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Structural test at the laboratory scale for the utilization of stabilized fine-grained soils in the subgrades of High Speed Rail infrastructures: Analytical and numerical aspects

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HIGHLIGHTS

- The stress states in the capping layer of several HSRs structures have been modeled.
- Results are compared with stress paths induced by several laboratory fatigue tests.
- A test is highlighted and a design dedicated to treated/stabilized soils is proposed.

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ABSTRACT

The utilization of *in situ* fine-grained soils treated with lime and/or hydraulic binders as subgrade in common infrastructures of civil engineering is a sustainable upgrading process for natural materials with low mechanical performances. In the case of the projects of High Speed Rail (HSR), the expected life of structures and the stresses caused by traffic have led to ask about the fatigue mechanical behavior of these stabilized materials. Therefore, for the design of HSR structures, a characterization of these performances must be defined with a suitable test. Fatigue tests referenced from the literature are studied in comparing the stress paths induced by these tests with those obtained in the HSR capping layer. An appropriate fatigue test for the design of HSR structures is presented and the dimensions of the test-pieces are validated using Finite Element Method (FEM).

1. Introduction

The utilization of *in situ* fine grained soils treated with lime and/or hydraulic binders as subgrade in civil engineering projects is a common process in accordance with sustainable development issues. The treatment improves the mechanical performances of materials (Bell [1], Chew et al. [2], Choudhury et al. [3]) and minimizes the environmental impact and the economic cost of infrastructures (Nunes et al. [4], Salem et al. [5], Ferber et al. [6], Patrick and Arampamoorthy [7], Pratico et al. [8], Jullien et al. [9]).

Currently, in the French railway sector, the use of those materials in the capping layers of High Speed Rails (HSRs) structures is not allowed due to the lack of knowledge on their fatigue mechanical behavior (RFF and SNCF [10]). Therefore, *in situ* fine-grained soils present in the right-of-way of railway projects are stripped, landfilled and substituted by materials from quarries. Therefore, to rationalize the costs of these infrastructures, the definition of design rules for these materials in relation to their mechanical fatigue is a major technical, economic and environmental challenge.

For stabilized fine-grained soils used in subgrade layers, as for other hydraulically bound materials, the fatigue criterion is characterized by the maximum tensile strength (Larson and Nussbaum [11]; Raad et al. [12], Dac Chi and Mulders [13], Matthews et al. [14], AFNOR [15], SETRA-LCPC [16], SETRA-LCPC [17], Xuan et al. [18]) after a given number N of loadings ($N = 10^8$ for HSR infrastructures). Recently, numerical calculations (Preteseille et al. [19]) have shown that the position of the worst tensile stress in HSR capping layers under loading is located at the bottom of the layers. These results allow the determination of the most critical mechanical stress paths in the capping layers to translate the stress states in the subgrade of HSR infrastructures.

It is therefore important to correctly reproduce these stress paths at the laboratory scale. This will allow considering the materials behavior (e.g. mechanical damage) in the field, to

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enhance the models, understand the structure responses and optimize designs.

From the stress tensor T (Eq. (1)), the stress path is represented by the evolution of the deviatoric stress q (Eq. (2)) as a function of the mean stress p (Eq. (3)).

$$T = \begin{pmatrix} \sigma_{xx} & \sigma_{xy} & \sigma_{xz} \\ \sigma_{xy} & \sigma_{yy} & \sigma_{yz} \\ \sigma_{xz} & \sigma_{yz} & \sigma_{zz} \end{pmatrix} \tag{1}$$

$$q = \sqrt{\frac{(\sigma_{xx} - \sigma_{yy})^2 + (\sigma_{yy} - \sigma_{zz})^2 + (\sigma_{zz} - \sigma_{xx})^2}{2} + 3\left(\sigma_{xy}^2 + \sigma_{yz}^2 + \sigma_{xz}^2\right)} \tag{2}$$

$$p = \frac{\sigma_{xx} + \sigma_{yy} + \sigma_{zz}}{3} \tag{3}$$

At the laboratory scale, numerous fatigue tests are performed to estimate the long-term mechanical performances of materials (Bofinger [20], Dac Chi and Mulders [13], Guo et al. [21], Gnanendran and Piratheepan [22], Boshoff and Adendroff [23]). All these tests can be cyclically performed, but the mechanical stress paths generated by these tests are generally not considered as representative of the stress state in the real structure and they cannot be directly used for design studies.

Based on numerical and analytical calculations, the aim of this paper is to determine an appropriate test at the laboratory scale to predict the long-term behavior of the treated layers in HSR infrastructures. First, the critical stress paths in these structures are discussed. Then, the stress paths generated by referenced laboratory tests performed on civil engineering materials are defined and compared with the structural stress paths. An appropriate test for HSR structural design is thus determined.

2. Materials and methods

2.1. Determination of the stress paths of the HSR structures

Recent numerical calculations (Preteseille et al. [19]) on different HSR infrastructures have been performed using Finite Element Method (FEM) with CESAR-LCPC software, and a semi-analytical approach with ViscoRoute 2.0©, both in linear elasticity and static mode (Fig. 1). These calculations allowed determining the maximum tensile strength in the capping layer under the dynamic loading of a HSR bogie with two axles of 170 kN, 3 m distant, multiplied by a dynamic amplification factor of 1.5. This dynamic amplification factor is set for a speed of 300 km/h. The maximum frequency of axle traffic is 27.8 Hz. Three thicknesses of capping layers (t = 400, 350 and 300 mm) and five moduli of materials were studied (E = 500, 1000, 2000, 5000 and 10,000 MPa), to match with the rules of art of earthworks and to represent a wide range of treated natural materials (Bell [1], Kolias et al. [24]). Structures and loadings are fully described and referenced in Preteseille et al. [19].

These calculations have shown the maximal tensile strength in the subgrade of the HSR infrastructures is located in the middle of the loaded tie (T8) at the bottom of the capping layer and the results allow the determination of the stress paths at this point.

2.2. Determination of the stress paths of the laboratory tests

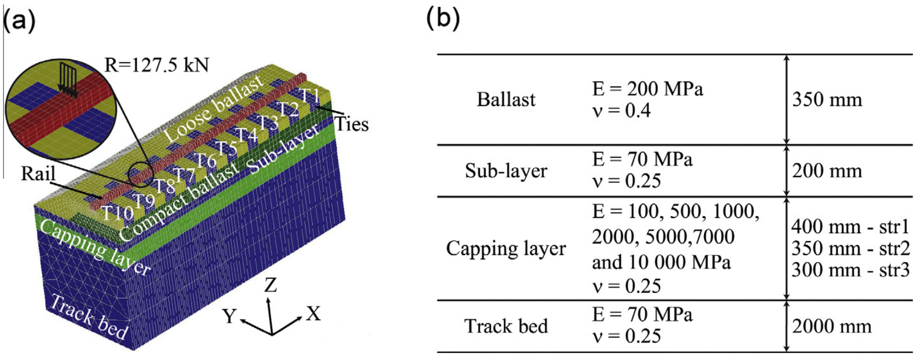
The stress paths of the different laboratory tests have been calculated with analytical calculations. For the biaxial flexure test, because of simplifying assumptions in the analytical approach, additional calculations using FEM modeling have been performed in linear elasticity with commercial finite element code ABAQUS. Due to symmetry condition only a quarter of the circular slab is modeled with 20-node quadratic brick. Parameters used for the modeling are a Young modulus of 5000 MPa and with three Poisson's ratios (0.20, 0.25 and 0.30).

3. Results and discussion

3.1. Stress paths in HSR infrastructures

Fig. 2a shows the stress paths at the bottom of the capping layers for a HSR loading with three different thicknesses t (400 mm, 350 mm and 300 mm) and an elastic modulus E = 10,000 MPa (Preteseille et al. [19]). For each case, the shape of the stress paths is similar. The path ABCBA corresponds to the passage of bogie with two axles spaced 3 m apart. Point A transcribes the stress state 4 m from the axis of the bogie. The mean stress p is negative, reflecting a temporary state of compression. The mean stress increases, becomes positive (reflecting a state of tension) and reaches its maximum at point B, which corresponds to the passage of the first axle. At this point, the thicker the layer, the lower the values of p and q. The mean stress is 0.226 MPa for t = 400 mm, 0.245 for t = 350 mm and 0.263 for t = 300 mm. The increase of mean stress and deviatoric stress between t = 400 mm and t = 300 mm is equal to 17–18%. Between t = 400 mm to t = 350 mm and t = 350 mm to t = 300 mm, a decrease of 50 mm of the thickness leads to an increase of mean stress and deviator close to 9%. The mean stress and the deviator then decrease until point C, which coincides with the axis of the bogie, each axle is 1.5 m distant. Then, due to the bogie symmetry, the stress paths go back through points B and A. Interestingly, for each thicknesses, the critical points B are aligned.

Fig. 2b compares the stress paths at the bottom of capping layers with 6 different moduli and a thickness of 400 mm. At point A, the higher the modulus, the lower the values of p and the higher the values of the deviatoric stress q. The compressive state increases with the modulus of the materials. At point B and C, the higher the modulus, the higher the values of p and q. At point B, p and q increase from 0.019 MPa and 0.082 MPa for E = 500 MPa to 0.228 and 0.375 for E = 10,000 MPa. At point C, p and q increase from −0.009 MPa and 0.043 MPa for E = 500 MPa to 0.094 and 0.282 for E = 10,000 MPa. The tensile stress state also increases



Ballast	E = 200 MPa ν = 0.4	350 mm
Sub-layer	E = 70 MPa ν = 0.25	200 mm
Capping layer	E = 100, 500, 1000, 2000, 5000,7000 and 10 000 MPa ν = 0.25	400 mm - str1 350 mm - str2 300 mm - str3
Track bed	E = 70 MPa ν = 0.25	2000 mm

Fig. 1. (a) Modeled structures in Preteseille et al. [19] with Finite Element Method and (b) with the semi-analytical approach.