesting its replacement if it does not meet the required standards.

The optimal behavior of the track is determined by the characteristics of the support materials. Therefore, conducting plate tests, topographic monitoring campaigns, and laboratory tests are recommended to carried out a continuous performance evaluation of the track with numerical models, as part of the maintenance process.

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