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Assessment of the Bearing Capacity of a Subballast Layer Using a Numerical Model in a Railway Context

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Abstract

Trackbed mechanical quality, and more precisely bearing capacity, is one of the key parameters to plan renewal projects. It depends on the subballast's properties (aggregate's physical and mechanical properties, layer thickness, and compaction) and on the types of materials below the subballast (capping layer and subgrade). The interaction between all these geotechnical parameters governs the overall load-bearing behaviour of the railway trackbed. Predicting the real-world results of various combinations of the aforementioned parameters is often difficult. The main objective of this study is to assess the load-bearing capacity of a railway trackbed (top of the subballast layer) by performing a cyclic plate loading test (NF P 94-117-1). A methodology implementing a numerical modelling approach is proposed. The continuum-based numerical model is 2D-axisymmetric, using the commercial software FLAC2D. A numerical procedure simulating the 2-stage plate loading test is developed. A wide range of trackbed layer configurations are simulated, leading to a numerical estimation of its bearing capacity.

Keywords: trackbed mechanical performance, bearing capacity, plate load test, numerical modelling, subballast performance, Ev2 modulus.

1 Introduction

According to SNCF Reseau's standards, the acceptance of railway trackbed works currently consists of load-bearing tests on top of the subgrade and of the capping layer and verification of the compaction of the subballast layer using a gamma-densimeter, the different layers are presented in Figure 1. Hence, the subballast bearing capacity is not directly known because no loading test is performed on top of the subballast layer. The bearing capacity loading test is not included in the acceptance procedure because of the high compaction of the subballast layer (97 to 100 % of the Modified Proctor Optimum).

The present work aims to assess the bearing capacity on top of the subballast layer by implementing a numerical model simulating the standardized Plate Loading Test (PLT) [1].

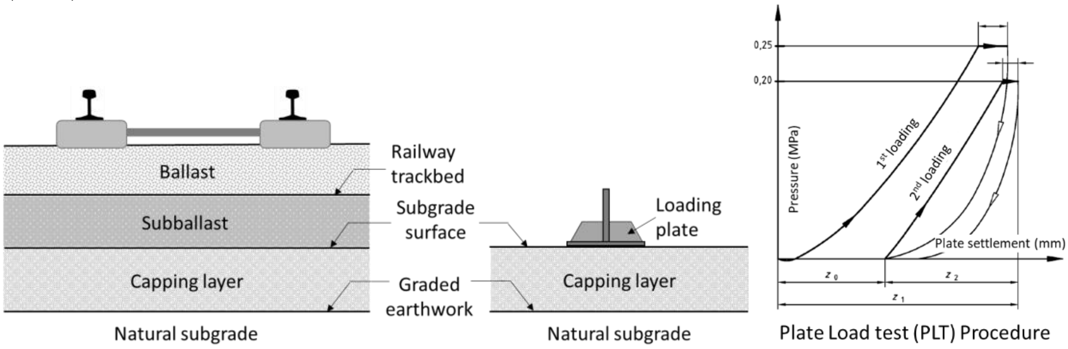

Figure 1: Trackbed profile according to SNCF Reseau's standards (left) and PLT procedure (right) ([1] and [2]).

The static Plate Load Test (PLT) currently performed on the French rail network follows the NF P 94-117-1 standard [1]. The test involves applying multi-stage vertical loading on a rigid plate with a 600 mm diameter and measuring the corresponding vertical displacement. A first loading cycle is applied up to 7,068 daN (or 70.68 kN), corresponding to an average pressure equal to 0.25 MPa under the plate. The plate is completely unloaded, and a second loading up to 5,654 daN (average stress equal to 0.2 MPa) is applied. The procedure is depicted in Figure 1. The settlement occurring during the second loading is termed z_2, and the PLT deformation modulus E_{v2} is defined using Boussinesq formula (Equation 1), where:

- p is the average pressure under the plate (p = 0.2 MPa),
- d is the plate diameter (d = 600 mm)
- ν is the soil Poisson's ratio.

The formula (Equation 1) can thus be simplified as $E_{v2} = \frac{90}{z_2}$, with z_2 in mm and E_{v2} obtained in MPa.

$$E_{v2} = \frac{\pi}{4}(1 - \nu^2)\frac{p \times d}{z_2} \tag{1}$$

According to the E_{v2} value (mechanical quality) on top of the natural subgrade, the graded earthwork is classified into four bearing classes, as indicated in Table 1.

According to the E_{v2} value on top of the capping layer, the capping layer surface is classified into three bearing classes, as indicated in Table 2.

In this numeral study, the PLT procedure described above is implemented in a numerical model that simulates the different combinations of trackbed layers and gives the corresponding E_{V2} modulus (to assess the load-bearing capacity).

Class	Bearing capacity	E_{v2}	E_{v2} target value in the study
S0	Insufficient	< 30 MPa	Not addressed
S1	Passable	30 MPa ≤ Ev_2 < 50 MPa	40 MPa
S2	Good	50 MPa ≤ Ev_2 < 80 MPa	70 MPa
S3	Very good	≥ 80 MPa	120 MPa

Table 1: Bearing classes of the subgrade

Class	E_{v2}	E_{v2} target value in the study
P1	≥ 30 MPa	40 MPa
P2	≥ 50 MPa	70 MPa
P3	≥ 80 MPa	120 MPa

Table 2: Bearing classes of the capping layer.

2 Methods

The methodology adopted in this study consists of the following:

- Developing a numerical model appropriate for the simulation of the PLT on railway trackbeds, implementing relevant soil constitutive model(s),
- Determining soil constitutive model parameters for the natural subgrade and capping layer to obtain the target bearing capacities (cf. Table 1 and 2),
- Selecting a set of relevant parameters for the subballast layer,
- Performing numerical PLT on the railway trackbed to assess the bearing capacity (through the E_{v2} modulus value).

A total of 27 configurations in subgrade class, capping layer class, capping layer thickness and subballast thickness are simulated.

Given the geometry of the structure (trackbed) and the type of loading (PLT involving a vertically loaded disk), a 2D-axisymmetric numerical model is developed. The numerical tool used is the “continuum modelling for geomechanics” software FLAC2D v9 [3], based on the explicit finite-volume method to reach mechanical equilibrium or steady-state flow in the model.

The study requires the creation of three types of numerical models to simulate the PLT at the top of the various layers of the railway structure:

i) a model containing only the natural subgrade for the assessment of the class S1 to S3 (cf. Table 1);

ii) a model of the natural subgrade and capping layers for the assessment of the class P1 to P3 (cf. Table 2);

iii) a model of the whole structure up to the railway trackbed, *i.e.* including the subballast layer, to evaluate the bearing capacity on top of the subballast layer (Figure 2).

An example of a model to perform a numerical PLT on top of the subballast is given in Figure 2. The global size of the model (size of the zones, depth of the natural subgrade and position of the lateral limits), as well as the density of the mesh, were chosen after performing a model parametric study so that the boundary conditions and the mesh density do not (significantly) influence the bearing capacity result (E_{v2} value).

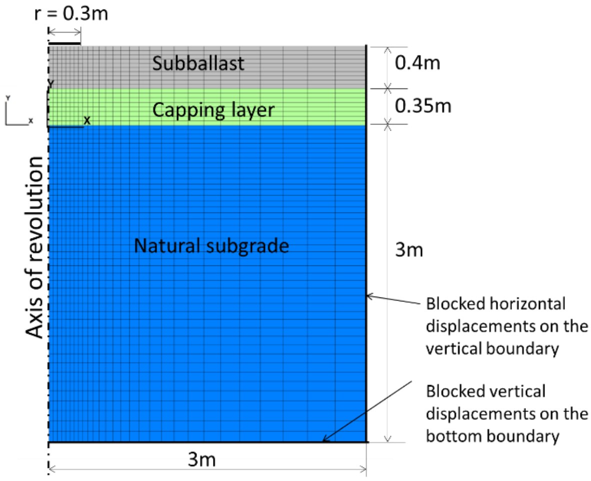

Figure 2: Numerical model to simulate a Plate Load Test on the trackbed(FLAC2D mesh).

A numerical procedure to simulate the PLT, as described in Figure 1, is implemented in the code for this study. As the plate is considered infinitely rigid, its driving into the soil is simulated by applying a uniform vertical displacement on the mesh nodes on top of the soil layer under the location of the circular plate (on a radius r = 0.3 m, cf. Figure 2). The displacement is applied at a sufficiently slow rate to maintain a quasi-static mechanical equilibrium throughout the model. The optimization of this displacement rate was also the subject of a parametric study, not detailed in this communication. In return, a routine is written to determine the corresponding average vertical stress below the plate (using the nodal forces) and to apply the loading path as indicated in the PLT French Standard [1] (Figure 1). The plate settlement during the second loading up to 0.20 MPa can be easily computed (z_2 value), so as the E_{v2} modulus, according to Equation 1.

The “Plastic Hardening” constitutive model [4], termed PH, is used to simulate the behaviour of the railway structure’s soil layers. The PH model is a two-mechanism elastoplastic model (volumetric and shear hardening). The main features of the PH model are, cf. [4]:

i) hyperbolic stress-strain relationship in uniaxial drained compression [5],

ii) generation of plastic strain associated with mobilized friction (shear hardening),
iii) generation of plastic strain in primary compression (volumetric hardening),
iv) stress-dependent modulus according to a power law,
v) elastic unloading-reloading compared to virgin loading,
vi) a memory of pre-consolidation stress,
vii) and Mohr-Coulomb failure criterion.

However, in this current study, only the shear-hardening mechanism is activated.

The first numerical modelling task is determining the PH soil constitutive model parameters for the natural subgrades and capping layers to obtain the target bearing capacities with the E_{V2} values, as indicated in Tables 1 and 2. This task is done by performing numerical PLT on top of the layers and retrofitting the constitutive parameters to obtain the target E_{v2} value.

The reference type of natural subgrade considered in this study could be silty soil. The calibrated sets of parameters for the three natural subgrade classes S1 to S3 and the obtained E_{v2} modulus are indicated in Table 3.

The capping layer considered in this study is made of silty gravel and has a thickness equal to 0.35 or 0.5 m, according to SNCF Réseau's standards. The bearing capacity on top of the layer depends on both its thickness and the bearing capacity of the natural subgrade below. The PH model parameters for this layer to obtain the target class P2 or P3 in combination with its thickness and the natural subgrade class are indicated in Table 3, as well as the resulting E_{v2} modulus, corresponding to the target with a tolerance of a few MPa.

				Natural subgrade class (and Ev_2 [MPa])				
				S1 (40.6)	S2 (70.3)	S1 (40.6)	S1 (40.6)	
				capping layer class (and thickness [m])				
				P2 (0.35)	P3 (0.35)	P2 (0.5)	P3 (0.5)	
Parameters	**Natural subgrade**			**Capping layer**				**Subballast**
	S1	S2	S3					
p_{ref} (kPa)	100	100	100	100	100	100	100	100
E_{50}^{ref} (MPa)	43	75	120	75	150	65	190	180
m	0.7	0.7	0.7	0.5	0.5	0.5	0.5	0.5
ν	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
E_{ur}^{ref} (MPa)	129	225	360	225	450	195	570	540
ϕ' (deg.)	30	30	35	40	42	38	42	42
c' (kPa)	5	5	5	3	3	3	3	5
Ψ (deg.)	0	0	5	10	10	8	10	10
R_f	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9
Ev_2 (MPa)	40.6	70.3	120.8	63	114	63	107	See results

Table 3: Soil parameters for the PH model for each trackbed layers.

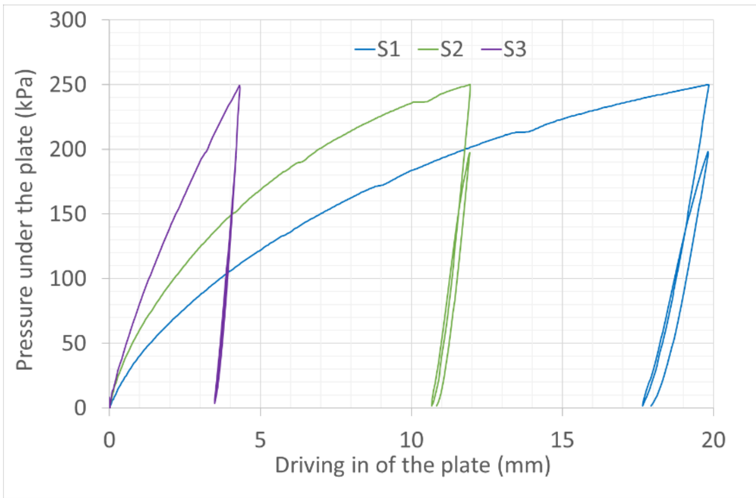

Figure 3: Numerical results of the PLT simulation for natural subgrades S1 (blue line), S2 (green line) and S3 (purple line).

A subballast layer made of natural granular material is considered in this study. The layer is compacted to obtain a high compaction of 97 to 100 % of the Modified Proctor Optimum. A panel of thicknesses of this layer, ranging from 0 (no subballast layer) to 0.55 m, is considered. There is no target E_{v2} value on top of the subballast layer, as this current numerical work aims to estimate this E_{v2} value. A set of reference values of PH model parameters for this layer is proposed in Table 3. A secant modulus at 50 % of the maximum deviatoric stress for a reference pressure p_{ref} = 100 kPa, E_{50}^{ref} = 180 MPa is adopted, and an unloading-reloading secant modulus E_{ur}^{ref} equal to three times E_{50}^{ref}. Besides, a parametric study on the PH model parameters for the subballast has also been performed to assess their influence on the resulting E_{v2} modulus on top of it. The results of this study for a chosen subgrade case are presented in the next section.

3 Results

A set of subballast parameters for the use of the PH constitutive model is proposed in Table 3. To assess the influence of the parameters of primary importance on the resulting E_{v2}, a parametric study is performed by varying:

- E_{50}^{ref} between 180 and 250 MPa, thus E_{ur}^{ref} between 540 and 750 MPa,
- the ultimate friction angle between 37 and 42°,
- the cohesion between 0 and 10 kPa,
- the initial earth coefficient K_0 from 0.1 to 1.

The other parameters are kept constant and equal to the reference set. This preliminary parametric study is performed on a chosen case:

- a natural subgrade of class S2,
- a capping layer of 0.35 m thickness with a bearing class P3.

On top of the capping layer, the numerical E_{v2} is equal to 114 MPa (Table 3). For the reference subballast parameters (given in the last column of Table 3), the PLT simulation on top of the subballast leads to E_{v2} = 135 MPa for a subballast thickness equal to 0.15 m and E_{v2} = 144 MPa for a subballast thickness equal to 0.2 m.

Table 4 and Figure 4 synthesize the results of the several cases envisaged in the parametric study. The results show that both the shear strength parameters (c' and ϕ') and deformation parameters impact the resulting E_{v2} modulus, thus the trackbed bearing capacity. In the range of values investigated, the E_{v2} varies from -12 % to +6 % compared to the reference subballast set of parameters for a thickness equal to 0.15 m (E_{v2} between 118 MPa for c'= 0 kPa, to E_{v2} = 144 MPa for E_{50}^{ref} = 250 MPa), and from -15 % to +7 % for a 0.2 m-thick subballast layer. Note that the initial earth pressure coefficient has no impact.

	Subballast thickness	
	0.15 m	0.2 m
	E_{v2}	
Reference case	135	144
E_{50}^{ref} = 250 MPa	144	154
c' = 10 kPa	143	153
c' = 0 kPa	118	122
ϕ' = 37°	133	141
K_0 = 1	135	144

Table 4: Calculated E_{v2} values on top of the subballast layer, results of the numerical modelling

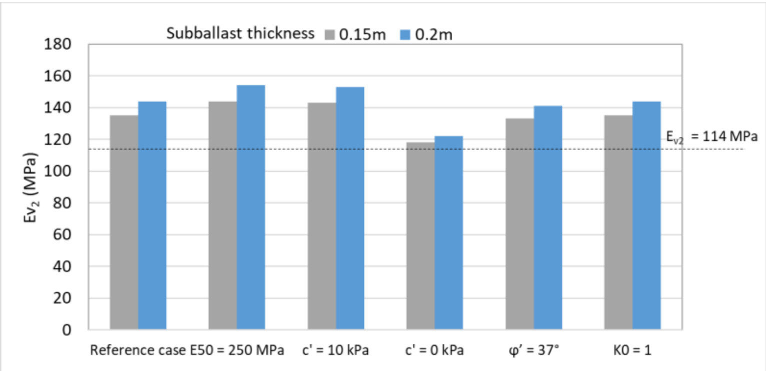

Figure 4: Calculated E_{v2} values on top of the subballast layer. E_{v2} = 114 MPa on top of the capping layer is depicted by the dashed line (class P3). Grey bars correspond to the results using a 0.15 m-subballast thickness while bleu bars correspond to a 0.2 m-subballast thickness.

The rest of the presented results are obtained with the reference set of subballast's parameters with the PH model (indicated in Table 3). Various configurations in terms of subgrade class, capping layer class and thickness and subballast thickness are simulated in this study, considering SNCF Réseau's standards.

Figure 5 depicts the values of the numerical E_{v2} modulus obtained on top of the subballast layer, according to the subballast layer's thickness, for the case of a capping layer of thickness 0.35 m with class P1, P2 or P3. The dashed lines depict E_{v2} on top of the capping layers. The results with a capping layer thickness of 0.5 m are similar (and not presented) as the E_{v2} value to characterize the subgrade class is the same (P1, P2 or P3), whatever the capping layer thickness (see E_{v2} values for P1, P2 and P3 in Table 3). The case of the subgrade with class P1 corresponds to a natural subgrade S1. The figure shows the increase of the bearing capacity of the railway trackbed with the increase of the subballast layer thickness in a linear manner. This type of figure could be helpful to determine the subballast thickness required to reach a target railway trackbed bearing capacity, according to the subgrade class, but within the limits of the proposed numerical model conditions. Furthermore, the subgrade classes were only characterized by a unique E_{v2} value instead of a range of possible values.

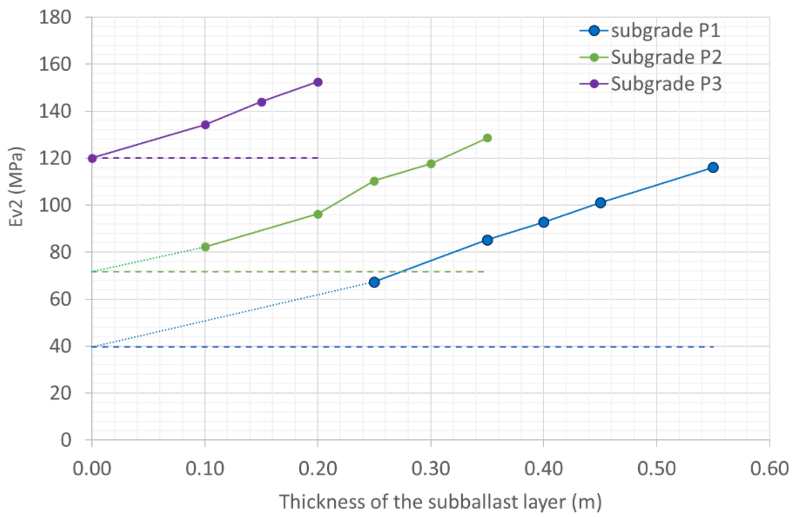

Figure 5: E_{v2} values on top of the subballast layer, according to the subballast layer's thickness, for the case of a capping layer of thickness 0.35 m with bearing class P1 (bleu line), P2 (green line) or P3 (purple line). E_{V2} on top of the capping layers are depicted by the dashed lines.

The same results are depicted in Figure 6 in terms of a ratio between the E_{v2} obtained on top of the subballast layer and the E_{v2} on top of the capping layer. This figure highlights the linear increase of the bearing capacity of the trackbed according to the subballast layer thickness. Moreover, the slopes of the several different curves indicate that the gain of bearing capacity is more significant for subgrades of lower quality (slope equal to 3.4 for P1, 2.1 for P2 and only 1.3 for P3).

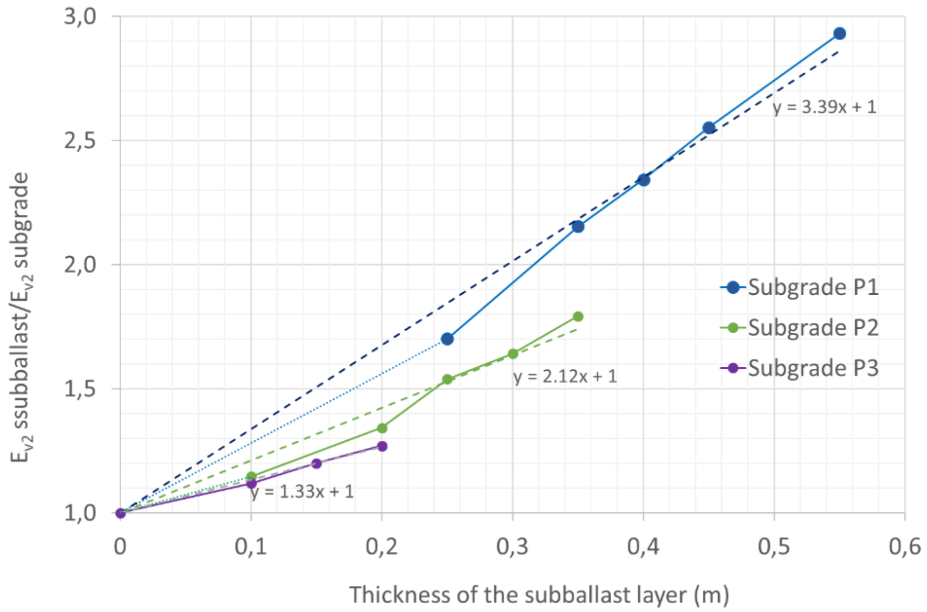

Figure 6: Ratio between the E_{v2} obtained on top of the subballast layer and the E_{v2} on top of the capping layer, according to the subballast layer's thickness, for the capping layer of class P1 (bleu line), P2 (green line) and P3 (purple line). Dashed lines represent the linear regression for each curve (with their equation y = ax + 1).

4 Conclusions and Contributions

This study used a continuum-based numerical model devoted to assessing the bearing capacity of railway trackbeds, comprising a numerical procedure to simulate the PLT as defined by the French standard [1]. An elastoplastic model with shear hardening has been used, necessitating the determination of relevant sets of model parameters for the different layers constituting the trackbed structures.

A numerical parametric study was performed, considering several trackbed configurations suggested by SNCF Réseau. A numerical assessment of the PLT modulus E_{V2} on top of the subballast layer was obtained according to the subgrade bearing capacity class (only defined by a target E_{v2} value), the capping layer thickness and bearing capacity class, and the subballast layer thickness. The influence of the variation of some relevant model parameters for the subballast on the layer's bearing capacity has also been highlighted. Additional experimental data, such as laboratory tests (to determine the mechanical properties of a standard subballast material) and in situ PLT results (whole curve), would be helpful to enrich and validate the proposed numerical model with the aim of implementing it in a design purpose.

The used numerical model also gives access to a lot of additional data throughout the structure and along the loading process, such as the fields of stresses and displacements, the development of plastic zones, etc. The numerical in-depth analysis would be helpful for future studies on the trackbed behaviour regarding its bearing capacity.

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