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IMPACT OF DIFFERENT SUBBALLAST SOLUTIONS ON THE SERVICE LIFE OF THE RAILWAY SUBSTRUCTURE

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Abstract *The use of bituminous materials in railway trackbeds has been pointed out as an interesting alternative to the granular-only subballast design traditionally applied in most European railroad tracks. The present paper focuses on the use of bituminous subballast layers in railway trackbed design and on their potential to protect the substructure over its service life. It describes a suitable methodology to account for the effects of traffic loading and environmental actions in the hydro-thermo-mechanical performance of the subgrade and consequent deformational behaviour over time. Thus, the effect of using bituminous subballast layers instead of the conventional granular-only design may be assessed.*

The developed methodology is based on a mechanistic-empirical design approach where railway track finite-element models are developed to perform the mechanistic and hydro-thermic analyses, and empirical equations are applied to relate the computed response to subgrade long-term deterioration. The mechanical design of the railway track considers the elastoplastic behaviour of railway track materials as well as an adequate modelling of the sleeper-ballast interface contact. The hydro-thermic analysis of the railway track, accounts for environmental variables such as hydro-geological conditions (groundwater table) and atmospheric actions (precipitation, temperature, and relative humidity) and models the runoff of superficial rainwater.

Combined with empirical equations, the results from the mechanical and hydro-thermic analysis were used to predict the long-term deformational behaviour of the subgrade. The solutions incorporating bituminous materials showed a better performance than the granular-only design concerning the predicted substructure service life. Furthermore, the phreatic level was found to have great influence on the substructure's deformational behaviour, thus proving the importance of an adequate design of subsurface deep drainage systems.

1. INTRODUCTION

In recent years, the application of alternative materials has been studied with the aim of improving the performance of high speed substructure. In particular, the use of a bituminous subballast layer has been pointed as an interesting alternative to the granular-only subballast design traditionally applied in most European railroad tracks. This interest has been corroborated by the good practical results obtained on the use of bituminous subballast trackbeds in some conventional and high-speed (HS) ballasted tracks in countries like the United States, Japan, Italy and most recently in France and Spain [1].

Theoretically, as discussed previously by the authors [2][3] this track design solution may bring an improvement of the long term deformational behaviour reducing maintenance needs. Among other advantages the authors referred: a better homogenization of the track vertical stiffness, a reduction of the vibration levels transmitted to the track structure (particularly important at higher speeds) and a better protection of the subgrade regarding atmospheric actions. This last advantage, related to the impervious properties of the bituminous material is believed to have a great impact: being almost completely water resistant the bituminous layer enables maintaining low moisture levels during the year which play an important role regarding subgrade deformation process.

The present paper focusses on the use of bituminous subballast layers in railway trackbed design and on their potential to protect the substructure over its service life. It is described a methodology suitable to account for the effects of traffic loading and environmental actions in the hydro-thermo-mechanical performance of the subgrade and consequent deformational behaviour over time. Thus, the impact of using bituminous subballast layers instead of the conventional granular-only design might be assessed.

The developed methodology is based on a mechanistic-empirical design approach. Railway track FE models are developed to perform the mechanistic and hydro-thermic analysis using the concepts of continuous mechanics, and then, empirical equations are applied to relate the computed response to subgrade long-term deterioration.

To achieve that purpose, the paper is divided in three sections:

- Mechanistic design of the railway track considering the complex sleeper-ballast interface contact modelling and the use of elastic-plastic constitutive models governing material behaviour;
- Hydro-thermic analysis of the railway track accounting for environmental variables such as hydro-geological conditions (phreatic level) and atmospheric actions (precipitation, temperature and relative humidity) while modelling the rainwater run-off;
- Long-term deformational behaviour of the subgrade for the different considered subballast solutions by combining the results from the mechanistic and hydro-thermic analysis.

2. RAILWAY TRACK MECHANISTIC DESIGN

3D FE models featuring spatial and temporal variations of physical and geomechanical material properties still provide an effective tool to assess the impact of different railway track design solutions. The analysis developed in the present section aims to evaluate the mechanistic performance of railway track structures with different subballast configurations. The chosen computational tool was the CESAR-LCPC [4] FE method based formulation.

The loading system of the FE model was designed considering the AVE HS train configuration composed by 13 bogies (26 axles) with a static load of 17 ton per axle and a distance between axles of 3 m. The relative small distance between axles is responsible for non-negligible effects associated to superimposed stresses due to the simultaneous loading of both axles belonging to the same bogie. Hence, a design approach accounting for the bogie double axle loading is adopted instead of the simple assumption of a single axle load. The longitudinal dimension of the FE model – 4.05 (m) – allows modelling a total of seven sleepers (60 cm between sleepers) meaning that the wheel load must be applied in the 3rd sleeper counting from the XZ symmetry plan as shown in Figure 1.

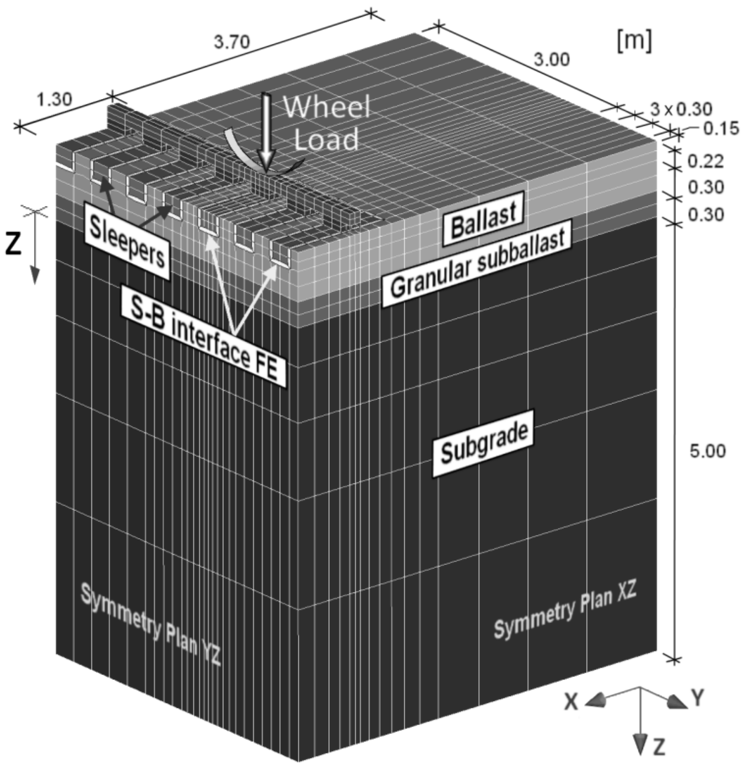

Figure 1 – 3D FE model: railway track components, mesh and boundary conditions

In order to consider the dynamic effects of a moving train over a rail with geometric defects, a quasi-static load is calculated using an algorithm developed by the authors based on the French Railways criteria as explained in [2]. The algorithm accounts for the main parameters influencing the magnitude of the transmitted load: sprung and unsprung masses of the different axles of the AVE HS train; running speed (300 km/h); the geometric quality of the railway track (standard deviation of longitudinal defects, assumed $\sigma = 0.9$ mm for this analysis); and the global vertical stiffness of the railway track depending on the subballast design solution.

2.1. Material mechanical constitutive models

Table 1 describes the mechanical constitutive models defined for railway track components as well as the different layer thicknesses associated to the analysed subballast solutions.

Table 1 – Mechanical constitutive models and material properties

Material	Mechanical behaviour	E (MPa)	ν	c (MPa)	φ(°)	**Layer thickness** (m) Gran30Bit00	Gran20_Bit06	Gran00_Bit12
Ballast	Drucker-Prager	130	0.20	0	45	0.35	0.35	0.35
Granular subballast		200	0.30	0	35	0.30	0.20	0.00
Subgrade QS3		80	0.30	0	35	5.00	5.00	5.00
Bituminous subballast	Linear Elasticity	6000	0.45	-	-	0.00	0.06	0.12
Rail UIC 60 (60 kg/m)		210 x 10^3	0.30	-	-	-	-	-
Concrete sleepers		64 x 10^3	0.25	-	-	-	-	-
Railpad (K = 100 kN/mm)								

The elastic-plastic mechanical behaviour characterizing ballast, granular subballast and subgrade is assumed to be defined by the Drucker-Prager constitutive model. In the case of ballast material the chosen internal friction angle for ballast aggregates, φ, is in accordance with the laboratory experimental results [5] which revealed a basic friction angle (exclusion of particle breakage and dilatancy effects) of approximately $44°$ for fresh ballast (latite basalt). Also, a relatively low elastic modulus of 130 MPa associated to bearing conditions occurring after tamping operations is considered for ballast material. Granular subballast is intended to represent a relatively stiff medium of compacted well-graded material which is assumed to have an elastic modulus of 200 MPa. The elastic modulus of the subgrade soil (80 MPa) matches the minimum bearing capacity required to be classified as a "good quality" subgrade class – QS3 – of the UIC 719 code [6], mandatory for HS lines.

For the bituminous mechanical behaviour, although its response is better described by elastic-viscoplastic constitutive laws accounting for temperature effects, for this analysis a linear elastic model is assumed for numerical reasons (large domain with elastic-plastic constitutive laws for granular and soil materials and contact interface models, all using quadratic interpolation already represents a very large computation time). The value adopted for the bituminous Poisson Ratio is $\nu = 0.45$.

Rail, railpads and monoblock sleepers are modelled as prismatic elements with an isotropic linear elastic constitutive model, as commonly used on FE modelling for trackbed design.

2.2. Sleeper-ballast interface

A realistic mechanistic modelling of railway track system has to take into account the complex behaviour of the sleeper-ballast interface, as referred by Profillidis and Poniridis [7] in a pioneer approach on this issue.

Sleeper-ballast interface behaviour involves friction, sliding and detachment phenomena. In the present FE analysis, the sleeper-ballast interface is modelled using contact elements

with 16 nodes. Three different interface conditions are considered to rule the contact behaviour: bonding, friction and sliding.
In the case of the bonding contact condition, no relative displacements are allowed between merged nodes of sleeper and ballast FE (continuity of the displacements field). The sliding interface condition can be viewed as a particular case of friction which is assumed to be modelled by the Coulomb friction law. In the case of cohesionless materials such as fresh ballast the Coulomb friction criterion may be written as follows:

$$|\tau| \leq \sigma_n \tan(\delta) \tag{1}$$

where τ and σ_n are respectively shear stress and normal stress at points located on the interface with effective contact and δ is the friction angle associated to contact elements. When criterion (1) is reached, the two sides of the sleeper-ballast interface slide one against the other and only normal displacements remain continuous. In the case of perfect sliding conditions, friction between material is defined as null ($\delta = 0°$) whereas in the definition of the Coulomb friction criterion it is assumed a friction angle of $\delta = 26.57°$ (note that $\tan(\delta) = \tan(\varphi)/2$).

In order to solve kinematic contact constraints, the model uses a penalization method which assures that the non-interpenetration criterion is verified. Penalty parameters should in theory be infinitely large to avoid surface penetration under compressive normal contact stress. However, in order to enable numerical implementation a factor of 10^4 compared to the concrete stiffness was chosen in the definition of the contact element stiffness modelling the sleeper-ballast interface.

Detachment phenomenon is modelled by a separation criterion which forces the creation of two independent and free element surfaces whenever the normal stress reaches the traction limit resistance in the normal direction of the interface. The developed 3D railway track FE model assumes that contact elements in the sleeper-ballast interface have zero traction strength.

2.3. Results of the mechanistic analysis

The mechanistic analysis was performed comparing the results of a reference structural solution (the design configuration used in recent Spanish HS lines with a 35 cm ballast layer and a 30 cm depth granular subballast on top of the formation layer, as shown in previous Figure 1) and those of the alternative solutions including a bituminous subballast layer. The reference configuration will be further designated by Gran30_Bit00. Among the different possible alternatives to guarantee a structural equivalence with bituminous subballast layers, two alternative solutions were selected: a bituminous-only subballast solution (Gran00_Bit12) where the 30 cm granular-only layer is replaced by a 12 cm layer of bituminous material; and a “mixed” subballast design (Gran20_Bit06) combining a 6 cm bituminous layer on the top of 20 cm of granular material.

In order to analyze the sleeper-ballast interface modelling, Figure 2a shows the results for the vertical stresses developed between the bottom of the loaded sleeper and the top of the subgrade for the different described contact models (it is analyzed the Gran30_Bit00 solution with a wheel static load of 85 kN). As it can be seen, using different contact models can give rise to a difference of up to 25% on the stress level below the loaded sleeper, which reinforces the importance of the sleeper-ballast interface modelling. Figure 2b illustrates the relative displacement between sleeper and ballast when using the sliding interface criterion.

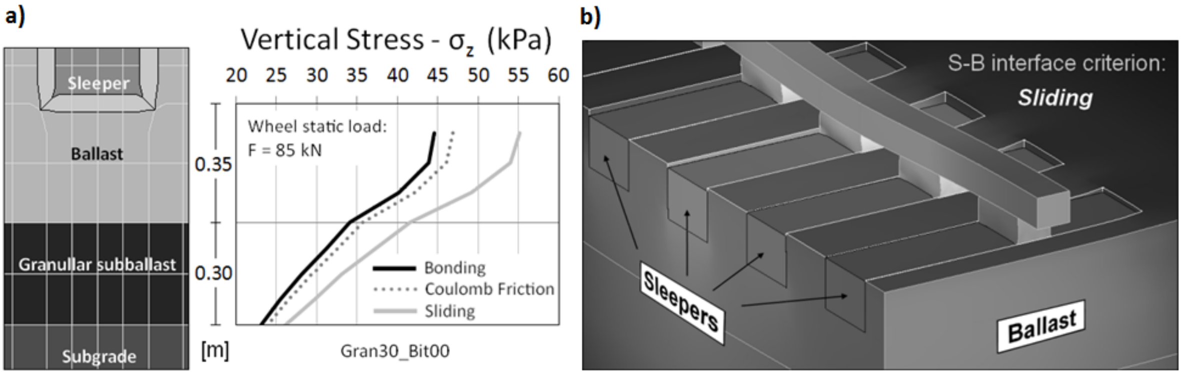

Figure 2 – Sleeper-ballast contact model: a) stresses on ballast and subballast; b) sleeper-ballast sliding.

Figure 3 presents the vertical stress results on the subgrade as a function of depth for the three structural solutions studied: it is used the sliding interface contact model and the applied quasi-static wheel load (approximately 120 kN for the three configurations) accounts for dynamic effects as previously described. As it can be seen, the alternative configurations with bituminous subballast guarantee a very similar stress level on the subgrade. The three configurations present a global vertical stiffness close to 80 kN/mm, a recommended value for HS ballasted tracks as discussed in López-Pita et al. [8].

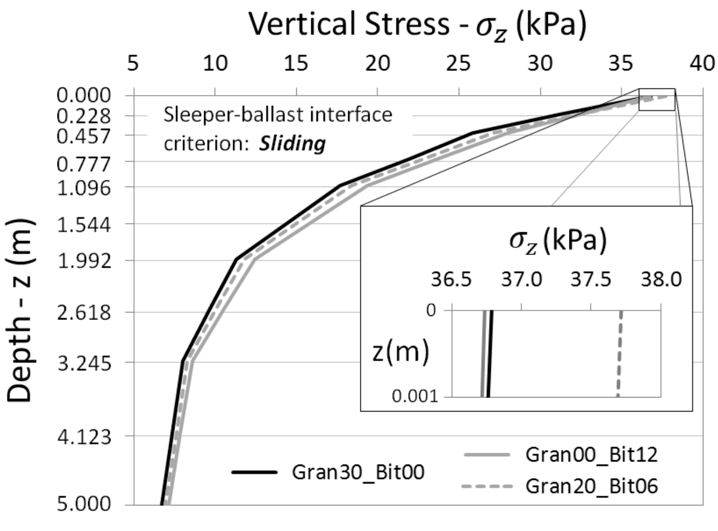

Figure 3 – Vertical stresses on the subgrade as a function of depth for the different subballast solutions

3. MODELLING ENVIRONMENTAL ACTIONS ON RAILWAY TRACK

Railway track materials and underlying soil layers are subjected to traffic loading and their mechanistic behaviour is highly controlled by hydro-geological conditions, temperature and water transfer due to atmospheric actions. Geotechnical engineers describe water flow and moisture changes in unsaturated conditions in terms of soil suction gradients. Water content variations, especially excess moisture in trackbed layers, combined with traffic loads might significantly reduce railway track service life.

The aim of the analysis developed in the present paper is to assess the impact of using different subballast solutions in the hydro-thermic behaviour of railway trackbed layers. The two-dimensional (2D) hydro-thermic analysis performed here models the physical run-off of rainwater and accounting for its dependence on: material permeability and saturation degree; railway track geometric layout (e.g. cross-slope inclination); and superficial drainage systems performance. The amount of infiltrated rainwater results from the interaction of the previous variables and its *a priori* definition is not required. Also, the overall environmental effects are considered through the definition of the atmospheric actions and phreatic level location. A FE numerical tool based on a THM formulation – CODE_BRIGHT [9] – is used to perform the coupled 2D analysis following described.

In accordance with the railway track model presented before, the 2D FE cross section models a 5 m high embankment. The hydro-thermic behaviour of railway trackbeds is compared for the conventional 30 cm granular-only layer (Gran30_Bit00) and the alternative 12 cm bituminous subballast layer (Gran00_Bit12). In both cases, the subballast layer is designed with a cross-slope of 5%, the embankment side slope is 3H:2V and a drainage ditch is located at the base of the embankment allowing the collection of run-off water.

Figure 4 presents the developed FE numerical model illustrating part of the total discretized domain (mesh), general boundary conditions and the physical processes involving water and temperature transfers.

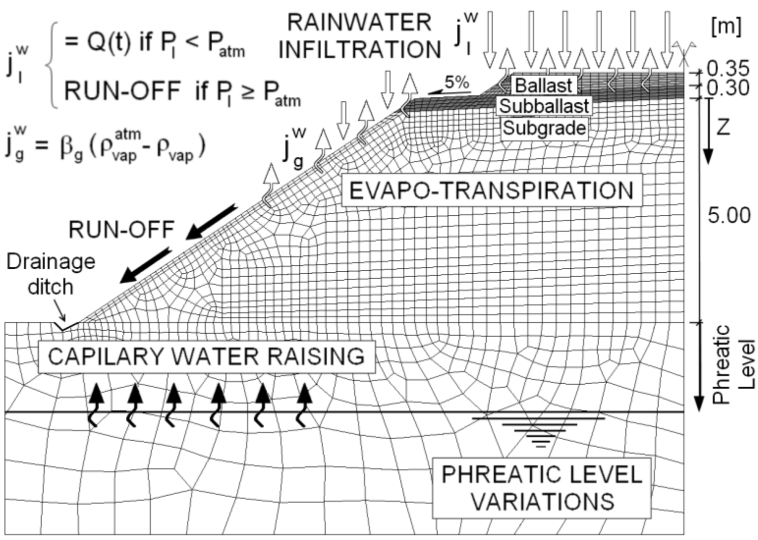

Figure 4 – 2D FE model: hydro-thermic phenomena, mesh and boundary conditions

In particular, the following hydro-thermic phenomena are featured by the FE numerical model:

- Waterflow through unsaturated railway trackbed layers according to suction gradients and depending on material constitutive models and overall balance equilibrium;
- Run-off of superficial water and its collection in drainage ditches;
- Penetration of water through shoulders resulting from rainwater infiltration and superficial water run-off;
- Capillary rise from the foundation fine-grained soil up to the railway underlying layers;
- Evolution of temperature distribution in railway trackbed layers;
- Evapo-transpiration of water from the embankment fill and foundation soils;
- Phreatic level variations due to changes in hydro-geological conditions.

3.1. Atmospheric actions and boundary conditions

The FE numerical model considers daily atmospheric data concerning temperature, relative humidity and precipitation registered in the city of Barcelona (Mediterranean climate) during 2010 (Figure 5). Multiyear simulations are performed by aggregation of annual data. This technique excludes extreme events but it is judged appropriate to investigate the long term response of the railway trackbeds.

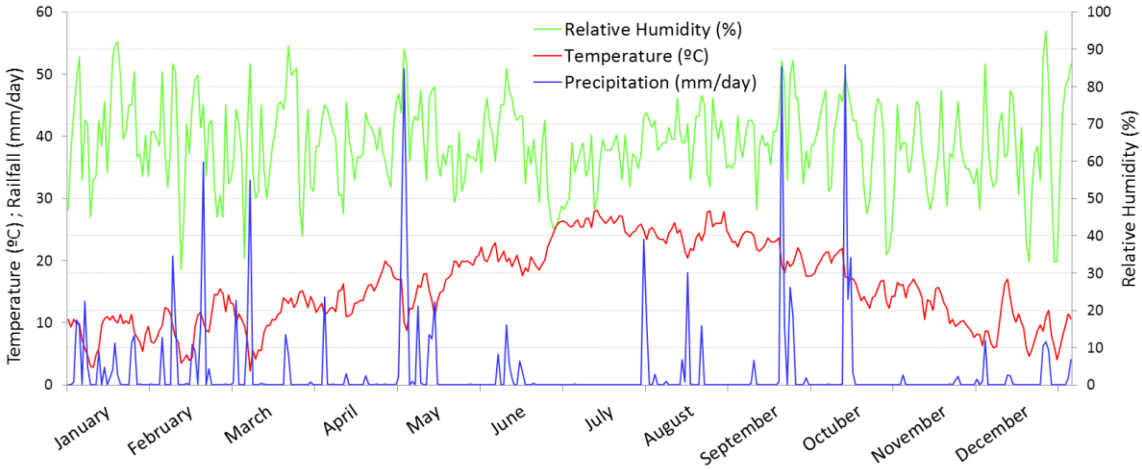

Figure 5 – Barcelona atmospheric data during 2010 (Mediterranean climate)

The initial water content distribution corresponds to an equilibrium situation consistent with the phreatic level depth (Figure 4) which is defined as a boundary condition and may vary according to the scope of the analysis to be performed.

3.2. Material hydro-thermic constitutive models

The hydro-thermic behaviour of railway trackbed layers is governed by the constitutive models previously introduced when describing THM theoretical formulation and summarised in Table 2.

Table 2 – Hydro-thermic constitutive models and material properties

PROPERTY	MODEL	BALLAST	GRANULAR SUBBALLAST	BITUMINOUS SUBBALLAST	SUBGRADE	Legend
Water Retention Curve	$S_e = \left(1 + \left(\frac{P_g - P_l}{P_0}\right)^{\frac{1}{1-\lambda}}\right)^{-\lambda}$	$\lambda = 0.30$ $P_0 = 0.003\ MPa$ $S_{rl} = 0.01$ $S_{ls} = 1.0$	$\lambda = 0.50$ $P_0 = 0.035\ MPa$ $S_{rl} = 0.05$ $S_{ls} = 0.98$	$\lambda = 0.50$ $P_0 = 0.150\ MPa$ $S_{rl} = 0.05$ $S_{ls} = 1.0$	$\lambda = 0.60$ $P_0 = 0.05\ MPa$ $S_{rl} = 0.0$ $S_{ls} = 1.0$	S_{ls} : maximum saturation S_{rl} : residual saturation P_0 : Pressure for a measured λ : shape function
Liquid Flow	$q_l = \frac{Kk_{rl}}{\mu_l}(\nabla P_l - \rho_l g)$ $\kappa_{rl} = A(S_e)^\alpha$	$A = 1.0; \alpha = 3.0$ $K = 5.0 \times 10^{-9}$ $S_{rl} = 0.01$ $S_{ls} = 1.0$	$A = 1.0; \alpha = 3.0$ $K = 1.0 \times 10^{-14}$ $S_{rl} = 0.05$ $S_{ls} = 0.98$	$A = 1.0; \alpha = 3.0$ $K = 1.0 \times 10^{-20}$ $S_{rl} = 0.05$ $S_{ls} = 1.0$	$A = 1.0; \alpha = 3.0$ $K = 8.0 \times 10^{-15}$ $S_{rl} = 0.0$ $S_{ls} = 1.0$	K : intrinsic permeability (m^2) μ_l : liquid viscosity ρ_l : liquid density q_l : liquid advective flux g : gravity λ and α : power
Air flow	$\kappa_{rg} = 1 - \kappa_{rl}$					κ_{rl} and κ_{rg} : coef. for liquid and gas relative permeability
Conductive Heat Flow	$i_c = -\lambda \nabla T$	$\lambda = 2(W/mK)$	$\lambda = 2(W/mK)$	$\lambda = 2(W/mK)$	$\lambda = 2(W/mK)$	i_c : conductive heat flux λ : Thermal conductivity
Diffusion of Vapour	$i_g^w = -(n\rho_g S_g D_m^w I)\nabla \omega_g^w$ $D_m^w = \tau D_0^w \left(\frac{T^t}{P_g}\right)$ $S_g = 1 - S_l$	$t = 2.3\,; \tau = 1.0$ $D_0^w = 5.9 \times 10^{-6}$	$t = 2.3\,; \tau = 1.0$ $D_0^w = 5.9 \times 10^{-6}$	$t = 2.3\,; \tau = 1.0$ $D_0^w = 5.9 \times 10^{-6}$	$t = 2.3\,; \tau = 1.0$ $D_0^w = 5.9 \times 10^{-6}$	i_g^w : non-advective flux n : porosity I : identity matrix τ : tortuosity coefficient D_0^w and t: parameters
Porosity	$n = \frac{e}{1+e}\ ;\ e = \frac{G_S w_c}{S_l}$	$n = 0.420$	$n = 0.375$	$n = 0.150$	$n = 0.250$	e : void ratio G_S : soil specific gravity w_w : water content

3.3. Results of the hydro-thermic FE analysis

The main variables concerning the scope of the present hydro-thermic analysis are the evolution of saturation degree and water content. Atmospheric actions on railway track infrastructures are responsible for water pressure variations and consequent changes on material saturation degree according to the respective soil water retention curve. Results for the impact of the different design solutions are shown for simulations comprising a period of 3 years (1095 days) and concerning daily atmospheric data.

A comparison between the granular-only (Gran30_Bit00) and bituminous (Gran00_Bit12) subballast solutions is presented in Figure 6. Evolution of saturation degree is shown for different subgrade depths (Z = 0 m, Z = 3 m and Z = 5 m) over the railway track symmetry axis and considering the particular case of a phreatic level located 1 m below the base of the embankment (see Figure 4 for "Z" and "Phreatic Level" illustration). Water content evolution is computed from saturation degree using relations for unsaturated soils (see Table 2).

From Figure 6 it is possible to identify general features shared by both subballast design solutions: points near embankment upper boundaries present higher saturation degree variations due to a great exposition to atmospheric actions. Also, deeper points suffering strong influence from the phreatic level present an almost invariant saturation degree close to saturated conditions.

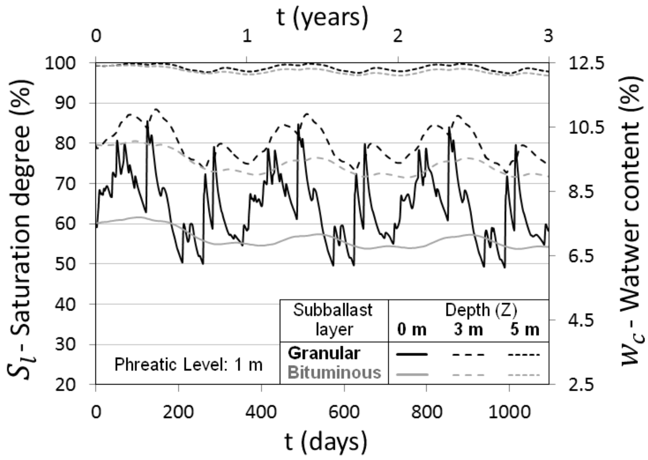

Figure 6 – Effect of subballast design solution on the evolution of saturation degree for different depths (phreatic level located 1 m below the embankment base)

Depending on the subballast design, the evolution of saturation degree exhibits distinct profiles: granular solution performs significant saturation degree variations along the year (≈ 35% in subgrade upper points) in opposition to the bituminous one which has a smother evolution associated to small seasonal oscillations (≈ 5%) and lower average moisture levels. In rainy periods, the bituminous solution is able to perform reductions in saturation degree up to 30% in the upper trackbed layers evidencing its potential for protection against atmospheric actions.

The spatial distribution of water inside the railway track embankment for both granular and bituminous cross sections is shown in Figure 7 in terms of material saturation degree. The presented distribution refers to a particular event associated to the intense rainfall registered in the month of May. As for Figure 6, it is assumed a phreatic level located 1 m below the base of the embankment meaning that saturated conditions and positive water pressures develop for points located below this level. The bituminous cross section presents lower saturation degrees than the granular one, mainly for inner zones close to the upper boundary which suffer higher influence on subballast nature.

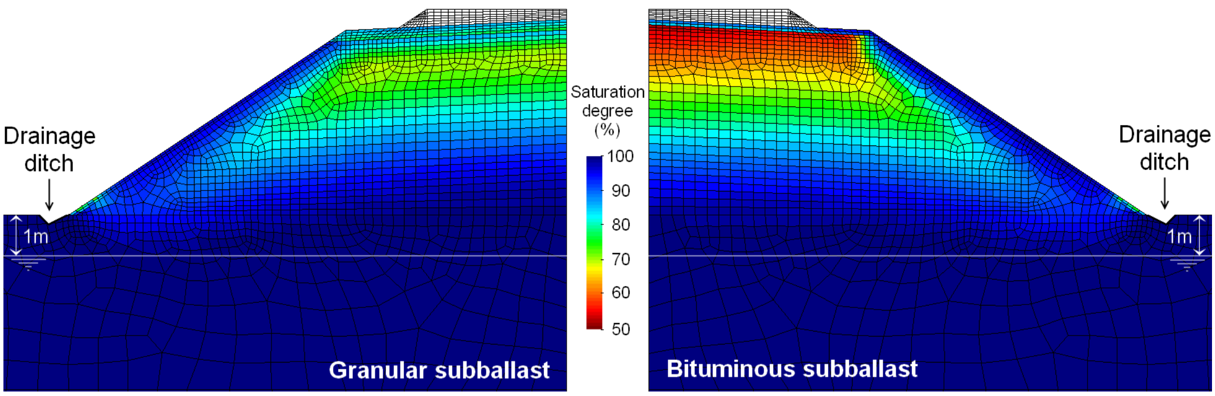

Figure 7 – Spatial distribution of sat. degree for granular and bituminous solutions subballast after rainfall

4. LONG-TERM DEFORMATIONAL BEHAVIOUR

From a long term design perspective, the cyclic nature of both traffic loading and environmental actions must be considered when assessing the fatigue problems and maintenance needs of track subgrades. As evidenced by Selig and Waters [10] the primary modes of traffic-induced deterioration in the subgrade are progressive shear failure, excessive rate of plastic strain which must be prevented in the design of railway trackbeds in order to provide adequate service conditions.

The present analysis recurs to the work hardening model developed by Tseng and Lytton [11] which estimates the permanent deformation of unbound materials using the basic relation given by equation (3):

$$\varepsilon_p(N) = \left(\frac{\varepsilon_0}{\varepsilon_r}\right) \cdot e^{-\left(\frac{\rho}{N}\right)^{\beta}} \cdot \varepsilon_v \tag{3}$$

where ε_p is the permanent strain associated to the loading cycle N; ε_0 , β and ρ are material parameters; ε_r is the resilient strain imposed in laboratory tests to obtain material parameters; and ε_v is the vertical strain in the subgrade obtained from the primary response model (FE railway track mechanistic analysis).

Tseng and Lytton also proposed a set of equations concerning the calibration of subgrade material parameters for the permanent deformation model which depend on the water content of the soil and its current stress state.

Given the equivalent mechanistic behaviour of granular-only and bituminous subballast solutions, the water content evolution is the main variable governing the different performances presented by both railway track structures. In this sense, it is worth to notice that the deformation model proposed by Tseng and Lytton explicitly considers the water content (w_c) of the soil (in opposition to the most part of the permanent deformation models available in literature). This feature combined with the application of the strain hardening procedure offers a methodology suitable to assess the evolution of the subgrade deformational behaviour performed by the different railway track subballast solutions due to environmental and traffic actions.

4.1. Service life prediction

Following the described methodology, results from the mechanistic and hydro-thermic analysis were used in order to compute the evolution of subgrade permanent deformation. Concerning traffic conditions, it was idealized a HS line with a daily reference traffic of 100 trains per track where only AVE trains (17 ton per axle) circulate. For the traffic scenario it was assumed an annual traffic of 16 MGT [12] which is common in European HS lines.

Regarding railway trackbed design criteria, the procedure used within the present analysis is the one proposed by Li et al. [13] which intends to limit the stresses on the subgrade such that plastic strain is of an acceptable level. As general design criteria, Li et al. suggested that the total permanent deformation (δ_p) and permanent strain (ε_p) on the top of the subgrade should be limited to 25 mm and 2%, respectively.

Figure 8 and Figure 9 show the development of the permanent deformation and strain on the top of the subgrade for the different analysed subballast solution and accounting for the effect of phreatic level depth.

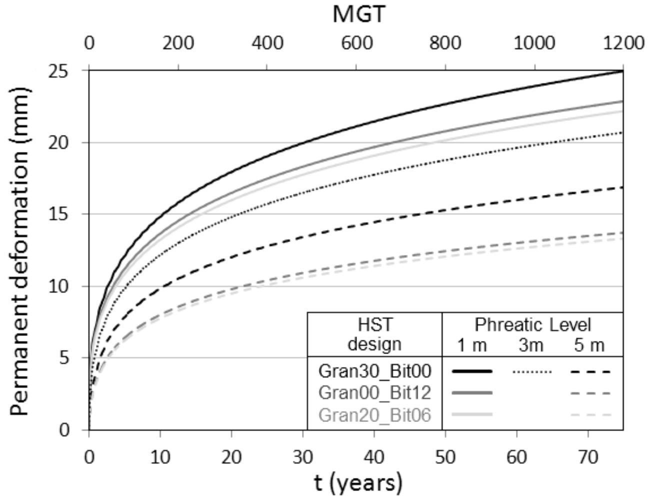

Figure 8 – Evolution of permanent deformation on the top of the subgrade

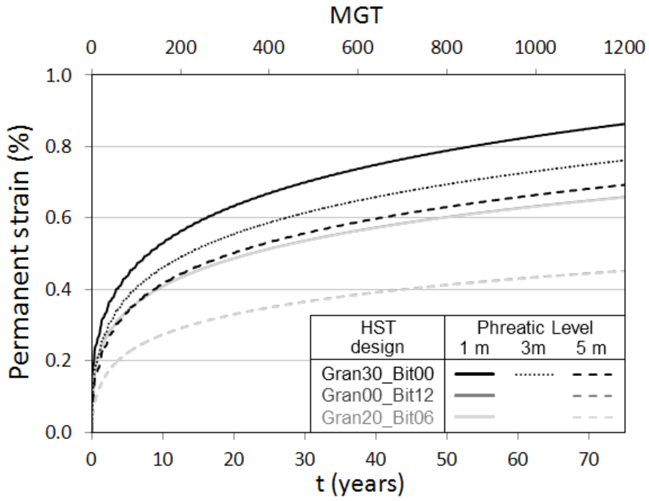

Figure 9 – Evolution of permanent strain on the top of the subgrade

Despite the equivalent mechanistic behaviour presented by the conventional and alternative subballast solutions, the protection provided by bituminous subballast layers against rainwater infiltration leads to lower seasonal water content variations and reduced moisture levels along the year which result in better structural conditions to support traffic loading. This fact is evidenced by results from Figure 8 and Figure 9 showing that the subballast configurations incorporating bituminous subballast layers accumulate permanent deformations and strains on the top of the subgrade at lower rates than the conventional subballast design.

The limit design criteria proposed by Li for subgrade permanent deformation is attained at the end of 75 years – corresponding to a total accumulated traffic of 1200 MGT – for the granular-only subballast solution when considering a phreatic level depth of 1 m (Figure 8). A substructure lifetime of 75 years is in line with advisable values when performing life cycle costs analysis involving HS infrastructures.

5. CONCLUSIONS

The impact of using bituminous subballast layers as an alternative to the conventional granular-only solutions in railway trackbed design was studied assessing the effects of traffic loading and environmental actions with different FE models.

The mechanistic behaviour of both the granular-only conventional design and the alternative bituminous solutions was properly addressed through a 3D FE analysis (accounting for the modelling of the sleeper-ballast interface contact) and the potential benefits associated to the impervious properties of the bituminous materials were assessed by performing a hydro-thermic analysis. The developed 2D FE model accounted for environmental variables such as hydro-geological conditions and atmospheric actions enabling superficial run-off of excess rainwater. The comparison between the conventional and alternative subballast design revealed that the use of bituminous layers allow significant reductions concerning water content variations due to atmospheric actions leading subgrade materials to present lower average moisture levels along the year.

The proposed solutions incorporating bituminous layers showed a better performance than the granular-only design concerning substructure predicted service life. Also, phreatic level was found to have great influence regarding substructure deformational behaviour, hence evidencing the importance of an adequate design of subsurface deep drainage systems.

REFERENCES

[1] J. Rose, P. F. Teixeira, and N. Ridgway. “Utilization of Asphalt/Bituminous Layers and Coatings in Railway Trackbeds - A Compendium of International Applications”, *Joint Rail Conference* - ASME, Urbana, Illinois, USA. (2010)

[2] P. F. Teixeira, A. López-Pita, C. Casas, A. Bachiller, and F. Robusté. “Improvements in high-speed ballasted track design: benefits of bituminous subballast layers.” *Transportation Research Record: Journal of the Transportation Research Board*, 1943, 43-49. (2006)

[3] P. F. Teixeira, A. López-Pita, and P. A. Ferreira. "New possibilities to reduce track costs on high-speed lines using a bituminous sub-ballast layer." *International Journal of Pavement Engineering*, 11(4), 301-307. (2010)

[4] P. Humbert, P. *CESAR-LCPC - Un code général de calcul par éléments finis*, Paris. (1989)

[5] B. Indraratna, W. Salim, and C. Rujikiatkamjiorn, *Advanced Rail Geotechnology - Ballasted Track*, CRC Press. (2011)

[6] UIC. “Earthworks and Trackbed Layers for Railway Lines.” *UIC code 719 R*, International Union of Railways, Paris, France. (2006)

[7] V. Profillidis, and P. Poniridis. "The mechanical behaviour of the sleeper-ballast interface." *Computers & Structures*, 24(3), 437-441. (1986)
[8] A. López-Pita, P. F. Teixeira, and F. Robuste. "High speed and track deterioration: The role of vertical stiffness of the track." *Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit*, 218(1), 31-40. (2004)
[9] S. Olivella, A. Gens, and E. E. Alonso. "Numerical formulation for a simulator (CODE_BRIGHT) for the coupled analysis of saline media." *Engineering Computations*, 13(7), 87-112. (1996)
[10] E. T. Selig and J. Waters. *Track Geotechnology and Substructure Management*, ICE Publishing, London. (1994)
[11] K. H. Tseng and R. L. Lytton. "Prediction of permanent deformation in flexible pavement materials." *Implication of aggregates in the design, construction, and performance of flexible pavements*, ASTM, Philadelphia, P.A., 154-172. (1989)
[12] A. López-Pita, P. F. Teixeira, C. Casas, A. Bachiller and P. A. Ferreira. "Maintenance costs of high-speed lines in Europe: State of the art." *Transportation Research Record: Journal of the Transportation Research Board*, 2043, 13-19. (2008)
[13] D. Li, T. R. Sussman, and E. T. Selig. "Procedure for railway track granular layer thickness determination." *Report No R-898*, Association of American Railroads, Transportation Technology Center, Colorado, USA. (1996)