Fatigue Behavior in Flexure of Treated Soils for Sustainable Railways Structures

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ABSTRACT

High Speed Rail (HSR) projects are multiplying and need technological innovations to be economically, socially and environmentally reliable. The upgrading of fine graded soils treated with lime and/or hydraulic binders for the capping layer of HSR infrastructures is a process in accordance with sustainable development. The expected life of railways structures and the stresses caused by HSR traffic lead to ask about the fatigue mechanical behavior of treated materials. Numerical modeling of the infrastructure of HSR allowed determining stresses in the structure. Then results are used to estimate the thickness of the capping layer using treated materials for which fatigue behavior is characterized. This process highlights that fine treated soils can be used for the capping layer of HSR structure.

Keywords. Railway; modeling; treated soils; fatigue; Sustainable development

1. INTRODUCTION

The *in-situ* soils present in the coverage of civil engineering projects have generally mechanical characteristics inconsistent with stress rates generated by the infrastructure they have to support. To upgrade these materials by using them in subgrade layers, it is common to mix them with a few percent of hydraulic binders to improve their mechanical performances (Bell 1996; Chew et al. 2004; Cokca 2001). Besides, this process has the advantage to minimize the environmental impact and to reduce the economic cost of the infrastructures (Ferber et al. 2010; Jullien et al. 2012; Nunes et al. 1996; Patrick and Arampamoorthy 2010; Pratico et al. 2011; Salem et al. 2003).

This approach is widely used in numerous civil engineering applications such as road construction, embankments, foundations, slabs and piles (Al-Amoudi et al. 2010; Al-Rawas et al. 2005).. In the French railway sector, soils treatment for HSR subgrade layers (capping layers) is strongly discouraged (RFF and SNCF. 2006), due to the expected life of railways structures (one hundred year) and the stresses caused by HSR traffic that lead to ask about the fatigue mechanical behavior of treated materials. To date, this process has been used only on several kilometers of line in France for experiments (Delhomel and Robinet 2006; Hervé et al. 2011) and at the present time, in classic HSR projects, the *in-situ* materials that don't have sufficient characteristics are stripped, landfilled and substituted by quarries materials. Based on numerical calculations and on the approach followed in the road sector where the fatigue criterion is characterized by the maximum tensile stress at the bottom of the capping layer (AFNOR 1994b, Matthews et al. 1993), the aims of this paper are to:

- Demonstrate that treated materials can be considered for their use for the capping layer of HSR structures instead of the granular solution;
- Give a process to design these layers in function of the mechanical fatigue features of materials.

First a modeling by Finite Element Method (FEM) of the entire structure is performed to determine the load distribution under the ties (Preteseille et al. 2012). Then this load distribution is used as an input of a semi-analytical model. This type of model is more adapted to design studies than FEM ones because input parameters are more simple and computing time is less expensive to calculate the response of the structure. The differences in the results given by the two approaches are discussed (Preteseille et al. 2012). Then the process is applied to estimate the thickness of the capping layer using treated materials for which fatigue behavior is characterized (Bhattacharya and Pandey 1986; Dac Chi and Mulders 1984; Khay et al. 2010; Swanson and Thompson 1967).

2. MATERIALS AND METHODS

2.1. Modeling

2.1.1. CESAR-LCPC

CESAR-LCPC (Humbert et al. 2005; Wang et al. 2012) is an FEM software dedicated to civil engineering (structural analysis, soils and rocks mechanics, thermal, hydrology, etc). This software can model complex structures and solve various problems (mechanical calculation of structures, stresses in concrete at an early age, etc). Calculations are done in linear elasticity and static mode.

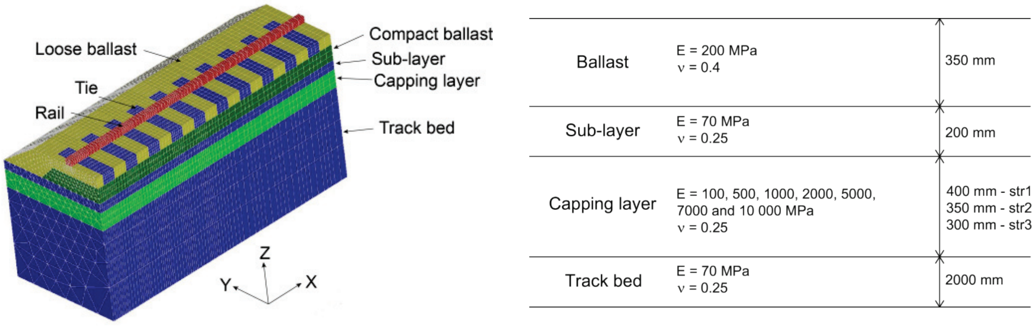
2.1.2. ViscoRoute© 2.0

The software ViscoRoute© 2.0 (Chabot et al. 2010; Chabot et al. 2006; Chupin et al. 2010) is based on semi-analytical methods and a model of semi-infinite multilayer structure. The mechanical behavior of layers can be considered as elastic or thermoviscoelastic, according to the Huet and Sayegh law (Huet 1963; Sayegh 1965). Note that this software cannot model other structures than those composed of semi-infinite layers (involving rails and ties).

2.2. Structures studied

For the FEM modeling, the entire railway structure is modeled (Fig. 1a). The structure complies with the requirements of French standard for the construction of HSR structure (RFF and SNCF 2006). The track bed has a Young's modulus equal to 70 MPa, a constant density of 2000 kg.m-3, a constant Poisson's ratio of 0.25 and a thickness of 2000 mm. The treated capping layer rests directly on the track bed. To represent a wide range of treated materials and to take into account their mechanical kinetic evolution in time (Hervé et al. 2011; Lenoir et al. 2011) three Young's modulus (100, 5000 and 10,000 MPa) were selected. Two thicknesses (400 and 300 mm) corresponding to usual thicknesses for capping layers were considered. On the capping layer is laid an unbound granular sub-layer (ρ=2000 kg.m^{-3}, E = 70 MPa, ν = 0.25). The upper layer is the ballast. The ballast is divided in two zones. The first zone is constituted of compact ballast under the ties with a 45 degree angle, with a Young's modulus of 200 MPa and a second zone of loose ballast around the ties (Al Shaer et al. 2008) with a Young's modulus of 8 MPa, a density of 1300 kg.m^{-3} and a Poisson's ratio of 0.2. The ties are embedded in the ballast. The ties have a density of 2400 kg.m^{-3}, a modulus of 34,000 MPa and Poisson's ratio of 0.2. The concrete ties support the rails made up with 60 El rails profile. For the sake of simplicity, the rail is modeled by a rectangular section of width equal to the real rail. The height was determined to keep an equivalent second moment of area, 134 mm. The density, the Young’s modulus and the Poisson's ratio of the rail are respectively 7800 kg.m-3, 210,000 MPa and 0.28. Due to symmetry conditions only one quarter of the structure is modeled.

For the semi-analytical modeling, the layers are modeled by semi-infinite layers (Fig. 1b). The track bed, the sub-layer and the ballast keep the same properties as explain above. For the capping layer, the density and the Poisson’s ratio stay unchanged, but seven cases of Young’s modulus and three thicknesses are studied. All the dimensions and mechanical characteristics are given in table 1.



(a) (b)

Figure 1: (a) modeled structure with CESAR-LCPC; (b) modeled structure with ViscoRoute©2.0.

2.3. Loadings

For the FEM modeling, the considered loading is a bogie with two axles spaced 3 m apart. It is assumed that two different bogies do not affect each other in terms of mechanical responses due to the large distance between them (18.7 m). Each axle load is 170 kN. To consider the dynamic effects in the static FEM calculation, a coefficient of 1.5 is applied to the loading (Preteseille et al. 2012). This method (Eisenmann 1977; Riessberger 1995) is commonly applied by German Railway Authorities.

As a result, wheel load is modeled with a loading of 127.5 kN placed in the middle of a tie and linearly distributed along the rail width at 1.5 m from the symmetry axis. It can be shown that this position is the worst in terms of tensile stress at the bottom of the capping layer (Preteseille et al. 2012).

Table 1: Structures characteristics.

FEM modeling	**Thickness (mm)**	**ρ (kg.m^{-3})**	**E (MPa)**	**ν**
Rail (modeling)	172 (134)	7800	210,000	0.28
Ties	229	2400	34,000	0.2
Loose ballast	350	1300	8	0.2
Compact Ballast	350	1700	200	0.4
Sub-layer	200	2000	70	0.25
Treated capping layer	400 (str1), 300(str3)	2000	100, 5000, 10,000	0.25
Track bed	2000	2000	70	0.25
Semi anal. modeling				
Ballast	350	1700	200	0.4
Sub-layer	200	2000	70	0.25
Treated capping layer	400(str1), 350(str2), 300(str3)	2000	100, 500,1000, 2000, 5000, 7000, 10,000	0.25
Track bed	2000	2000	70	0.25

3. RESULTS

3.1. Study of the tensile stresses produced by the railway loading in the capping layer

Fig. 2 shows the evolution of the principal stresses in str1 with depth in the railway structure and with the modulus of the capping layer. The studied axis passes through the centre of the most stressed tie. The tensile stress in the capping layer is maximal at the intersection between this axis and the bottom of the layer. Along the axis, in the ballast and in the sub layer, the modulus of the capping layer has little impact on the stresses. The top of the capping layer works in compression while the bottom works in traction. The compressive and the tensile stresses have the same order of magnitude. The point of zero stress is almost independent of the module and is at the same depth following longitudinal σ_{xx} or lateral σ_{yy} stresses. The higher the modulus of the capping layer, the higher the stresses. Longitudinal σ_{xx} and lateral σ_{yy} stresses are close and correlated with more than 99%.The tensile stress at the bottom of the capping layer σ_{xx} increases from 0.003 MPa for a modulus of 100 MPa, to 0.365 MPa for a modulus of 10 000 MPa for str1. The evolution of main stresses in str2 and str3 are similar to str1. The values of the maximal tensile stress at the bottom of the capping layer are presented in table 2. It is a function of the thickness of the capping layer. The maximal tensile stresses for str2 are ranging from 0.002 MPa for 100 MPa to 0.382 MPa for 10,000 MPa and from 0.002 MPa to 0.422 MPa for str3. Between str1 and str2 and for a modulus of 10,000 MPa an increase of 5% of the maximal tensile stress is observed whereas this increase is 16% between str1 and str3. Stresses seem to be small (0.050 MPa to 0.400 MPa) that's why it is adapted for mechanical resistance of stabilized soils.

This modeling allows determining the maximal tensile stress in the capping layer in function of the properties of the material, i.e. the Young's modulus and in function of the thickness of the capping layer. As a result, knowing the treated material characteristics, i.e. the Young's modulus and the fatigue strength, the optimal thickness of the capping layer can be assessed.

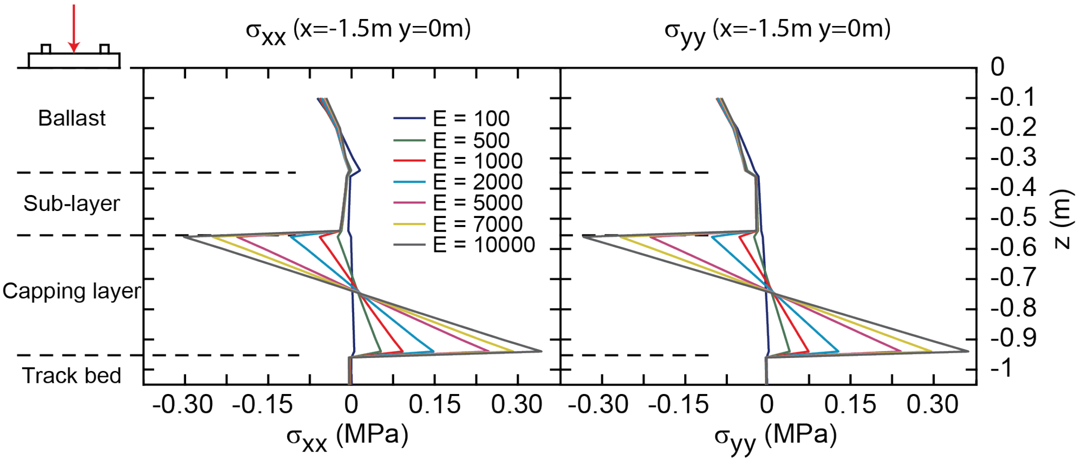


Figure 2: Evolution for str1 of main stresses in function of depth and of the modulus of the capping layer.

Table 2: Stress at the bottom of the capping layer for the different structures.

	E (MPa)	100	500	1000	2000	5000	7000	10,000
Str1	σ_{xx} (MPa)	0.005	0.053	0.092	0.147	0.248	0.291	0.342
	σ_{yy} (MPa)	0.003	0.042	0.077	0.129	0.240	0.296	0.365
	E (MPa)	100	500	1000	2000	5000	7000	10,000
Str2	σxx (MPa)	0.005	0.054	0.096	0.156	0.269	0.320	0.379
	σyy (MPa)	0.002	0.043	0.078	0.132	0.246	0.307	0.382
	E (MPa)	100	500	1000	2000	5000	7000	10,000
Str3	σxx (MPa)	0.005	0.056	0.098	0.162	0.291	0.351	0.422
	σyy (MPa)	0.002	0.044	0.079	0.132	0.251	0.314	0.396

3.2. Optimization of the capping layer thickness

To be suitable, the fatigue strength of treated materials needs to be higher than the maximal tensile stress in the capping layer determined previously by the modeling. This fatigue strength is estimated thanks to fatigue tests. The principle of fatigue tests is to determine, for a given frequency, the tensile stress σ_N leading to the failure after a number of N applications of this stress. This number N corresponds to the life expectancy of the structure. It is generally equal to 10^6 in the road sector and 10^8 in the rail sector.

Most studies on materials of civil engineering such as asphalt and concrete (Diakhate et al. 2011; Hornych 2007; Li and Metcalf 2004; Sun et al. 2003; Lee and Barr 2004; Li et al. 2007; Suaris et al. 1990), and the few studies on treated fine soils show that tensile strengths of materials behave in a linear function of the logarithm of the number of cycles materials and fatigue law σ(N) can be expressed as, with σ_0 simple tensile strength and β the slope of the straight line:

$$\frac{\sigma}{\sigma_0} = 1 + \beta \log N \tag{1}$$

Table 3 presents the characteristics (Young's modulus E and σ_8) of treated materials from literature (Bhattacharya and Pandey 1986; Dac Chi and Mulders 1984; Khay et al. 2010; Swanson and Thompson 1967). In all the studies tests are limited to one million of cycles and the tensile strength σ_8 corresponding to one hundred million of cycles have been extrapolated using previous equation.

Table 3. Assessment of the thicknesses of the capping layer using fines treated materials from literature.

	Material	Treatment	σ (MPa)	E (MPa)	σ_8 (MPa)	t (m)
(Dac Chi and Mulders 1984)	Rouen's silt	1%L + 7%C	1.03	4800	0.20	0.58
	Autun's clay	1%L + 7%C	0,61	2800	0.04	1.29
	Lille's silt	1%L + 7%C	1,86	8300	0.63	<0.2
	St-Brieuc's arena	1%L + 7%C	1,39	5000	0.64	<0.2
(El Euch Khay et al. 2010)	F1	13.6% C	2.7	21 100	1.11	<0.2
	F2	12.9% C	2.7	21 000	1.12	<0.2
	F3	15.1% C	1.7	18 100	0.71	<0.2
(Bhattacharya and Pandey 1986)	Laterite (low)	5%L	-	2952	0.28	<0.2
	Laterite (medium)	5%L	-	3596	0.45	<0.2
	Laterite (heavy)	5%L	-	4240	0.56	<0.2
(Swanson and Thompson 1967)	Champaign county till	3%L	0.33	3000	0.20	0.35
	Bryce B	5%L	0.62	3000	0.30	<0.2
	Sable B	3%L	0.57	3000	0.17	0.49
	Illinoian till	3%L	0.51	3000	0.23	0.2

In the first study (Dac Chi and Mulders 1984), the fatigue laws of four different naturals soils have been obtained from flexion tests on trapezoidal specimens with a frequency of 50 Hz (AFNOR 1994a; AFNOR 1994b). In the second study, flexion tests on trapezoidal specimens were carried out on three different mixtures of compacted sand concrete with a frequency of 10 Hz (El Euch Khay et al. 2010). In the third study, lime-laterite soil mixture with three different compaction rates were investigated and were tested using beam flexion test under third point loading with a frequency of 2 Hz (Bhattacharya and Pandey 1986). In the fourth study, four different soils treated with lime were investigated using the third beam flexion test with a frequency of 12 Hz (Swanson and Thompson 1967). In this last study, no measure of the Young's modulus was carried out, and average value of 3000 MPa is used in order to estimate the thickness of the capping layer.

From the maximal tensile stress in the capping layer previously determined and the fatigue strength σ_8, the thickness t of the capping layer can be established (Table 3). The required thickness for ten materials on fourteen is inferior to 0.2 m. This finding shows that the use of these materials in the capping layer of the rail structure is possible. More, the fatigue strength of these materials is largely sufficient and the treatment could be reduced in order to decrease their economic and environmental costs. The calculated thicknesses for the Champaign County till and the Sable B are ranged into 0.2 and 0.5 m. The use of these materials for the capping layer is also suitable. To end, the required thickness for Rouen's silt is 0.58 m and 1.29m for Autun's clay. These thicknesses are not compatible with the rules of art of earthworks and in order to reuse these two materials, additional fatigue tests are needed with a different treatment to increase their fatigue strength.

4. CONCLUSION

A rail structure was modeled on CESAR-LCPC. The distribution that leads to the maximal tensile stress at the bottom of the capping layer has been exported to ViscoRoute© 2.0 to estimate the stresses in the capping layer according to different modulus and different thicknesses.

Following the road sector approach and using fatigue strength results from literature the thickness of the capping layer were established. Results are in accordance with the rules of art of earthworks and highlights that *in situ* soils treated with hydraulic binders can be used for the capping layer of rails structure. The reuse of in situ soils avoids the production of large amount of waste.

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