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Influence of the subgrade geomechanical classification on the short term and long-term performance of a railway track

Influence de la classification géomécanique de la plate-forme sur la performance à court et à long terme d'une voie ferrée

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ABSTRACT: The type of subgrade of a railroad foundation is an important aspect in the evaluation of a railway track. Indeed, with the environmental changes and tonnage and train speed increase, the influence and type of subgrade are vital in the railroad track structure performance. The subgrade geomechanical classification includes the combination of both short and long-term behaviour through the evaluation of the stiffness (resilient modulus) and permanent deformation, respectively. This work aims to evaluate the impact of this classification on the global performance of the track. Thus, a ballasted track is analysed which is associated with different values regarding the subgrade geomechanical classification (QS1 and QS2). Thus, the performance of the tracks is analysed in detail and compared. This work is supported by advanced numerical modelling tools and includes a hybrid methodology that combines both short and long-term performance. This is a first attempt to deeply estimate the influence of subgrade geomechanical classification, which can be a useful tool in the evaluation and modelling of the foundation of railway structures.

RÉSUMÉ: Le type de plate-forme d'une fondation ferroviaire est un aspect important de l'évaluation d'une voie ferrée. En effet, avec les changements environnementaux et l'augmentation du tonnage et de la vitesse des trains, l'influence et le type de plate-forme sont vitaux pour la performance de la structure de la voie ferrée. La classification géomécanique de la plate-forme comprend la combinaison du comportement à court et à long terme par l'évaluation de la rigidité (module réversible) et de la déformation permanente, respectivement. Ce travail vise à évaluer l'impact de cette classification sur la performance globale de la voie. Ainsi, une voie ballastée est analysée, associée à différentes valeurs concernant la classification géomécanique de la plate-forme (QS1 et QS2). Les performances des voies sont ainsi analysées en détail et comparées. Ce travail s'appuie sur des outils de modélisation numérique avancés et comprend une méthodologie hybride qui combine à la fois les performances à court et à long terme. Il s'agit d'une première tentative d'estimation approfondie de l'influence de la classification géomécanique du sol, qui peut être un outil utile dans l'évaluation et la modélisation de la fondation des structures ferroviaires.

Keywords: Railways; short and long-term performance; geomechanical classification; numerical modelling.

1 INTRODUCTION

The understanding of the deformation and failure mechanisms of geomaterials under cyclic loading is of utmost importance for designing and planning maintenance in railway structures (Luo et al., 2017, Mones Ruiz et al., 2019, Alabbasi and Hussein, 2021). Typically, the subgrade layer of a railway track consists of mainly coarse-grained soils, chosen for their superior performance compared to fine-grained soils.

The subgrade layer exhibits two types of deformation when subjected to cyclic loads: resilient and permanent deformations. These two types of deformation significantly impact the short and the long-term performance of the substructure (Ling et al., 2017, Lu et al., 2021).

Resilient deformation, which was first introduced by AASHTO (1994) in 1986, is a property frequently used to characterise materials in various railway layers (Liang et al., 2008, Nguyen and Mohajerani, 2016, Titi and Matar, 2018). On the other hand, accurately estimating the cumulative settlement is crucial for railway structures to ensure optimal long-term performance and reduce annual maintenance costs (Puppala et al., 1999).

Indeed, both resilient and permanent deformations are essential parameters for designing railway structures (Burrow et al., 2007, Sun et al., 2016). However, laboratory tests to determine these deformations can be complex and time-consuming, especially when evaluating permanent deformation. Therefore, predictive models based on available data from laboratory and field results have been developed.

In this context, the primary objective of this study is to compare the performance of a ballasted track when considering different subgrade materials with different classifications. These materials were already classified based on their properties and are included in a ballasted track model in order to assess the short and long-term performance using a novel hybrid methodology that includes a 3D model of the track and the implementation of an empirical permanent deformation model.

2 GEOMECHANICAL CLASSIFICATION

The geomechanical classification is based on a previous work developed by Gomes Correia and Ramos (2022). In this study, a parametric study was conducted to classify different materials. Thus, two models were selected to characterise the resilient modulus and permanent deformation of geomaterials. Indeed, this choice represents an attempt to establish a relationship between the resilient modulus and permanent deformation under specific stress conditions.

In this analysis, only two materials were selected. The selected materials are described in Table 1. This choice is dependent on the type of material, resilient modulus value, and permanent deformation value.

Regarding the well-graded sand, the resilient modulus was obtained based on the RLT from the laboratory. The sample was first subjected to confining stress (6 kPa, 12 kPa, 24 kPa, 48 Kpa and 96 kPa), and then, in a force-controlled mode, a minor static vertical stress was applied. Posteriorly, the actuator applied a half since shaped cyclic stress. Since granular materials show a stress-dependent behaviour, the cyclic triaxial test was performed at various stress combinations. Based on the tests performed and coefficients obtained, and considering a cyclic deviator stress of 24 kPa and a constant confining stress of 60 kPa (representative of the stress state at the subgrade level (Ramos et al., 2020)), a resilient modulus of 509 kPa was determined.

Table 1. Properties of the materials.

UIC ASTM	Materials	Properties	Obs.
QS1 SM	Silty Sand (42.2% fines)	Cu≈28; Cc≈0.54; Gs=2.68; Fine content=42.2%; Maximum dry density =19.6 kN/m3; Wopt =10.1%. c=15.82 kPa ϕ=36.18°	Compacted at optimum compaction – standard Proctor
QS2 SP	Well-graded Sand	C_u=2.10; C_c=1.05; Maximum dry Density = 16.90 kN/m^3; W_{opt}=12.5%; c=5.60kPa; ϕ=48.2^0;	Compacted at optimum compaction – standard Proctor

The resilient modulus and permanent deformation of the selected materials are presented in Table 2. The resilient modulus of the silty sand was determined in the laboratory from the RLT (repeated loading testing). During the tests, Erlingsson et al. (2017) defined different approaches: 1) resilient modulus as a function of various w (S) where the cyclic deviator stress is constant and equal to 69 kPa (w=3% - S=30%, w=6.4% - S=50%, w=10.1% - S=79.3%, w=12% - S=94.3%); 2) resilient modulus as a function of S for various deviator stresses (28 kPa, 48 kPa, 69 kPa, 98 kPa, 165 kPa). Based on several tests, Huurman (1997) defined the model parameters that conduct a resilient modulus of 258 MPa in the geomechanical analysis (considering a cyclic deviator stress of 24 kPa and a constant confining stress of 60 kPa).

Table 2. Resilient modulus and permanent deformation of the selected materials.

Materials Classification	Resilient Modulus	Permanent Deformation
Silty Sand (42.2% fines) QS1-SM	M_r= 258 MPa	ε_p=0.01385 %
Well-graded sand QS2-SP	M_r= 509 MPa	ε_p=0.00003%

From the previous work (Gomes Correia and Ramos, 2022), it was possible to define guiding values associated with UIC classification: QS1, QS2, and QS3 (UIC, 2008). The preliminary geomechanical classification should be viewed as a preliminary version.

The presented geomechanical classification serves as an innovative and practical guide intended to support the modelling and design of substructures. This novel classification system aims to rank soils in a manner closely aligned with the approach pioneered by Coronado et al. (2011), which drew inspiration from EN13286-7 (2004). The presented work provides valuable insights into acceptable values of permanent deformation and resilient modulus based on the material type and its classification. Specifically, the UIC (2008) classification was adopted, as illustrated in Figure 1, to facilitate the establishment of the mechanical classification.

Analysing Figure 1, it becomes evident that a significant range of values has been observed within each classification. This variability is expected, given the diverse mineralogical nature and physical properties inherent to each material. These factors can exert a notable influence on several parameters employed in determining both resilient modulus and permanent deformation.

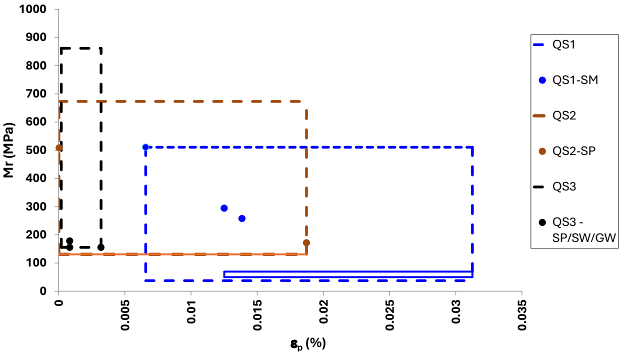

Figure 1. Mechanical classification based on the resilient modulus and permanent deformation (Gomes Correia and Ramos, 2022).

In the case of materials falling under the QS1 classification (comprising fine soils), the material type (CL, CH, ML, or MH), in conjunction with its plasticity's characteristics, consistency index, and the percentage of fines can exert a substantial impact on both permanent deformation and resilient behaviour. This relationship is evidently illustrated in Figure 1.

Similarly, for materials categorized as QS2 and QS3, factors such as material type (sand or gravel), granulometry (well-graded or poorly graded), and the presence of fines (particularly in well-graded materials) can significantly influence the material's response in terms of both resilient and permanent deformations.

In Figure 1, it is possible to perfectly identify the materials selected in this work: QS1-SM (blue point) and QS2-SP (brown point). More details can be found in Gomes Correia and Ramos (2022).

3 NUMERICAL MODELLING

The numerical model represents a ballasted track consisting of rails, railpads, ballast, sub-ballast, and a substructure that encompasses subgrade, as depicted in Figure 2. The ballast presents a thickness of 0.3, the sub-ballast has a thickness of 1 m and the subgrade has a thickness of 11.5 m The material characteristics can be found in Table 3.

In this analysis, damping coefficients were determined using the *Rayleigh* damping matrix. Assuming equal damping $\xi_1 = \xi_2$ and using $\xi = 0.01$ for concrete materials and $\xi = 0.03$ for geomaterials, the αi and βi values were derived from receptance curves and the chosen frequency range, identifying the resonant frequencies. A hysteretic damping of $\xi = 0.05$ was applied to rail pads, considering their solid element representation. Additional details on this methodology are available in Ramos et al. (2022). A frequency range of 5 Hz to 200 Hz was adopted, which is sufficient for an accurate track response.

The numerical model, as illustrated in Figure 2, spans a total length of 30 meters. To enhance computational efficiency, the symmetric boundary conditions were employed as well as an optimized mesh structure. The distance between the symmetry plane and the vertical boundary measures 6 meters.

The analysis is focused on the passage of the Portuguese *Alfa Pendular* train at 220 km/h. The train model properties can be found in Table 4. In this study, the train's components include the bogies, primary suspension, mass, and wheelset axles, while incorporating Hertzian stiffness to replicate the vehicle-track interaction. The properties of the track were adjusted by a factor of two since only half of the track's was considered. Concerning the applied load, a constant value of 67.5 kN (135/2) was adopted. Although load distribution varies slightly along the train, these variations are negligible. To simulate both short-term and long-term track responses, the passage of the initial first bogie was simulated.

To avoid spurious reflections and attenuate the waves that impinge the vertical boundaries, viscous dampers were adopted using the *Lysmer* formulation. Indeed, this approach has been used in the scope of 3D modelling with effective results.

The materials were modelled with solid elements with 8 nodes using linear elastic models. The rail was modelled using the beam theory (2D element) and the railpads were modelled with a spring-damper element.

Moreover, contact elements were implemented between the train and track to simulate the interaction between the two bodies and between the sleepers and the ballast. More details about the modelling of the contact elements can be found in Ramos et al. (2022), which includes information about the Normal penalty stiffness factor. The dynamic analysis was performed in the software *ANSYS* using the *Newmark-Raphson* method with a time step equal to 0.002 s.

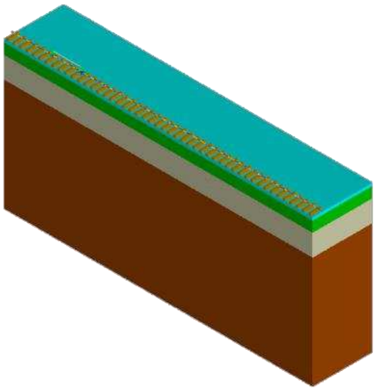

Figure 2. Numerical model.

Table 3. Material Properties.

Ballast	E=67.5 MPa; ν=0.20; ρ=1800 kg/m^3 α=1.84; β=4.66× 10^{-5}
Sub-ballast	E=161.7 MPa; ν=0.30; ρ=2100 kg/m^3 α=1.84; β=4.66× 10^{-5}
Subgrade 1: QS1	E=258.3 MPa; ν=0.3; ρ=1998 kg/m^3 α=1.84; β=4.66× 10^{-5}
Subgrade 2: QS2	E=508.62 MPa; ν=0.3; ρ=1723 kg/m^3 α=1.84; β=4.66× 10^{-5}

Table 4. Characteristics of the Alfa Pendular train adopted in this study.

Component		**Values**
Bogie: $M_b/2$		4932/(2*2.7) [kg]
Primary suspension	$K_p/2$	3420×10^3 (/2) [N/m]
	$c_p/2$	36×10^3 (/2) [N.s/m]
Wheelset Mass: $M_e/2$		1800 (/2) [kg]
$K_h/2$		2.4×10^9 (/2) [N/m]

3.1 Short-term performance

The objective of this study is to examine the impact of the subgrade type and classification on the dynamic response of a ballasted track Consequently, two different simulations considering two distinct subgrades were conducted. These materials were selected to assess the performance of a high-speed railway line.

The short-term performance assessment encompasses the analysis of displacements and stresses induced in different track components during the passage of the *Alfa Pendular* train. In this case, the focus is the subgrade material.

Thus, the maximum displacements in the top of the rail and subgrade were obtained in the alignment under the load (Figure 3 and Figure 4). The results indicate higher displacements in subgrade QS1 when compared to the subgrade QS2. However, the differences are higher at the subgrade level than at the rail. At the subgrade, there is an increment in the displacement's maximum magnitude of 92% between QS2 and QS1. At the rail level, this increment is only 11%. Moreover, at the subgrade level, it is not possible to identify the axles of the bogie in both subgrades.

3.2 Long-term performance

In this analysis, the prediction of the permanent deformation is only carried out on the subgrade. The permanent deformation is determined by applying the empirical model developed by Chen et al. (2014):

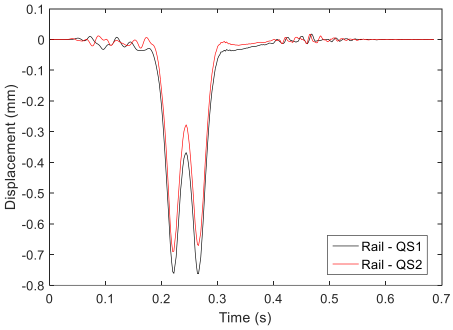

Figure 3. Rail displacement.

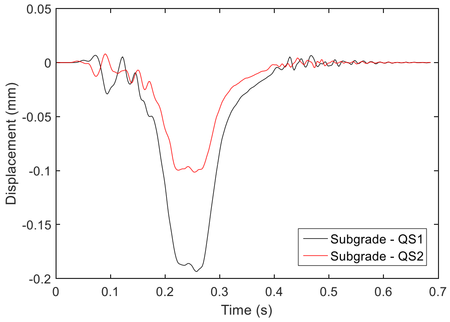

Figure 4. Subgrade displacement.

$$\varepsilon_1^p(N) = \varepsilon_1^{p0}\left[1 - e^{-BN}\right]\left(\frac{\sqrt{p_{am}{}^2+q_{am}{}^2}}{p_a}\right)^a \cdot \frac{1}{m\left(1+\frac{p_{ini}}{p_{am}}\right)+\frac{s}{p_{am}}-\frac{(q_{ini}+q_{am})}{p_{am}}} \tag{1}$$

where the parameters ε_1^{p0}, B and a are the material's constants of the model, m and s are defined by the yielding criterion q=s+m·p, N is the number of loading cycles, p_{ini} and q_{ini} are the initial stress state and p_{am}

and q_{am} are the stress levels induced in the subgrade during the passage of the train. The constants employed to characterize the empirical permanent deformation model are presented in Table 5.

Table 5. Materials constants of the permanent deformation model.

Material	ε_1^{p0}	B	a
Subgrade 1 - QS1	0.0067	0.2	0.65
Subgrade 2 – QS2	0.0505	0.0018	0.0104

The developed methodology relies on the number of load cycles, and it is intricately tied to the stress levels experienced by the substructure due to the passage of the train. In this context, each cycle (N) corresponds to the passage of one of the axles of the *Alfa Pendular* train. However, the material constants values and stress values are not enough to obtain the induced permanent deformation. It is necessary to characterize the materials considering their mechanical properties: Subgrade 1 (QS1): ϕ=36.18° and c=15.82 kPa; Subgrade 2 (QS2): ϕ=48.20° and c=5.60 kPa.

This methodology involves the development of a powerful 3D numerical model of the vehicle-track system within ANSYS software. Thus, a dynamic analysis is performed considering the vehicle-track interaction and including contact elements. From the numerical results, the stresses in the subgrade are obtained in all directions and all elements and nodes. These stress values are then exported to MATLAB to predict the permanent deformation based on the implementation of the empirical permanent deformation model.

In this analysis, each curve of the permanent deformation corresponds to 1 million load cycles. Thus, during the calculation of the permanent deformation.

Despite the importance of the permanent deformation, the results are analysed in terms of cumulative permanent settlements to have the magnitude of the track's settlement:

$$\delta = \sum_{i=1}^{n} \varepsilon_{p;i} H_{s;i} \tag{2}$$

where i corresponds to the number of elements that constitute a certain material, $H_{s;i}$ corresponds to the thickness of each element (in m), $\varepsilon_{p;i}$ is the permanent deformation at the center of each element, and δ is the cumulative permanent deformation (in m).

Following the developed methodology, the maximum cumulative permanent settlements occurring in the subgrade were calculated under the load alignment, as illustrated in Figure 5. The results show the variation of the maximum cumulative permanent deformation along the track. The influence of the loading on the first meters (-30<x<-18) is not presented as well as the influence of the end of the model (x=0). The results show that there is a difference between the subgrade QS1 and QS2 in terms of permanent displacements. However, the difference is not significant, and it is close to 0.1 mm.

4 CONCLUSIONS

This work presents the performance of the ballasted track considering two different subgrades: subgrade QS1 and subgrade QS2, classified according to UIC. The results show, as expected, that the performance is better when considering a better material. In this case, regarding the short-term performance, the difference is significantly higher at the subgrade level when compared to the rail level. Concerning the long-term performance, the difference between the QS1 and QS2 subgrades is for the data used as input parameters not significant (below 0.1 mm).

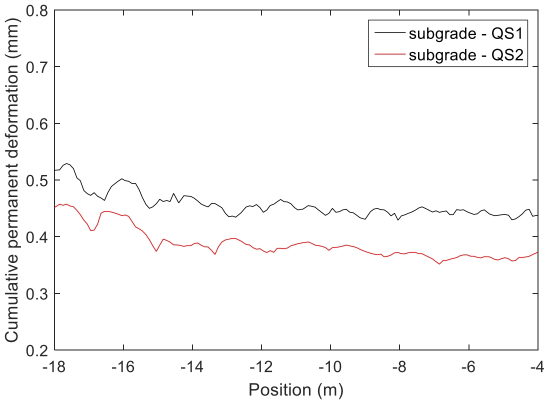

Figure 5. Maximum cumulative permanent deformation.

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