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Evaluation of urban train support systems

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Abstract

This paper presents the results obtained from numerical simulations carried out with two-dimensional finite element models, developed to evaluate the behavior of the typical materials that constitute the support of railway sleeper systems of urban trains. Several loads to which this type of system is subjected and other factors such as the speed at which they operate are considered. Likewise, the substitution of some of the elements is evaluated to improve the performance of the system. The results obtained are compared with those obtained with some of the empirical equations most used in practical engineering to know the level of variability involved in using them.

Keywords: railway support, urban train, dynamic load, numerical analysis.

1 Introduction

In general, the stress to which the ballast and the base material are subjected is estimated by means of methods based on semi-empirical equations. Two of the most used methods are presented by [1] and [2], which have been developed in the middle of the 20th century. Although the methodology presented by [1] has been updated, in calculating the mean pressure under the sleeper, both methods (i.e. [1] and [2]) use the equation developed by Talbot [3] in 1920, for the estimation of the pressure distribution with the depth to the center of the sleeper. Likewise, both methodologies do not consider the calculation of deformations (elastic and plastic), so they are not capable of evaluating the real performance of the system.

The models developed were able to compute the actual stress distribution and clearly showed that a permanent deformation occurs due to the cyclic load acting on the track. Permanent deformation (i.e.plastic) needs to be evaluated to avoid costly maintenance and potentially unsafe designs. This paper presents the results obtained from the numerical simulations carried out with two-dimensional finite element models, developed to evaluate the behavior of the typical materials that constitute the support of railway sleeper systems of urban trains.

2 Methods

Based on documentation and field visits, a typical configuration of the sleeper-track system of urban train systems in Mexico was selected and is presented in Figure 1. A two-dimensional finite element model was developed with the software PLAXIS 2D, which is shown in Figure 2. The properties of the materials simulated in the numerical models are presented in Table 1, where γ, is the unit weight, c, is the cohesion, ϕ, is the friction angle, E is the Young's Modulus, and ν, is the Poisson ratio.

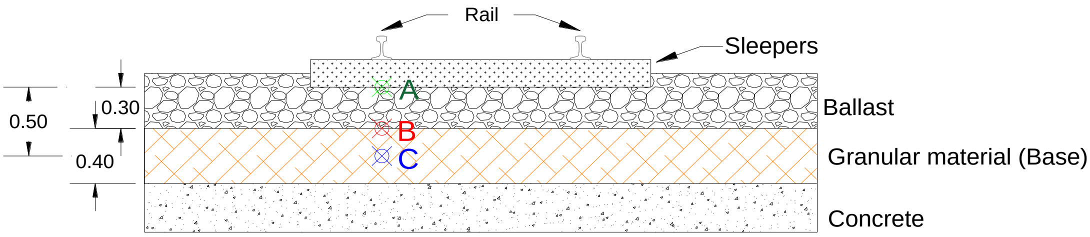

Figure 1. Configuration of the support system and control points.

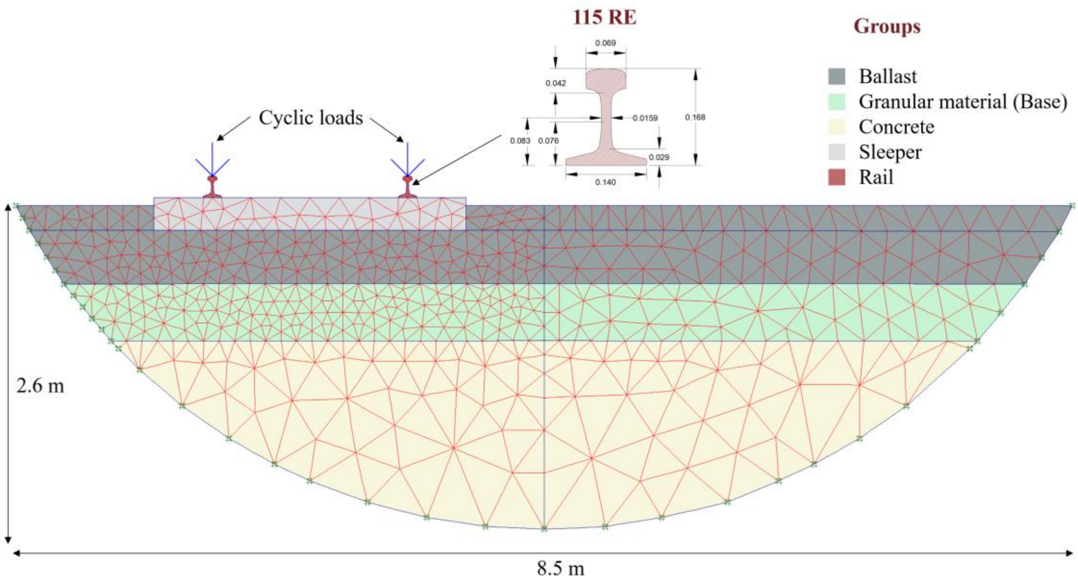

Figure 2. Two-dimensional finite element model.

Table 1. Material properties.

Group	Constitutive model	γ [kN/m^3]	c [MPa]	ϕ [°]	E_{50} [MPa]	ν [-]
Ballast	Hardening Soil*	18.6	0	50	200	0.30
Granular material (Base)	Mohr-Coulomb	17.0	0	43	143	0.35
Concrete	Elastic	22.0			9,590	0.30
Sleeper	Elastic	24.0			47,500	0.18
Rail	Elastic	79			210,000	0.30

*This constitutive model has the additional parameters $E_{oed}= E_{50}$, $E_{ur}= 3E_{50}$.

To characterize the cyclic load transmitted by the boogüie, it was considered a maximum magnitude of 147.1 kN tons per axle, a design speed of 85 km/h, and a wheel diameter of 0.914 m. An impact factor, IF, was taken into account through the methodology presented in [1]. The cyclic load was applied 1000 times with a frequency of 10 Hz, which simulate the mentioned speed, and an assumed distance between each axle of 2.40 m. Figure 3 presents the loads considered in the different analyzes (i.e., Case I and II). It has been observed that when the train enters a curve, the load concentrates on one wheel axis, as assumed for Case II, which was considered as the most unfavorable loading condition. The substitution of the subgrade base-like material for a fluid concrete fill, and ballast was evaluated considering the properties presented in Table 2. Table 3 presents a summary of the cases analyzed.

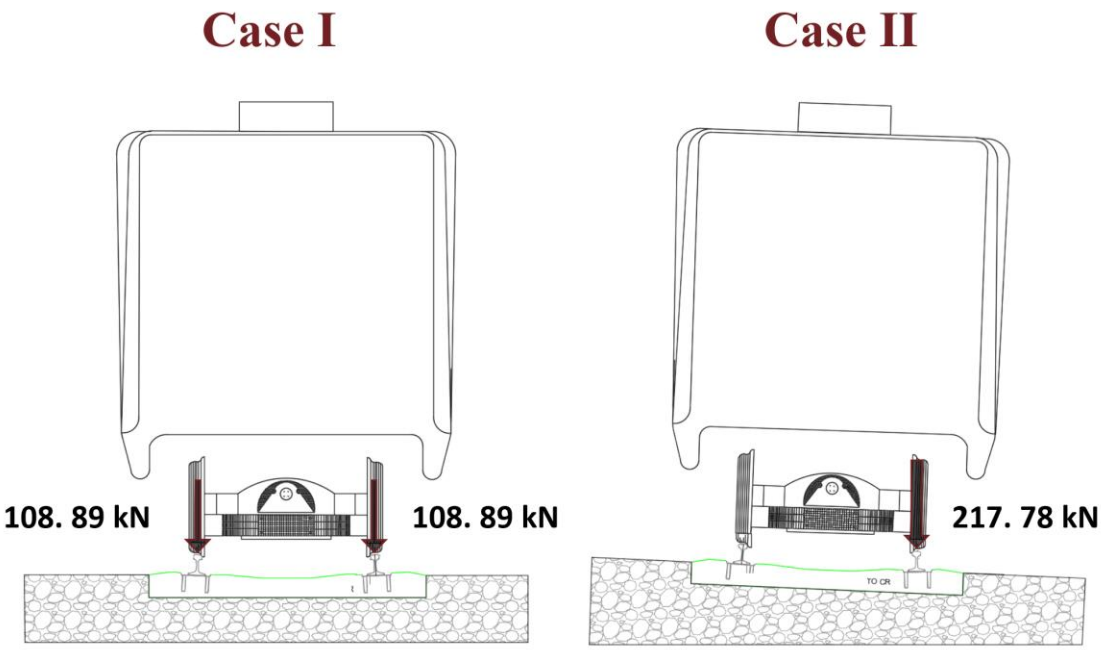

Figure 3. Considered loads.

Table 2. Properties of substituted materials

Material	Constitutive model	γ [kN/m³]	c [MPa]	ϕ [°]	E [MPa]	ν	Reference
Ballast	Hardening Soil	15.3	0	60	280	0.30	[5]
Fluid Concrete	Mohr-Coulomb	17.1	0.981	0	4561	0.30	[6]

Table 3. Cases analyzed.

Case	Load per wheel [kN]	Impact factor, IF	Load per wheel with IF [kN]	Substituted material
I	73.55	0.48	108.89	
II	147.1	0.48	217.78	
III	147.1	0.48	217.78	Ballast
IV	147.1	0.48	217.78	Base material and ballast

3 Results

For each case of analysis, the vertical stresses, safety factors and vertical displacements were obtained, considering the deviatoric stresses in the geomaterials and the resistance to shear stress through Equation 1, for the base-type material. Figure 4 presents the control sections for the models developed.

$$FS = \frac{\tau_{res}}{\tau_{oct}} \quad (1)$$

where

$$\tau_{res} = c + p' \tan \varphi \quad (2)$$

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

$$p' = \frac{\sigma_1 + \sigma_2 + \sigma_3}{3} \quad (4)$$

$\sigma_1, \sigma_2, \sigma_3$ are the principal stress

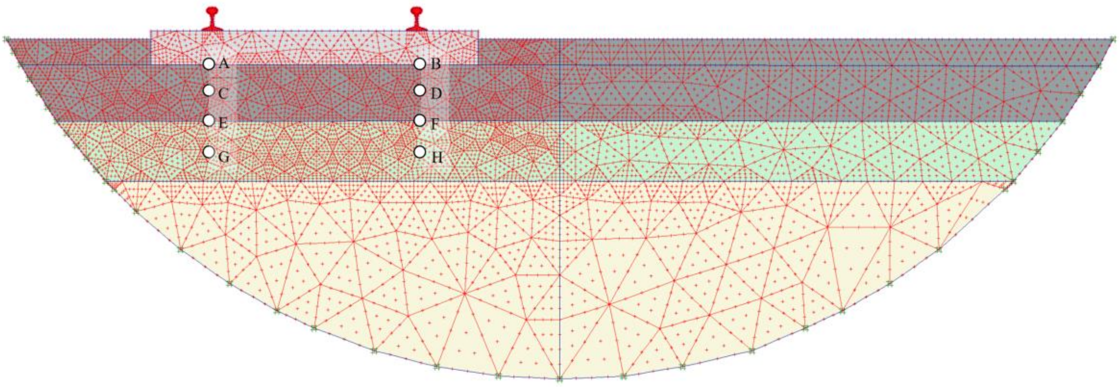

Figure 4. Control points.

Table 4 presents the comparison of the maximum vertical stress obtained for all cases during the application of the cyclic load, and the stress obtained from the semi-empirical methodologies presented by [1] and [2], for the control points presented in Figure 1. Figures 5, 6 and 7 present the contours of vertical stress of cases II, III and IV respectively. Table 5 presents the minimum safety factors for the base material and the fluid concrete. Figure 8 show the accumulated vertical displacement in the control point B, for all the cases analyzed. Figure 9 present the vertical displacement histories for first five load cycles.

Table 4 Vertical stress of the cases analyzed

Control point	AREMA [1] kPa	Hay William W [2] kPa	Case I kPa	Case II kPa	Case III kPa	Case IV kPa
A/B	226.61	434.38	250.15	340.03	316.25	788.56
E/F	173.63	352.17	236.42	302.14	258.00	354.52
G/H	91.23	181.48	131.45	243.28	178.54	254.57

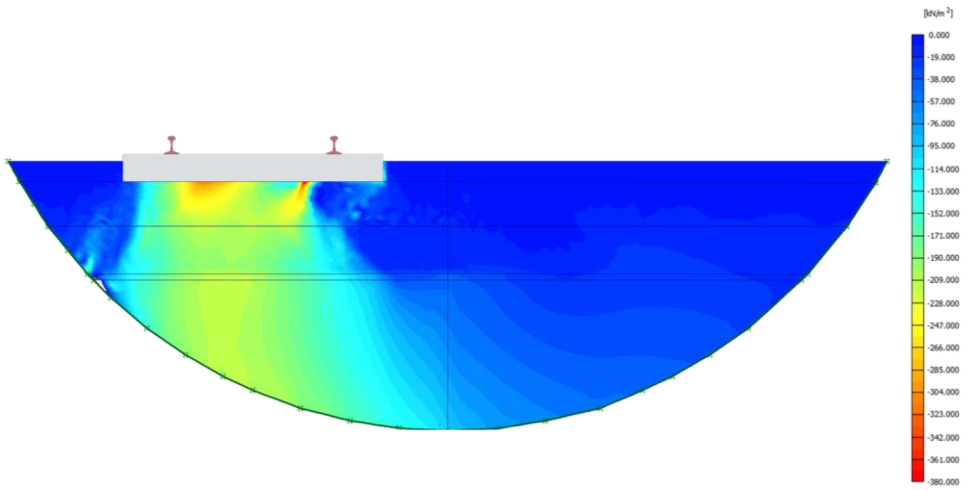

Figure 5. Vertical stress (Case II).

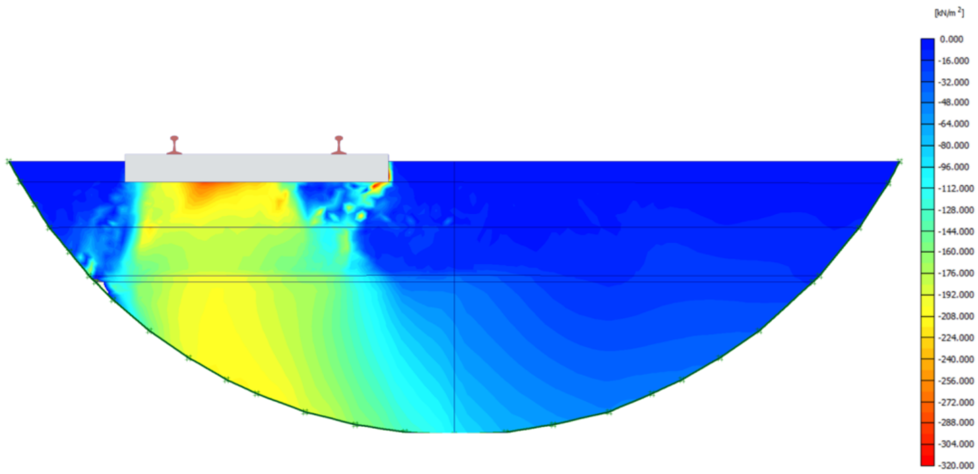

Figure 6. Vertical stress (Case III).

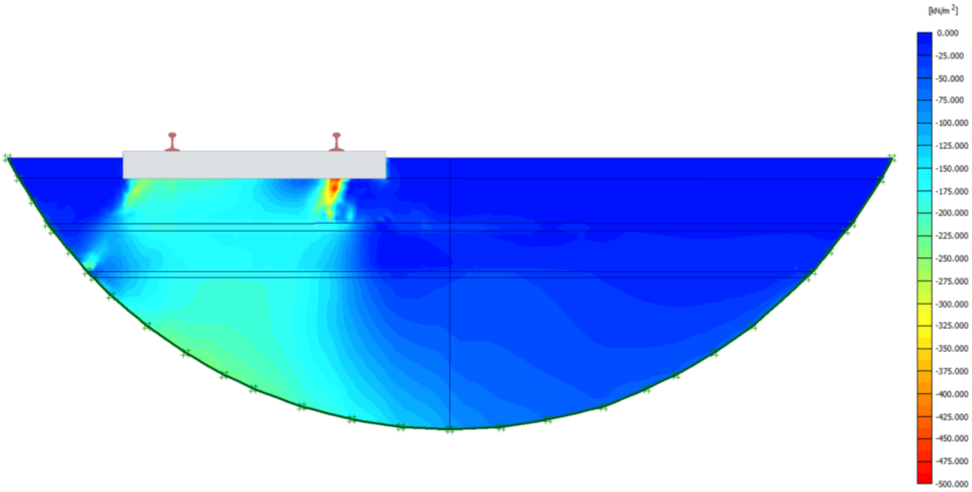

Figure 7. Vertical stress (Case IV).

Table 5 Minimum Safety Factors of the cases analyzed.

Case	Minimum Safety Factor in Base material or fluid concrete
I	1.37
II	1.01
III	1.12
IV	1.51

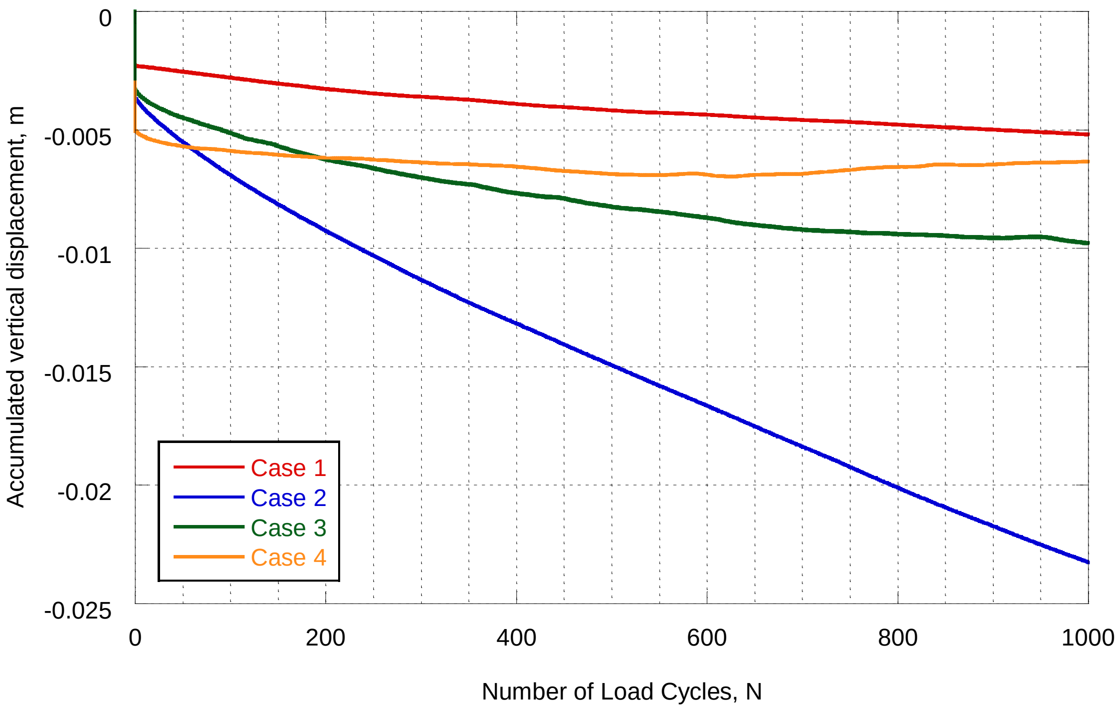

Figure 8. Vertical displacement histories.

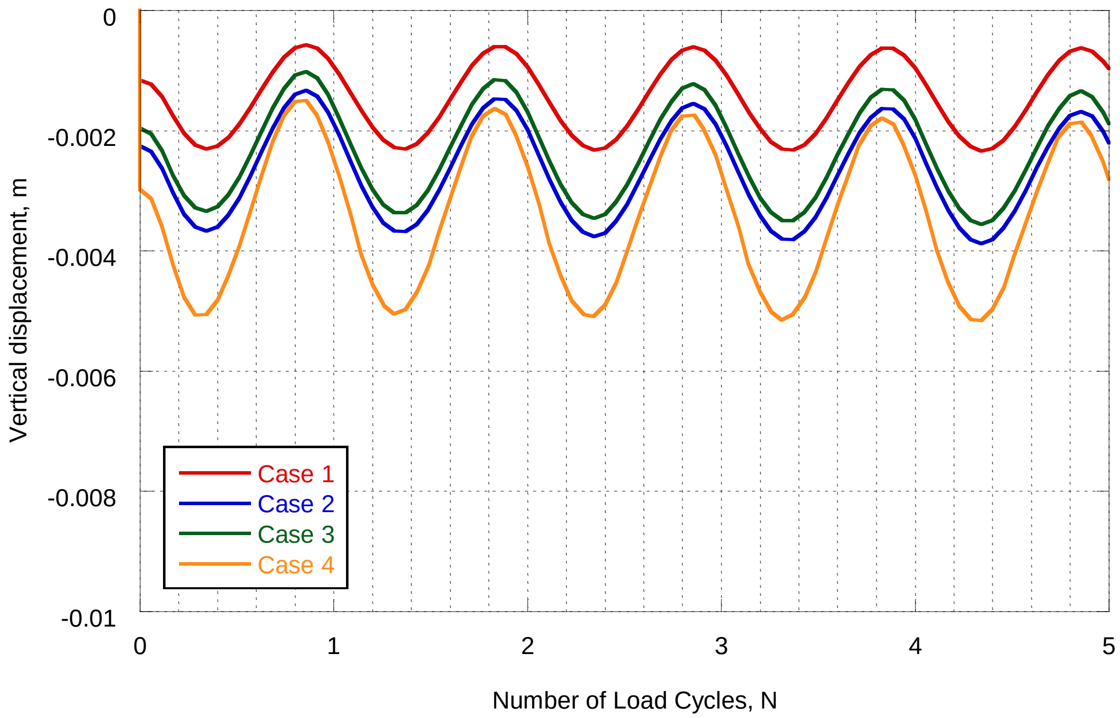

Figure 9. Vertical displacement histories.

4 Conclusions and Contributions

As presented in Table 5, the safety factors of the cases that consider the typical materials of the rail-sleeper system, are between 1.36 (Case I) and 1.01 (Case II) for the base-like material. Therefore, the base-like material can be identified as the weakest element in the case studied. Due to the cyclical nature of the load during the operation of urban trains throughout their useful life, safety factors close to 1 (ie 1.2), lead to the potentializing of plastic deformations when the stresses exceed the linear range on the subgrade materials, or ballast. These results are consistent with the deformations and the greater wear of the ballast in those zones of curved track. Thus, a design that does not consider the increase in loads due to the curvature of the track is considered inadequate. It is recommended to have a Safety Factor greater than 1.5 to minimize maintenance costs.

With the substitution of the ballast (Case III) minimum safety factor of 1.12 was obtained, so that it was decided to evaluate the replacement of the base type of material for a fluid concrete fill of f´c = 2 MPa, (Case IV), with which the safety factor increased to 1.51. As can be seen in Figure 8, in Case II the stabilization of plastic deformation is not reached for the maximum number of load cycles of applied (i.e., 1000), as in Case III and IV. The maximum vertical plastic deformation is 23, 9.5, and 6.5 mm for Cases II, III, and IV respectively, so the replacement of both materials (material type base and ballast) is necessary to ensure the good performance of the track support system. The semi-empirical methods presented by [1] and [2] are limited to providing the distribution of vertical stresses both the expected plastic deformation during cyclic loading.

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