Impact of different drainage solutions in the behavior of railway trackbed layers due to atmospheric actions

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ABSTRACT

The presence of water, along with the cyclic loading due to passing trains, has a great importance on the railroad deterioration process. Even small increases in the moisture content of trackbed layers can often result in significant reductions in the bearing capacity and stability of the composing soils contributing to a deficient deformational behavior which, in general, will affect track geometry degradation rates. In this sense, the design of an adequate drainage system maintaining low levels of moisture in the subsoil layers plays an important role in the maintenance needs of a railway track highly influenced by the condition of its infrastructure along the entire life cycle.

The aim of this paper is to expose a methodology to assess the performance of the track formation against atmospheric actions when using different drainage solutions. Rainfall, changes in the atmospheric relative humidity and temperature are associated to water infiltration/evaporation phenomena into the ground, which lead to seasonal soil moisture variations responsible for elastic and/or plastic deformations of the track infrastructure. The use of an adequate formulation is necessary to rule the described processes between soil and atmosphere. Since this calculation is mathematically complex, a finite element code is used to perform a fully coupled thermo-hydro-mechanic analysis which allows assessing the impact of different drainage solutions in the mechanical behavior of railway trackbeds.

The paper analyses different drainage solutions in the railway track design: incorporation of lateral superficial drains in the case of embankments; use of bituminous material as subballast instead of granular layers; lateral protection of embankment slopes with a relatively impermeable material; it is also analyzed the effects that fouled ballast may have in the drainage functions of this superficial railway track layer. The described methodology offers a practical tool to simulate railway substructure performance under general boundary conditions and assess the impact of the adoption of different drainage solutions.

KEYWORDS: Track design; drainage; bituminous subballast; unsaturated soils; track deterioration

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1. INTRODUCTION

The deterioration of railroad track geometry due to both ballast and subgrade differential settlement is usually responsible for the most relevant part of track maintenance costs. Recent studies have shown that the contribution of the subgrade settlement can play an important part on this degradation phenomenon, even in the case of new high-speed lines (López Pita et al., 2007).

Railway track materials and underlying soil layers are subjected to traffic loading and their mechanical behavior is highly controlled by the initial state, hydraulic conditions, temperature and water/moisture transfer due to atmospheric actions. Changes in water content, especially excess moisture in trackbed layers combined with traffic loads can significantly reduce railway track service life.

Atmospheric actions such as rainfall, changes in relative humidity and temperature are responsible for infiltration/evaporation phenomena resulting in changes in the water content of the soil. For railway trackbeds, soil layers are usually unsaturated and saturation is a limit condition that is often not attained. Processes involving water flow through unsaturated soils are complex and difficult to quantify. Geotechnical engineering researches since about 1965 describe moisture movement in these conditions in terms of soil suction, which is usually treated as a water potential (e.g. Richards 1965, Pufahl and Lytton 1992, Wray 1998, Fredlund and Hung 2001, among others). Gradients of suction are responsible for water flow in unsaturated soils and explain moisture changes. Seasonal changes in soil moisture content, or suction changes, lead to volumetric deformations of soil materials. On wetting these deformations are swelling (volume increment), or collapse (volume decrease); drying processes are related to shrinkage deformations (volume decrease).

The aforementioned justifies that suction must become an additional variable that has to be taken into account in the assessment of rail track performance along time. In the scope of road pavements, the effect of suction on base, sub-base and subgrade properties has been reported by many authors. Suction effects on resilient and deformation moduli have been described by Thompson and Robnett (1979), Uzan (1985) and Phillip and Cameron (1995), among others. Integrated analyses of road pavement performance from the perspective of unsaturated soil mechanics are, however, scarce. Flow (and temperature) models have been described by Wallace (1977), Pufahl et al. (1990) and McEnroe (1994). These studies lead to reasonable distributions of moisture conditions in the layered pavement structure under simplified conditions. A simulation of road pavement performance under environmental actions was also described by Alonso (1998).

The mechanical performance of railway track layers is controlled by moisture transfer. Water entry in the compacted unsaturated material increases water pressure or decrease suction, and in turn, reduces the effective stress. Hence, the strength and the elastic (and plastic) stiffness of the underlying layers and subgrade is reduced. The rate of traffic-induced deterioration of the railroad increases during this time and the loss of strength and stiffness can lead, in the extreme, to rutting and other forms of surface deformation. In the case of high-speed lines this issue can be particularly critical since settlement tolerances are very restrictive. The worst situations occur with poorly-compacted granular material (as a result of shear strength reduction) and cohesive swelling clays (resulting from damaging volume changes).

The cyclic nature of traffic loading and atmospheric actions is related to fatigue problems in the infrastructure as well as an increase in the number of maintenance operations. Therefore, an efficient drainage system is crucial to maintain low levels of moisture in trackbed layers which assure an adequate mechanical behavior of these materials and reduce the deterioration rate of the overall...
substructure. The motivation of this paper is to assess the impact of different drainage solutions in the mechanical behavior of railway trackbeds. Once this calculation is mathematically complex, in the present study a finite element code named CODE_BRIGHT (Olivella 1996) is used to perform a fully coupled thermo-hydro-mechanic (THM) analysis which calculates the soil moisture distribution and deformations caused by suction changes considering the transference of water in the liquid and gas phases (rain and relative humidity) affected by temperature. The theoretical formulation of this computational toll is described in Section 2. The authors believe that the adoption of concepts from the Mechanics of Partially Saturated Soils as well as THM coupled analysis can bring an important contribution towards the improvement of railway track design.

2. THEORETICAL FORMULATION

The impact of different drainage solutions in the mechanical behavior of railway trackbeds is numerically analyzed by using CODE_BRIGHT. This code incorporates a finite element method (FEM) which solves thermo-hydro-mechanical problems in unsaturated soils assuming them as a deformable porous media and considering the mechanical, hydraulic and thermal properties of materials. Therefore, in opposite to other general formulations, CODE_BRIGHT solves flow-deformation coupled problems.

In the present study, it is considered that the hydraulic constitutive equations controlling the balance of water in the liquid and gas phases are described by Darcy’s Law in the calculation of the conductive flux and Fick’s Law in the calculation of the advective flux. The intrinsic permeability is calculated by Kozeny’s model and the definition of the water retention curve uses the Van Genuchten model (1980).

BASIC PRINCIPLES

CODE_BRIGHT is formulated in order to consider different balance conditions: (i) solid mass; (ii) water mass; (iii) air mass and (iv) energy; and the overall mechanical equilibrium (v). In the following presented relationships, $\vartheta$ is the porosity. Besides it appears explicitly in many equations, porosity is also hidden in variables that depend on it (e.g. intrinsic permeability). The other presented variables include a superindex to refer to species ($w$ for water and $a$ for dry air) and a subindex to represent the phases ($s$ for solid, $l$ for liquid and $g$ for gas). Volumetric deformations are calculated through porosity variations, $\Delta \varphi$, resulting from solving the storage terms of balance equations described as follows. Flows and deformations are therefore coupled.

(i) Mass Balance of Solid

Equation 1 represents the balance of the mass of solid, assumed to be constant in time.

$$\frac{\partial}{\partial t}(\theta_s(1-\varphi)) + \nabla \cdot (j_s)$$  \hspace{1cm} (Eq. 1)

where $\theta_s$ is the mass of solid per unit volume of solid and $j_s$ is the flux of solid.

Porosity variation is related with the volumetric displacements $\varepsilon$ through Equation 2, the material derivative with respect to the solid. This derivative allows considering fluid flux generated by the changes in solid skeleton and the different velocities of solid and fluid motion. Porosity changes are also considered in the definition of some constants used in the other balance equations (e.g. permeability).
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\[
\frac{D_s \phi}{Dt} = \frac{1}{\theta_s} \left[ (1 - \phi) \frac{D_s \theta_s}{Dt} \right] + (1 - \phi) \nabla \cdot \frac{du}{dt} \tag{Eq. 2}
\]

(ii) Water Mass Balance

Equation 3 represents the balance of the mass of water (in the liquid and gas phases):

\[
\frac{\partial}{\partial t} \left( \theta_l^w S_l \phi + \theta_g^w S_g \phi \right) \nabla \cdot \left( j_l^w + j_g^w + i_g^w \right) = f^w \tag{Eq. 3}
\]

where \( \theta_l^w (= \omega_l^w \rho_l) \) represents the water mass per unit of volume in liquid phase (product of the mass fraction of that species, \( \omega_l^w \), and the bulk density of the phase, \( \rho_l \)) and \( \theta_g^w (= \omega_g^w \rho_g) \) is the water mass per unit of volume of gas (vapor) (similar meaning as for the liquid phase); \( S_l \) is the liquid volumetric fraction with respect to pore volume (degree of saturation) and \( S_g \) is the gas volumetric fraction with respect to pore volume \( (S_g = 1 - S_l) \); liquid and vapor water convective mass flow are represented by \( j_l^w \) and \( j_g^w \), respectively; \( i_g^w \) is the vapor diffuse flow in air and \( f^w \) represent the water sources or sinks per total unit of volume.

(iii) Air Mass Balance

Air mass balance is expressed by Equation 4:

\[
\frac{\partial}{\partial t} \left( \theta_l^a S_l \phi + \theta_g^a S_g \phi \right) \nabla \cdot \left( j_l^a + j_g^a + i_g^a \right) = f^a \tag{Eq. 4}
\]

where \( \theta_l^a \) and \( \theta_g^a \) are the dry air masses per unit of volume of liquid and gas, respectively; \( j_l^a \) and \( j_g^a \) are the mass convective flows of air in liquid and gas phases; \( i_g^a \) is the air diffusive flow in gas phase and \( f^a \) represents the external air source per unit of volume.

(iv) Energy Balance

Equation 5 expresses the energy balance:

\[
\frac{\partial}{\partial t} \left( E_s \rho_s (1 - \phi) + E_l \rho_l S_l \phi + E_g \rho_g S_g \phi \right) + \nabla \cdot \left( i_c + j_{Es} + j_{El} + j_{Eg} \right) = f^Q \tag{Eq. 5}
\]

where \( E_s, E_l \) and \( E_g \) are the specific energies for each phase; \( i_c \) is the heat conduction term (non-advective); \( j_{Es}, j_{El} \) and \( j_{Eg} \) are the advective terms for each of the existent flows (heat transfer convective terms through the solid, liquid and gas phase, respectively) and \( f^Q \) represents the external energy supply per unit of volume.

(v) Mechanical Equilibrium

The momentum balance reduces to the equilibrium of stresses if the inertial terms are neglected:
where $\sigma$ is the stress tensor and $f$ is the vector of body forces. As mentioned before about the adoption of unsaturated models, in the definition of the stress tensor defining the problem, a convenient option is to consider suction, $\psi$, besides “net” mean stress, $\bar{\sigma}$, as the main state variables. Assuming that osmotic suction is negligible, then total suction is equal to matric suction:

$$\psi \approx \bar{\sigma}.$$ 

“Net” mean stress is defined as the excess of total stress over air pressure:

$$\bar{\sigma} = \sigma - p,$$

where $p$ is the gas pressure assumed to be constant and equal to the atmospheric pressure and $\sigma$ is the liquid pressure. Considering full saturated conditions, $\sigma = \bar{\sigma}$, and net stress become the known effective stress.

3. NUMERICAL MODEL

ATMOSPHERIC ACTIONS

Moisture distribution for a given structure varies in time as a response to environmental changes and subgrade layers tend to reach equilibrium suction conditions for a given climate (Russam and Coleman, 1961). In the present study, the impact of different surface drainage solutions is assessed by a THM analysis which simulates the Mediterranean climate of the city of Barcelona. The numerical model considers daily atmospheric data concerning temperature ($T$), relative humidity (water in gas phase, corresponding to a given gas density, $\rho$) and rain ($Q$) registered during the year of 2010 (Figure 1). In the cases of multiyear simulations, the annual data is simple aggregated.

![Figure 1 – Atmospheric data of the Mediterranean climate of the city of Barcelona registered in 2010.](image)

Cauchy type boundary conditions are adopted. The boundary conditions for balance equations are incorporated by means the simple addition of nodal flow rates. Water vapor flow is controlled by a linear law (Equation 7), which specifies that the evaporative flux $q_e$ is proportional to the difference between vapor density at the boundary of the embankment and the water vapor density on the atmosphere.

$$q_e = k \left( \rho_v - \rho_w \right)$$

(Eq. 7)
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BOUNDARY CONDITIONS

The design of the railway cross section simulates a 5 meters high embankment and is based in typical geometry and layer thicknesses of ballasted high-speed lines with a granular subballast layer of 30 cm under a ballast material with a minimum of 30 cm. The subballast presents a transversal slope of 5%. The initial water content distribution corresponds to an equilibrium situation consistent with a water table located 10 m below the railway track level.

The following physical phenomena involving water transfer (Figure 2) are considered in the THM analysis:

- Waterflow, though the unsaturated railway trackbed layers depending on suction gradient and materials’ permeability coefficient;
- Distribution of temperature in the railway substructure
- Evaporation of water from the foundation soil;
- Penetration of water through shoulders resulting from rainwater infiltration and run-off of superficial water which depends on material permeability, slope inclination and surface drainage;
- Capillary rise from the foundation soil. The water rises from the foundation soil through the fine-grained soil up to the railway substructure (governed by suction gradients).

Figure 2 – Boundary conditions and physical phenomena involving water transfer.

MATERIAL CONSTITUTIVE MODELS

The railway trackbed layers are described by constitutive models and parameters given in Table 1 and match the expected properties of materials adopted in high-speed lines construction.

Table 1 – Material models and parameters

<table>
<thead>
<tr>
<th>PROPERTY</th>
<th>MODEL</th>
<th>BALLAST</th>
<th>GRANULAR SUBBALLAST</th>
<th>BITUMINOUS SUBBALLAST</th>
<th>SUBGRADE</th>
<th>Legend</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water Retention</td>
<td></td>
<td>ξ = 0.30</td>
<td>ξ = 0.35</td>
<td>ξ = 0.50</td>
<td>ξ = 0.50</td>
<td>ξ = 0.50</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Ρ dealloc = 0.003 MPa</td>
<td>Ρ dealloc = 0.035 MPa</td>
<td>Ρ dealloc = 0.15 MPa</td>
<td>Ρ dealloc = 0.075 MPa</td>
<td>Ρ dealloc = residual saturation</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Sι = 0.01</td>
<td>Sι = 0.05</td>
<td>Sι = 0.05</td>
<td>Sι = 0.10</td>
<td>Ρ dealloc = Pressure for a measured T</td>
</tr>
</tbody>
</table>
**4. IMPACT OF SUPERFICIAL DRAINAGE**

**SURFACE OPEN DRAINS**

Railway track granular layers and subgrade are sensitive to water content and its performance is strongly dependent on variations of moisture conditions which vary in time due to atmospheric actions. In this sense, an adequate drainage system is fundamental to the well-functioning of substructure layered system.

Similar integrated analysis of pavement performance concerning rainwater infiltration generally assumed that only a given percentage of the total rain intensity penetrates into the pavements layers (wide ranges from 15% to 70% are found in bibliography). In the present analysis a mechanism was developed in order to allow for surface run off and incorporation of surface drainage systems. Hence, the quantity of rainwater that flows through the railway trackbed layers depends on material permeability, water retention curve and porosity (compaction level), duration and intensity of rainfall as well as on transversal and lateral slope inclination and does not need to be estimated.

The design of surface drains in railway lines, although considered a good practice, is often neglected due to construction costs. The present analysis considers the existence of a surface open drain in the base of the embankment slope (this drain is common to all models that will be further introduced). In order to assess the impact of the construction of a surface drain in the edge of the granular subballast, the saturation degree distribution inside the railway embankment is shown in Figure 3 for 18th February when an intense rainfall was registered evidencing the difference between solutions.
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Concerning saturation degree distribution the effect due to the presence of the surface drain in the edge of the granular subballast is more evident in the zone below this element and along the embankment slope. The drain collects run off water from upper layers avoiding its infiltration on the subgrade through lateral slope and maintaining lower saturation levels. The evolution of the saturation degree in several control points (Figure 3) of the railway subgrade is illustrated in Figure 4 as a result of the performed THM analysis for both solutions with and without surface drains on the edge of the granular subballast.

Although from the present results it is clear a reduction on the saturation degree due to the presence of the surface open drain, it is expected that the influence of this drainage element may be higher when considering atmospheric conditions characterized by rainfall regimes more intense and with shorter durations than the ones from the present analysis.

**BITUMINOUS SUBBALLAST**

Subballast layer functions are, among others, to protect subgrade from atmospheric actions mainly rainwater infiltration. Usually unbound granular materials are adopted in most European railway lines. However, innovative solutions such as the adoption of bituminous layers may bring important benefits on subgrade protection and railroad track performance, especially for the case of high-speed lines (Teixeira et al., 2006; 2010). Being almost completely impervious, the use of bituminous subballast layers is expected to allow an optimal drainage of superficial rainwater while contributing to minimize fluctuations of soils moisture content (Rose et al., 2000; Ferreira et al., 2009; 2011).

In the present study, the alternative railway track design of replacing the conventional granular subballast by a bituminous impervious layer is analyzed. In order to reach an equivalent structural...
behavior between a granular subballast layer with 30 cm thickness and a bituminous one, the latter must be design with 12-14 cm (Teixeira et al. 2006). The material parameters used for this layer are presented in Table 1.

The results concerning the saturation degree of granular and bituminous subballast solutions (with surface open drain only at the base of the embankment) are present in Figure 5 for 18th February and allow a comparison between both railway track alternatives.

![Figure 5 - Results of saturation degree for the granular and bituminous subballast solutions: Influence of bituminous protection against rainwater infiltration.](image)

It is evident the protection conferred by the bituminous material especially in the inner points which are less exposed to the influence of lateral slope infiltration. The evolution of the saturation degree for different control points of the subgrade is also shown in Figure 6.

![Figure 6 - Evolution of saturation degree for the granular and bituminous subballast solutions at control points (2years): Influence of bituminous protection against rainwater infiltration.](image)

From the analysis of Figure 6 it is possible to verify that the variation of saturation degree along time associated to the bituminous solution is much smaller than the one from the granular subballast. Again, this fact is more evident when considering the inner points (B and D located bellow the rail axis line) where moisture fluctuations are almost inexistent. It is worth to refer that not only variations on the
saturation degree are reduced in the case of bituminous subballast but also the equilibrium moisture value inside the embankment. These results show that the design of railway tracks with an impermeable bituminous layer may have a significant impact on the overall behavior of the substructure.

Considering the performance of the bituminous solution it is worth to refer that the subgrade used in the present simulation is a relatively impervious material \((K = 10^{-14} \text{ m}^2; K_{sat} = 10^{-7} \text{ m/s})\), in the case of more permeable trackbed soils the gain provided by the bituminous subballast solution will be higher. However, an accurate simulation must also take into account the deterioration of the bituminous material and incorporate crack behavior and rainwater infiltration through this layer.

Figure 7 - Influence of surface open drain at the edge of the bituminous subballast: left) Distribution of saturation degree inside the embankment; right) Evolution of saturation degree at control point A.

In order to assess the impact of the surface open drain at the edge of the bituminous subballast, Figure 7 presents the distribution of the saturation degree inside the embankment on 18th February and the evolution during 2 years of the saturation degree at control point A where the effects of the open drain are more evident. The presence of this drainage element allows for a reduction of 50% on the seasonal amplitude of the saturation degree. Nevertheless, as registered for the granular solution, the surface open drain performs better for the zones along the embankment slope.

Besides the effect of cyclic loads due to passing trains, subgrade differential settlement might also occur due to atmospheric actions. Indeed, the existence of a great variety of soils composing a railroad trackbed is responsible for important differential vertical displacements along the longitudinal development. This evidence is related with the fact that different soils composing a railroad trackbed shrink or swell in distinct ways leading to different vertical displacements between successive transversal cross sections. These differential displacements contribute to a gradual increase of the longitudinal defects associated to the railroad track geometry. In the case of high-speed lines this issue can be particularly critical since settlement tolerances are very restrictive.

The performed THM analysis allows computing long term deformations associated to the hydraulic behavior of both subballast design solutions. Figure 8 shows accumulated vertical settlement at the end of 5 years for both granular and bituminous subballast solutions and evidences that the protection of bituminous layer against rainwater infiltration contributes to a significant reduction in the overall settlements.
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**Figure 8 – Accumulated vertical settlements for granular and bituminous subballast solutions (5 years).**

**EMBANKMENT SLOPE PROTECTION**

The penetration of water through embankment shoulders and lateral slope depends on the material permeability, the compactness of the surface, the slope inclination and the drainage from upper layers. In order to understand the effect that controlling the infiltration of rainwater through these zones may have on the behavior of railway trackbed, different solutions concerning the protection of the embankment slope were analyzed.

The embankment slope was modeled with a protection layer of 15 cm which has a variable intrinsic permeability \( K \) \( m^2 \) – depending on the material in analysis. Figure 9 presents the results for the different tested permeability values. It is shown the saturation degree distribution inside the embankment on 18th February and the its evolution along 2 years at the control points A and C where the embankment slope protection is more relevant.

The use of an impervious material acting as a barrier against rainwater infiltration is first analyzed. The material matches the properties of the bituminous subballast layer \( K = 1 \times 10^{-20} m^2 \) described in the previous section. The use of a material with an intrinsic permeability 10 times less permeable than the subgrade \( K_{Sub} = 1 \times 10^{-15} m^2 \) layer is also presented \( K = 1 \times 10^{-16} m^2 \) in Figure 9. More permeable materials were also analyzed corresponding to intrinsic permeability values of \( K = 1 \times 10^{-14} m^2 \) and \( K = 5 \times 10^{-9} m^2 \). The later one matches the behavior of the ballast layer described in Table 1.

![Granular subballast with slope protection](image1.png)

![Granular subballast with slope protection](image2.png)
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Results presented in Figure 9 show that both approaches (the use of materials with intrinsic permeability values higher and lower than the one from subgrade) have a positive impact on the saturation degree of the embankment. In the case of impermeable materials, rainwater infiltration through shoulders and slope is avoided, but, due to its high impermeability, evaporation processes are difficult to occur and the reduction performed in the saturation degree is relatively small. The performance of permeable materials is much more effective once these materials provide a good drainage of the rainwater and allow evaporative processes to occur reducing the saturation levels in summer months.

5. CONCLUSION
The described thermo-hydro-mechanical analysis presents a suitable methodology to assess the impact of different drainage solutions in the behavior of railway trackbed layers exposed to general atmospheric actions. Not only suction gradients and moisture transfer are predicted but other important aspects such as deformational behavior and interaction with mechanical parameters are easily incorporated into the analysis.

In the case of new lines constructed over embankments, the presented results showed that surface open drains, lateral slope protections and, in particular, bituminous subballast layers are effective in protecting trackbed layers from atmospheric actions and maintaining low levels of moisture along time.
Ongoing research is improving the presented numerical model in order to allow the study of the influence of several factors such as rainfall duration and intensity (different reference climates), geometry design as well as water table variations and the associated performance of subsurface longitudinal drainage systems.

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7. REFERENCES


