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ANALYSIS OF THE INFLUENCE OF THE PERMANENT DEFORMATION OF BALLAST LAYER IN THE RAILWAY TRACK DEGRADATION BASED ON NUMERICAL SIMULATIONS

D. Catarino*, C. Alves-Ribeiro[2] and C. Vale[3]

1: Civil Engineering Department
University of Porto
R. Dr. Roberto Frias 4200-465 Porto
ec09287@fe.up.pt

2: Construct, Civil Engineering Department
University of Porto
R. Dr. Roberto Frias 4200-465 Porto
ana.ribeiro@fe.up.pt

3: Construct, Civil Engineering Department
University of Porto
R. Dr. Roberto Frias 4200-465 Porto
cvale@fe.up.pt

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Abstract *This paper presents a numerical analysis of the influence of permanent deformation of the ballast layer in the degradation of railway track. The evolution of the deformed track profile caused by railway traffic is numerically simulated considering the permanent deformation of the ballast material in the numerical model using a deformation law that depends on the number of loading cycles and the stress state the materials are subjected to. For this study it was adopted the deformation law proposed by ORE [1] to simulate the long term behaviour of ballast layer. A parametric study was carried out in order to understand the influence of several parameters in the track deformation. It was analysed the influence of the porosity of the ballast layer that is considered as a parameter in the deformation law adopted. It was also analysed the influence of an initial stabilization period of the ballast layer, discounting an initial part of the deformation law, corresponding to some number of cycles and different values were tested in this analysis. The influence of the train speed was also considered in this parametric analysis.*
The study was carried out in a perfect track and in a track having an isolated defect. This way it was possible to conclude about the influence of the settlement of ballast layer in the degradation process of railway track at different maintenance phases.

1. INTRODUCTION

The constant passage of rail traffic causes permanent and gradual settlement of the granular layers of ballasted tracks: ballast layer, sub-ballast layer and foundation. Several studies carried out in this context confirm that when the materials are cyclically loaded they experience permanent deformation.

The settlement due to the passage of moving loads is composed of an elastic component recovered after discharge and a residual component that represents the permanent settlement accumulated along the loading path history [2].

In the evolution of the permanent settlement, two separate phases may be considered: the first phase takes place during the compaction of the material and it has a high and rapid development; the second phase of the settlement occurs during operation and it has a slower evolution [3, 4].

Since the settlement of the ballast layer represents the most significant component of the overall settlement of the railway track, in this study, the prediction of the evolution of the track permanent settlement only considers the contribution of the ballast layer.

In literature there are a great variety of laws and models that are used to predict the permanent settlement and/or the deformation of the ballast layer.

These laws are usually established by laboratory tests of the materials that constitute the ballast layer, by field testing or by tests at a reduced scale. A summary of the laws to estimate the ballast permanent settlement can be found in Catarino [5]. In addition to the ballast settlement models, other authors consider the permanent deformation of ballast materials to determine the settlement of the ballast layer. Catarino [5] also summarizes on his master thesis the laws of ballast permanent deformation.

In this paper, the authors focus on the ORE law [1] to estimate the ballast permanent deformation. The authors of the ORE law concluded that the growth rate of the ballast permanent deformation reduces significantly with the increase of the number of loading cycles. They also verified that the first loading cycle produces a very high strain and that the subsequent strain progresses according to a logarithmic law as expression (1).

$$\varepsilon_N = \varepsilon_1 \left(1 + C \log(N)\right) \tag{1}$$

where ε_N is the ballast permanent deformation after N loading cycles; c, a constant equal to 0,20; N, the number of the loading cycle; ε_1, the permanent deformation due to the first loading cycle estimated by (2).

$$\varepsilon_1 = 0{,}082\left(100 n_p - 38{,}2\right)\left(\sigma_1 - \sigma_3\right)^2 \tag{2}$$

where np is the porosity of the ballast layer; (σ_1-σ_3), the deviation stress at which the material is subjected.

The porosity of the ballast layer is a function of the initial degree of compaction and of the type of ballast material, typically varying between 0.40 and 0.50 [1].
As mentioned above, the permanent deformation of the ballast layer can be divided into two phases: the first phase is characterized by a large increase in permanent deformation which is normally associated with the initial stabilization ballast layer and the second phase of the evolution of permanent deformation of the track is due to the passage of trains.
In this study only the second loading stage is considered. Therefore, the law that reflects the evolution of the ballast deformation shall be given, as proposed by Alves Ribeiro [6] by the expression (3)

$$\varepsilon_N = \varepsilon_1 \left(C \log\left(\frac{N + N_i}{N_i} \right) \right) \tag{3}$$

where N_i corresponds to the number of cycles of the first phase, ε_1, to the permanent deformation experienced during the first loading cycle and c, to a constant taken equal to 0.20.

Ionescu [7] also examined experimentally the evolution of permanent deformation of the ballast and found that the estimation of ballast deformation based on the law proposed by the ORE seems to be a good approximation of this phenomenon, especially from 10000 loading cycles.
The study of the long term behavior of different materials when subjected to cyclic loading (especially in terms of the axial response) is a well explored field. However, the incorporation of these results into complete track models is still a little studied field. Bruni et al. [8] performed a simulation of the evolution of the settlement due to the permanent deformation of the ballast layer in a transition zone. The numerical model used by the authors allows to consider the vehicle-track interaction and to determine the forces induced by the train on the top of the ballast layer under each sleeper. The settlement of each sleeper after a certain number of loading cycles is calculated based on a law which depends on the forces applied on top of the ballast layer. These settlements are then applied in the model through a static calculation obtaining a new profile of the track that is used to upgrade the rail irregularities profile, which serves as a basis for making new dynamic analysis. This procedure is repeated depending on the number of the loading cycles that are to be simulated. Similar procedures to simulate the permanent settlement are also adopted by other authors as Abdelkrim et al. [2], Fröhling [9], Hunt [10] and Ferreira [11].

The simulation of the evolution of the permanent settlement of the track based on this procedure is extremely versatile and it can be adopted regardless of the model and the adopted settlement laws. However, the formulation of the settlement laws must be in accordance with the type of the adopted track model.

2. DESCRIPTION OF THE NUMERICAL MODELLING

2.1. Track model

The track model used in this work was developed by Alves Ribeiro et al. [12] and consists of a two-dimensional model where the rail is modelled through Euler-Bernoulli beam elements with equivalent characteristics to the stiffness and to the mass of the UIC60 rail. The rail pads are represented by spring-dashpot assemblies. The rest of the track components are 4-nodes finite elements in plane stress that enable width the definition.. The track section corresponds to a complete structure, since i) the rail beam elements consider the properties of the two rails; ii) the mass of the sleepers is equal to 315 kg; iii) the spring-damper placed between the rail and the sleeper simulate two rail pads, each one under each rail. The 2D model was statically and dynamically calibrated using a three-dimensional finite element model with geometric and mechanical characteristics similar to those of the two-dimensional model [6]. The track model considered for the dynamic analysis has a length of 72.3 m and comprises a total of 26500 finite elements. Detailed information about the boundary conditions can be found in Catarino [5]. For a better vision of the considered track model, Figure 1shows a part of the two-dimensional model in plane stress state modelled in ANSYS, the finite element software used in this research.

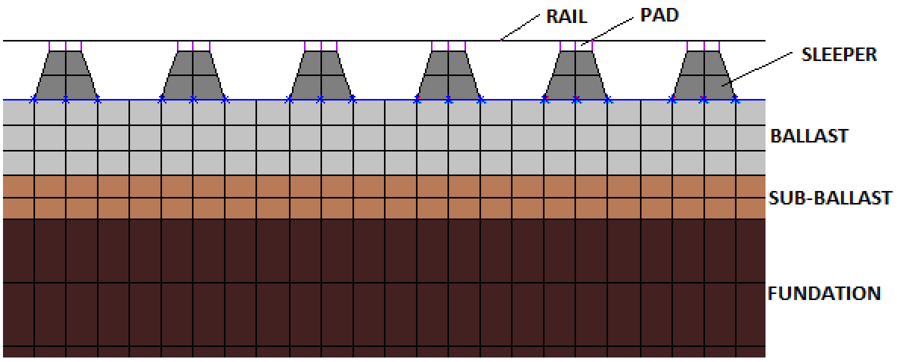

Figure 1 – Part of the two-dimensional track model

One refers that for the track model the contact between the sleeper and ballast layer was taken into account so it was necessary to consider the effect of gravity on the upper part of the model (the rail and sleepers).

Erro! A origem da referência não foi encontrada. presents the characteristics of the components of the tracks considered in this study.

Track layer	E (MPa)	ρ (kg/m^3)	ν (-)
Ballast	130	1530	0,2
Sub- ballast	120	1935	0,3
Foundation	80; 300	2040	0,3

Table 1 - Characteristics of the track components

2.2. Train model

In this study, a model of half axle model is considered (Figure 2) to represent the vehicle. This model is then composed by a concentrated mass that represents the mass of the wheel-axle (M), and a contact stiffness (K_H) simulates the rigidity of the wheel-rail contact. However, since the modelling of the track considers the two track rails, the half axle of the vehicle will consider the characteristics of a complete axle (two wheels).
Taking into account the above, the ANSYS program model is done considering a concentrated mass element and a spring element.

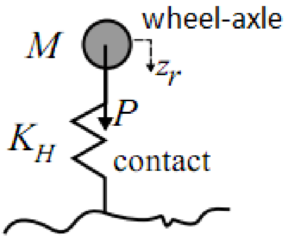

Figure 2 – Half axle vehicle model

Table 2 indicates the values adopted in calculations to simulate the first axle of the EUROSTAR locomotive.

Locomotive	
Mass wheel-axle (M)	1700 kg
Axle load	170 kN

Table 2 – Characteristics of the locomotive of the EUROSTAR

2.3. Train-track interaction

To consider the influence of the dynamic characteristics of the vehicle into the dynamic behaviour of the track, it is necessary to define not only the vehicle and the track models, but also the contact between these two elements [13]. Since there is no deformability between the wheel and the rail it is necessary to consider a spring that simulates the deformability of those contact bodies [6].
For this reason, the vehicle used in this study considers a linear stiffness contact interaction, as it is not expected to have a great variation of the dynamic load, situation that requires the consideration of non linear contact stiffness. Thus, the vehicle-track contact stiffness (K_H) was defined based on the fundamentals of the Hertz theory used in other similar studies and it is considered to be $1.35x10^9$ N / m (per wheel).
In this study, the contact modelling in ANSYS program was made up by a point-line contact between the lower end of the sprung mass and the beam elements of the rail, as shown in

Figure 3 .

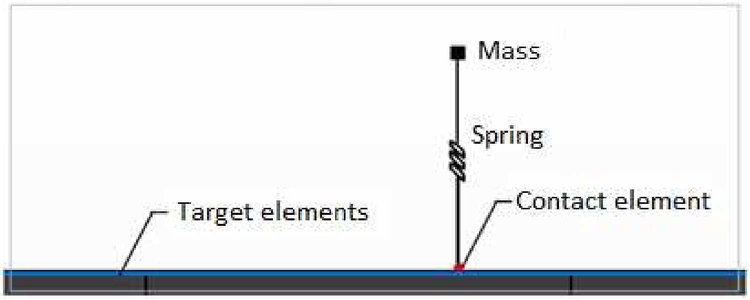

Figure 3 - Contact modelling in ANSYS

2.4. Settlement model

The procedure used in this work to simulate the permanent settlement of the track was proposed by Alves Ribeiro [6] and it consists of an iterative process through the articulation between the ANSYS software and MATLAB program. ANSYS carries out the numerical modelling of the vehicle and the track, the process of pre- and post-processing results and MATLAB performs the reading of the results of dynamic analysis, the application of the deformation law and the determination of the permanent deformation. Figure 4 shows the iterative scheme simulation of permanent deformation of the track.

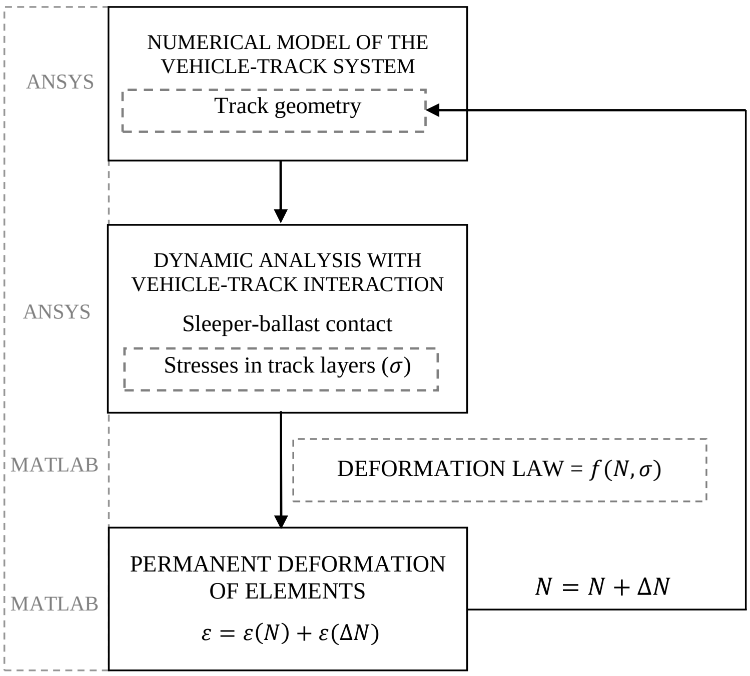

Figure 4 - Iterative procedure for the simulation of the permanent deformation of the track.

To do this simulation procedure it is important to model the track layers using finite elements that enable the accurate simulation of the stress state installed on the track. After the dynamic analysis the information about the vertical, the horizontal and the tangential stresses at all finite elements is stored. Since the variation of the stresses over time on each finite element is known, the evolution of the principal stresses over time for each finite element may be calculated. The maximum values of the principal stresses are used as input for the calculation of permanent deformation. The permanent deformation in each finite element is determined in MATLAB, and then it is stored and provided to the ANSYS program to be imposed on each finite element, thus automatically changing the geometry of the track.
Since the passage of only one train axle causes a very small permanent deformation, the simulation process is not performed cycle to cycle but in a set of cycles (ΔN), assuming that the stress state of the track layers remains constant in each set of cycles.
After each set of cycles ΔN the new stress state is evaluated. This procedure induces that for the same period different permanent deformation values are obtained, which make necessary to do the transition between the stress states, as proposed by Ford [14].
After each dynamic analysis, the effects of the new track geometry on its dynamic behaviour are assessed. The described process is repeated as often as needed.
A summary of the considerations and simplifications with respect to the proposed method for the simulation of the permanent settlement of the track is presented: i) the vehicle-track interaction is considered in all the dynamic analyses; ii) the sleeper-ballast contact is taken into account; iii) the finite element stress remain constant in each loading cycles of the iterative process; iv) the determination of the permanent deformation is made up element by element; v) the deformation of the track layers is exclusively a function of the adopted laws, which means that the track degradation due to other factors, such as, meteorological conditions, creep or settlement by the consolidation of the foundation soils is not taken into account.

Finally, it must be mentioned that when the track foundation presents homogeneous conditions, with no significant variation of the dynamic forces, the estimation of the settlement through a static or quasi-static analysis is acceptable [9]. However, if the track presents variations in geometry or in the dynamic stiffness, the dynamic component should always be considered.

3. LONG-TERM ANALYSIS OF A BALASTED TRACK

This section presents the influence of several parameters in the long-term behaviour of the ballast track: the vehicle speed, the porosity of the ballast track, the influence of the initial stabilization period and the influence of the track geometry quality.

This study the following aspects were taken into account as Alves Ribeiro [6] did: i) it is assumed that all the vehicle axes have the same characteristics and circulate at the same speed; ii) it is considered that the permanent deformation is due only to the increase of the stresses caused by the passage of the vehicle axles, neglecting the contribution of the geostatic tensions; iii) the damping and stiffness characteristics of the materials are not updated along the track deformation process.

3.1. Influence of the vehicle speed

In this section, the results obtained with the speeds of 200 km/h and 300 km/h are compared. The other inputs that remain constant in this comparison are: porosity of the ballast equal to 0.4; initial stabilization of the ballast equivalent to 100000 loading cycles.

3.1.1. Stress level and deformation

Fig. 5 and Fig. 6 present the evolution of the deviatoric stress in the ballast layer and the permanent deformation of the ballast layer function of the number of loading cycles respectively for 300 km/h and 200 km/h speeds.

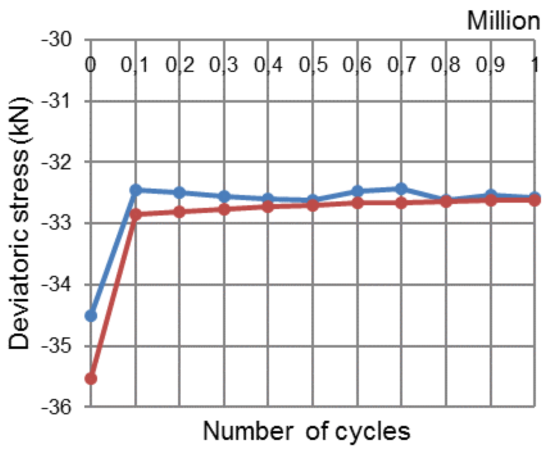

Figure 5 - Evolution of the deviatoric stress in the ballast layer: V = 200 km/h (red line); V = 300 km/h (blue line)

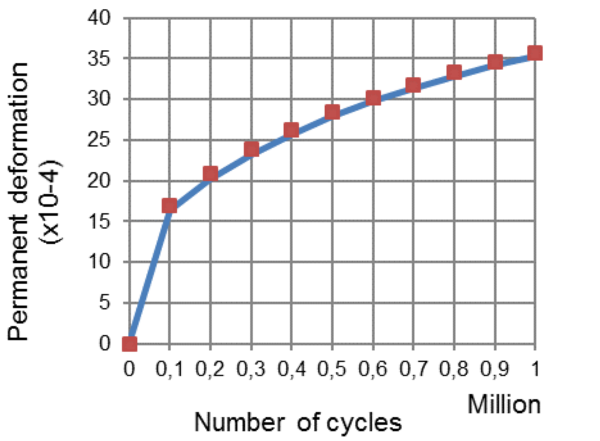

Figure 6 - Evolution of the permanent deformation of the ballast layer: V = 200 km/h (red line); V = 300 km/h (blue line)

The results show that the deviatoric stresses present a very similar progression in relation to the shape and to the magnitude for the two vehicle speeds. The deviatoric stress is an input to the estimation of the evolution of the track deformation. Therefore, taking into account this aspect, the evolution of deformation of the ballast layer is necessarily coincident for the two vehicle speed, as shown in Fig. 6.

3.1.2. Dynamic results

Figure 7 presents the evolution of the settlement of the ballast layer along the track with the number of loading cycles for vehicle speed of 200 km/h. The dots presented in the graphic correspond to the settlement obtained in the vertical alignment of each sleeper.

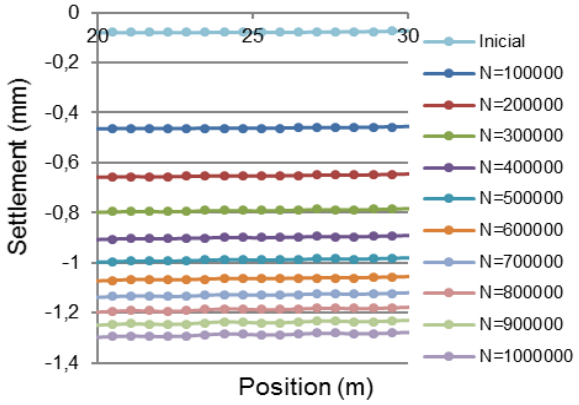

Figure 7 - Evolution of the settlement of the ballast layer along the track with the number of loading cycles (V=200 km/h)

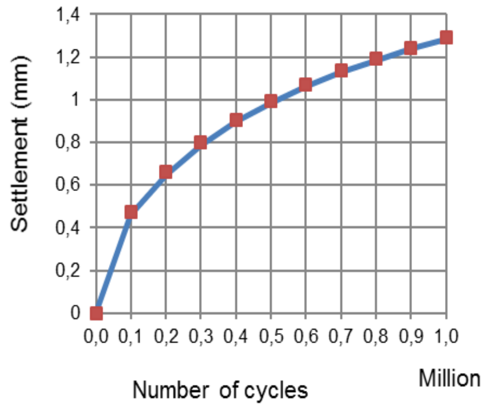

Figure 8 - Evolution of the settlement of the ballast layer: V = 200 km/h (red dots); V = 300 km/h (blue line)

As it can be seen, the evolution of the settlement is constant along the track due to the fact that there is any defect.

Figure 8 presents the evolution of the settlement of the ballast layer function of the number of loading cycles for vehicle speed of 200 km/h and 300 km/h. By looking at this it appears that both evolutions practically coincide for the two vehicle speeds.

Figure 9 shows the evolution of the sleeper-ballast interaction force for the vehicle speeds of 200 km/h and 300 km/h, with the increase of the number of the loading cycles. From the results, the sleeper-ballast interaction force decreases with the decreasing of the speed, but that difference is very small, since for 1 million cycles and the speed of 300 km/h, the interaction is 80.1 kN and for the speed of 200 km/h, is 78.6 kN, a difference of 2%. Figure 10 presents the evolution of the track vertical displacement for the two vehicle speed with the increase of the number of loading cycles.

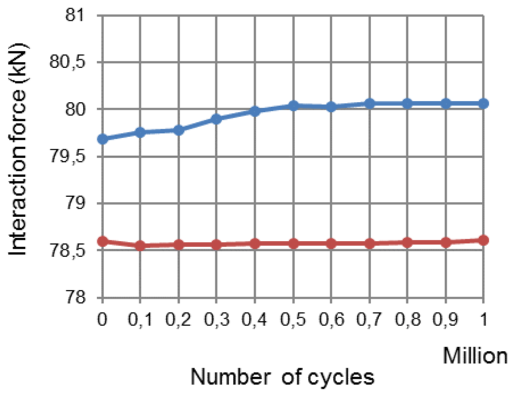

Figure 9- evolution of the sleeper-ballast interaction force with the increase of the number of the loading cycles: V = 200 km/h (red line); V = 300 km/h (blue line)

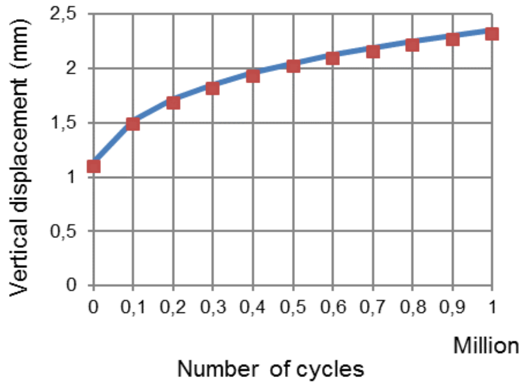

Figure 10 - Evolution of the track vertical displacement with the increase of the number of loading cycles: V = 200 km/h (red dots); V = 300 km/h (blue line)

In Figure 10, the evolution of vertical track displacement is similar for both speeds (slightly superior for 300 km/h), whereby it is likely that the vehicle speed does not affect the vertical displacement of the track, in the case of a perfect track.
Figure 11 presents the evolution of the wheel-rail interaction force function of the number of loading cycles for the speeds of 200 km/h and 300 km/h. which is approximately coincident for both speeds because a perfect track is being considered.
The evolution of the vertical acceleration (maximum and minimum) of sleeper with the increase in the number of loading cycles for the two speeds is presented in Fig. 12.

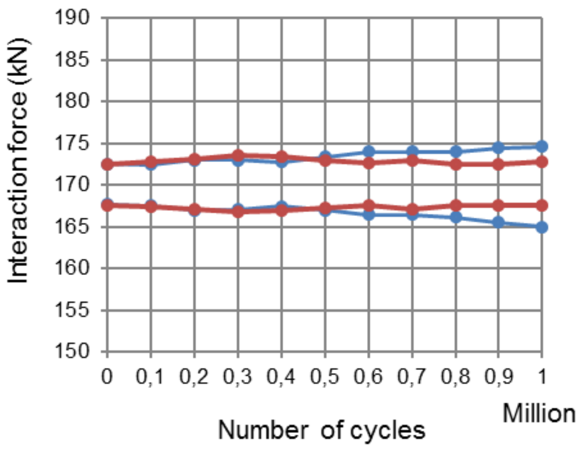

Figure 11 – Evolution of the wheel-rail interaction force with the number of loading cycles: V = 200 km/h (red line); V = 300 km/h (blue line)

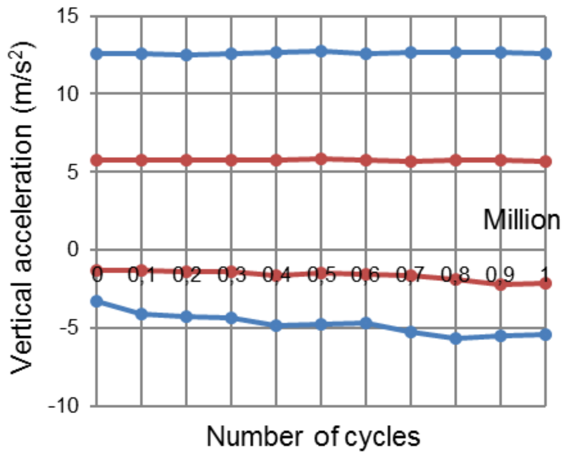

Figure 12 - Evolution of the vertical acceleration (maximum and minimum) of a sleeper with the number of loading cycles: V = 200 km/h (red line); V = 300 km/h (blue line)

The evolution of the vertical acceleration of the sleeper is approximately constant over the number of loading cycles in the two vehicle speeds rates (Figure 12) but smaller for the speed of 200 km/h.

3.2. Influence of the ballast porosity

The influence of the ballast porosity refers to the comparison of the results obtained with porosities of 0.40 and 0.42 (parameter n_p on the deformation law), vehicle speed of 300 km/h and initial stabilization period of the ballast layer corresponding to 100000 loading cycles.

3.2.1. Stress level and deformation

In Figure 13 and Figure 14, the evolution of the deviatoric stress in the ballast layer and the permanent deformation of the ballast layer function of the number of loading cycles respectively for porosities of 0.4 and 0.42 are presented.

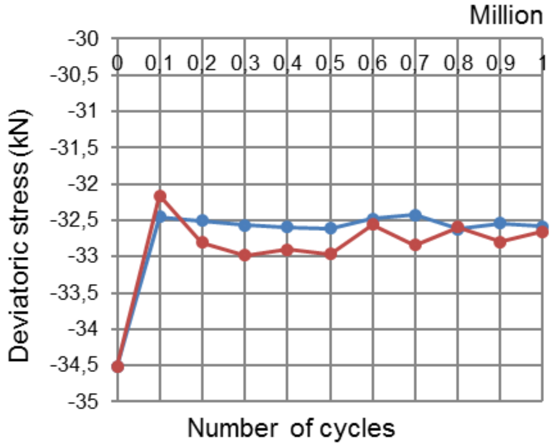

Figure 13 – Evolution of the deviatoric stress function of the number of loading cycles: porosity of 0.4 (blue line); porosity of 0.42 (red line)

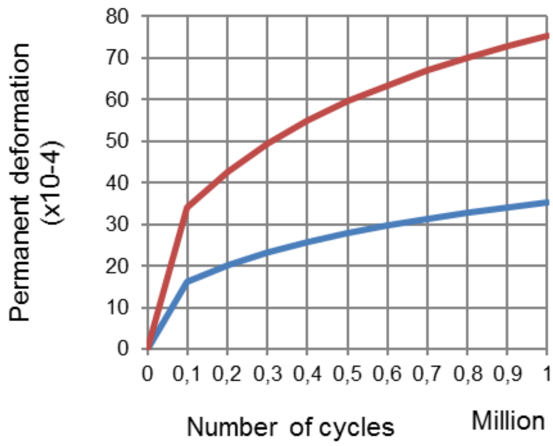

Figure 14 - Permanent deformation of the ballast layer function of the number of loading cycles: porosity of 0.4 (blue line); porosity of 0.42 (red line)

The analysis of Figure 13 shows that the deviatoric stress has a similar trend with respect to the shape and magnitude in both cases, so that the variation of the porosity value seems not to influence the deviatoric stress of the ballast layer. However, the analysis of Figure 14 shows that the evolution of the permanent deformation is far superior for the porosity of 0.42 compared with the value of 0.40. For the 1 million of cycle, the permanent deformations more doubles with the increase in porosity of the ballast layer from 0.40 to 0.42.

3.2.2. Dynamic results

In Figure 15, the evolution of the settlement of the ballast layer function of the number of loading cycles for porosities of 0.4 and 0.42 is presented. From these results it can be concluded that the evolution of the permanent settlement of the ballast layer is far superior for the porosity value of 0.42. After 1 million cycles, the permanent settlement is 1.28 mm and 2.67 mm, respectively, porosity for 0.40 and 0.42.

The analysis of the results of the settlement of the top of ballast layer and on the sleeper base for the two porosity values enable to conclude that there is no loss of contact between the sleeper and the ballast.

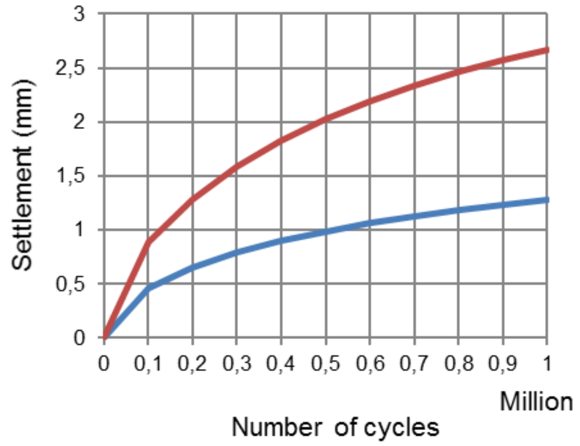

Figure 15 – Evolution of the settlement of the ballast layer function of the number of loading cycles: porosity of 0.4 (blue line); porosity of 0.42 (red line)

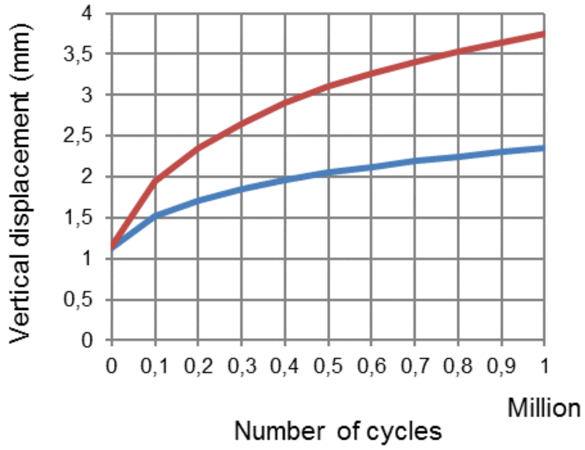

Figure 16 – Evolution of the vertical track displacement function of the number of loading cycles: porosity of 0.4 (blue line); porosity of 0.42 (red line)

Since a track with no defect is being considered, the wheel-rail interaction force is approximately constant over the loading cycles for the two porosity values and similar for both cases. Similar conclusions can be taken when analysing the sleeper-ballast contact force and the vertical acceleration of the sleepers.

However, the variation of porosity from 0.40 to 0.42 implies in this case study an increase of approximately 60% of the vertical displacement of the track, for 1 million cycles as show in Figure 16.

3.3. Influence of the initial stabilization period

In this study two values for the initial stabilization period are considered: 100000 and 50000 loading cycles.

3.3.1. Stress level and deformation

In Figure 17 and Figure 18, the evolution of the deviatoric stress in the ballast layer and the permanent deformation of the ballast layer function of the number of loading cycles respectively for an initial stabilization period of 100000 and 50000 are presented. From Figure 3.17, the evolution of the deviation is practically coincident in both cases.

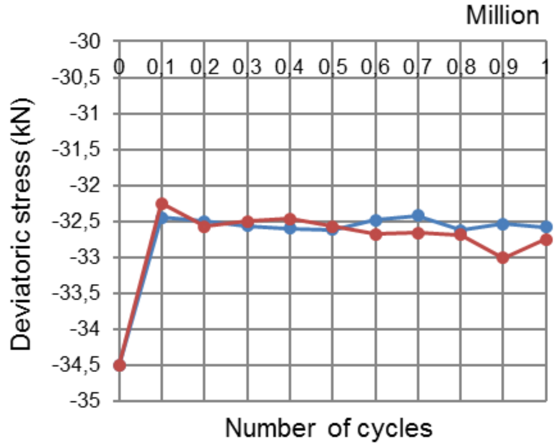

Figure 17 - Evolution of the deviatoric stress in the ballast layer: Ni= 50000 (red line); Ni= 100000 (blue line)

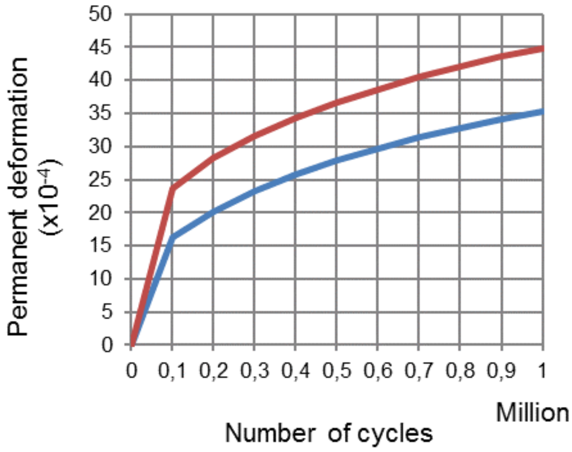

Figure 18 - Evolution of the permanent deformation of the ballast layer: Ni= 50000 (red line); Ni= 100000 (blue line)

The evolution of the deformation of the ballast layer is not coincident in the two cases, because the settlement of the initial stabilization period the ballast layer is different: the evolution of permanent deformation is greater for the consideration of a smaller initial stabilization period. After 1 million loading cycles, there is an increase in the permanent deformation by about 25% when considering Ni= 50000 instead of 100000.

3.3.2. Dynamic results

In Figure 19, the evolution of the settlement of the ballast layer function of the number of loading cycles for the two initial stabilization periods is presented. By the analysis of Fig. 3.19 it can be concluded that the settlement of the ballast layer is higher for Ni equal to 50000 cycles. The settlement of the ballast layer at 1 million loading cycles is 1.28 mm and 1.62 mm, respectively, for an initial stabilization period of the ballast layer (Ni) equivalent to 100000 and 50000 cycles.

Figure 20 presents the evolution of the vertical track displacement function of the number of loading cycles for the two values of the initial period of stabilization of the ballast layer: 50000 and 100000 loading cycles.

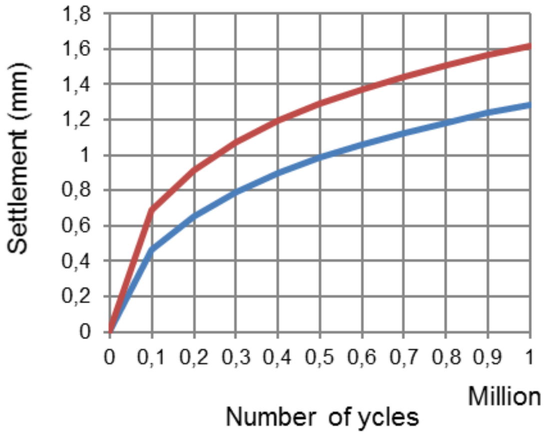

Figure 19 – Evolution of the settlement of the ballast layer function of the number of loading cycles: Ni= 50000 (red line); Ni= 100000 (blue line)

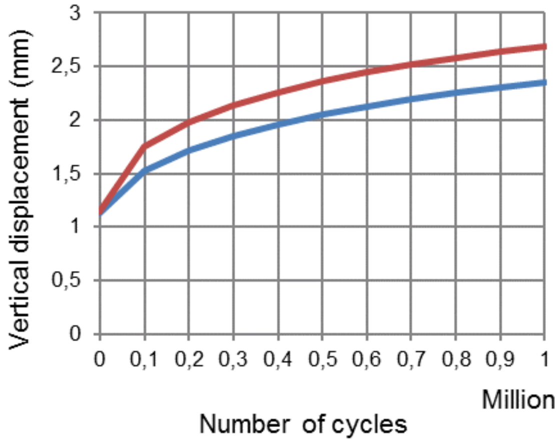

Figure 20 - Evolution of the vertical track displacement function of the number of loading cycles: Ni= 50000 (red line); Ni= 100000 (blue line)

From Figure 20, the vertical track displacement is higher for an initial period of stabilization of the ballast layer equivalent to 50000 cycles. When changing the number of cycles from the initial period to stabilize the ballast layer from 100000 to 50000, after 1 million loading, the wheel displacement increases from 2.35 mm to 2.69 mm (15%).

In terms of contact between the ballast and the sleepers the results attained show that as in the previous analysis, no loss of contact occurs. The change of the initial period of stabilization of the ballast layer is not felt in the interaction sleeper-ballast force as shown in Figure 21.

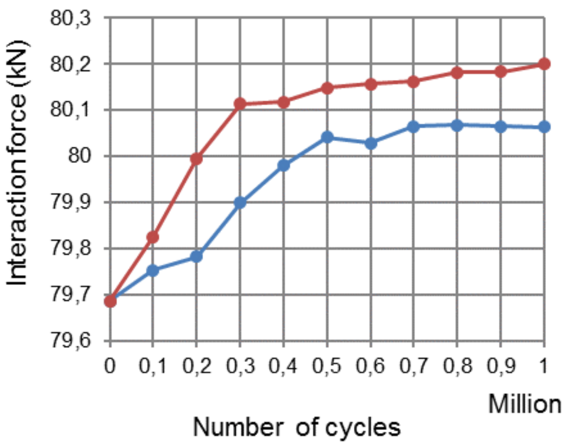

Figure 21 - Evolution of the sleeper-ballast interaction force function of the number of loading cycles: Ni= 50000 (red line); Ni= 100000 (blue line)

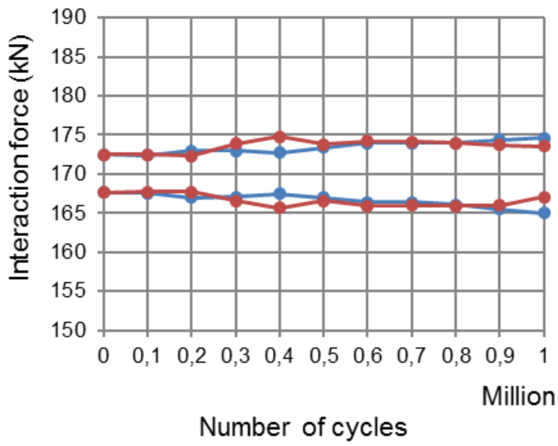

Figure 22 – Evolution of the wheel-rail interaction force function of the number of loading cycles: Ni= 50000 (red line); Ni= 100000 (blue line)

Figure 22 presents the evolution of the wheel-rail interaction force function of the number of loading cycles for initial periods of stabilization of the ballast layer of 50000 and 100000 and it is evident that the initial periods of stabilization of the ballast layer does not influence the maximum and minimum wheel-rail interaction force at least in perfect tracks.

3.4. Influence of the track geometrical quality

In this section, a vehicle speed of 300 km/h a porosity of 0.40 and initial stabilization period the ballast layer equivalent to 100000 cycles load was considered in the analysis of the influence of the track geometrical quality on the long term behaviour of ballast track.

3.4.1. Stress level and deformation

The shape of the defect is shown in Figure 23 and it presents a total length of 12 m and amplitude of 8 mm. In Figure 24, the evolution of the deviatoric stress in the ballast layer along the track for each loading cycle due to isolated defect is presented.

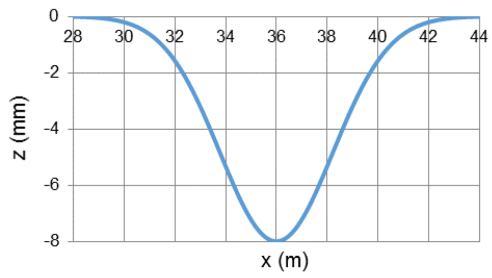

Fig. 23 - Geometry and analytical expression of isolated defect ($z = Ae^{(-1/2)(\bar{k}x)^2}$, A= 8 mm; $\bar{k}$= 0,45)

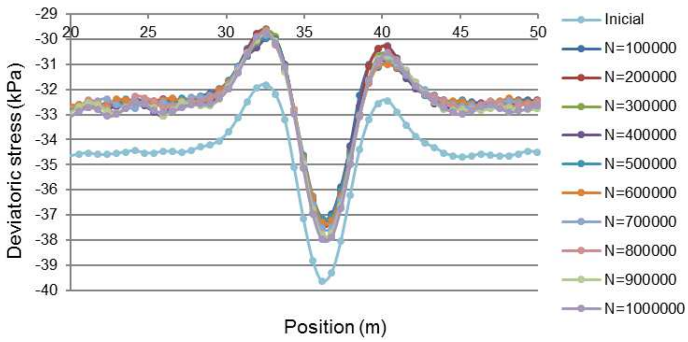

Fig. 3.24 – Evolution of the deviatoric stress in the ballast layer along the track for each loading cycle

Figure 25 and 26, presents respectively the evolution of the deviatoric stress in the ballast layer and the permanent deformation of the ballast layer both function of the number of loading cycles for perfect track and track with isolated defect. In Figure 25 the deviatoric stress is evaluated for a sleeper approximately near the maximum amplitude of the defect. The following results refer to this same sleeper. From Figure 25 a variation of the deviatoric stress occurs in the influence area of the defect. The evolution of the deviatoric stress over the loading cycles is practically constant for the track with the isolated defect (similarly to what happens for perfect track) but 15% higher compared to the case of perfect track.

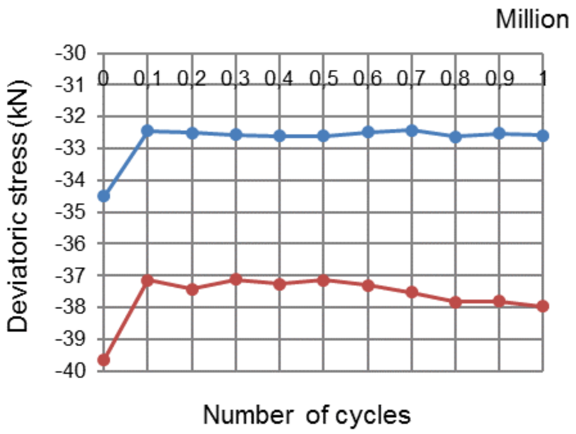

Figure 25 - Evolution of the deviatoric stress in the ballast layer: track with defect (red line); perfect track (blue line)

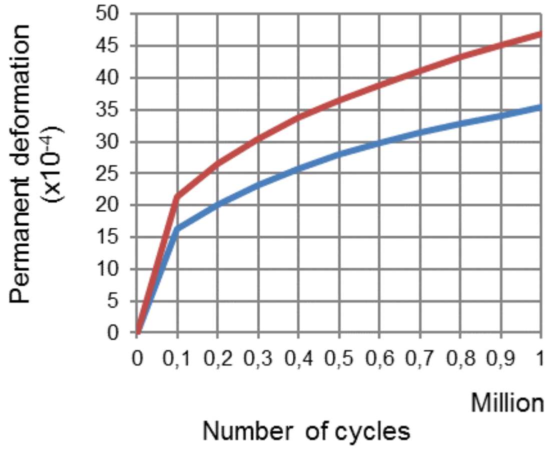

Figure 26 - Permanent deformation of the ballast layer: track with defect (red line); perfect track (blue line)

As it was expected, the permanent deformation of the ballast layer is also higher (about 30%) in the track with defect compared to the perfect track (figure 26).

3.4.2 Dynamic results

Figure 27 presents the settlement on the top of the ballast layer along the track for each loading cycle. The dots in the graph correspond to the value of the settlement obtained in vertical alignment of each sleeper. The evolution of the settlement of the ballast layer for perfect track ad track with defect is shown in Figure 28.

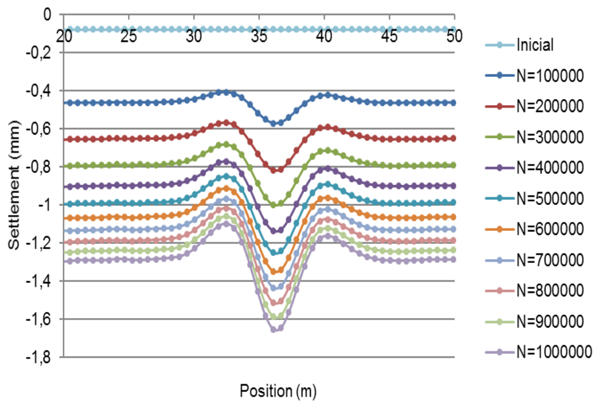

Figure 27 – Settlement on the top of the ballast layer along the track for each loading cycle

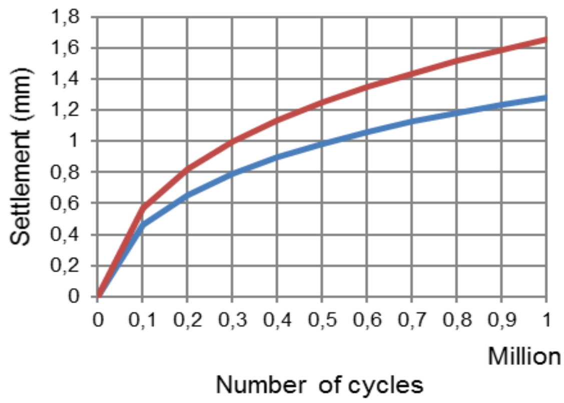

Figure 28 - Evolution of the settlement of the ballast layer: track with defect (red line); perfect track (blue line)

The evolution of the permanent settlement of the ballast layer is higher when the track presents a defect. After 1 million loading cycles, the permanent settlement is 1.28 mm and

1.65 mm, respectively, for perfect track and track with isolated defect.
The evolution of settlement at the top of the ballast layer and the base of the sleeper with the number of loading cycles in the vertical alignment of the defect is presented in Figure 29. Figure 30 shows the settlement on the top of the ballast layer and the base of the sleeper along the track for 1 million of loading cycles.

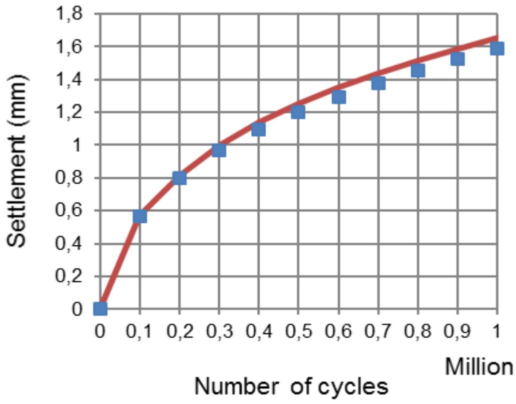

Figure 29 - Settlement at the top of the ballast layer and the base of the sleeper function of the number of loading cycles: sleeper base (blue line); top of the ballast layer (red line)

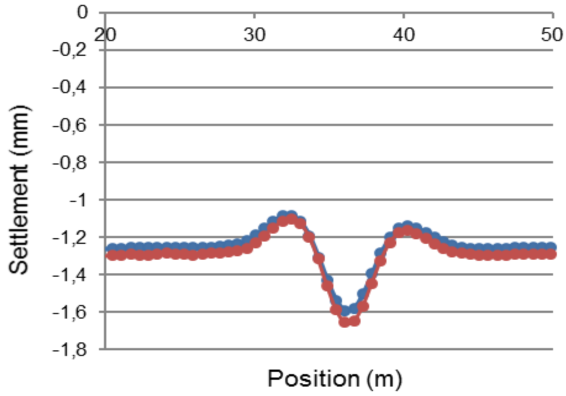

Figure 30 - Settlement along the track for 1 million of loading cycles: sleeper base (blue line); top of the ballast layer (red line)

By analyzing the results in Figures 29 and 30 it can be seen that the ballast-sleeper contact is maintained till 0.5 million cycles and then the gap between the base of the sleeper and the top of the ballast layer starts to increase.
Figure 31 shows the evolution of the vertical acceleration of a sleeper with the number of loading cycles for the perfect track and for track with isolated defect. The evolution of the vertical acceleration of the sleepers is slightly higher for the track with isolated defect and its evolution over the loading cycles is approximately constant.
Figure 32 presents the maximum values of the sleeper-ballast interaction force function of the number of loading cycles for the two scenarios in terms of track quality.

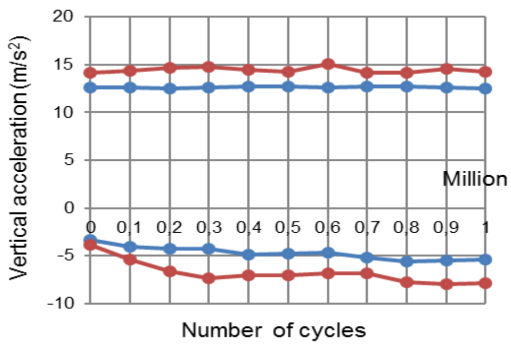

Figure 31 – Evolution of the vertical acceleration of a sleeper function of the number of loading cycles: track

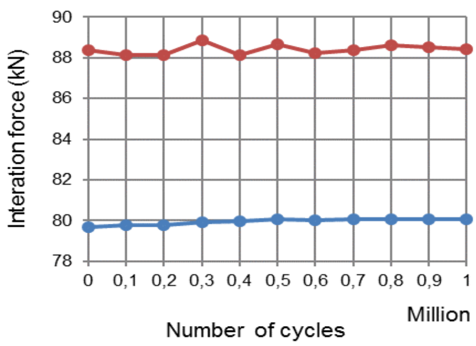

Figure 32 - Maximum values of the sleeper-ballast interaction force function of the number of loading

with defect (red line); perfect track (blue line)

cycles: track with defect (red line); perfect track (blue line)

By analyzing the results, it is found that the sleeper-ballast interaction force undergoes a change in the area of influence of the defect, being higher for the track with defect when comparing to the results of perfect track.

Figure 33 shows the evolution of vertical displacement function of the loading cycles for perfect track and track with irregularity. From this figure, the maximum vertical displacement of the track (at 1 million of loading cycles) is about 10.8 mm corresponding to the defect amplitude (8 mm) plus the track displacement (2.8 mm).

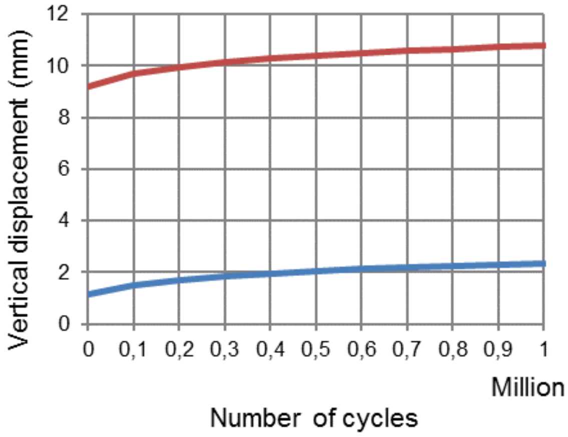

Figure 33 – Evolution of vertical displacement function of the loading cycles: track with defect (red line); perfect track (blue line)

4. CONCLUSIONS

In this paper it is presented the analysis of the long term behaviour of the ballast track using a methodology that enable to simulate the evolution of the permanent deformation of the track for the passage of railway vehicles.

The main scope of this study was to understand the influence of some parameters in the long-term behaviour of the ballast track. For a perfect track it was observed that the evolution of the settlement was constant along the track for all the scenarios.

The variation of the vehicle speed enabled to conclude that this parameter has little influence on the evolution of the track deformation and on the dynamic behaviour of perfect track. However the ballast porosity has a great influence on the evolution of the permanent deformation of the ballast layer. It was verified that after 1 million cycles, the permanent settlement was 1.28 mm and 2.67 mm, respectively, for porosity values of 0.40 and 0.42. A small variation of this parameter of the ORE deformation law has a great influence on the evolution of the ballast layer.

In order to exclude the initial stabilization period of the ballast layer and only consider the part that is due to the passage of traffic a set of cycles were discounted in the deformation law: 100000 cycles and 50000 cycles were the two scenarios considered. As it was expected, the settlement of the ballast layer is higher when a stabilization period of 50000 cycles is considered. The settlement of the ballast layer at 1 million loading cycles is 1.28 mm and 1.62 mm, respectively, for an initial stabilization period of the ballast layer equal to 100000 and 50000 cycles.

An isolated defect with a total length of 12 m and amplitude of 8 mm was considered in the track. The long-term behaviour of the track was analysed considering a vehicle speed of 300 km/h a porosity of the ballast layer equal to 0.40 and initial stabilization period of the ballast layer equivalent to 100000 cycles. Comparing this scenario with the similar scenario of the perfect track it was concluded that after 1 million loading cycles, the permanent settlement was equal to 1.28 mm for perfect track and 1.65 mm for the track with isolated defect. It was also identified the loss of sleeper-ballast contact in the track with the defect after 0.5 million cycles. In the presence of the defect the ballast-sleeper contact force presents a variation on the region of the defect and the maximum values of this force are higher than those obtained in a perfect track.

As future developments the author find it interesting to further analyse influence of the track quality by testing other type of defects and study the influence of some parameters of the deformation law on the evolution of the track deformation.

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